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THz Outdoor Communication System Design: Link Budget Analysis for Performance Optimization in Dynamic Atmospheres

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***Abstract*— Terahertz (THz) communication systems promise ultra-high data rates for next-generation wireless networks but face significant challenges in outdoor environments due to atmospheric attenuation. This paper investigates THz wave propagation through various atmospheric conditions, including clear air, rain, and fog, using comprehensive link budget analysis. We examine the 300-900 GHz range, to identify optimal frequency windows and quantify performance degradation under adverse weather. Our MATLAB-based simulations reveal the range which offers the best compromise between capacity and atmospheric resilience. We analyze different modulation schemes. These findings highlight the need for adaptive, multi-frequency approaches in THz network design to optimize performance in dynamic atmospheric conditions.**

***Keywords* — Terahertz, atmospheric attenuation, link budget, adaptive modulation, outdoor propagation**

I. INTRODUCTION

Terahertz (THz) communication, which is a promising high-speed and broadband candidate technology for next-generation networks, has kept its rapid growth over the years.

Atmospheric attenuation of THz waves is mainly determined by the interaction of THz waves with 3 major parts in atmosphere, and their variations are very different with frequency, moisture content level (conditions), as well as specific gas composition. Oxygen and water vapor absorb THz radiation, which results in amplitude absorption as well as a shift of the polarization plane due to out-of-synch phase. In the presence of fog or rain, these effects are additionally complicated as aspects including low visibility in foggy scenarios, temperature accompanied with fogs and intensity of rainfall profoundly influence on signal attenuation. The complex relations among these atmospheric parameters and THz wave propagation are one key factor in constructing an appropriate channel model for a correct prediction of THz system performance under different weather conditions.

These models are essential to design outdoor Terahertz communication links that are resilient. Nonetheless, there is a missing step that must be similarly investigated for moving beyond propagation modeling and converting the atmospheric effects into realistic system level design parameters: conducting in-depth link budget analysis. Based on our previous work [1], this study aims to present reasons explaining how the atmospheric phenomena influence THz waves focusing on attenuation, among other air parameters and we provide a recommendation for choosing proper THz windows. We strive to compare their performance under different atmospheric circumstances and modulation schemes by providing a detailed link budget analysis. In the end, this work intends to fill the gap between theoretical models and system implementation considerations to push forward THz communications for dense outdoor wireless networks of tomorrow.

II. LINK BUDGET ANALYSIS FRAMEWORK

A. Review of key components (fspl, atmospheric attenuation)

Understanding signal behavior in various atmospheric conditions is crucial for designing reliable outdoor Terahertz (THz) communication systems. This section will address two key factors impacting signal strength: Free-Space Path Loss (FSPL) and atmospheric attenuation. Understanding these components allow to better appreciate the limitations and challenges of THz communication systems. Molecular absorption, especially from oxygen and water vapor in the air has a significant effect on atmospheric attenuation of THz waves [2]. These interactions lead to frequency-dependent signal attenuation, as well as phase shift of the transmitted beams. Moreover, attenuation forces can be created in the presence of precipitation (e.g., rain and snow) or particulates (e.g., fog). Signal propagation is highly dependent on several factors including rain rate, weather conditions, air density and visibility. Modeling rigorously these complex relationships is key in accurately designing of THz channel models able to predict performance of such systems during adverse weather conditions.

1. Free-Space Path Loss (FSPL)

Even without additional attenuation in the transmission path, the power received is much lower than the transmitted power. This difference is because, unlike in a waveguide, in a wireless link, the power spreads over an area that increases quadratically with distance. Consequently, since the effective area of the receiving antenna remains constant, the received power decreases quadratically with distance.

Free-Space Path Loss (FSPL) is one of the most basic loss factors in wireless communication system link budget. This is the loss of signal strength when it passes through free space without physical structure in-between. The Friis transmission equation [3] can be used to calculate the FSPL:

$$\text{FSPL (dB)} = 32.4+20\log f_{MHz} +20\log d_{Km}-GTx-GRx \qquad (1)$$

Where:

f_{MHz} is the the frequency in megahertz (MHz),

d_{Km} is the distance between the transmitter and the receiver in kilometers (km),

GTx/GRx are the gain of the antennas in dBi.

This equation shows that received power not only depends quadratically on distance but also on frequency. Understanding this relationship is crucial to determine the viability of an outdoor transmission link and to design systems that can maintain adequate signal strength over the required distances.

2. Atmospheric Attenuation

Building on our previous work, an m atmospheric attenuation model is used in combination of ITU-R recommendations. The total atmospheric loss is given by:

$$TLoss\_atm = \gamma o(f) + \gamma w(f) + \gamma r(f) + \gamma f(f) \qquad (2)$$

Where:

$\gamma o(f)$ and $\gamma w(f)$ represent attenuation due to dry air and water vapor respectively, as per ITU-R P.676.

$\gamma r(f)$ accounts for rain attenuation (ITU-R P.838).

$\gamma f(f)$ represents fog attenuation (ITU-R P.840).

These models, implemented in our custom MATLAB-based simulation tool, allow for a nuanced analysis of THz link performance across a spectrum of atmospheric conditions. The specific formulations and parameters for each component were detailed in our previous article and form the basis of our current analysis tool.

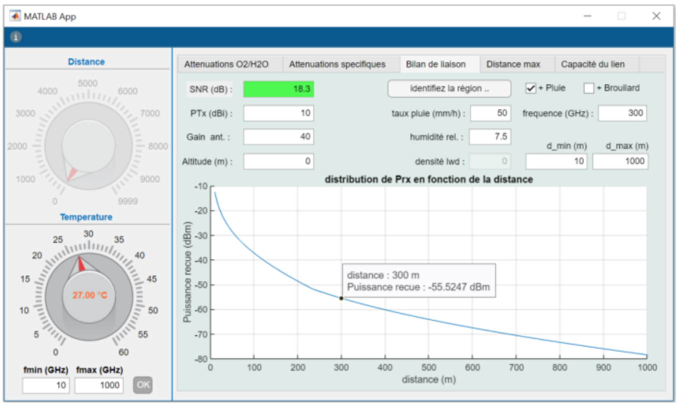
B. Systems Parameters and Assumptions

To develop a comprehensive link budget analysis framework for THz wireless outdoor communications, the system parameters are carefully determined by considering potential current technological restrictions and operational deployment scenarios. We chose a transmit power of 10 dBm requiring at least highly directional antennas with gains specified to be around 50 dBi for both the transmitter and receiver.

A noise figure of 10 dB has been defined to be consistent with the state-of-the-art THz receivers [3], making an accurate assessment of link performance. A channel bandwidth of 1 GHz was selected to utilize the extensive range offered by THz frequencies, enabling high data rates and making this spectrum particularly appealing for future wireless systems.

Performance of the link is modeled from 10 meters to a kilometer, which also includes higher capacity short range links and longer-reach backhaul network requirements.

To provide a comprehensive view of system performance under typical outdoor conditions, different atmospheric scenarios are simulated. These include visibility conditions such as clear atmosphere, various rain rates, and fog densities. Figure 1, generated using our custom tool, illustrates the relationship between distance and received power.



SNR (dB) : 18.3
PTx (dBi) : 10
Gain ant. : 40
Altitude (m) : 0
☑ + Pluie
☐ + Brouillard
taux pluie (mm/h) : 50
humidité rel. : 7.5
densité lwd : 0
frequence (GHz) : 300
d_min (m) 10
d_max (m) 1000
fmin (GHz) 10
fmax (GHz) 1000
distance : 300 m
Puissance recue : -55.5247 dBm

Fig. 1. Power received over distance from 0m to 1Km

The minimum received power necessary for reliable communication depends on several factors, including transmit power, antenna gain, background noise, and receiver sensitivity. To complete, we employ the Signal-to-Noise Ratio (SNR) as a comprehensive metric for link quality assessment. The SNR at the receiver can be calculated using the following formula:

$$SNR = PRx/FkTB \qquad (3)$$

Where F, k, T and B are respectively the noise figure, the Boltzmann's constant, the system temperature, and the bandwidth.

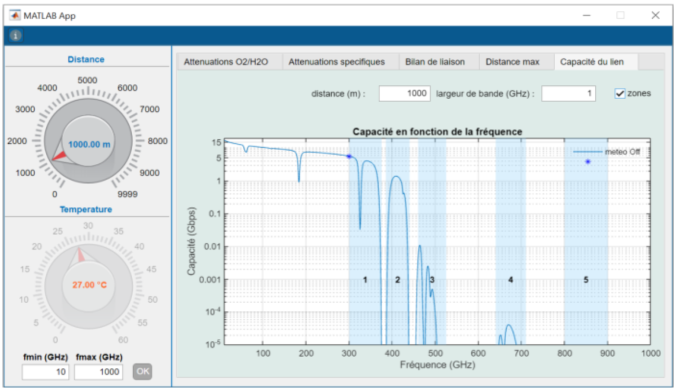
This approach helps to understand how power levels decay with distance under various atmospheric conditions, so we can develop more robust and adaptive THz communication systems.

III. PERFORMANCE ANALYSIS UNDER VARIOUS ATMOSPHERIC CONDITIONS

A detailed analysis of THz link performance under various atmospheric conditions is conducted using our link budget framework. Three key scenarios are examined: clear air, rain, and a combination of rain and fog, representing the most significant atmospheric challenges for outdoor THz communications.

A. Clear Air Scenario

Figure 2 illustrates the achievable data rate per GHz of bandwidth for a 1 km link under clear air conditions.



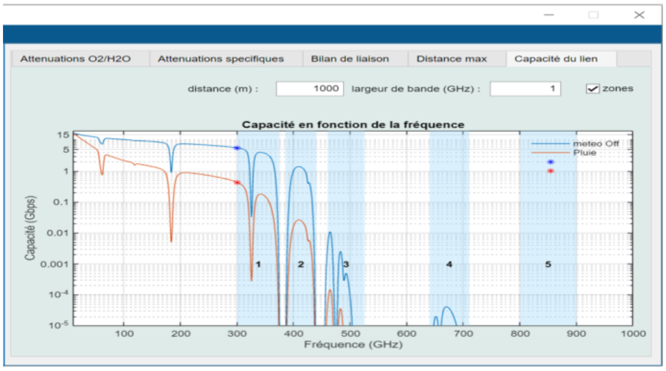
distance (m) : 1000
largeur de bande (GHz) : 1
☑ zones
fmin (GHz) 10
fmax (GHz) 1000

Fig. 2. Maximum Data Rate per 1 GHz Bandwidth for a 1 km Link in Clear Air

As evident from Figure 2, the achievable data rate varies significantly across the 300-900 GHz range. Distinct peaks in performance correspond to the atmospheric transmission windows identified in our previous work. The analysis reveals that in the 300-370 GHz window, under clear air conditions, data rates exceeding 8 Gbps/GHz are achievable over a 1 km link. However, under heavy rainfall (50 mm/h), this performance degrades significantly, with achievable rates dropping below 1 Gbps/GHz, representing a reduction factor greater than 8. This stark contrast underscores the critical need for adaptive techniques in THz communication systems.

B. Impact of Rain

Rain presents a significant challenge for THz communications due to scattering and absorption by water droplets. Figure 3 demonstrates the impact of heavy rainfall (50 mm/h) on the achievable data rate for 1 kilometer.



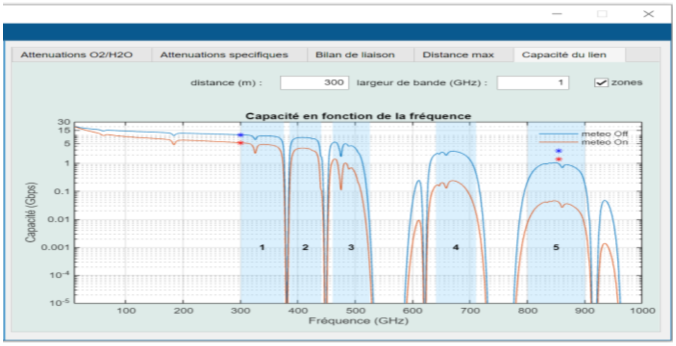
distance (m) : 1000 largeur de bande (GHz) : 1 ☑ zones

Fig. 3. Maximum Data Rate per GHz with 50 mm/h Rainfall

The effect of rain is profound, with a substantial reduction in achievable data rates across all frequencies. The first window (300-370 GHz) remains the most resilient, but even here, the maximum achievable rate drops to very low throughput, a tenfold decrease from clear air conditions.

C. Combined Effects of Rain and Fog

To fully understand the challenges of outdoor THz communications, we analyze the combined effects of rain and dense fog. Figure 4 illustrates the achievable data rate for a shorter link distance of 300 m under conditions of clear air and heavy rain (50 mm/h) with dense fog (visibility of 50 m).



distance (m) : 300 largeur de bande (GHz) : 1 ☑ zones

Fig. 4. Maximum Data Rate per GHz with 50 mm/h Rainfall and 50 m Visibility Fog for a Distance of 300 m (red)

The combined effect of rain and fog is severe, with achievable data rates significantly reduced across all frequencies. However, this analysis reveals important insights:

- Short-range viability: Despite the harsh conditions, THz communications remain viable over shorter distances. By reducing the link distance, we can partially mitigate the effects of adverse weather. At 300 GHz, we can still achieve rates above 5 Gbps/GHz over a 300 m link.
- Frequency window resilience: The first three windows (300-510 GHz) demonstrate superior performance under these conditions, suggesting their suitability for robust outdoor links.

The performance degradation at higher frequencies can be attributed to increased free-space path loss and molecular absorption, primarily due to water vapor. Despite this, we note from Figure 4 that even at 900 GHz for clear air, data rates of approximately 1 Gbps/GHz are achievable, highlighting the potential of these higher frequencies for short-range, high-capacity links in a controlled environment.

These results shows that the significant variability in performance across weather conditions suggests that dynamic frequency selection, adaptive modulation and coding will be essential features of robust THz communication systems. Having established the fundamental propagation characteristics of THz waves in various atmospheric conditions, attention now shifts to the practical implications for system design. The following section presents a comprehensive analysis of modulation schemes, a critical factor in optimizing THz link performance.

IV. MODULATION SCHEME ANALYSIS FOR THZ COMMUNICATIONS

The choice of modulation scheme and coding plays a crucial role in determining the performance and reliability of THz communication systems [4]. In this section, we analyze the impact of different modulations on link performance, considering the unique challenges posed by THz frequencies and different atmospheric conditions.

A. BER Calculations for QPSK, 16-QAM, and 64-QAM

The performances are compared over three common modulation schemes: Quadrature Phase Shift Keying (QPSK), 16-Quadrature Amplitude Modulation (16-QAM), and 64-QAM. These schemes represent a range of spectral efficiencies and complexity levels especially for an Additive White Gaussian Noise (AWGN) channel. The Bit Error Rate (BER) for each modulation scheme is calculated using the following approximations:

$$\begin{aligned} BERQPSK &\cong 1/2 \,.\, erfc\,(\sqrt{1/2 \,.\, SNR}) \\ BER16QAM &\cong 3/8 \,.\, erfc\,(\sqrt{1/10 \,.\, SNR}) \\ BER64QAM &\cong 7/24 \,.\, erfc\,(\sqrt{1/42 \,.\, SNR}) \end{aligned} \tag{4}$$

These calculations allow us to assess the relation between data rate and link reliability for each modulation scheme under various atmospheric conditions.

B. Maximum Achievable Distances

Using our link budget model and the BER calculations, the maximum achievable distances is determined for each modulation scheme. Figure 5 illustrates these distances for different modulation schemes under a specific atmospheric condition.

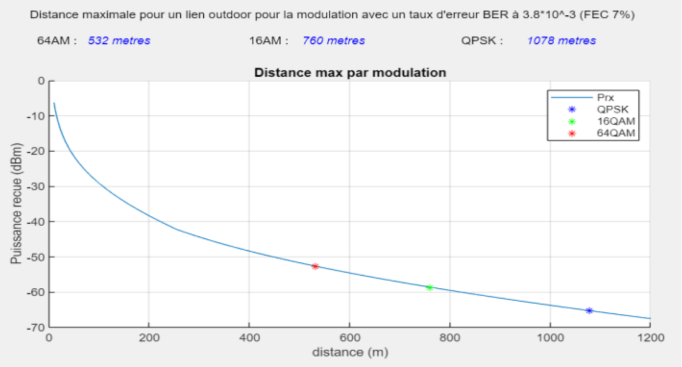


Fig. 5. Maximum Distance per Modulation for an Outdoor Link under Moderate Rainfall at 20 mm/h

As shown in Figure 5, QPSK offers the longest transmission range due to its robustness, while 64-QAM provides higher data rates but over shorter distances.

Table I. presents a detailed breakdown of the maximum achievable distances for each modulation scheme across our identified frequency windows under moderate rain conditions (20 mm/h).

TABLE I. OPTIMISED FREQUENCY WINDOWS FOR TERAHERTZ OUTDOOR COMMUNICATION

Window #	***Frequency (GHz)***	***d_QPSK (m)***	***d_16QAM (m)***	***d_64QAM (m)***
1	300	*1944*	*1501*	*1153*
2	409	*1064*	*854*	*682*
3	464	*627*	*518*	*427*
4	669	*440*	*365*	*302*
5	846	*355*	*295*	*245*

The results in Table 1 demonstrate that:

- Lower frequencies generally allow for longer transmission distances across all modulation schemes.
- Higher-order modulations (16-QAM, 64-QAM) offer increased data rates but at the cost of reduced range.
- The impact of atmospheric attenuation is more pronounced at higher frequencies, further limiting the achievable distances.

These findings have significant implications for THz system design:

- Adaptive Modulation: The substantial variation in achievable distances suggests that adaptive modulation techniques could be highly beneficial in THz systems. By dynamically switching between modulation schemes based on link conditions, we can optimize the trade-off between data rate and reliability.
- Frequency Selection: The choice of frequency window significantly impacts the achievable distance for all modulation schemes. This shows the importance of careful frequency planning in THz networks and hauls.
- Link Margin Considerations: The significant impact of atmospheric conditions on achievable distances highlights the need for adequate link margin in THz system design to ensure reliable communication under varying weather conditions.

V. CONCLUSION

Our analysis of THz outdoor communication systems reveals the intricate relationship between atmospheric conditions and link performance. The range from 300 to 434 GHz has potential for high-capacity links in clear air with impressive tolerance to atmospheric effects as well as bids for practical communication over relatively long distances. But intense weather conditions notably impair their performance, at that heavy precipitation (50 mm/h) leads to tenfold decrease in achievable data rates from over 8 Gbps/GHz to less than 1 Gbps/GHz at 300 GHz across a 1 km link.

Under moderate rain (20 mm/h) the modulation scheme analysis revealed that QPSK can maintain viable links up to almost 2 kilometers at 300 GHz, while 64-QAM is limited to 1153 meters under the same conditions. These findings underline the need for adaptive modulation techniques in THz communication systems. Our results suggest a hybrid approach taking advantage of the lower frequency band (300-510 GHz) for longer-range backhaul links and higher frequency band (640-900 GHz) for high-capacity short-range communications via dynamic adaptation based on real-time atmospheric conditions.

The weather's visible effect on THz propagation underscores also the possibility of using satellites to deploy THz communication in a confined area. For instance, THz links between satellites or from satellites to high-altitude platforms could make full use of this spectrum's capacity with minimal atmospheric interferences. The current progress in compact THz transceivers and high-gain antenna arrays has increased its feasibility thereby potentially transforming global high-speed data networks [5]. The considerable impact of weather on THz (terahertz) propagation underscores the promise of satellite-based THz communications. By establishing THz links between satellites or from satellites to high-altitude platforms, the full potential of this spectrum can be harnessed without the hindrance of atmospheric interference. This is especially pertinent for the higher frequency bands (640-900 GHz), which our research identified as being significantly affected by atmospheric conditions in terrestrial environments. This strategy could transform global high-speed data networks, providing a valuable complement to ground-based THz systems in regions susceptible to adverse weather.

There were also some findings that can have significant implications for the design of systems: adaptive frequency selection mechanisms should be employed; modulation schemes must be flexible.

However, our simulations may not capture all aspects of real-world environments for an outdoor link, such as complex multipath propagation and urban obstacles which can pose additional challenges. Further work is needed to develop more sophisticated channel models that take these real-world complexities into account and examine advanced beamforming techniques suitable for use at THz frequencies.

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