Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Volume 13, Issue 03 March 2024

Terahertz Frequency Windows: Investigating Atmospheric Attenuation for Outdoor Communication

Ahmed Sidi Aman
PhD Candidate, TASI, ED-STII, ESPA
University of Antananarivo,
Madagascar

Ramafiarisona Hajasoa Malala
PhD, TASI, ED-STII, ESPA
University of Antananarivo,
Madagascar

***Abstract*— Terahertz (THz) technology, which bridges optical waves and microwaves, is expected to enable unprecedented data rates and bandwidths to serve the demands of new highly disruptive communication infrastructures. This paper investigates the attenuation of THz waves, one of the most important metrics for next-generation telecommunications when propagated through different atmospheric conditions, like fog, rain. We used MATLAB as a tool for modeling and simulating THz signal propagation through the atmosphere and along molecular absorption, in order to lay out THz technology's fundamental limits and reveal its potentials, and determine the appropriate frequency windows that should be used for outdoor THz communication.**

***Keywords*— Terahertz, communications, atmospheric,attenuation**

I. INTRODUCTION

Terahertz communication is expected to be one of the foundations for the development of next generations network due to its high transmission speeds and wide bandwidths. However, the use of THz waves in communication is severely limited by atmospheric attenuation, as a result of its too high frequencies. Indeed, from being a passive medium, the atmosphere dynamically interacts with THz waves. The atmospheric attenuation is subject to the interaction between the atmosphere and the THz waves, which depends on the frequency, the relative humidity, and the atmospheric components. In particular, atmospheric gases, such as oxygen and water vapor, absorb this energy, determining the loss of amplitude and the phase shift of the wave polarization. Therefore, accurate models of this interaction are very important for the design of strong Terahertz communication systems [1]. Moreover, when the atmosphere is obstructed by fog or crossed by the fall of rain, the propagation of THz waves becomes very complex. These effects are such that visibility in foggy environment, the frequency and temperature of the fog, the frequency of rainfall, are such they have a significant impact on the attenuation. Hence the relationship between these atmospheric parameters and the THz waves, as well as among the former, needs to be understood, calling for channel models that reproduce all weather conditions, which are needed to design reliable outdoor Terahertz links [2].

The objective of this study is to explain how atmospheric phenomena effect THz waves with emphasis on attenuation among others and give guideline to select the optimal THz windows for communication.

II. FUNDAMENTAL PHYSICS OF THZ WAVE

Atmospheric conditions pose a fundamental challenge to the efficacy of terahertz (THz) communication, affecting signal strength even in clear weather. The interaction of THz electromagnetic waves with the vibratory and rotational motions of atmospheric constituents, like oxygen and water molecules, affect wave propagation. These molecular interactions, integral to the atmosphere's composition, are an unavoidable source of signal degradation.

A. Molecular Absorption Dynamics in Clear Atmosphere

The propagation of terahertz (THz) waves is highly influenced by their interaction with the molecular composition of the Earth's atmosphere. This interaction is predominantly through molecular absorption, where the energy of THz waves is absorbed by atmospheric gases, especially oxygen and water vapor, due to resonant vibrational and rotational energy transitions. This molecular resonance occurs at specific frequencies where the wave's energy matches the energy difference between the molecular quantum states [3].

At the quantum level, the absorption process involves transitions between discrete energy levels of atmospheric molecules, conforming to selection rules that govern the allowed transitions. In the absence of condensed water, such as clouds or precipitation, gaseous attenuation remains the primary concern for THz wave propagation. the complexity of their transitions is further heightened by their polyatomic nature, leading to a dense spectrum of lines, particularly within the THz region.

The specific attenuation of the atmosphere at frequencies up to 1 THz due to dry air and water vapor can be evaluated at any value of pressure, temperature, and humidity using the ITU-R [4] and AM [5] models.

To conduct this study, a MATLAB tools has been done with several propagation models which calculates specific attenuation (attenuation per kilometer) as a function of temperature, pressure, water vapor density, and signal frequency.

The atmospheric gas model is valid for frequencies from 1 to 1000 GHz [6] and applies to both polarized and unpolarized fields. The formula for specific attenuation at each frequency is

$$\gamma = \gamma_o(\mathrm{f}) + \gamma_w(\mathrm{f}) = 0.1820 f N''(f) \quad (1)$$

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Volume 13, Issue 03 March 2024

Where γo (f) is the attenuation due to dry air, which is mainly affected by oxygen and other non-water vapor atmospheric gases. This component is crucial for understanding how THz waves interact with the atmosphere in the absence of humidity. γw (f) accounts for the attenuation contributed by water vapor. This aspect is particularly variable and critically impacts THz wave propagation in moist or humid conditions.

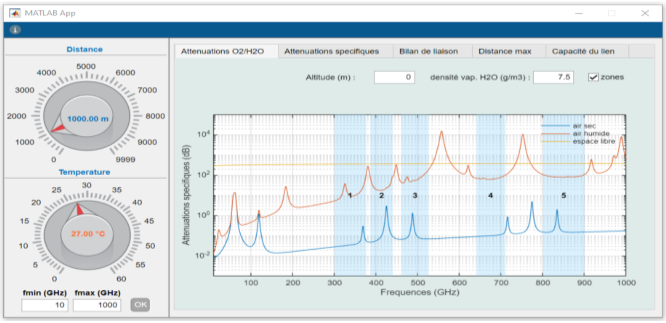

Fig. 1. Atmospheric Gas Attenuation at Sea Level between 0-1 THz in Dry Air (blue curve) and in Humid Air with a Water Vapor Density of 7.5g/m^3 (orange curve)

The result analysis reveals specific absorption characteristics within the 300 GHz to 1 THz frequency range, manifested as dips in signal strength corresponding to the resonant frequencies of atmospheric gases. These dips are prominently observed around 550 GHz & 750 GHz due mostly to water vapor, indicating significant signal loss, with attenuation levels reaching as high as 104 dB/km under the proposed conditions on Fig-1. The computational model underscores that temperature can slightly influence these attenuation peaks. In addition, when the altitude increases, this led to lower pressure and humidity, and the attenuation due to oxygen and water vapor decreases. The variability observed between the major oxygen absorption peaks and before the significant rise due to water vapor, there appear to be regions where the attenuation is relatively lower, potentially acting as 'windows' for THz communications. These windows could be key to optimizing frequency selection for THz systems, aiming to minimize atmospheric loss.

B. Rain Attenuation in Terahertz Wave Propagation

Rain, composed of varying sizes of droplets, significantly attenuates THz waves through absorption and scattering. This attenuation is quantified using a model where the specific attenuation due to rain, increases with frequency and rainfall intensity. The ITU-R P.838 recommendation provides a widely accepted formula [7] for this calculation:

$$\gamma_R = kR^\alpha \quad (2)$$

Where R is the rain rate. Units are in mm/h. The parameter k and the exponent α depend on the frequency, the polarization state, and the elevation angle of the signal path.

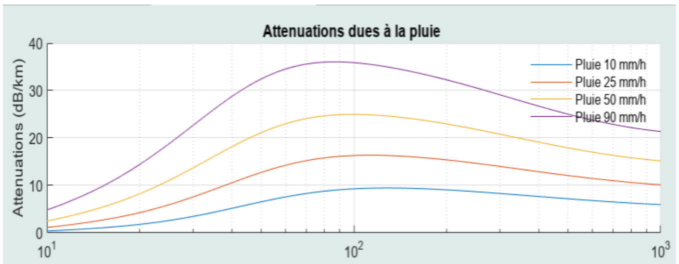

Fig. 2. Specific attenuation due to rain as a function of frequency in the 0.3-1THz window for distributions at 10mm/h, 25mm/h, 50mm/h, and 90mm/h

Results in simulation illustrate that at higher frequencies within the THz range, the attenuation increases substantially with the rainfall rate. The results suggest that during heavy rainfall, signal loss can be significant, potentially exceeding tens of dB per kilometer, posing a challenge for THz communications.

C. Fog Attenuation in Terahertz Wave Propagation

Fog and clouds consist of small droplets with a diameter of less than 0.01 cm. Due to the scattering of optical waves by water droplets, dense fog or clouds would lead to a complete failure of transmission in an optical link. However, fog attenuation follows a different principle due to the smaller size of the water droplets compared to raindrops. In our tool, we used the ITU model, Recommendation ITU-R P.840-6. This model calculates the specific attenuation (attenuation per kilometer) of a signal based on the density of liquid water, signal frequency, and temperature [8]. The attenuation in fog is primarily due to scattering, and the specific attenuation due to fog can be expressed by a formula similar to that of rain but adjusted for the characteristics of fog :

$$\gamma_c = K_l(f)M \quad (3)$$

Where M is the liquid water density in g/m^3. The quantity Kl (f) is the specific attenuation coefficient and depends on the frequency.

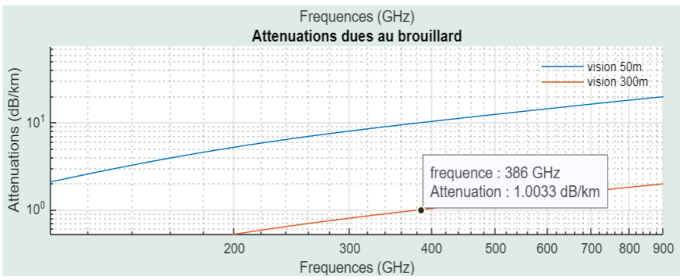

Fig. 3. Specific attenuation of THz waves over 1 kilometer for fog vision range of 300m (0.05g/m3, red) and 50m (0.5g/m3, blue) at a temperature of 27°C

Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Volume 13, Issue 03 March 2024

The result indicates that the relationship between frequency and specific attenuation is exponential, suggesting a non-linear interaction between THz waves and the particulates in fog. The orange curve, representing lighter fog conditions (visibility of 300m), indicates comparatively lower attenuation values across the frequency range, implying that THz waves could be suitable for communication over short distances even in the presence of fog. For instance, at 386 GHz, the specific attenuation is slightly above 1 dB/km, which could be considered manageable for THz communication systems. The blue curve, which depicts denser fog conditions (visibility of 50m), shows a significant increase in attenuation. At the same frequency of 386 GHz, the attenuation exceeds 10 dB/km, which present a substantial challenge to the reliability and range of THz communication links. This suggests that, in dense fog, such communication systems would require either increased transmission power or more sensitive receivers to counteract the attenuation effects.

III. STRATEGIC SELECTION OF THZ FREQUENCY BANDS

The advancement of Terahertz (THz) communication technologies necessitates a thorough understanding and strategic selection of frequency bands that are minimally affected by atmospheric absorption. To identify atmospheric windows suitable for communication and determine their transmission levels, we utilized the HITRAN database. This last contains a large amount of spectral information such as transmission and absorption rates in many wavelength ranges, which is valuable for atmospheric studies. We have used detailed computational analysis to calculate the transmittance at a distance of 150 meters and then determined the frequency windows with the highest peaks by using MATLAB.

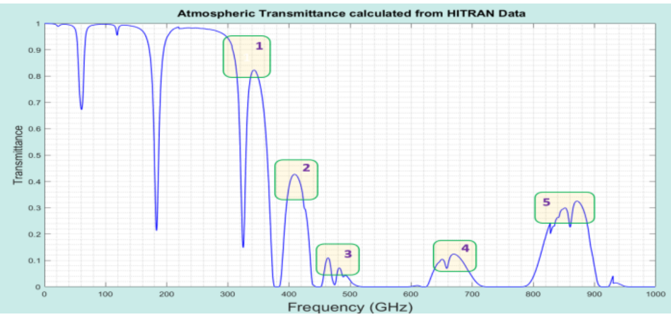

Fig. 4. Transmittance for 150m at tropical conditions, sea level and temperature of 27°C

Combining the predictive insights from the ITU-R atmospheric attenuation model with HITRAN simulation results, we can reveal precise frequency range windows that are most favorable to high-throughput communication. These frequency ranges can be considered as windows for which minimal attenuation in the atmosphere and minimal impact on the signal quality are experienced over distance, making sure that a communication system works with high performance and reliability under different atmospheric conditions as would be the case at these dimensions.

TABLE I. OPTIMISED FREQUENCY WINDOWS FOR TERAHERTZ OUTDOOR COMMUNICATION

Window #	$f_{min} - f_{max}$ *(GHz)*	*Bandwidth (GHz)*
1	300 – 370	70
2	386 – 434	48
3	460 – 510	50
4	640 – 700	60
5	800 – 900	100

IV. CONCLUSION

This study conducts a comprehensive analysis of the atmospheric attenuation characteristics of Terahertz (THz) waves, delving into the impacts exerted by rain, fog, and molecular absorption phenomena. Our work highlights the critical necessity of determining specific frequency windows that can significantly mitigate atmospheric signal degradation. Such identification is important for the progressive development of outdoor THz communication systems. Furthermore, our investigations reveal that while current findings lay a solid foundation, there is a compelling need for more research to extend this groundwork like studying THz signal-to-noise ratio (SNR), a key determinant of communication system performance. Additionally, exploring the maximum transmission distances under varying atmospheric conditions and quantifying the achievable data capacities within the optimal frequency windows will provide valuable insights. Such efforts will serve to not only quantify the possible limitations of THz communications in practical environments, but also unlock the exciting future potential for integration of THz technology in the next generation of communication networks.

REFERENCES

[1] G. Siles, J. Riera, P. Garcia-del-Pino, "Atmospheric Attenuation in Wireless Communication Systems at Millimeter and THz Frequencies [Wireless Corner]," IEEE Antennas and Propagation Magazine, vol. 57, pp. 48-61, 2015.

[2] X. Liao, L. Fan, Y. Wang, Z. Yu, G. Wang, X. Li, J. Zhang, "Attenuation Characterization of Terahertz Waves in Foggy and Rainy Conditions at 0.1–1 THz Frequencies," Electronics, 2023.

[3] X. Xin, H. Altan, A. Saint, David Matten, R. Alfano, "Terahertz absorption spectrum of para and ortho water vapors at different humidities at room temperature," Journal of Applied Physics, 2006.

[4] Song Junyuan, Fu Zihao, Zhao Xiongwen, Geng Suiyan, "Correction of pseudo-line of ITU atmospheric absorption model in low terahertz band," 2021. Link

[5] Y. Yorozu, M. Hirano, K. Oka, and Y. Tagawa, "Electron spectroscopy studies on magneto-optical media and plastic substrate interface," IEEE Transl. J. Magn. Japan, vol. 2, pp. 740-741, August 1987 [Digests 9th Annual Conf. Magnetics Japan, p. 301, 1982].

[6] ITU-R P.676-11, "Attenuation by atmospheric gases and related effects," International Telecommunication Union, Radiocommunication Sector (ITU-R), September 2016.

[7] ITU-R P.838, "Specific attenuation model for rain for use in prediction methods," International Telecommunication Union, Radiocommunication Sector, 2005.

[8] ITU-R P.840, "Attenuation due to clouds and fog", International Telecommunication Union, Radiocommunication Sector, 2023.