Advanced Technologies Journal of University of Benghazi (ATJOUB)

ATJOUB (2026) 1 (1), DOI:
Original Article– Communication Engineering

Intelligent Reflecting Surface-Empowered Terahertz Wireless Communications

Mawada Abdulaziz Algaddari, Arwa Raouf Alfalah, Arwa Ahmed Alagoury, Basmalah Yousef Abdulhadi and Abdelhamid Salem

Department of Electrical Engineering, Faculty of Engineering, University of Benghazi, Libya

Authors' emails: eng.30290@uob.edu.ly; eng.28803@uob.edu.ly; eng.30303@uob.edu.ly; eng.30068@uob.edu.ly;

abdelhamid.albaraesi@uob.edu.ly

Abstract

This article investigates the integration of Intelligent Reflecting Surface (IRS) technology into Terahertz (THz) wireless communication systems to enhance transmission reliability and coverage. Although THz communications can support ultra-high data rates and massive network capacity, they are highly susceptible to severe path loss, molecular absorption, and blockage effects, which significantly restrict transmission distance and link stability. To overcome these limitations, an IRS is deployed to intelligently reconfigure the wireless propagation environment by reflecting and steering THz signals toward the receiver, particularly when the direct link is obstructed. The study analyzes the impact of IRS-assisted THz communications on system coverage and overall performance. The results demonstrate that the incorporation of IRS technology substantially enhances system capacity, coverage, and communication reliability. Furthermore, the findings highlight that efficient IRS configuration and system design are essential for realizing the full potential of THz communications in next-generation wireless networks.

1. Introduction

Over the past decades, wireless systems have evolved significantly from early technologies to advanced cellular networks, leading to substantial improvements in data rates, coverage, and communication reliability. With the emergence of sixth-generation (6G) networks, research attention has shifted toward high-frequency bands, particularly the terahertz (THz) spectrum, due to its extremely wide bandwidth and its ability to support ultra-high-speed communication services [1]. THz communication systems can deliver data rates in the order of terabits per second (Tbps), making them suitable for advanced applications such as ultra-high-definition video streaming, holographic communication, immersive technologies, and smart connected systems [1]. Despite these advantages, THz systems face significant challenges, especially in indoor environments. The high carrier frequency leads to severe propagation losses, while molecular absorption and sensitivity to obstacles further degrade signal quality. These issues are particularly critical in non-line-of-sight (NLoS) scenarios, where the direct path between the transmitter and receiver is blocked, resulting in weak and unstable received signals and limiting the overall reliability of the communication system [1] [2]. From a standardization perspective, ETSI has initiated efforts to define technical foundations for THz communication systems, including use cases, deployment scenarios, and strict performance requirements such as multi-Tbps data rates and sub-millisecond latency [1]. In addition, several studies have investigated THz wireless channel modeling and measurement techniques. These include frequency-domain-based methods and time-domain sliding correlation [2]. Environmental effects such as fog, rain, and atmospheric absorption significantly impact THz communication performance. Results in [3], showed that frequency, visibility, and rainfall rate strongly influence attenuation, while temperature and particle distribution have less impact, these effects degrade link quality and require accurate channel modeling [3]. Furthermore, the study in [4] explained that molecular absorption, scattering, and turbulence not only degrade performance but also increase vulnerability to eavesdropping, requiring more robust system designs [4].

In addition, IRS technology is described as a passive surface capable of controlling phase and amplitude of signals to achieve directional beamforming, signal enhancement, and interference mitigation, making it a key enabler for future wireless networks. IRS-assisted THz communication has been investigated to overcome the limitations in THz communications. In [5] IRS has been used to enhance coverage by intelligently reconfiguring the propagation environment using passive reflecting elements, enabling signal direction control and performance improvement [5]. The authors in [6], presented a survey on intelligent surfaces, highlighting their integration with THz systems, including architecture, operation, and channel modeling approaches [6]. In [7] IRS-assisted THz systems have been studied with a focus on beamforming, beam steering, and practical implementation strategies. This work showed that joint active and passive beamforming improves communication quality and reduces blockage effects in THz networks [7]. In [8]-[10] IRS-assisted communication systems are analyzed under far-field and near-field conditions. The results in these works showed that increasing IRS size improves the communications quality and enhances coverage performance, making it an effective technique for THz systems. Finally, IRS assisted THz systems introduce advanced coverage capabilities. However, system performance is affected by inter-user interference, beam misalignment, fog, and quantization errors, which significantly impact capacity and reliability [10].

Accordingly, this work investigates IRS-assisted THz communication systems under realistic channel conditions, aiming to enhance coverage and mitigate severe propagation losses. The study provides a comprehensive performance evaluation considering environmental effects and system configurations to improve the reliability of future wireless networks. The study aims to analyze the impact of propagation challenges, including path loss and molecular absorption, and to evaluate the IRS deployment in effectively mitigating these impairments. In addition, the work seeks to assess overall system performance under realistic conditions and explore suitable approaches to enhance communication reliability in future wireless networks.

2. System model

We consider a THz communication system where a base station (BS) equipped with N antennas transmits data to a user with the assistance of an IRS equipped with M elements. Due to severe path loss and molecular absorption in the THz frequency bands, the direct BS–user link may be weak or even blocked. To mitigate this, an IRS is deployed to enhance signal propagation by intelligently reflecting incident signals. The overall system model is illustrated in Fig1.

The IRS consists of M passive reflecting elements, each able to adjust the phase of incoming signals. By configuring these phase shifts, the IRS coherently combines reflected signals to enhance the received signal strength at the user. Communication mainly depends on the cascaded base station BS-IRS and IRS-user links, with the direct BS-user link considered depending on propagation conditions. Path loss, atmospheric absorption, and additive noise affect the quality of the received signal. The IRS enhances communication performance by compensating channel impairments and improving signal quality at the receiver. Furthermore, the channels are modeled using Rician fading to account for both Line-of-Sight and Non-Line-of-Sight propagation conditions.

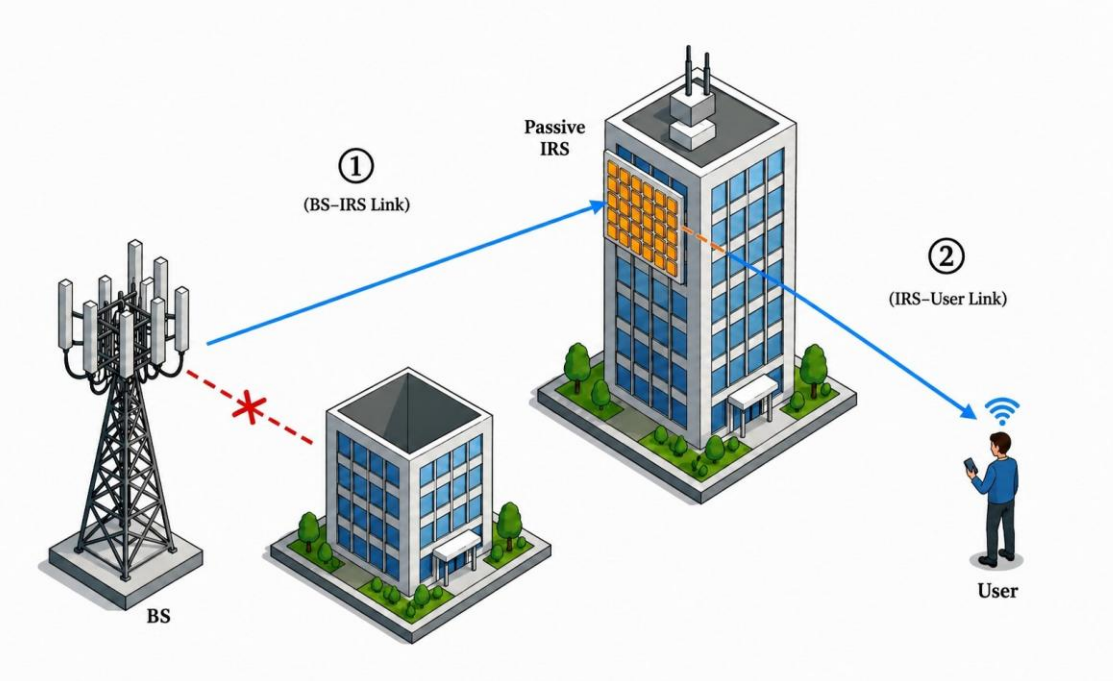

Fig1. IRS-assisted THz system.

2.1 THz Channel model

a) Path Loss and Molecular Absorption

In THz wireless communication, signal attenuation is significantly influenced by both free space path loss and molecular absorption. The latter is primarily caused by atmospheric particles such as water vapor and oxygen, which absorb THz energy during propagation. channel coefficient for path loss and molecular absorption, h_r, captures these effects and is mathematically expressed as follows:

$$h_r = \sqrt{\frac{G_{Bs}G_r}{64\pi^3}\frac{c}{f d_{BS} d_r}} exp\left(-\frac{k_\alpha(f)(d_{BS}+d_r)}{2}\right) \quad (1)$$

where G_{Bs} and G_r denote the antenna gains of the BS and the IRS–user link, respectively; f is the carrier frequency and c is the speed of light; and d_{BS} and d_r represent the distances between the BS and the IRS and between the IRS and the user, respectively. Moreover, $k_\alpha(f)$ it is the frequency-dependent molecular absorption coefficient. The frequency-dependent molecular absorption coefficient $k_\alpha(f)$ quantifies the signal attenuation caused by atmospheric molecules. It varies with frequency and atmospheric composition and plays a key role in modeling THz propagation loss and is given by.

$$k_\alpha(f) = \frac{\alpha_1(\rho)}{\alpha_2(\rho)+(\frac{f}{100c} - C_1)^2} + \frac{\alpha_3(\rho)}{\alpha_4(\rho)+(\frac{f}{100c} - C_2)^2} + \varrho_1 f^3 + \varrho_2 f^2 + \varrho_3 f + \varrho_4 \quad (2)$$

Where $\alpha_1(\rho) = 0.2205\rho(0.1303\rho + 0.0294)$, $\alpha_2(\rho) = (0.4093\rho + 0.0925)^2$, $\alpha_3(\rho) = 2.014\rho(0.1702\rho + 0.0303)$, $\alpha_4(\rho) = (0.537\rho + 0.0956)^2$, $C_1 = 10.835\ cm^{-1}$, $C_2 = 12.664\ cm^{-1}$, $\varrho_1 = 5.54 \times 10^{-37} Hz^{-3}$,

$\varrho_2 = -3.94 \times 10^{-25} Hz^{-2}$, $\varrho_3 = 9.06 \times 10^{-14} Hz^{-1}$, $\varrho_4 = -6.36 \times 10^{-3}$, and ρ is the volume mixing ratio of the water vapor. After modeling the THz channel coefficient and the molecular absorption effect, the parameter ρ, which represents the water vapor concentration in the propagation environment, is introduced and is expressed as

$$\rho = \phi \mathrm{H} \left(\frac{0.06116}{\varrho} + \frac{2.1148}{10^{7}} \right) \exp\left(\frac{17.502T}{240.97 + T} \right) \quad (3)$$

where ϕ, H , ϱ and T denote the relative humidity, atmospheric pressure, and temperature, respectively.

b) Misalignment Fading Coefficients

In THz systems, highly directional beams are vulnerable to pointing errors caused by thermal expansion, vibrations, or mechanical misalignment. These errors lead to fluctuations in the received signal power, commonly referred to as misalignment fading. To model this phenomenon, a probability density function (PDF) is used to characterize the random variations in the received power fraction due to beam misalignment. The misalignment fading coefficient is expressed as follows,

$$f_{h_{p,m}}(X) = \xi_m {A_m}^{-\xi_m} x^{\xi_m - 1} \quad , \quad 0 \leq x \leq A_m \quad (4)$$

With

$$A_m = \left[erf\left(\sqrt{\frac{\pi}{2}} \frac{a_r}{\omega \, d_{BS}} \right) \right]^2 \quad (5)$$

where $\xi_m = \frac{w^2{}_m}{4\sigma^2{}_m}$ denotes the ratio between the equivalent beamwidth and the pointing error displacement severity. $\sigma^2{}_m$ represents the variance of the pointing error displacement. while A_m represents the fraction of power collected by the receiver under perfect alignment conditions . Furthermore, $w^2{}_m$ and X_m are given as follows:

$$w^2{}_m = \frac{w^2{}_{d_{BS}} \, \mathrm{erf}(X_m)\sqrt{\pi}}{2X_m \exp(-X^2{}_m)} , \quad X_m = \sqrt{\frac{\pi}{2}} \frac{a_r}{w_{d_{BS}}} \quad (6)$$

c) Random Foggy Conditions

In order to incorporate the effect of random foggy conditions on the terahertz wireless channel, an additional attenuation term is introduced. This attenuation arises due to reduced visibility caused by fog particles, which results in signal degradation along the propagation path. Assuming spatially uniform fog distribution, the total fog-induced loss is modeled as an exponential decay function, dependent on the combined distance between the base station and the receiver. The corresponding channel attenuation due to fog is expressed as follows:

$$h_{f,m} = \exp\left(-\frac{\beta\,(d_{BS}+d_r)}{4343}\right) \quad (7)$$

Where β denotes different fog conditions, ranging from light to dense fog.

3. Signal Model

We can write the received signal at the user as:

$$\mathrm{y} = \zeta g^{H}\Theta\mathrm{H}\mathrm{w}x + n \; (8)$$

Where H denotes the small-scale fading channel matrix between the BS and IRS, while g^{H} represents the Hermitian transpose of the channel vector between the IRS and the user, $\zeta = h_r\, f_{h_{p,m}}\, h_{f,m}$ and Θ represents the IRS reflection matrix that controls the phase shifts of the reflecting elements. The precoding vector w is designed using Maximum Ratio Transmission (MRT). The transmitted symbol x denotes the information-bearing signal, while n represents the additive white Gaussian noise (AWGN).

The received signal propagates through the cascaded BS-IRS-user channel, where the IRS optimizes its phase shifts to enhance signal propagation and improve the received signal quality.

The received signal to noise ratio (SNR) can be written as,

$$\gamma = \frac{p|\zeta g\Theta Hw|^2}{\sigma^2} \quad (9)$$

And the rate at the user in (bits/s) can be written as

$$R = B\log_2(1+\gamma) \quad (10)$$

where B is the Band-width.

3.1 IRS Phase Shift Design

The phase shifts should be designed to maximize the received signal power in IRS-assisted THz systems. Therefore, the optimal phase shifts are selected to maximize the rate at the user. we can formulate the optimization problem as

$$\max_{\Theta} R \quad (11)$$

Assuming perfect channel state information (CSI) , in this work for simplicity we select the phase shifts to achieve coherent combining at the user. Therefore, the phase shift at k-th element is designed as

$$\Theta_k = \exp(j[\arg(h_k) - \arg(g_k)] \ (12)$$

This phase adjustment aligns the cascaded channel phases, enabling constructive interference and thereby enhancing the received signal strength.

4. Results

This section presents the simulation results of the IRS-assisted THz communication system. The analysis assesses the impact of multiple transmit antennas on signal strength, diversity, and overall system capacity. Furthermore, it examines the effects of environmental factors such as molecular absorption, fog attenuation, and the IRS-user distance on system performance, offering insights into system behavior under practical conditions.

The simulation parameters are summarized as follows: The carrier frequency and bandwidth are both set to **1 THz**. The Rician K-factor is fixed at **9 dB**. The transmit power, $\boldsymbol{Pt}$ varies from **0 to 10 W** to evaluate its impact on the capacity performance of the proposed IRS-assisted THz communication system. The number of IRS elements is set to **M = 32**, and the number of transmit antennas is **N = 4**. Noise Variance $\boldsymbol{\sigma^2} = \mathbf{10^{-7}}$W. The distance between the BS and the IRS is fixed at **10 m**, while the IRS-user distance varies as **2 m, 6 m, and 12 m**.

The comparison between IRS-assisted and conventional THz systems is illustrated in Fig.2 It is observed that the IRS-assisted system achieves significantly higher capacity, especially at higher transmit power, while the conventional system, without IRS remains limited due to obstacles.

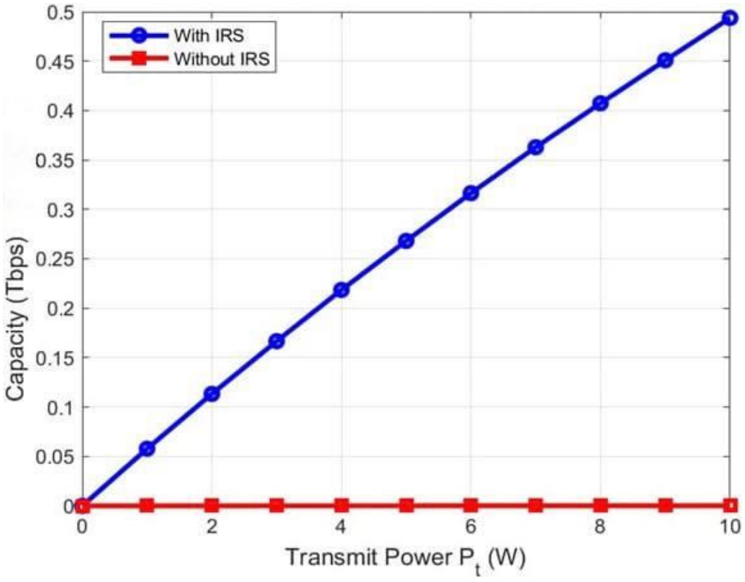

Fig2. Capacity comparison with/without IRS.

Fig.3 illustrates the impact of molecular absorption and the transmit power on the system capacity. As we can notice from this result, the system capacity increases with transmit power, indicating that higher power improves SNR and enhances overall system performance. In addition, increasing the molecular absorption (a_l) reduces system capacity due to higher signal attenuation in the propagation medium.

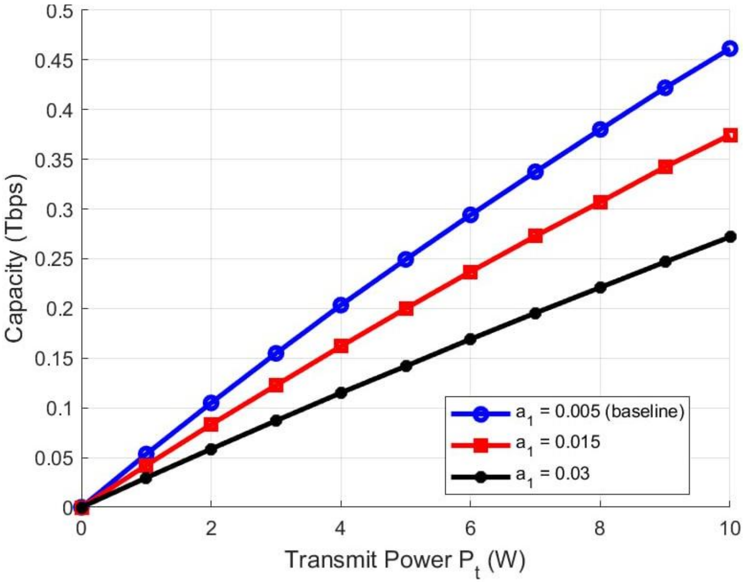

Fig3. Impact of Molecular Absorption on Capacity.

Fig.4 examines the impact of fog attenuation factor on system capacity. Higher fog attenuation significantly degrades system capacity due to increased channel losses.

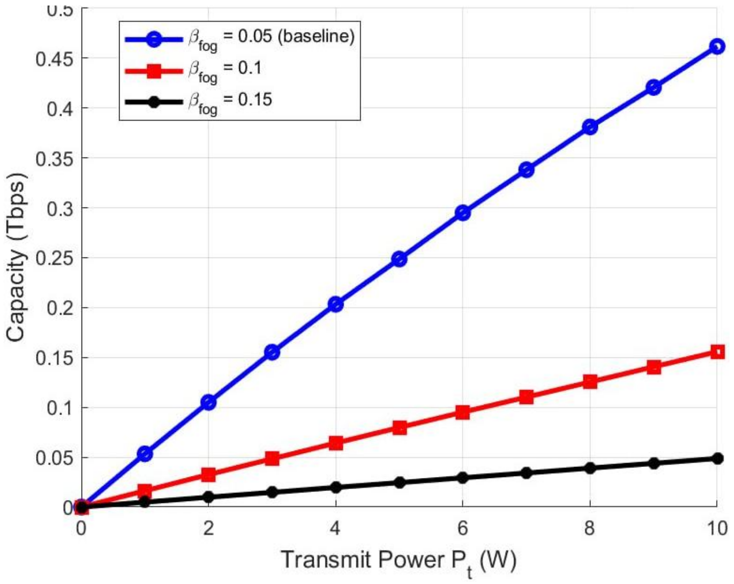

Fig4. Impact of Fog Attenuation on Capacity

Fig.5 analyzes the impact of the IRS-to-user distance on system capacity. Reducing the IRS-to-user distance improves system capacity by minimizing propagation losses and enhancing the received signal strength.

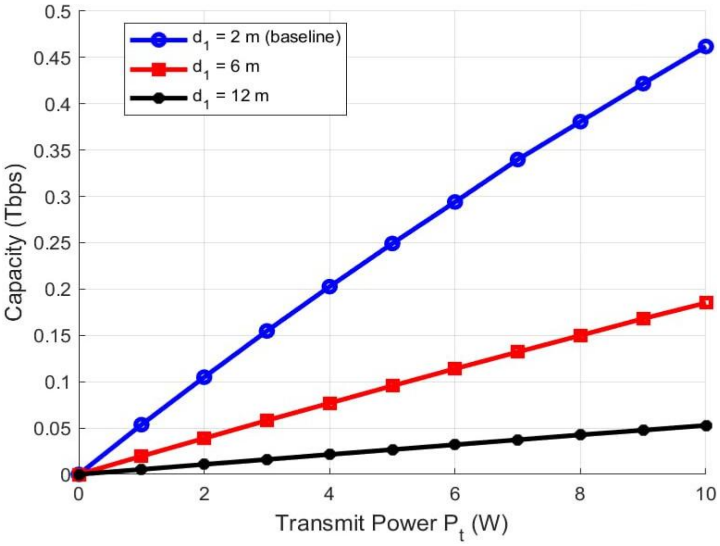

Fig5. Impact of IRS-to-User Distance on System Capacity

The effect of IRS phase shift variation on system capacity is illustrated in Fig.6. The optimal phase shifts have better performance than the random ones. Thus, IRS phase shifts should be designed to maximize the THz system performance.

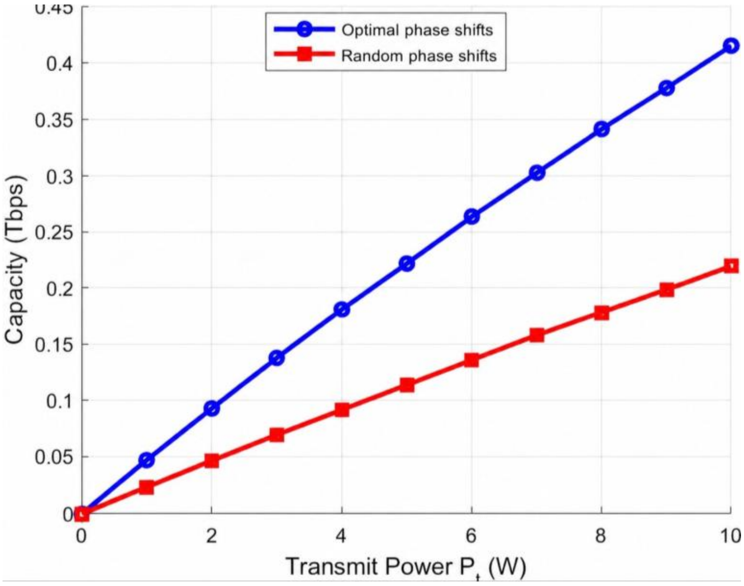

Fig6. Impact of IRS Phase Shift Variation on System Capacity.

5. Conclusion

This article investigated the performance of an IRS-assisted THz communication system through extensive simulations, focusing on environmental impacts, IRS-to-user distances, and phase shift designs. The results demonstrate that the IRS significantly enhances THz communication performance by improving signal propagation in obstructed environments by up to 0.5Tpbs. The IRS provides spatial diversity and beamforming gains, leading to a marked improvement in achievable capacity. Additionally, channel impairments such as molecular absorption, fog attenuation, and increased IRS-to-user distance were found to degrade system capacity due to higher propagation losses, whereas lower attenuation conditions improved spectral efficiency and overall performance.

References

[1] T. Zugno et al., "Use Cases for Terahertz Communications: An Industrial Perspective," *in IEEE Wireless Communications*, vol. 32, no. 1, pp. 90-98, February 2025, doi: 10.1109/MWC.001.2400060.

[2] X. Liao, L. Fan, Y. Wang, Z. Yu, G. Wang, X. Li, and J. Zhang, "Attenuation Characterization of Terahertz Waves in Foggy and Rainy Conditions at 0.1–1 THz Frequencies," *in Electronics,* vol. 12, no. 7, Art. no. 1684, 2023, doi: 10.3390/electronics12071684.

[3] C. Han et al., "Terahertz Wireless Channels: A Holistic Survey on Measurement, Modeling, and Analysis," *in IEEE Communications Surveys & Tutorials,* vol. 24, no. 3, pp. 1670-1707, third quarter 2022, doi: 10.1109/COMST.2022.3182539.

[4] J. Ma, Y. Song, M. Zhang, G. Liu, W. Li, J. F. Federici, and D. M. Mittleman, "Terahertz Channels in Atmospheric Conditions: Propagation Characteristics and Security Performance," *Fundamental Research*, vol. 5, no. 2, pp. 526-555, 2025, Mar. 2025, doi: 10.1016/j.fmre.2024.09.012.

[5] H. Cao, M. Boban, and J. Eichinger, "Terahertz Communications Enhanced by IRS," *in 2021 IEEE 32nd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Helsinki, Finland, 2021, pp. 1-5, doi: 10.1109/PIMRC50174.2021.9569557.

[6] E. Silva, J. D. S. Ribeiro, V. F. Adanvo, S. B. Mafra, L. L. Mendes, Y. Li, and R. A. A. de Souza, "A Survey on the Impact of Intelligent Surfaces in the Terahertz Communication Channel Models," *in Sensors*, vol. 24, no. 1, Art. no. 33, 2024, doi: 10.3390/s24010033.

[7] Z. Chen, B. Ning, C. Han, Z. Tian, and S. Li, "Intelligent Reflecting Surface Assisted Terahertz Communications Toward 6G," *in IEEE Wireless Communications*, vol. 28, no. 6, pp. 110-117, December 2021, doi: 10.1109/MWC.001.2100215.

[8] Q. Wu and R. Zhang, "Towards Smart and Reconfigurable Environment: Intelligent Reflecting Surface Aided Wireless Network," *in IEEE Communications Magazine,* vol. 58, no. 1, pp. 106-112, January 2020, doi: 10.1109/MCOM.001.1900107.

[9] X. Fu, R. Peng, G. Liu, J. Wang, W. Yuan, and M. Kadoch, "Channel Modeling for RIS-Assisted 6G Communications," *in Electronics,* vol. 11, no. 19, Art. no. 2977, 2022, doi: 10.3390/electronics11192977.

[10] A. M. T. Khel and K. A. Hamdi, "Analytical Performance Evaluation of STAR-RIS Assisted Terahertz Wireless Communications," *in IEEE Transactions on Vehicular Technology,* vol. 73, no. 4, pp. 5500-5515, April 2024, doi: 10.1109/TVT.2023.3336260.

Cite this paper as: