Proceedings of CONF-CDS 2026 Symposium: Computer Vision-Based Multimodal Cognitive Load Estimation for Adaptive Media Communication
DOI: 10.54254/2755-2721/2026.GL36378

Attenuation Prediction for 6G Terahertz Satellite-Ground Links: A Review of Mechanisms, Models and Future Directions

HAN Yitong*, WU Chenxi

Reading Academy, Nanjing University of Information Science and Technology, Nanjing, China
**Corresponding Author. Email: hanyitong2006@nuist.edu.cn*

Abstract. Terahertz communication has become a key enabling technology for 6G space-air-ground integrated networks, offering ultra-wide bandwidth and Tbps-level transmission capacity to meet the demands of global seamless coverage. However, the propagation of terahertz signals is highly susceptible to the atmospheric boundary layer, where absorption by water vapor/oxygen, scattering by aerosols, and rainfall-induced attenuation collectively cause severe degradation of the satellite-ground link. It has become a central research focus in leading international conferences. This paper systematically reviews the state-of-the-art in terahertz attenuation prediction and classifies existing models into three categories: classical empirical models (e.g., ITU-R P.676), physics-based models (e.g., radiative transfer models), and machine learning-based models (e.g., LSTM and random forests). It comprehensively compares their computational efficiency, prediction accuracy, and applicability across scenarios (e.g., dry vs. humid regions, low vs. high terahertz bands). Finally, this paper identifies key challenges, including scarce high-quality measured data and poor cross-regional adaptability and proposes future directions such as adaptive model design and multi-source data fusion. By delineating the full research context and key development trends in this field, this review delivers a structured, up-to-date reference for fellow researchers and engineering practitioners.

Keywords: 6G Communication, Terahertz, Satellite-Ground Link, Attenuation Prediction, Atmospheric Multi-Parameter Coupling

1. Introduction

With the explosive growth of emerging applications, including the metaverse, the industrial Internet of Things, and global real-time sensing, 6G mobile communication is evolving toward ultra-high speed, low latency, massive connectivity, and seamless global coverage. The space-air-ground (SAG) integrated network, which integrates low-earth orbit (LEO) satellites, high-altitude platforms (HAPs), and terrestrial communication nodes, has become the core architecture for overcoming the geographical limitations of traditional terrestrial networks and achieving ubiquitous connectivity. Among various 6G enabling technologies, terahertz communication (0.1-10 THz band) stands out for its ultra-wide bandwidth up to hundreds of GHz, supporting Tbps-scale ultra-high-speed

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.GL36378

transmission far beyond microwave and millimeter-wave systems, making it an indispensable solution for massive data traffic in 6G SAG networks, such as inter-satellite high-speed backhaul and remote ultra-broadband access. However, unlike low-frequency signals, terahertz waves are highly sensitive to the atmospheric boundary layer (typically 0-1 km altitude), where water vapor and oxygen molecules cause frequency-selective absorption, and aerosols and hydrometeors induce significant scattering attenuation. These atmospheric effects lead to severe signal degradation, a key bottleneck to the practical application of terahertz SAG links.

In particular, interactions between terahertz signals and multiple atmospheric components result in synergistic absorption and scattering, severely degrading link performance [1]. Moreover, aerosol hygroscopic growth under high-humidity conditions can markedly increase scattering attenuation [2].

To enable reliable link design, accurate prediction of such attenuation is therefore essential. Accordingly, accurate attenuation prediction has emerged as a frontier research topic at recent cross-disciplinary conferences.

This paper systematically reviews the state-of-the-art progress in terahertz attenuation prediction for 6G satellite-ground links. The study classifies existing models into three categories: classical empirical models, physics-based models, and machine learning-based models, and compares their accuracy, efficiency, and applicability across scenarios. It presents challenges, including multi-parameter coupling, data scarcity, and future research directions. It aims to provide theoretical guidance for the research on 6G terahertz satellite-ground communication.

2. Overview of terahertz satellite-ground link attenuation mechanism

2.1. Classification of link attenuation

The total attenuation of 6G terahertz satellite-ground links during propagation stems from the combined effects of inherent propagation loss and environment-driven variable attenuation. This total loss comprises two core components: free-space propagation loss (FSPL) and atmospheric attenuation [2].

FSPL is an unavoidable physical effect of electromagnetic wave propagation, with its magnitude entirely independent of atmospheric conditions. It originates from the spherical divergence of electromagnetic waves, signal energy spreads uniformly in space as the propagation distance increases, leading to a decrease in power density at the receiving end.

In contrast to FSPL, atmospheric attenuation is a variable component dynamically influenced by the atmospheric environment, especially the atmospheric boundary layer (ABL, 0~1 km altitude) [3]. It arises from the interaction between terahertz signals and atmospheric components (gas molecules, aerosols, hydrometeors). Atmospheric attenuation is highly dependent on weather conditions and frequency. For satellite-ground links, although its magnitude (typically 10-50 dB) is much smaller than FSPL (which exceeds 280 dB), it is the dominant factor determining link availability across different weather scenarios. In short-range terrestrial links (e.g., <1km), atmospheric attenuation can account for 60%-90% of the total loss, but in satellite-ground links, the proportion is usually below 20%. Atmospheric attenuation directly governs a link's transmission distance, communication quality, and overall reliability. Accurate quantification of atmospheric attenuation is therefore the key to realizing reliable 6G terahertz satellite-ground communication.

DOI: 10.54254/2755-2721/2026.GL36378

2.2. Main types of atmospheric attenuation

Atmospheric attenuation of terahertz satellite-ground links is dominated by three synergistic types: gas absorption attenuation, aerosol scattering attenuation, and rainfall attenuation, each with distinct formation mechanisms and frequency-dependent characteristic..

2.2.1. Gas absorption attenuation

The primary contributor in clear weather is induced by water vapor (H_2O) and oxygen (O_2) molecules in the atmospheric boundary layer. Oxygen (O_2) has a strong absorption peak near 0.06 THz (60 GHz, which is below the conventional terahertz band of 0.1-10 THz; within 0.1-10 THz, oxygen absorption is negligible compared to water vapor. These molecules exhibit frequency-selective absorption. Signal energy is absorbed when its frequency matches the molecular energy-level gap. Key absorption peaks include: water vapor at 0.17 THz, 0.3 THz, and 1.6 THz (up to 50 dB/km under saturated humidity) [2]. Its intensity depends on gas concentration, temperature, and air pressure, and it defines the "transmission windows" (low-attenuation bands such as 0.2~0.3 THz) prioritized for 6G applications.

2.2.2. Aerosol scattering attenuation

Caused by interactions between terahertz signals and aerosol particles (haze, dust, fog/cloud droplets), governed by Mie (particle diameter ≈ terahertz wavelength) and Rayleigh (particle diameter << wavelength) scattering theories [1]. Key influencing factors include aerosol optical depth (AOD), particle size, and ambient humidity—hygroscopic growth of particles in high humidity (RH > 80%) can enhance scattering attenuation by 30%~80% [2]. For example, under typical heavy haze (AOD=1.0), the attenuation at 1 THz can reach 15~25 dB/km, while heavy fog can reach 40 dB/km, potentially blocking short-range communication.

2.2.3. Rainfall attenuation

Rain attenuation is the most dominant source of link degradation in rainy conditions, caused by the combined absorption and scattering effects of raindrops. Its intensity correlates with rainfall rate (nonlinear) and raindrop phase state—liquid raindrops (temperature > 0°C) cause 2~3 times stronger attenuation than solid ones. For a typical scenario at 1 THz, light rain (5 mm/h) induces about 2-5 dB/km attenuation, while heavy rain (50 mm/h) increases this to 30~50 dB/km. As a key engineering bottleneck, adaptation strategies such as adaptive frequency switching have been proposed to mitigate its impacts.

2.3. Atmospheric multi-parameter coupling characteristics

Meteorological parameters in the atmospheric boundary layer, including temperature (T), relative humidity (RH), air pressure (P), aerosol optical depth (AOD), and rainfall rate (R), are not independent variables but form a complex nonlinear multi-parameter coupling system. This coupling effect arises from the dynamic interactions between atmospheric processes (e.g., convection, condensation, particle transport) and significantly increases the complexity of terahertz attenuation prediction. As a key research gap highlighted in recent conference papers, multi-parameter coupling is the main shortcoming of traditional attenuation prediction models.

DOI: 10.54254/2755-2721/2026.GL36378

Typical multi-parameter coupling relationships and their impacts on terahertz attenuation include: Temperature-Humidity-Aerosol Coupling, Humidity-Rainfall Coupling and Air Pressure-Temperature-Gas Absorption Coupling.

Temperature directly affects the saturation vapor pressure of the atmosphere: higher temperatures increase water vapor holding capacity, promoting the hygroscopic growth of aerosol particles. For example, a 5°C increase in temperature (at constant RH=70%) can increase aerosol particle size by 20%, leading to a 10~15% enhancement in scattering attenuation [1].

High relative humidity (RH > 90%) is a prerequisite for rainfall formation—rainfall rate is positively correlated with humidity, while rainfall further increases near-surface humidity, creating a positive feedback loop. This coupling leads to synergistic enhancement of gas absorption and rainfall attenuation: under heavy rain conditions (R=50 mm/h, RH=95%), the total atmospheric attenuation at 1.6 THz (water vapor absorption peak) reaches 80~100 dB/km, which is 30% higher than the sum of individual attenuation effects [2].

Air pressure and temperature jointly affect the concentration of water vapor and oxygen molecules. According to the ideal gas law, a 10 kPa decrease in air pressure (equivalent to a 1 km increase in altitude) reduces the gas concentration by ~10%, thereby decreasing gas absorption attenuation by 8~12%.

The core challenge of multi-parameter coupling lies in its nonlinearity and spatiotemporal variability, the coupling strength varies with region (e.g., tropical vs. temperate zones) and time (e.g., day vs. night), making it difficult to model with simple linear superposition [4]. Traditional models (e.g., ITU-R P.676, radiative transfer models) often treat these parameters as independent, leading to prediction errors exceeding 30% under complex meteorological conditions (e.g., haze-fog-rain mixed weather) [5].

3. Review and categorization of terahertz satellite-ground link attenuation prediction models

3.1. Classical empirical models

Classical empirical models, represented by the ITU-R series (P.676, P.838, P.840), are widely used in engineering. Constructed from large-scale measured data, they feature simple calculations and high efficiency, making them suitable for rapid link evaluation and preliminary design. However, recent studies point out critical limitations: they do not account for synergistic coupling effects among different attenuation types (e.g., gas-aerosol-rain interactions) and have poor adaptability across regions/frequency bands, leading to prediction errors exceeding 25% under complex meteorological conditions. For 6G high-frequency terahertz bands (1~10 THz), the lack of targeted measurement data further reduces their accuracy, making adaptability optimization a key research focus.

3.2. Physical models

Physical models (e.g., radiative transfer models, Mie/Rayleigh scattering models) are built on rigorous propagation mechanisms, ensuring high prediction accuracy (error < 15% under ideal conditions). They accurately describe terahertz interactions with atmospheric components, making them suitable for high-reliability applications such as inter-satellite backhaul. However, these models have well-documented limitations highlighted: complex computations, reliance on fine-scale micro-meteorological parameters (e.g., aerosol particle size distribution) that are difficult to measure in real time, and inherently low computational efficiency [2]. Preserving prediction accuracy while improving efficiency has become a major focus of recent conference research.

DOI: 10.54254/2755-2721/2026.GL36378

3.3. Machine learning-based prediction models

Machine learning models (BP neural networks, LSTMs, random forests, SVMs) are valued for their strong ability to handle multi-parameter coupling and nonlinear relationships. LSTM excels at capturing the temporal dynamics of atmospheric parameters, random forests avoid overfitting, and SVMs perform well with small samples—all achieving high accuracy (<20% error) under complex meteorology [1]. However, studies highlight key issues: extreme dependence on scarce, high-quality measured data (especially under extreme weather), poor physical interpretability due to black-box models, and weak adaptability to unknown regions/frequency bands [5]. These problems remain core challenges for subsequent research.

4. Future research directions and challenges

4.1. Future research directions

Future research on 6G terahertz satellite-ground link attenuation prediction will focus on multi-parameter coupling attenuation modeling, covering three interrelated directions that reflect the cross-disciplinary integration trend of atmospheric science, communication engineering, and artificial intelligence [2].

4.1.1. Multi-parameter coupling attenuation modeling and full-link theoretical framework

Building a complete multi-parameter coupling attenuation model and a full-link theoretical framework is the primary direction. Traditional models typically treat atmospheric parameters as independent variables, leading to large prediction errors in complex weather. To solve this problem, future research will overcome the limitation of traditional models, which only calculate attenuation for each parameter separately. Based on basic atmospheric and electromagnetic propagation rules, studies should systematically clarify how key meteorological parameters (temperature, humidity, pressure, aerosols, and rainfall) interact with each other, quantify the combined effect of these interactions on terahertz signal attenuation, and establish a full-link theoretical model covering the entire space-to-ground transmission path [1].

4.1.2. Prediction model optimization for high-frequency terahertz bands

With the development of 6G ultra-high-speed communication, model optimization for high-frequency terahertz bands (1~10 THz) will be the second key research direction. High-frequency terahertz bands can support ultra-wideband transmission, but they also face new attenuation challenges: denser gas absorption peaks and stronger scattering from tiny particles, such as fine aerosols. Most existing mainstream models (e.g., ITU-R series) are designed for low-frequency terahertz bands (0.1~1 THz) and do not account for multi-parameter coupling effects on high-frequency attenuation, leading to prediction errors exceeding 30% in extreme scenarios. Future research will focus on the unique attenuation characteristics of high-frequency bands, adjust core model parameters based on multi-parameter coupling rules, supplement high-frequency measured data under complex weather conditions, and build a prediction model tailored to 1~10 THz bands to achieve high-precision attenuation prediction for high-frequency terahertz links.

DOI: 10.54254/2755-2721/2026.GL36378

4.1.3. Multi-source atmospheric data fusion and engineering adaptation of models

The third direction addresses the severe shortage of measured terahertz attenuation data, particularly under extreme weather. To build a robust and diverse training dataset, future research will fuse multi-source atmospheric information, including ERA5 global reanalysis, satellite remote sensing products, and ground-based meteorological observations. This integration is intended to expand data volume, improve representativeness across climatic regions, and reduce model training errors [5]. On this basis, the development of region-adaptive prediction models becomes feasible, enabling the balance between prediction accuracy and computational efficiency that is essential for practical 6G deployments.

4.2. Challenges

Despite significant progress in recent research, systematic analysis of papers reveals three unresolved key problems that restrict the practical application of terahertz attenuation prediction technology

4.2.1. Difficulty in modeling nonlinear multi-parameter coupling effects

The greatest barrier to improving model accuracy lies in the intrinsic difficulty of capturing nonlinear interactions among atmospheric parameters. Temperature, humidity, pressure, and aerosol loading do not simply combine additively; their mutual influences vary substantially across regions and weather regimes. The underlying physical rules governing these couplings are poorly represented by explicit parametric equations, and no generalized scheme currently exists to encode them into attenuation models. Attempts to compensate through empirical fitting or black-box machine learning often produce models that fail when transferred to unobserved conditions, with errors exceeding 30% in complex mixed weather. Thus, the core challenge is not merely computational but deeply rooted in the incomplete physical understanding of coupled atmospheric processes at terahertz frequencies.

4.2.2. Poor adaptability of existing models to high-frequency terahertz bands (1–10 THz)

High-frequency terahertz bands present a severe technical gap for 6G systems. At these frequencies, molecular absorption spectra become much denser and fine-aerosol scattering intensifies, yet almost all widely adopted models (e.g., ITU-R series) are calibrated against data below 1 THz. Their internal parameters are often extrapolated from lower frequencies without considering the unique coupling mechanisms that dominate above 1 THz. Furthermore, dedicated high-frequency measurement campaigns under realistic weather conditions are extremely scarce, leaving model developers with insufficient data to recalibrate or validate new formulations. Prediction errors routinely exceed 30% in extreme scenarios, and the models cannot be trusted for engineering design of high-frequency links.

4.2.3. Scarcity of high-quality measurement data and insufficient multi-source data fusion

Both physics-based and machine-learning models depend heavily on large volumes of labeled attenuation data, yet terahertz link measurements remain sparse worldwide. Test platforms are still at an early stage, and data collected under normal conditions are limited; measurements in complex or extreme environments (heavy rain, mixed haze-fog, extreme temperatures) are virtually absent.

DOI: 10.54254/2755-2721/2026.GL36378

Although multi-source atmospheric datasets such as ERA5 reanalysis and satellite remote sensing products can partially fill the gap, their spatial and temporal resolutions often misalign with the fine scale required for link attenuation modeling, reducing the effective training error reduction to only 15-20%. This fundamental shortage of real-world measurements, combined with insufficient data fusion techniques, severely degrades model performance when applied to new climatic regions. The atmospheric environment exhibits strong regional variability, tropical humidity, arid-zone aerosol dominance, and temperate seasonal coupling, yet most models are parameterized for specific locales. Their accuracy drops sharply elsewhere, requiring labor-intensive manual recalibration that limits large-scale engineering adoption [2].

4.3. Limitations

This paper gives a comprehensive review of 6G terahertz satellite-ground link attenuation prediction, but it relies entirely on published data and existing literature. It does not include original field measurements or simulation experiments. Future research will use real test data to verify and optimize the coupling-aware prediction framework discussed herein, thereby strengthening the practical foundation for terahertz link design.

5. Conclusion

Terahertz communication is a core enabling technology for 6G space-air-ground integrated networks (SAGINs). Accurate attenuation prediction is a critical prerequisite for its real-world engineering deployment, and has thus emerged as a key research focus at leading international conferences in recent years. This paper systematically reviews the research progress of 6G terahertz satellite-ground link attenuation prediction technology: it elaborates on the core attenuation mechanisms (free space propagation loss and atmospheric attenuation), classifies and compares three types of mainstream models (classical empirical, physical, machine learning-based), and summarizes current research hotspots (multi-parameter coupling, high-frequency model optimization, multi-source data fusion) and key problems (poor regional adaptability, scarce measured data, unbalanced accuracy and efficiency).

However, this paper has limitations as it relies on second-hand data and existing literature, without independent experimental validation. Addressing this gap through field measurements represents an essential next step toward robust, deployment-ready prediction models for next-generation satellite-ground links.

References

[1] Gao, W., Han, C., & Chen, Z. (2023). Scintillation and attenuation modelling of atmospheric turbulence for terahertz UAV channels. *arXiv Prepr. arXiv:2305.08820*. https://doi.org/10.48550/arXiv.2305.08820

[2] Yang, Z., Gao, W., & Han, C. (2023). A universal attenuation model of terahertz wave in space-air-ground channel medium. *ResGate*.

[3] Tamosiunaite, M., Tamosiunas, S., Zilinskas, M., & Valusis, G. (2017). Atmospheric attenuation of the terahertz wireless networks. In A. Haidine & A. Aqqal (Eds.), *Broadband communications networks - recent advances and lessons from practice* (pp. 115–142). InTechOpen. https://doi.org/10.5772/intechopen.72205

[4] Strecker, K., Ekin, S., & O'Hara, J. (2021). Fundamental performance limits on terahertz wireless links imposed by group velocity dispersion. *arXiv Prepr. arXiv:2104.00611*. https://doi.org/10.48550/arXiv.2104.00611

[5] Yi, J., Gao, W., & Han, C. (2025). Diffusion-driven terahertz air-ground communications under dynamic atmospheric turbulence. *arXiv Prepr. arXiv:2511.03290*. https://doi.org/10.48550/arXiv.2511.03290