RESEARCH PAPER

COMPREHENSIVE TERAHERTZ (THZ) LINK-BUDGET MODELING AND ATMOSPHERIC-AWARE PROPAGATION ANALYSIS FOR HIGH-FREQUENCY 6G WIRELESS COMMUNICATION SYSTEMS

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ABSTRACT

The fast development of the fifth generation (5G) wireless technology has necessitated the need to have high-frequency communication systems that have the potential of supporting ultra-high data rates at short distances. The frequency bands of terahertz (THz) and within the frequency band of 0.1-1 THz can offer immensely broad spectral resources capable of providing the next generation of wireless communication. Practical implementation of THz communication is, however, limited by very high free-space path loss and by high atmospheric absorption. Thus, to design and optimize antennas and Frequency-Selective Surface (FSS) structures in the terahertz band, proper propagation modeling and link-budget analysis are needed. In this study, a framework of terahertz link-budget analysis has been presented to provide estimation of received power and Signal-to-Noise Ratio (SNR) depending on the distance of transmission in 6G communication in the future. The model is proposed by incorporating the most important factors of propagation, such as free-space path loss, antenna gains, system losses, and frequency-dependent atmospheric attenuation. The Python-based simulation is created to assess key performance indicators, including, but not limited to, FSPL, atmospheric loss, total channel attenuation, received power, SNR, and link margin. Using both graphical and numeric data in CSV format, terahertz link feasibility can be conveniently analyzed in received-power and SNR plots and numerical values. The results of the simulation show that the range of communication is greatly influenced by atmospheric absorption. These findings imply that high-gain antennas and optimized FSS designs are needed to minimize propagation loss and maximize THz communication.

Keywords: 6G wireless, Terahertz (THz) banding, Atmospheric absorption, FSL, High-gain antennas, FSS, Signal-to-Noise Ratio (SNR).
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I. INTRODUCTION

The advances in wireless communication systems have always been influenced by the demanding requirements of the users, such as higher data rates, low latency, massive connectivity, and improved reliability. After the worldwide implementation of fifth-generation (5G) networks, the scientific community has shifted its research focus quickly to sixth-generation (6G) wireless systems, which, among others, are expected to provide applications like holographic communication, extended reality (XR), ultra-high-definition sensing, wireless brain–computer interfaces, and intelligent autonomous networks. To give the users the possibility for data-intensive and latency-sensitive services, the 6G systems will have to utilize the new spectral windows that are far beyond the conventional microwave and millimeter-wave bands. In this sense, the terahertz (THz) band, which is generally considered to cover the range from 0.1 to 10 THz, has become a potential candidate for this extremely wide band of frequencies.

THz communication will be able to provide data rates of the order of hundreds of gigabits per second or even terabits per second, thus opening the way for short-range and ultra-high-capacity wireless links. On the other hand, THz communication is confronted with several fundamental problems that limit its realizations in different scenarios and its practical deployment. One of the most serious problems is the very high propagation loss that occurs at high frequencies. Free-Space Path Loss (FSPL) increases quadratically with frequency; thus, it can cause very significant attenuation of the signal even at short distances. Besides that, the THz signals can be attenuated by the atmosphere because some molecules in the air can resonate with the signals. In particular, the water vapor and the oxygen peaks cause frequency-dependent attenuation of the links, which leads to their performance degradation.

Therefore, the accurate models of THz propagation are the backbone of the 6G communication systems design and performance evaluation. Unlike lower-frequency bands where empirical models are well established, THz channels demand a more sophisticated link-budget analysis that considers both deterministic losses and environment-dependent attenuation effects. The factors of antenna gain, system losses, transmit power, noise characteristics, and atmospheric conditions are of paramount importance in deciding the communication range and the quality of the signal. In fact, the Signal-to-Noise Ratio (SNR) at the receiver is the principal performance metric that has a direct impact on the modulation schemes, data rates, and system reliability.

It is physically and practically impossible to install THz communications without severe path losses. A gamut of hardware solutions can provide ingenious ways to access the world of high frequencies. High-gain directional antennas, beamforming methods, and FSS-based components are the most effective ways to resolve the issue of the radiation efficiency and make communication path margins better. If an FSS element is combined with an antenna, it can be an ideal device for specific band transmission or reflection since it possesses selective properties that pave the way for the better control of the electromagnetic wave propagation and thus performance improvement of the system at peak THz frequencies. However, the performance of these designs must first be confirmed through precise link-level studies under genuine operating conditions.

Bringing together theoretical study and real-world system design, simulation-based analytical frameworks play an indispensable role here. A link-budget model that is flexible and configurable gives scientists and technologists a chance to examine the practicability of THz links under various scenarios of frequency, distance, and atmospheric conditions. Such innovative tools, by creating measurable parameters such as received power, total channel attenuation, SNR, and link margin, facilitate the decision-making process in 6G antenna designing, FSS structure utilization, and the overall link configuration. This paper is dealing with the mentioned issues and aims to develop an analytical framework of THz link budget that is suitable for future 6G wireless communication systems.

II. RELATED WORK

Ullah et al. The idea of terahertz (THz) communications being a major factor for 6G and beyond has been significantly developed lately. Near-field THz communication systems: From physics to hardware, a paper by Singh et al. [1], constitutes a comprehensive overview of near-field THz communication systems, moving the focus from the conceptual domain to the experimental realm.

The authors elucidate the system architectures, channel characteristics, and the influence of antenna designs in achieving ultra-high data rates and low latency, thus laying the groundwork for understanding THz network deployment scenarios. On the other side of the spectrum, Greenberg and Klodzh [2] pinpoint the difficulties involved in the high-frequency propagation modeling. Confirming that the traditional radio-frequency (RF) models are inadequate, they offer solutions for the precise prediction of path loss, scattering, and atmospheric absorption in THz bands.

Abdellatif [3] goes further in this field by inventing a Python-based simulator for THz satellite communications that facilitates cross-band analysis and offers a playground for channel models, antenna setups, and system-level performance metrics testing. The work of Nahin et al. [4] is centered around the conceptualization and realization of advanced MIMO antenna designs that are just right for the THz communication. Additionally, their performance is fine-tuned by the use of machine learning methods. The main point of the paper is how fractal and tessellated patterns can be used to heighten the channel efficiency and reliability in dense 6G scenarios. Katwe et al. [5] are keen on sub-THz and cmWave spectra as mutually supportive sources of 6G. They advocate for band integration to reach uninterrupted coverage and support ultra-high-speed links. Jiang et al.'s [6] manuscript is a comprehensive review paper on terahertz communications and sensing. They report the latest improvements in transceiver design, channel characterization, and also integration with the sensing applications, which is very important for smart and autonomous network operations. Inomata et al. [7] build and test sub-THz massive MIMO channel sounders that provide real-world data to guide channel modeling and beamforming strategies for upcoming mobile networks. AbdlNabi et al. [8] talk over the fusion of the optical and RF technologies, pointing out the cellular networks that are heterogeneous and the modeling of hybrid channels merging optical and THz links. Shi et al. [9] are on this subject, and they present a link-level simulator for MIMO integrated sensing and communication (ISAC) systems working in the THz band. The main focal points of their work are time-division duplexing (TDD) frameworks and interference management. Mahmood et al. [10] analyze the detailed aspects of THz propagation in the context of federated learning. They consider path loss, molecular absorption, and link design as the main pillars of distributed AI in wireless systems. Cai et al. [11] shed light upon the components of THz propagation and place great emphasis on reflection, diffraction, and absorption phenomena that are among the main coverage and system design factors. Bhardwaj et al. [12] construct a comprehensive statistical model for THz channels experiencing random atmospheric absorption situations and thus, make robust network planning more feasible under diverse weather conditions. Saeidi et al. [13] direct their effort primarily on resource allocation in extremely dense THz networks. They come up with user assignment, spectrum, and power allocation techniques that are aware of molecular absorption and whose ultimate goal is to serve system efficiency. Basherlou et al. [14] promote the idea of the compactness of high-gain phased array antenna designs that are the perfect match for 6G. Their main points are the enhanced beamforming capabilities and the spatial multiplexing extension. Zubair [15] takes a look at the development of THz antennas as a part of the 6G wireless network and concentrates on the design issues such as miniaturization, gain, and radiation efficiency.

Premanand et al. [16] explain the utilization of the intelligent reflecting surface (IRS) idea in the THz networks, assessing system-level modeling and the performance enhancements that could be attained by environment-aware reflection control. Ullah et al. [17] examine a multiuser massive MIMO-OFDM THz system suffering from intercarrier interference and propose hybrid beamforming as the main technique for alleviating the resultant performance drop. The work of Arshad [18] involves the conduction of sub-THz propagation ray-tracing simulations. Their goal is to gain knowledge that can be used for deterministic modeling in 6G network planning. Shafie et al. [19] highlight the main problems, improvements, and chances in THz communications for future networks and put a strong emphasis on channel estimation, hardware restrictions, and smooth integration with present network infrastructures. Chaccour et al. [20] characterize the THz wireless system by listing seven fundamental properties, such as ultra-wide bandwidth, high data rates, and sensing capabilities, which, when taken together, provide the framework for 6G use cases going from holographic communications to ultra-dense network coverage.

III. PROPOSED SYSTEM MODEL

The proposed system conceptualizes a full-scale terahertz (THz) link-budget analysis and simulation framework specifically for sixth-generation (6G) short-range wireless communication systems. The fundamental aim of this system is to evaluate the feasibility of a THz link accurately by merging realistic propagation losses, antenna characteristics, and atmospheric effects into one analytical and computational model. The framework is meant to be used by antenna designers, FSS researchers, and system engineers to optimize THz-based communication links for next-generation applications.

A. System Overview

The system under consideration is a comprehensive end-to-end point-to-point THz wireless link model in the 0.1–1 THz frequency band. The key performance indicators the model evaluates include free-space path loss (FSPL), atmospheric absorption loss, total channel attenuation, received power, signal-to-noise ratio (SNR), and link margin as transmission distance varies. A Python-based simulation engine performs numerical calculations and provides graphical and tabular representations of the results for a quick visual check of the performance. The system is also modular and configurable, meaning that the users can change values of operating frequency, transmit power, antenna gains, system losses, bandwidth, and noise temperature, among others.

B. System Architecture

The architecture comprises five major functionally interdependent components: the transmitter module, the channel propagation module, the receiver module, the link-budget analyzer, and the visualization & data output module. The entire simulation-based architecture shown in fig. 1 is inspired by the THz system-level modeling framework proposed by Abdellatif [3].

1) Transmitter Module

This module defines the parameters for transmission, which include THz frequency of operation, transmit power, antenna gain, and feed/hardware losses. In addition, the module can be used to simulate the performance of high-gain directional antenna systems as well as FSS-enhanced radiators.

2) Channel Propagation Module

This module represents the wireless link/channel through which the data is transmitted by taking into account free space path loss as well as frequency-dependent path loss due to atmospheric absorption. Coefficients for absorption have been given to account for molecular absorption caused by water vapor and gases.

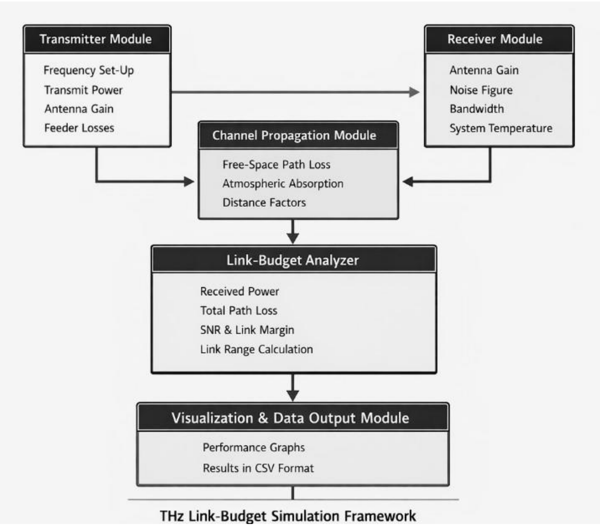

Fig. 1. System architecture

3) Receiver Module

The receiver module takes into consideration the receiver specifications, including the gain of the antenna, the losses in the receiver, the bandwidth, the noise factor/figure, and the system temperature. From these specifications, the receiver signal strength is estimated.

4) Link Budget Calculator

This section of the model merges the attributes of the transmitter, channel, and receiver to estimate the parameters of received power, total channel loss, SNR, and link budget margin. The model utilizes a distance-based study to determine the possibility of THz links in future 6G networks.

5) Visualization and Data Output Module

The visualization component generates graphs for received power and SNR as a function of distance and exports the metrics in CSV format.

C. Functional Significance

The proposed system is a practical, adaptable, and expandable analytical model of THz communication links. In addition to that, the system helps in the design and optimization of THz antennas, FSS structures, and link-level configurations for future 6G wireless communication systems by explicitly considering atmospheric absorption and the effects of high-gain antennas.

IV. LINK BUDGET FORMULATION

The methodology used in this instance employs a systematic analysis methodology involving link budgets. This technique integrates propagation models with numerical calculations to determine values such as the received power, SNR, and link margins at various distance ranges and frequencies. The basic equations used in this process were sourced from previous studies on the topic. For example, the formulas used in this section include those by Mahmood et al. [10] and Cai et al. [11].

A. Parameter Initialization

The very first move is setting up system parameters for the transmitter, channel, and receiver. Main inputs consist of operating frequency *f(Hz)*, transmission distance *d(m)*, transmit power $P_t(dBm)$, transmitter and receiver antenna gains G_t and G_r(dBi), bandwidth *B*(Hz), noise figure *NF*(dB), and miscellaneous system losses L_{sys}(dB). Absorption of the atmosphere is also described by the coefficients α(*f*) (dB/m) chosen correspondingly to the frequency band of the THz.

B. Free-Space Path Loss Modeling

The calculation of the free-space path loss (FSPL) is based on the F_r is transmission equation in logarithmic form:

$$FSPL(dB) = 20\log_{10}\left(\frac{4\pi df}{c}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where c is the speed of light (3×10^8 m/s). The present formula is able to reflect the very steep rise that path loss does with frequency and distance, the main reason for which is the THz regime.

C. Atmospheric Absorption Loss

The model for atmospheric attenuation follows a path-length-dependent loss caused by molecular absorption. It anticipates losses L_{atm} made by:

$$L_{atm}(dB) = \alpha(f) \times d \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where α(*f*) is the absorption coefficient that varies with the frequency. Here is the factor taken for attenuation due to water vapor and other gases, and it varies very much at different THz frequencies.

D. Total Channel Attenuation

The total propagation loss, L_{tot}, is the result of the combination of FSPL, atmospheric loss, and other system losses:

$L_{tot} = FSPL + L_{atm} + L_{sys}$ ……………………….(3)

This aggregate loss model serves as a faithful source of the THz emission channel.

E. Received Power Estimation

The received power P_r is figured out from the link budget equation:

$P_r(dBm) = P_t + G_t + G_r - L_{tot}$ ………………….(4)

This moment is giving the direct answer to the question of how much of that antenna gain and loss goes to the received signal strength at different distances.

F. Noise Power and SNR Calculation

The receiver's thermal noise power N is determined by the following formula:

$N(dBm) = 10\log_{10}(kTB) + 30 + NF$ ………..(5)

where k is Boltzmann’s constant (1.38×10^(-23) J/K) and T is the system noise temperature (K). Next, the signal-to-noise ratio is derived from the same information as follows:

$SNR(dB) = P_r - N$ ……………………..……….…….(6)

G. Link Margin Evaluation

The link margin M is the difference between the obtained SNR and the minimum SNR (SNR_min) necessary for the target modulation scheme:

$M(dB) = SNR - SNR_{min}$ ……………………….(7)

H. Simulation and Analysis

They have implemented all the formulas in a Python-based simulation environment. The model is capable of iteratively measuring performance indicators at various distances and frequencies, thus producing run power and SNR graphs together with numerical outputs in CSV format. This method allows for prompt, accurate, and flexible analyses, which can be re-performed and yield the same results.

V. RESULT AND DISCUSSION

The purpose of this discussion is to figure out the impact of each individual loss mechanism on link feasibility and, also, determine which design requirements are the most critical for reliable short-range THz communication systems.

A. Received Power Analysis

The variation of the received power with the transmission distance is shown in Fig. 2. The data demonstrate the power to the wireless receiver dramatically falls as the distance is extended from several meters to 100 m. In the neighborhood, the received power is still kept at a level that is not too low due to the minimal propagation losses; therefore, THz communication can be regarded as a very efficient technology for short-range applications. Unfortunately, as the distance goes up, the effect of free space path loss dominates, resulting in the significant dropping of the signal strength. This process validates the fact that THz links are susceptible to range limitations, and thus the system needs to be designed very carefully so high performance levels can still be attained at long distances.

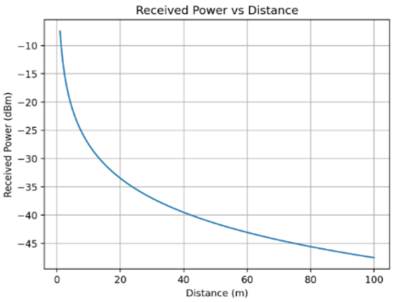

Fig. 2. Received Power vs. Distance

B. Signal-to-Noise Ratio (SNR) Performance

The signal-to-noise ratio (SNR) in relation to the distance is illustrated in Fig. 3. At smaller distances, a high SNR can be achieved that is a hallmark of a great quality link, and thus, very high-order modulation schemes can be used, which, in turn, will provide ultra-high data rates. After this point, the SNR continues to drop as the distance is extended, mainly due to the received power decrease while the noise floor is kept constant. However, the SNR locates far above the practical threshold within a wide distance range; thus, it can be concluded that THz links still have the capacity to function properly if high-gain antennas and link parameter optimization are used.

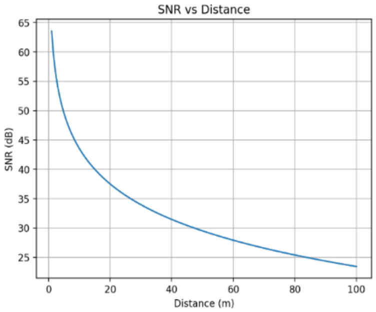

Fig. 3. SNR vs Distance

C. Atmospheric Absorption Loss Characteristics

The atmospheric absorption loss trend is demonstrated in Fig. 4.

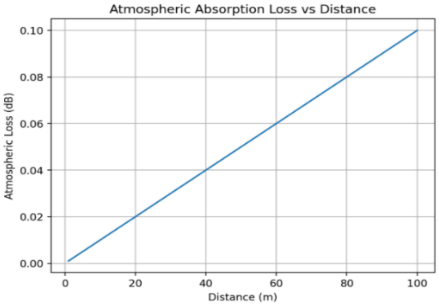

Fig. 4. Atmospheric Absorption Loss vs. Distance

The difference between atmospheric absorption and free-space path loss is that atmospheric absorption grows linearly with distance. While the absolute value of atmospheric loss seems to be quite low in the case of short distances, it becomes quite a significant cumulative effect at higher THz frequencies and long distances. The result is, therefore, stressing the importance of using the transmission windows that possess lower molecular absorption for real deployment scenarios.

D. Free-Space Path Loss Impact

The trends in the behavior of free-space path loss are given in Fig. 5. FSPL is directly proportional to the logarithm of the distance, and, in this respect, it is the main culprit of the losses when it comes to THz propagation. When put together with atmospheric absorption, it considerably limits the distance that can be used for communication. The sum of these findings collectively puts forward the idea that the 6G THz communication systems of the future ought to contain elements such as high-gain antennas, beamforming techniques, and FSS-based enhancements so they can offset the heavy losses and, therefore, ensure a dependable THz.

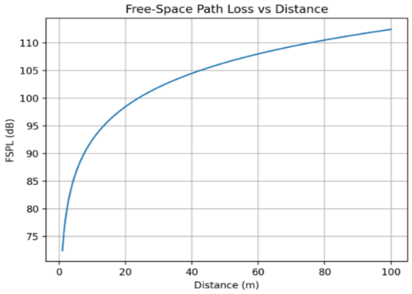

Fig. 5. Free-Space Path Loss vs. Distance

VI. CONCLUSION

This paper presented an elaborate terahertz (THz) link-budget analysis framework, whose main goal was to evaluate the feasibility of short-range sixth generation (6G) wireless communication systems. The proposed approach, by integrating free-space path loss, atmospheric absorption, antenna gains, and system-level losses into a single analytical model, provides an extremely realistic picture of THz propagation and link performance. Moreover, the Python-based simulation environment was aimed at producing quantitative metrics such as received power, signal-to-noise ratio (SNR), total channel attenuation, and link margin for different transmission distances. The results reveal that free-space path loss is the major cause of attenuation at THz frequencies while atmospheric absorption imposes a limitation that varies with distance and frequency. Although atmospheric loss may be negligible over short distances, its effect is quite substantial at higher THz bands because it determines the achievable communication range. The received power and SNR variations also demonstrate that THz communication is an ideal way to provide short-range, ultra-high-capacity links, however, the issue of performance stability over longer distances must be taken into account and properly addressed. The research further highlights the role of high-gain directional antennas, beamforming techniques, and frequency-selective surface (FSS)–based enhancements in overcoming the drastic propagation losses. The suggested platform, which enables parameter setting flexibility and performance metric visualization simplicity, is a perfect design and confirmation tool for the THz antenna and link-level architectures. To sum up, this study is a major step towards the real-world implementation of THz-based 6G systems and serves as a stepping-stone for the subsequent research on the advanced antenna designs, adaptive propagation models, and real-world deployment scenarios.

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