A systematic literature review on electromagnetic wave propagation challenges in 5G/6G mmWave and THz bands and emerging physics informed mitigation strategies

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Abstract: Basic physics governs the propagation of electromagnetic waves in the millimeter wave (mmWave: 24–100 GHz) and terahertz (THz: 0.1–10 THz) ranges, as well as Maxwell's equations, molecular resonance phenomena, and the dielectric response of materials. Although 5G and 6G systems utilize these high frequency ranges to achieve terabit per second data rates, their performance is inherently limited not by technical constraints, but by the intrinsic interaction of waves with matter. The main physical obstacles include atmospheric absorption due to water vapor, free space path loss that increases quadratically with frequency, and extremely shallow skin depth in common building and biological materials, making even thin barriers highly impervious to mmWave and THz signals. This paper provides a systematic literature review (SLR) that was carried out following the recommendation of PRISMA 2020 to synthesize physics grounded propagation challenges and mitigation strategies. From an initial collection of 46 Scopus indexed and peer reviewed articles published between 2020 and 2025, 20 high quality studies were selected for thematic synthesis based on a five-point methodological checklist. The study demonstrates that novel approaches like AI-based channel modeling cell-free Massive MIMO FeO_3 enriched building composites and Reconfigurable Intelligent Surfaces (RIS) strategically use wave interference tunable permeability and real-time environmental awareness to improve signal delivery rather than breaking the laws of physics. By bridging the conceptual divide between communications engineering and basic electromagnetics this study provides a cohesive physics framework that will direct future studies in 5G and 6G wireless systems.

Keywords: Reconfigurable Intelligent Surfaces (RIS), 5G, 6G mmWave, THz, Electromagnetic Wave Propagation

1. Introduction

The core idea behind wireless communication systems is classical electromagnetism in which data is encoded in time-varying electric and magnetic fields that move through material media or free space. At its heart is the process of electromagnetic wave propagation a phenomenon that Maxwells equations accurately describe. According to these equations electromagnetic waves interact with matter through absorption scattering diffraction refraction and reflection. Importantly these interactions are not just engineering roadblocks they are a direct expression of deeper physical principles like energy conservation materials frequency-dependent dielectric response and the quantum mechanical rotational transitions of atmospheric molecules at terahertz frequencies like water vapor (Salous et al. 2022).

The 5G and 6G wireless systems strategically shifted toward higher-frequency spectral bands particularly millimeter waves (mmWave: 24-100 GHz) and terahertz waves (THz: 0. 1-10 THz) to satisfy the increasing demand for terabit-per-second data rates and submillisecond latency (Akyildiz et al. in 2020). Nevertheless this change exacerbates the effects of inherent physical limitations. Compared to conventional sub-6 GHz bands which scale quadratically with frequency and suffer from significant atmospheric attenuation from resonant absorption by water vapor molecules the free space route loss for mmWave and THz communications is significantly greater (Serghiou et al. in 2022). Furthermore even thin barriers like walls vegetation or the human body are effectively impervious to signal penetration due to the incredibly shallow skin depth of these waves in common biological and building materials

Even though recent studies have brought attention to the shortcomings of a number of technologies including artificial intelligence (AI)-based channel prediction cell-free Massive MIMO and Reconfigurable Intelligent Surfaces (RIS) some of these solutions are used in difficult physical work environments. The adoption of communication technologies is one of the most difficult tasks and it frequently requires using fundamental electromagnetic theory to identify issues and create workable solutions (Giordani et al. 2020). Physical wave science principles and wireless application studies are therefore conceptually separated.

These difficulties stem from properties of the interaction between high-frequency waves and matter rather than from flawed hardware. For example, the complex permeability $\varepsilon' - j\varepsilon''$ of a mediu determines both energy storage (ε') and conductive loss $\left(\varepsilon'' = \frac{\sigma}{\omega}\right)$, which directly affect the attenuation coefficient α and phase constant β of the propagation constant $\gamma = \alpha + j\beta$. Therefore, a viable solution must respect these physical constraints rather than circumvent them.

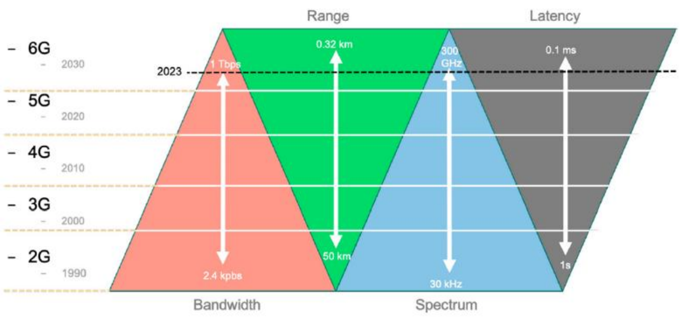

Figure 1. The Evolution of Mobile Technology from 2G to 6G (1990–2030): Relationship Between Bandwidth, Frequency Spectrum, Latency, and Range (Abbas et al., 2024)

Cellular technology has advanced significantly between 1990 and 2030, as evidenced by improvements in bandwidth, frequency spectrum, latency, and overall latency. The frequency range from 30 kHz to 300 GHz, the drop in latency from 1 s to 0.1 ms, and the increase in bandwidth capacity from 2.4 kbps to 1 Tbps are all depicted in the image. The relationship between bandwidth and range over time is explained, showing that more bandwidth results in a smaller signal range. By anchoring technological developments in first principles electromagnetism, this work aims to provide a theoretical foundation of relevance to physics oriented journals such as the Journal of Physics: Theories and Applications.

2. Method

A systematic literature review (SLR) technique was used in this study in compliance with the PRISMA 2020 standards (Page et al., 2021). In August 2025, a thorough search was carried out using IEEE Xplore, ScienceDirect, and SpringerLink, three databases that are indexed by Scopus. Peer-reviewed journal articles that addressed electromagnetic or radio wave propagation in the context of 5G or 6G networks, specifically within millimeter wave or terahertz frequency bands, and that addressed difficulties, constraints, mitigation strategies, or technical solutions were the main focus of the search strategy. The articles had to be published between January 2020 and December 2025.

Forty-six records were found in the first search. 26 records were deemed irrelevant after titles and abstracts were screened for relevance to mmWave/THz propagation physics. Three inclusion criteria, (i) empirical measurements or validated simulations carried out at frequencies of 24 GHz or higher, (ii) explicit discussion of underlying physical propagation mechanisms, and (iii) evaluation of mitigation strategies based on physical principles were used to rigorously evaluate the eligibility of the remaining 20 full-text articles. A five-point quality checklist was used to assess each study in order to ensure methodological rigor: (1) a clear operational frequency specification (≥24 GHz) (2) quantifiable results on mitigation efficacy or propagation properties (3) a repeatable technique (4) an explanation of physical processes like absorption diffraction or skin depth effects and (5) a reference to original measurement or simulation data. The final synthesis contained only those studies that received at least four out of five points.The PRISMA flow diagram is shown in Figure 2.

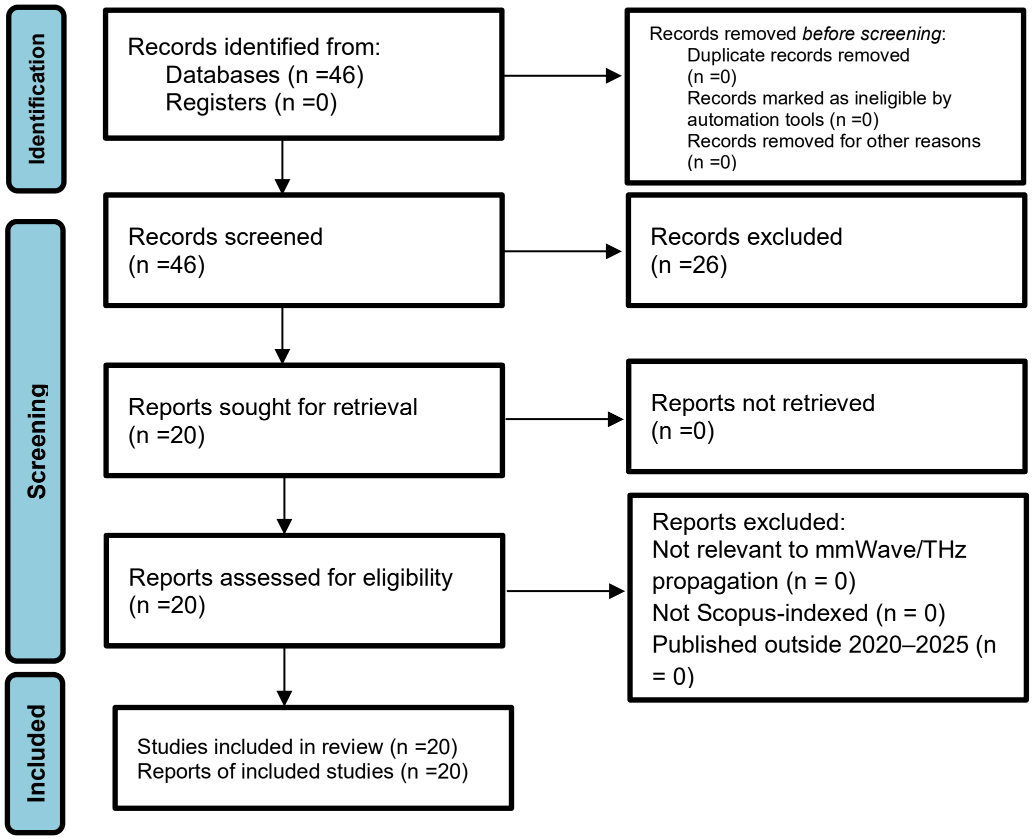

Figure 2. PRISMA Flow Chart

3. Results and Discussion

3.1 Propagation Challenges in 5G Networks (mmWave)

The main challenges of 5G propagation are summarized in Table 1, which shows that channel models such as NYUSIM are necessary for prediction accuracy.

Table 1. Propagation Challenges in 5G Networks (mmWave)

No	Author & Year	Title	Key Findings
1	(Sohaib, 2020)	Analysis of Channel Modelling for 5G mmWave Communication	Multipath modeling for channel modeling mmWave (28–73 GHz): is susceptible to rain and blockage and needs accurate multipath NYUSIM models.
2	(Ng et al., 2022)	Electromagnetic wave propagation through composite building materials in urban environments at mid-band 5G frequencies	Blocks (Fe2O3) mid band 5G attenuation which aids in building penetration.
3	(Oladimeji et al., 2022)	Propagation path loss prediction modelling in enclosed environments for 5G networks: A review	A final review study on 5G communications path loss prediction models found that Close-In (CI) and Floating Intercept (FI) models performed best in all instances and were stable across both circumstances of Line of Sight (LOS) and Non-Line of Sight (NLOS).
4	(Korkmaz et al., 2024)	A comprehensive review of 5G NR RF-EMF exposure assessment technologies: fundamentals, advancements, challenges, niches, and implications	5–25 GHz rain scattering and attenuation simulation: drops cause remarkable scattering.

5	(Yáñez-Casas et al., 2023)	Scattering and Attenuation in 5G Electromagnetic Propagation (5 GHz and 25 GHz) in the Presence of Rainfall: A Numerical Study	Electromagnetic waves' unstable air and building materials a complex propagation constant describes waves propagation in:

For free space propagation the dominant loss is free space path loss (FSPL) and is calculated using:

$$\boldsymbol{\gamma = \alpha + j\beta = j\omega\sqrt{\mu\varepsilon_c}}$$

Where $\varepsilon c = \varepsilon' - j\varepsilon''$ is the complex permittivity, with ε' representing the material's ability to store energy and $\varepsilon''=\sigma/\omega$ declaring conductive losses due to conductivity σ. From this, the attenuation coefficient α (in dB/m), which describes it is possible to calculate the signal attenuation per unit distance as follows:

$$\boldsymbol{\alpha = \omega\sqrt{\frac{\mu\varepsilon'}{2}\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right)}}$$

For propagation in free space, the dominant losses originate from the square law of distance and frequency governs free space path loss (FSPL):

$$\boldsymbol{FSPL = \left(\frac{4\pi df}{C}\right)^2}$$

5G mmWave signals (28–73 GHz) in the lines of sight conditions are limited, and the walls, rain, and human bodies highly attenuate the signals. With the increase of 10 in frequency, the power loss of 20 dB is shown in the above equation.

3.2 Propagation Challenges in 6G Networks (THz)

Table 2. Propagation Challenges in 6G Networks (THz)

No	Author & Year	Title	Key Findings
1	(Akyildiz et al., 2020)	6G and Beyond: The Future of Wireless Communications Systems	This article considers the case for capacity in the order of Tbps, latency thresholds of 1 ms, and ultra massive IoT. The primary constraints continue to be high attenuation within the THz band and the 5G spectrum. Suggested mitigations focus on the THz band, smart surfaces, cell-free massive MIMO, and the Internet of Space Things.
2	(Gustavsson et al., 2021)	Implementation Challenges and Opportunities in Beyond 5G & 6G Communication	There are hardware and energy consumption concerns for distributed MIMO at sub-THz frequencies; this drawback can be mitigated by radio stripes and energy harvesting.
3	(Chowdhury et al., 2020)	6G Wireless Communication Systems: Applications, Requirements, Technologies, Challenges and Research Directions	Research efforts have focused on vision for 6G, which integrates AI, the THz band, and IRS (intelligent reflecting surfaces), with proposed advances in holographic beamforming and UAV-assisted networking. The primary challenges continue to be the 5G limitations in network capacity, latency, and QoS expectations.
4	(Salous et al., 2022)	5G to 6G: A Paradigm Shift in Radio Channel Modeling	This work investigates the shift in channel modeling as practitioners move from 5G to 6G. The primary difficulties posed relate to

			high path loss, poor diffraction, and weak wave penetration across the mmWave to THz spectrum.
5	(Serghiou et al., 2022)	Terahertz Channel Propagation Phenomena, Measurement Techniques and Modeling for 6G Wireless Communication Applications	This work shows that channel measurements in THz range are interfered with by the environment and require deterministic and stochastic fusion. The channels are modeled with the Saleh-Valenzuela and NGBSM approaches, among others.

6G networks working at the terahertz (THz) spectrum encounter even more difficult obstacles. Between 0.1 and 10 THz, signals can vanish in mere centimeters. This is the result of molecular absorption, predominantly of water vapor. From a physical perspective, this is a manifestation of the Beer Lambert Law:

$$\boldsymbol{I = I_0 e^{-\alpha x}}$$

where the value of the attenuation coefficient α increases in the resonance in the range of H2O molecular absorption. (Serghiou et al, 2022) shows that at 0.56 THz and 1.1 THz, signals can drop by several dB in merely 10 cm. This is a fundamental physical law, not a mere technical challenge. Furthermore, because the skin depth is a great deal smaller, THz waves do not penetrate solid materials, even glass and clothing. (Akyildiz et al., 2020) calls these waves “existential barriers” and (Salous et al., 2022) calls for the creation of hybrid channel models that fuse constructive deterministic physics with stochastic processes to model real life unsupervised physics of the environment.

3.3 Technical Solutions to Overcome Propagation Challenges

Older literature speaks of Intelligent Reflecting Surfaces (IRS), and more recent work refers to Reconfigurable Intelligent Surfaces (RIS). Both terms define the same passive technologies that modify the directed flow of electromagnetic radiation to enhance the quality of signals. In this article, the term RIS is used in general analysis, while the original term (IRS) is retained when summarizing specific findings from related studies.

A review involving twenty studies indicates that there are three overarching strategies to reduce problems with propagation: manipulating the signal by utilizing advanced antennas (beamforming, Massive MIMO), engineering or adapting the environment to aid propagation (Reconfigurable Intelligent Surfaces/RIS) and automating via AI/ML. Engineering of building material also creates additional possibilities for signal propagation reduction. That is, for example, (Ng et. al, 2022) saw 5G waves greatly mitigated through the mortar, shown in Figure 3, because they added 2 wt% Fe_2O_3 to mortar. In particular, the attenuation constant (the control material) went down 16 dB/m (from 96.7 dB/m to 80.7 dB/m). The evidence suggests at mid band 5G frequencies (e.g., 3.5 GHz), the incorporation of 2 wt% Fe_2O_3 into mortar reduced the attenuation constant from 96.7 dB/m to 80.7 dB/m (Ng et al., 2022), suggesting potential for designing building materials with improved electromagnetic transparency. However, the dielectric response of such composites is highly frequency dependent, and their performance at mmWave (≥24 GHz) or THz frequencies remains unverified and requires dedicated characterization. Therefore, this would allow urban infrastructure to be ramified on cities to allow effective wave (i.e. 5G) propagation as opposed to blocking it.

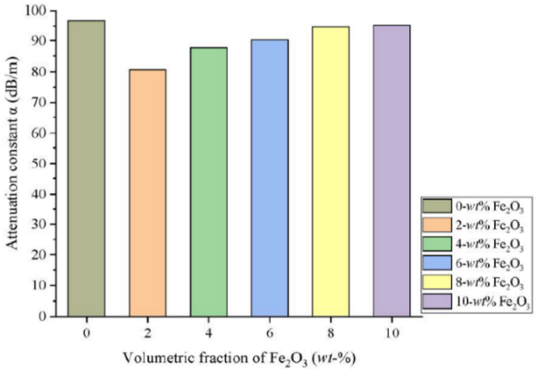

Figure 3. Attenuation constant (α) for mortar with varying Fe_2O_3 concentrations at a frequency of 3.5 GHz. The lowest attenuation (80.7 dB/m) was achieved at a concentration of 2 wt% Fe_2O_3, compared to the control material (96.7 dB/m).

The newest technical pathways are summarized in Table 3, including RIS integration, AI, and hybrid networks.

Table 3. Technical Solutions to Overcome Propagation Challenges

No	Author & Year	Title	Key Technical Approach	Summary Of Findings
1	(Shayea et al., 2024)	Integration of 5G, 6G and IoT with Low Earth Orbit (LEO) networks: Opportunity, challenges and future trends	LEO terrestrial network integration	Addresses challenges of multipath, shadowing, and satellite mobility for seamless global coverage.
2	(Wild et al., 2021)	Joint Design of Communication and Sensing for Beyond 5G and 6G Systems	Distributed MIMO + waveform design	Proposes efficient waveform design and distributed MIMO to enable real time sensing and communication.
3	(Omondi & Olwal, 2023)	Towards artificial intelligence aided MIMO detection for 6G	AI/ML for MIMO detection	AI can reduce computational complexity in large MIMO, but faces issues in generalization and channel dependency.
4	(Salameh & El Tarhuni, 2022)	From 5G to 6G Challenges, Technologies, and Applications	IRS, AI, IoT convergence	Highlights ultra low latency, energy efficiency, and security as core challenges; IRS and AI as enablers.
5	(Das et al., 2025)	A Comprehensive Survey on Emerging AI Technologies for 6G Communications: Research Direction, Trends, Challenges, and Opportunities	ML/RL/DL frameworks	AI dominates 6G research, but edge deployment faces hardware and data limitations.

6	(Alsabah et al., 2021)	6G Wireless Communications Networks: A Comprehensive Survey	Multi technology integration (IRS, LiFi, UAV, etc.)	Recommends holistic architecture combining IRS, V2X, SWIPT, and aerial platforms.
7	(Wang et al., 2020)	Security and privacy in 6G networks: New areas and new challenges	Quantum safe and distributed security	Introduces "H2.0" security model addressing quantum and decentralized threats.
8	(Abbas et al., 2024)	Towards zero energy: Navigating the future with 6G in Cellular Internet of Things	SWIPT + AI-driven energy harvesting	Promotes zero energy CIoT through simultaneous wireless information and power transfer.
9	(Chen et al., 2020)	Pervasive intelligent endogenous 6G wireless systems: Prospects, theories and key technologies	AI native, full spectrum, non orthogonal modulation	Envisions self evolving networks with mimic defense security and spectrum agility.
10	(Akbar et al., 2025)	On challenges of sixth-generation (6G) wireless networks	SDN/NFV + THz + AI automation	Proposes AI driven network automation and THz spectrum to meet ultra-low latency demands.

Signal manipulation by advanced antennas (beamforming, Massive MIMO) is already commercially available with 5G, whereas RIS and AI are still under investigation. Combining the three is supposed to be base of 6G structure. The goal of emerging mitigation techniques is not to get around basic electromagnetic limitations. Rather they employ physical phenomena such as tunable permittivity coherent wave interference and real-time environmental sensing to enhance signal delivery in scenarios with high path loss. Conventional techniques for mitigating path loss like boosting transmit power or utilizing numerous small cells attempt to address propagation loss by means of brute force engineering. On the other hand contemporary techniques like RIS and intelligent materials alter the propagation environment itself in order to operate within the bounds of Maxwells equations. Energy-intensive solutions give way to designs that take physics into account. Aerial based Passive Surface RIS is an innovative solution that is able to dictate the phase of reflected waves, forming new propagation paths in a way that avoids transmitting power based on wave reflection, for example, as implemented by Reconfigurable Intelligent Surfaces (RIS). Cell free massive MIMO uses hundreds of distributed antennas to generate narrow beams (each with a span on the order of 0.1°) enhancing array gain by tens of dB in the presence of high path loss. Recent advances in AI/ML (Omondi & Olwal, 2023) to predict the channel conditions in real time or materials like Fe_2O_3 (Ng et al., 2022) that are designed to change dielectric properties of stuff so it is more signal permeable. Even more impressive, SWIPT employs the signal power to recharge device batteries this solution is not just smart, but also more environmentally friendly.

This review has several limitations. First, it includes only Scopus indexed journal articles published between 2020 and 2025, potentially omitting relevant conference papers (e.g., from IEEE ICC or Globecom) where early 6G concepts are often introduced.

Second, the focus on physics grounded solutions may underrepresent purely algorithmic or network layer innovations. Lastly, possible linguistic bias is introduced by the exclusion of non-English literature. Future SLRs might expand the scope to include preprints patents and multilingual sources in order to capture a more comprehensive landscape.

As an example (Ng et al., 2022) revealed that the attenuation constant at 3. 5 GHz (mid band 5G) dropped from 96. 7 dB/m to 80. 7 dB/m when 2 weight percent FeO_3 was added to mortar. It is noteworthy that although this result suggests a promising direction for designing electromagnetically transparent building materials it was obtained well below the mmWave band. At THz (≥100 GHz) and mmWave (≥24 GHz) frequencies the dielectric and magnetic properties of FeO_3-based composites are highly frequency dependent and their performance has not yet been experimentally confirmed. Extrapolating these findings to higher bands without empirical support may lead to incorrect assumptions about their efficacy in 5G/6G deployment scenarios.

4. Conclusion

This comprehensive review of the literature comes to the conclusion that physical limitations mainly atmospheric molecular absorption and extremely shallow skin depths in common materials rather than engineering flaws are the primary cause of propagation limitations in the millimeter wave (mmWave) and terahertz (THz) bands. In contrast to brute-force methods recent mitigation strategies (2020–2025) operate within the confines of electromagnetic theory by employing wave interference tunable materials and real-time environmental awareness. Major advancements include hybrid physics-AI channel modeling cell-free Massive MIMO Reconfigurable Intelligent Surfaces (RIS) and engineered materials like FeO_3-infused composites. It is still unclear how effective such materials are at mmWave (≥24 GHz) and THz (≥100 GHz) frequencies where dielectric dispersion and molecular resonance are predominant extrapolating results below -6 GHz runs the risk of overestimation. Importantly by conforming to rather than defying Maxwells equations these solutions improve signal delivery even in the face of severe path loss. Future work must prioritize large-scale real-world measurements standardized benchmarks for RIS and metamaterials and experimental validation of materials at high frequencies in order to translate theoretical advancements into practical 5G/6G deployments. To make sustainable progress toward 6G it is imperative to respect and rationally operate within the laws of physics.

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