REVIEW ARTICLE

Exploring the Spectrum Frontier: Comparative Analysis of RF, mmWave, and THz Communication for 6G and Beyond

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Abstract

Wireless communication technologies are becoming increasingly important in today's rapidly developing technological world. The widespread use of the Internet, the popularity of smartphones and other mobile devices, and the rise in industrial applications have all contributed to the start of a new wireless communication technology revolution. As a result, 6th generation (6G) wireless communication technology is intended to provide enhanced performance features such as faster speeds, larger bandwidths, lower latency, higher connection density, and improved reliability. mmWave-band communications are already having a vital impact on 5G. Similarly, communications in the TeraHertz (THz)-band will be crucial for the next 6G and beyond. THz, mmWave, and RF communication technologies constitute the fundamental pillars of 6G; therefore, a comparative analysis of these technologies is essential for the robust design and development of future 6G networks. In this paper, a study of THz, mmWave, and RF communication technologies is presented with their roles in developing the 6G network. Firstly, an overview of THz, mmWave and RF technologies is presented. Then, the conventional channel modeling is discussed. After that, artificial intelligence (AI) based channel modeling is presented. Furthermore, challenges and future research directions are highlighted based on the current state of the art.

Keywords: AI, applications, challenges, channel modeling, mmWave, RF, THz, 6G.

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1 Introduction

The sixth generation (6G) is the next generation of wireless communication technologies and aims to provide higher speeds, lower latency, higher bandwidths, better security and more connection capacity compared to previous generations. Wireless communication provides wireless data transfer between different devices and is used in many areas of life today. Internet, smart phones, wireless networks, wearable devices and many other devices work with wireless communication technologies. By enabling the further development of wireless

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communication technologies, 6G aims to provide a better communication experience and enable new industries to develop [1–3].

In comparison to previous generation wireless technologies, 6G technology is intended to provide higher data rates, lower latency, higher bandwidths, improved security, and increased connection capacity. For 6G technology, three different bandwidths are generally proposed: radio frequency (RF) [4], millimeter wave (mmWave) [5], and TeraHertz (THz) [6].

The THz frequency band for 6G technology is particularly interesting because it allows for greater bandwidth and faster data transfer. The THz band has a much higher frequency (between 300 GHz and 10 THz) than other bands, allowing for faster data transfer rates. This bandwidth is also required for the construction of high-capacity networks for 6G technology. However, due to the extremely high propagation loss, the THz band is more effective over short distances. This implies that more antennas and shorter distances are required. Nevertheless, because this is also a problem with other previously used bands, the THz band may still be appropriate for high-density wireless communication, particularly in cities and densely populated areas [6–19].

The mmWave frequency band is of great interest for 6G technology because it provides high bandwidth and low latency. This band uses frequencies ranging from 30 GHz to 300 GHz and, unlike fifth generation (5G), allows for higher data transfer rates by using higher frequencies and wider bandwidths. The use of the mmWave frequency band provides numerous benefits for 6G technology. This bandwidth is especially suitable for high-bandwidth applications. High-speed and low-latency connections, for example, are required for applications like virtual reality, augmented reality, remote surgery, and autonomous vehicles [20–34].

The frequency band traditionally used for wireless communication is the RF band (20 kHz to 30 GHz). The RF band is best suited for low speeds and short distances. The RF bands for 6G technology provide greater bandwidth and lower frequencies, providing some benefits such as broader coverage and better penetration. The RF bands, particularly the sub-6 GHz bands, operate at lower frequencies and provide greater coverage and penetration, making wireless connectivity easier. Furthermore, RF bands may be better suited for devices with longer battery life, especially when using lower bandwidths. The RF band is also less expensive because it consumes less power [35–40].

In general, the THz band is best for high data transfer rates and low latency, but it is less effective over long distances, necessitating more antennas and closer spacing to transmit more data. The mmWave band has a lower bandwidth but can be used over longer distances more effectively. The RF band is best suited for slower speeds and shorter distances. Consequently, the most appropriate communication solution can be obtained by combining different frequency bands for 6G technology. THz, for example, can be used for high-speed data transfer, whereas mmWave or RF can be used for longer distances. Spectrum unification and the concurrent use of spectrum from completely different frequency bands, such as traditional mobile bands, mmWave bands, and THz bands, are acknowledged as critical components for 6G networks.

Table 1. Difference between our survey and other survey papers of similar nature.

Surveys	RF	mmWave	THz	AI
Attiah et al. [41]		√		
Kumar et al. [42]			√	
Ratul et al. [43]		√	√	
Liu et al. [44]		√	√	√
Gao et al. [45]			√	
Akyildiz et al. [46]			√	
Farrag et al. [47]		√	√	
Nabati et al. [48]				√
Sharma et al. [49]	√	√	√	
Our Survey	√	√	√	√

Despite the extensive literature on 6G technologies, current research exhibits significant limitations in scope. As detailed in Table 1, most previous studies analyze frequency bands in isolation; for example, references [41] and [44] focus solely on mmWave, while [42] and [46] are limited to the THz band. This piecemeal approach fails to address critical 6G challenges such as the operational complexity of spectrum aggregation and the management of heterogeneous networks. Furthermore, while studies such as [48] discuss AI integration, they often lack an in-depth comparative analysis of how AI techniques should be adapted to the different physical propagation characteristics between RF and THz bands. Consequently, the biggest drawback of previous studies is the lack of a holistic framework that simultaneously evaluates the physical layer trade-offs

Table 2. Comparative analysis of key performance indicators (frequency, data rate, latency, and range) for THz, mmWave, and RF bands in 6G networks.

Features	THz	mmWave	RF
Frequency range	0.1-10 THz	30-300 GHz	0-30 GHz
Data Rate	100 Gbps	10-100 Gbps	10 Gbps
Delay Time	Very Low (1 ms)	Low (1 ms)	High (ms)
Range	short (m)	Short (approximately 100m)	Long (km)
Blocking Sensitivity	High	High	Low
Measurement and Analysis	Difficult	Difficult	Easy
Cost	Expensive	Expensive	Cheap
Usage Area	Indoor, point-to-point, special applications	Indoor and outdoor, point-to-point, smart transportation systems, health	Indoor and outdoor, pervasive, mobile networks

and specific AI modeling requirements for the three key 6G spectrum candidates.

The use of mmWave and THz frequencies in mobile communication systems has drawn a lot of interest in recent years. mmWave and THz waves have been acknowledged for greatly increasing the data speeds due to their broad spectrum and high spatial reuse [50]. THz and mmWave transmissions, however, suffer from significant propagation losses. Additionally, consideration must be given while building the system because of their high penetration loss and great sensitivity to obstruction [30]. Studies that have already been done have attempted to solve the problems of mmWave/THz channel propagation. [13] is a detailed description of the mmWave/THz channels' measurement data. In [51], authors investigated spatial propagation and in-depth modeling techniques for mmWave channels. Due to the relatively short wavelengths of the mmWave and THz frequencies, massive antenna arrays may be coupled to mobile terminals. With the use of high gain directional antenna arrays, which in turn can compensate for propagation losses and reduce inter/intra-cell interference at mmWave/THz frequencies [31]. Massive data services will be available thanks to mmWave/THz-wave's tremendous bandwidth. Nevertheless, this will put a heavy pressure on transmission and drive-up energy prices.

A comparative analysis of key performance indicators (frequency, data rate, latency, and range) for THz, mmWave, and RF bands in 6G networks is presented in Table 2.

The distinction between our study and other survey publications is presented in Table 1. This research examines the roles that RF, mmWave, and THz communication technologies will play when developing the 6G network. First, a summary of RF, mmWave, and THz technologies is given. Next, the topic of traditional channel modeling is covered. Channel modeling based on artificial intelligence (AI) is then shown. In addition, difficulties and potential research prospects are pointed out based on the present state of the art.

While previous research has generally examined RF, mmWave, or THz bands in isolation or focused solely on AI algorithms without physical context, this paper establishes a unified comparative framework for 6G spectrum integration. Unlike the existing literature, we explicitly state the necessity of AI-based channel modeling not merely as an improvement but as a critical facilitator to address the differences in propagation characteristics, such as path loss and interference susceptibility, across these diverse frequency bands. By synthesizing physical layer challenges with AI-driven solutions, this work offers a novel roadmap for seamlessly integrating short-range THz/mmWave links with long-range RF coverage.

To address gaps in the existing literature and provide a holistic guide for 6G researchers, the key contributions of this research can be summarized as follows:

- Unlike previous research that analyzed RF, mmWave, or THz bands separately, we offer a combined, side-by-side comparison of these three spectrum domains based on fundamental metrics

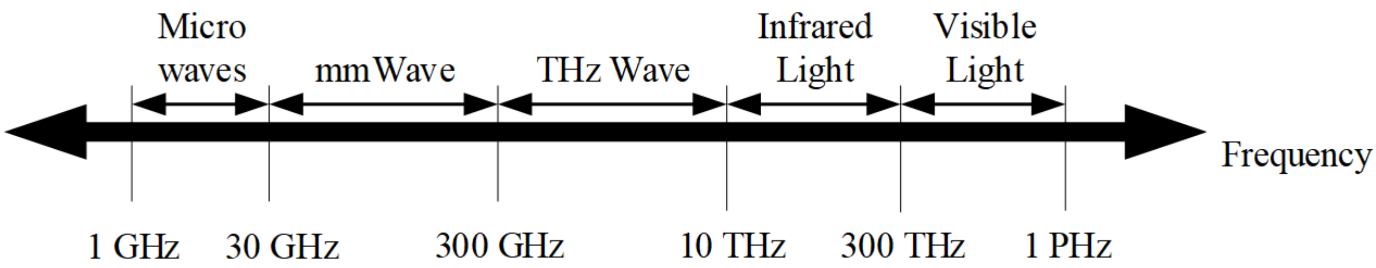

Figure 1. Spectrum from microwave to visible light.

such as path loss, interference susceptibility, and hardware complexity.

- Going beyond general AI reviews, we explicitly analyze how specific AI architectures address the unique physical propagation challenges of high-frequency bands.
- We initiate a critical discussion on hybrid AI-physical models and propose them as a solution to the data scarcity and generalization problems found in pure deep learning approaches.
- We identify cross-band spectrum aggregation as a significant operational challenge and discuss seamless vertical transition strategies between short-range THz links and long-range RF coverage.
- Based on the identified challenges, we outline a prioritized research roadmap, distinguishing between short-term hardware optimization goals and long-term system aggregation goals.

The remainder of this paper is organized as follows: Section 2 discusses the overview of THz, mmWave and RF technologies. Section 3 presents the conventional channel model. Section 4 provides AI based channel modeling. Section 5 describes the challenges and future directions. Section 6 draws conclusions.

2 Overview

This section presents an overview of RF, mmWave, and THz technologies and discusses the potential to use in 6G. 6G is a next-generation wireless communication technology that employs three distinct frequency bands with superior features: THz, mmWave, and RF. Comparison of THz, mmWave and RF for 6G is shown in Table 2. Figure 1 shows spectrum from microwave to visible light.

Application areas of THz, mmWave and RF communication technologies in 6G are as in Table 3. THz, mmWave, and RF communication technologies are potential candidates for high-speed and high-capacity wireless communication systems like 6G. Nevertheless, each technology has its own set of benefits and drawbacks. The application and factors such as bandwidth, data rate, and coverage determine which technology to use. Table 4 shows the advantages and disadvantages of THz, mmWave and RF [52, 53].

2.1 THz for 6G

6G wireless communication technology will follow the 5G mobile communication technology. The THz band is the highest frequency region of the electromagnetic spectrum, spanning frequencies ranging from 300 GHz to 3 THz. Because of its high bandwidth and low latency, this band is regarded as one of the key technological components of 6G [18]. Because of the high frequencies, communication in the THz band presents some technical challenges. Signals, for example, attenuate faster in this band than in low-frequency bands, and signals are easier to block due to higher frequencies. As a result, new technologies for communication over the THz band should be developed. Communication in the THz band provides a large amount of bandwidth, which is critical for 6G technology. 6G aims to achieve speeds of one terabit per second (Tbps), exceeding the 1-10 Gbps range offered by 5G. The bandwidth required to achieve these speeds can be provided by the z band. Communication in the THz band also has a low latency. Low latency is critical for real-time applications and is an important feature of 6G. The band is a technology capable of delivering low latency.

The development of devices that can operate at THz frequency, the use of modulated signal receiving and transmitting technologies, and frequency blocking technologies are among the technologies developed for communication over the THz band. Furthermore, new device designs and antenna systems should be created to take advantage of these technologies.

Practical measurement studies have confirmed

Table 3. Potential application scenarios tailored to the specific propagation characteristics and bandwidth capabilities of THz, mmWave, and RF technologies.

Technology	Applications
THz	High-speed data transfer, fast object-to-object communication, remote imaging, radar systems, spectroscopy, health scans, security, and defense applications
mmWave	Transportation, smart cities, the internet of things, broadcast and multimedia, health scans, wireless connections, virtual and augmented reality
RF	Remote sensing, satellite communications, networking, radio communications, data storage and transmission, and navigation are all examples of wireless connections

Table 4. Summary of the technical merits and demerits associated with deploying RF, mmWave, and THz bands.

Technology	Advantages	Disadvantages
THz	High bandwidth and data rate, high security, low energy consumption	High blocking and spanning, short range usage, difficult measurement and analysis, and high hardware costs
mmWave	High bandwidth and data rate, high security, low energy consumption	High blocking and spanning, short range usage, difficult measurement and analysis, and high hardware costs
RF	Wider coverage, lower hardware cost, easy measurement and analysis	Lower bandwidth and data rate, less blocking and spanning

these theoretical challenges. For example, indoor channel measurements at 300 GHz have shown that line-of-sight links can provide multi-Gbps throughput, but nonline-of-sight paths suffer from an additional attenuation of more than 20 dB due to reflection losses from common building materials such as drywall and glass. Furthermore, experimental test environments using indium phosphide transceivers have confirmed that water vapor absorption creates significant 'spectral windows' and necessitates adaptive modulation schemes that dynamically avoid high absorption frequencies during humid conditions.

Table 5 explains the potential of 6G over the THz band, comparing it to 5G technology from different aspects. The information in the table may change with future developments as 6G technology is under development.

2.2 Applications for THz Communications

THz communication technology has a wide range of applications. These industries include healthcare, defense, industrial sensors, security systems, remote sensing, and data centers.

THz technology can be used in medical imaging and diagnostic devices in the healthcare industry. THz technology is being researched for use in cancer diagnosis in particular. This technology can distinguish cancerous tissues from normal tissues, allowing for more precise diagnosis. THz technology can be used in the defense industry for detection systems, communication devices, and imaging devices. THz technology is especially important for military and security applications, particularly imaging systems. THz systems can be used specifically to detect invisible objects and thus have a significant military application. THz technology can be used in industrial sensors to monitor the quality of products on production lines. THz signals can be used to measure the thickness, density, and composition of materials, making them a valuable tool in industrial production. THz technology can be used in security systems to detect hidden objects on people. THz technology can be used for imaging systems and scanners, particularly in airports and other security controls. THz technology can be used for a variety of remote sensing applications, including soil moisture measurement, water vapor density measurement, and atmospheric component determination.

2.3 mmWave for 6G

6G wireless communication technology will follow the fifth generation (5G) mobile communication technology. mmWave is a high-frequency electromagnetic spectrum region ranging from 30 to 300 GHz. Because of its high bandwidth and low latency, mmWave is regarded as one of the key technological components of 6G [23]. Because of the high frequencies, communication via mmWave presents some technical challenges. Signals, for example, attenuate faster in this band than in low-frequency bands, and signals are easier to block due to higher frequencies. As a result, new technologies for mmWave communication must be developed. High bandwidth is provided by mmWave communication, which is critical for 6G technology. 6G aims to achieve 1 terabit per second speeds. 6G aims to achieve speeds of one terabit per second (Tbps), exceeding the 1-10 Gbps range offered by 5G. The bandwidth required to achieve these

Table 5. Evolution from 5G to 6G: A performance comparison highlighting the transition from microwave to Terahertz frequencies.

	5G	6G
Transmission System	microwave band (GHz)	TeraHertz band (THz)
Frequency range	1-100GHz	100-1000 GHz
Band width	~100MHz	1-10 GHz
Data Rate	10 Gbps - 10 Tbps	100 Gbps - 1 Tbps
Delay Time	1 ms	1 μs
Capacity	1-10 connections/km^2	10-100 connections/km^2
Modulation	OFDM	THz band-specific modulations
Channel Conditions	Fading, noise	Atmospheric effects, obstacles
Scaling	100 billion devices	1 trillion devices
Scope of application	Mobile communication, IoT	Smart cities, health, AI

Table 6. Comparison of mmWave between 5G and 6G.

	5G	6G
Transmission System	microwave band (GHz)	mmWave band
Frequency range	1-100GHz	30-300GHz
Band width	~100MHz	1-10GHz
Data Rate	10 Gbps - 10 Tbps	100 Gbps - 1 Tbps
Delay Time	1 ms	1 μs
Capacity	1-10 connections/km^2	10-100 connections/km^2
Modulation	OFDM	mmWave specific modulations
Channel Conditions	Fading, obstacles	High loss of free space, obstacles
Scaling	100 billion devices	1 trillion devices
Scope of application	Mobile communication, IoT	Smart cities, industry 4.0, autonomous vehicles

speeds can be provided by mmWave. Low latency is also provided by mmWave communication. Low latency is critical for real-time applications and is an important feature of 6G. mmWave is a technology with a low latency. The use of multi-antenna systems and modulated signal receiving and transmitting technologies can be counted among the technologies developed for mmWave communication, particularly the development of devices that can operate at mmWave frequency. Furthermore, new device designs and antenna systems should be created to take advantage of these technologies.

Field trials in dense urban environments, particularly at 28 GHz and 73 GHz frequencies, have provided critical information about mmWave propagation. Measurements from the New York City test site revealed that mmWave channels are spatially sparse, typically consisting of only 2 to 4 dominant clusters. This experimental data supports the necessity of directional beamforming, as omnidirectional path loss was measured to be significantly higher compared to sub-6 GHz bands. Additionally, penetration loss measurements indicate that tinted glass and brick walls can attenuate mmWave signals by 20–40 dB, practically isolating indoor users from outdoor base stations.

mmWave technology is a critical technology for 6G. Nevertheless, there are some technical challenges and security concerns associated with using this technology. For example, there are concerns about the potential effects of mmWave signals on human health, so standards for safe use must be developed.

Table 6 explains the potential of 6G over the mmWave band, comparing it from different aspects compared to 5G technology.

2.3.1 *Applications for mmWave Communications*

mmWave communication technology has a wide range of applications. Wireless communication, remote sensing, autonomous vehicles, virtual reality, augmented reality, and many other applications are examples.

mmWave technology provides high bandwidth and data rates for wireless communication. Consequently, it is ideal for faster internet access. It is especially well-suited for high-bandwidth applications like 4K and 8K resolution video streams and games. mmWave technology can be used for a variety of remote sensing applications, including weather radars, aircraft radars, and medical imaging devices. This technology can detect the position and speed of objects, making it ideal for a variety of applications such as traffic flow tracking and automated driving. mmWave technology can be used in autonomous vehicles to communicate between vehicles and detect objects in their surroundings. This technology allows vehicles to communicate with one another, improving traffic flow. mmWave technology provides higher bandwidth and lower latency for virtual and augmented reality. As a result, it offers a more realistic and fluid experience. Due to its low penetration depth, mmWave technology can be easily blocked by obstacles. Thus, mmWave technology may be unsuitable for wireless communication. mmWave technology, on the other hand, can be designed for use in less dense environments, such as outdoors and on the roofs of large buildings.

2.4 RF for 6G

6G wireless communication technology will follow the fifth generation (5G) mobile communication technology. RF is the electromagnetic spectrum's mid-frequency region, encompassing frequencies ranging from 3 kHz to 300 GHz. RF is one of the key technological components that will be crucial in 6G technology [35]. Because of the low frequencies, RF communication has some advantages. RF signals, for example, can travel farther and are less affected by obstacles than high-frequency mmWave signals. However, because of the low frequencies used in RF communication, the bandwidth is limited, limiting high-speed data transfer. 6G necessitates the development of new RF communication technologies. To provide high-speed data transfer over RF, various innovations such as multi-antenna systems, modulated signal receiving and transmitting technologies, fully digital RF technologies, and artificial intelligence-based data transmission technologies should be developed. 6G's goal is to have faster data transfer rates than 5G. To achieve this goal, RF technologies with higher bandwidths and better signal quality must be developed. Consequently, innovations such as high-speed RF devices, communication protocols optimized for high bandwidths, and more efficient signal processing techniques are critical.

Communication over RF should also be improved in order to provide low-power, low-cost devices. This necessitates the development of sensors, chips, and antennas that are less expensive and consume less energy. 6G advancements in the field of RF communication could revolutionize wireless communication technologies. These advancements could pave the way for faster and more reliable communication, as well as a broader range of applications.

2.4.1 *Applications for mmWave Communications*

RF communication provides numerous opportunities for 6G technology. These include features like high-speed data transfer, low latency, improved energy efficiency, expanded coverage, and enhanced security.

RF technology transfers data at higher bandwidth and frequencies for high-speed data transfer, resulting in higher data rates. This enables faster download and upload speeds as well as higher resolution videos. RF technology provides low latency, allowing faster signal processing and data transfer over shorter distances. This is perfect for real-time applications like games, virtual reality, and augmented reality. In terms of energy efficiency, RF technology provides better energy management and efficiency with devices that use less energy. This results in longer battery life and shorter charging times. RF technology provides greater coverage with better propagation characteristics. This results in a better signal and connection quality over a larger area. RF technology improves security by using better encryption and stronger security protocols. This means fewer security threats and a more secure data transfer. Nevertheless, due to limited bandwidth and data rates, RF technology has some limitations. As a result, higher frequency bands, such as mmWave or THz technologies, can be used for higher data rates.

2.5 Comparative Measurement Requirements for the 6G Spectrum

Developing a unified 6G network requires precise channel modeling in the RF, mmWave, and THz bands, each requiring different measurement capabilities. While all three bands require broadband measurement and high-resolution time measurements to capture multipath components, the specific hardware challenges differ significantly:

- The primary challenge for the THz and mmWave bands is severe path loss and molecular absorption. Therefore, measurement setups must utilize high-gain directional antennas and low-noise electronics to maintain adequate Signal-to-Noise Ratio (SNR). In contrast, signal strength is generally higher for the RF band; however, the challenge shifts to managing interference from existing pervasive networks, requiring measurement devices with advanced filtering capabilities.

- As frequencies increase towards THz, standard RF spectrum analyzers become inadequate. 6G research requires specialized down conversion mixers or bolometers capable of detecting submillimeter waves.
- Ultra-high data rates in the millimeter wave and terahertz bands imply extremely short symbol durations. Consequently, channel probes need to have picosecond-level timing accuracy to accurately resolve dense cluster arrivals and rapid temporal shifts; this is a less stringent requirement in conventional sub-6 GHz RF measurements.

3 Channel Modeling

This section discusses the conventional channel model of THz, mmWave and RF bands. The THz band channel gain can be given as [52].

$$h(f,d) = \sqrt{N_z}\sqrt{\frac{1}{L(f,d)}}\Omega a, \quad (1)$$

where Ω denotes the antenna gain, $L(f,d)$ denotes the path loss at d distance away from the base station (BS) at frequency f, a represents the array steering vector. Signals that are dispersed, reflected, and diffracted create non-line of sight (NLoS) routes. These pathways are often disregarded since the THz band has poor scattering and diffracting abilities. Since the NLoS link path loss is bigger than the line of sight (LoS) link route loss, the impact of the NLoS link may be disregarded while the LoS link is present [54]. It is impossible to disregard the spreading loss and molecular absorption loss in the THz region of the electromagnetic spectrum. The path loss of the THz signal at frequency f and traveled a distance of d is given as follows.

$$L^{THz}(f,d) = 20\log_{10}\left(\frac{4\pi}{\lambda_c}\right) + 10k(f)d\log_{10}e, \quad (2)$$

where λ_c is the wavelength of the carrier frequency and $k(f)$ is the frequency-dependent medium absorption coefficient. When compared to air molecules, water vapor molecules exhibit considerably greater atmospheric THz channel attenuation. In this research, just the effect of water molecules on atmospheric attenuation is taken into account for simplicity. The frequency absorption coefficient parameters of $k(f)$ are given in [55].

Experimental validation of these path loss patterns is crucial. Recent channel measurement experiments comparing 140 GHz (D band) and 28 GHz links in office environments have shown that the path loss exponent (PLE) for LoS is close to the free-space value, but for NLoS conditions, the PLE rises sharply to 4.0–5.5 at higher frequencies. These practical results support the theoretical prediction shown in Figure 2, confirming that THz and mmWave communication are strictly power-limited regimes requiring predominantly high-gain antenna arrays. For the mmWave, the path loss $L(d)$ of the mmWave channel model [56] at a traveled distance d is given by:

$$L^{\text{mmWave}}(d) = 20\log_{10}\left(\frac{4\pi}{\lambda_c}\right) + 10\gamma\log_{10}(d), \quad (3)$$

where γ represents the path loss exponent. For the RF, the path loss for RF channel [57], at a traveled distance d (km), is given as follows:

$$L^{\text{RF}}(d) = 148.1 + 37.6\log_{10}(d). \quad (4)$$

Figure 2 compares distance versus path loss and shows the performance of THz, mmWave and RF technologies. Path loss increases with distance due to the spreading of the signal over a larger area, absorption, scattering, reflection, diffraction, and other environmental factors that attenuate the signal as it travels further from the source. Higher frequencies generally experience greater path loss due to increased absorption, scattering, poorer diffraction, and greater reflection. Therefore, THz has the highest path loss, and RF has the lowest.

Figure 3 shows the variation of path loss versus frequency for THz, mmWave and RF frequency band. d is taken 100 meters. At low frequency (around 0.1 GHz), the path loss is quite low and the increase is slow. At high frequency (around 100 GHz), path loss increases rapidly and communication distance becomes shorter.

As shown in Figure 4, the relationship between distance and channel gain in different frequency bands (RF, mmWave and THz) is shown. Average

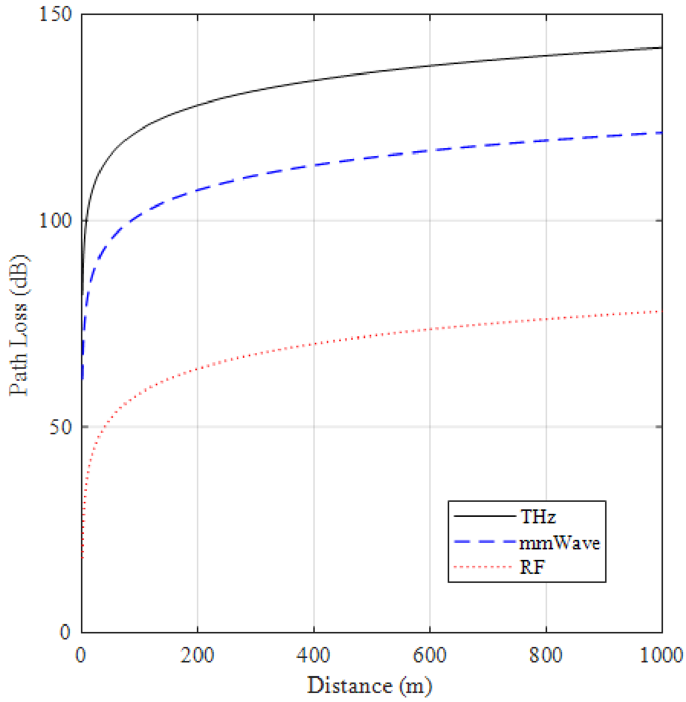

Figure 2. Comparison of Path Loss (dB) versus Distance (m) for THz, mmWave, and RF bands, highlighting the rapid signal decay in higher frequencies.

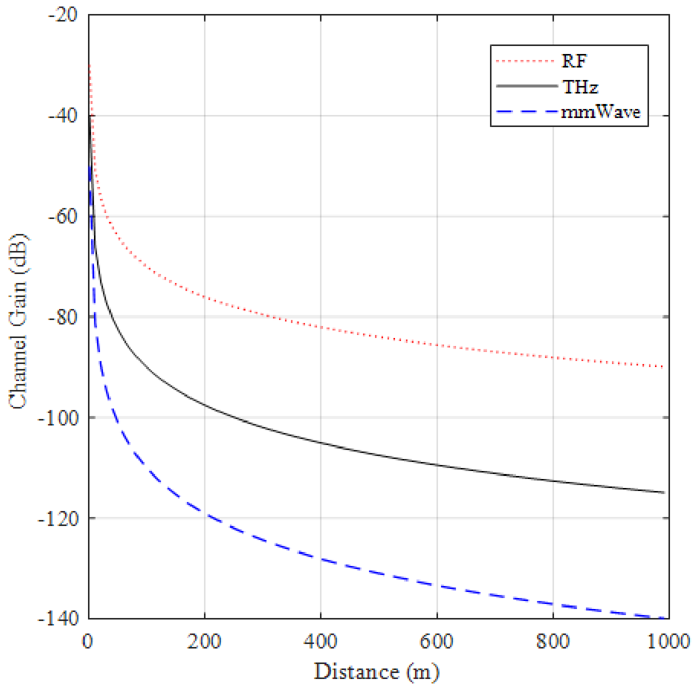

Figure 4. Relationship between Distance (m) and Channel Gain (dB) for RF (15 GHz), mmWave (60 GHz), and THz (300 GHz) bands.

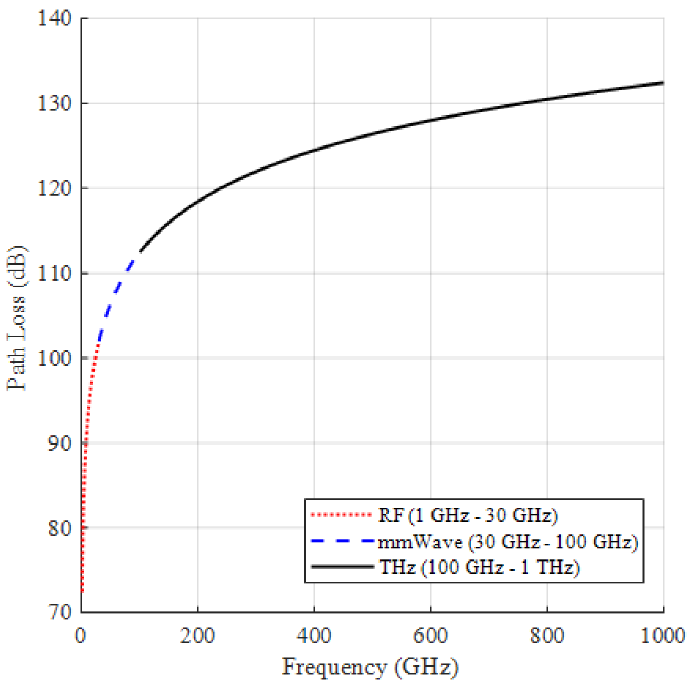

Figure 3. Characteristics between Frequency (GHz) and Path Loss (dB) show the exponential increase in attenuation from the RF to the THz spectrum.

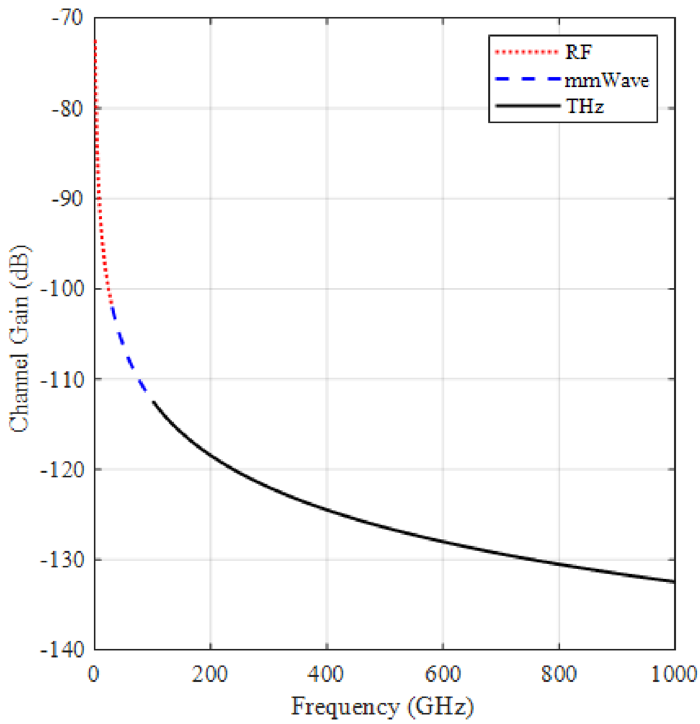

Figure 5. Variation of Channel Gain (dB) across the frequency spectrum (1 GHz – 1 THz) at a fixed distance of 100 meters.

frequencies of 15 GHz for the RF band, 60 GHz for the mmWave band, and 300 GHz for the THz band were used. The results obtained show that the channel gain decreases significantly with increasing distance. In particular, at higher frequencies (mmWave and THz) the channel gain decays more slowly than in the RF band. This shows that high-frequency communication systems have less losses at shorter ranges and therefore channel gain decreases slowly as distance increases.

Figure 5 shows the frequency-dependent variation of channel gain for RF, mmWave and THz frequency bands. d is taken 100 meters. Calculations made in the frequency range between 1 GHz and 1 THz reveal that the channel gain decreases as the frequency increases. While the channel gain is at the highest level in the RF band (1 GHz - 30 GHz), this gain decreases in the mmWave band (30 GHz - 100 GHz) and reaches the lowest levels in the THz band (100 GHz - 1 THz). This shows that high-frequency communication systems (mmWave and THz) have higher channel gain and therefore it is appropriate to use these bands over shorter distances.

4 AI based Channel Modelling

This section presents AI based channel modeling for THz, mmWave and RF communication. However, THz, mmWave and RF communication technologies face various challenges such as complex channel models, narrow bandwidth and high environmental sensitivity. At this point, AI techniques offer innovative solutions to overcome these challenges and maximize the potential of these communication technologies [43, 48].

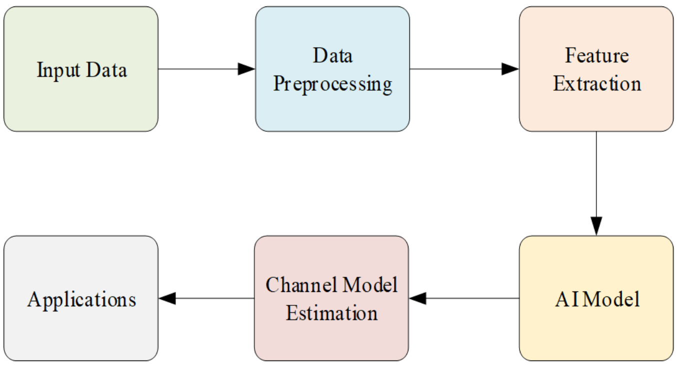

Figure 6. Details the AI-based channel modeling process, from acquiring input data to estimating channel parameters.

Traditional channel modeling methods are generally implemented by using mathematical models. Nevertheless, the complexity of these models limits their accuracy, especially in high frequency bands. AI-based channel modeling overcomes these limitations and significantly improves channel characterization by using models that learn on large datasets. Deep learning (DL) and machine learning (ML) algorithms play a critical role in understanding and modeling the complex dynamics of signal propagation. AI-based modeling methods are generally based on large datasets and these methods exhibit superior performance in modeling the dynamic structure of the channel, environmental variables, and SNR. Deep learning techniques can estimate and model complex channel parameters more accurately by using multilayer neural networks. Figure 6 shows AI-based channel modeling process. As shown in the flowchart, the process begins with data collection, where specific input types such as channel state information (CSI) matrices, SNR maps, and environmental geometry data are collected to train neural networks. Table 7 presents a comparative overview of DL and ML of AI in THz, mmWave and RF communications.

4.1 Channel Modeling with Deep Learning

DL is a powerful tool in the modeling and prediction processes of complex data, especially by providing multi-layered data processing capabilities through neural networks. In the context of channel modeling, DL techniques allow understanding and modeling the dynamic structure of the channel by taking into account environmental variability, moving objects, and multi-path propagation effects [58–66].

To give concrete application examples, convolutional neural networks (CNNs) have proven highly effective in spatial feature extraction, particularly in ray estimation tasks where CSI matrices are processed as images. Recent studies show that CNN-based estimators can achieve over 90% accuracy in dynamic mmWave scenarios and significantly outperform traditional Kalman filters.

Furthermore, generative adversarial networks (GANs) are increasingly used for channel synthesis. Given the scarcity of measurement data in the THz band, GANs can learn the fundamental distribution of channel parameters and generate synthetic, yet realistic, channel impulse responses to improve training datasets. However, in terms of performance trade-offs, while these DL models provide high accuracy, they exhibit high computational complexity and training latency compared to lighter machine learning algorithms, making them less preferable for resource-constrained edge devices.

While traditional stochastic and deterministic channel models are effective for low-frequency RF bands, they often struggle with the high sensitivity and complex

Table 7. A Comparison of DL and ML approaches in AI-based channel modeling for THz, mmWave and RF.

Criteria	Deep Learning	Machine Learning
Accuracy	It can model complex relationships especially on large data sets and exhibits superior performance with high accuracy.	It can perform depending on the structure of the data and the complexity of the model.
Data Set	It requires large and labeled data sets; more data provides better model performance.	Medium-sized data sets are sufficient; it has the ability to work with small data, but model performance depends on data quality.
Computational Power	It usually requires special hardware such as GPU/TPU.	It can work with CPU, requires less computational power.
Training Time	Processing large data sets and training multi-layer networks takes time.	Shorter; training time is usually shorter due to fewer parameters and simpler models.
Feature Extraction	The model automatically learns and extracts important features.	Feature extraction is done with human intervention.
Generalization	When trained on large data sets, it can be highly successful on different data sets and environments.	The performance of the model may be more dependent on the data set it is trained on, and generalizability may be limited.
Applications	Complex and large-scale data structures; fields such as image processing, natural language processing, big data analysis.	Various fields; classification, regression, time series analysis, etc.
Error Tolerance	Errors in complex models can be difficult to detect and the model can be sensitive.	Errors in simpler models can be detected more easily and are easier to fix.
Real-time Applications	Delays may occur due to high computational requirements.	It can be used in real-time applications with fast training and low computational requirements.

scattering environments specific to millimeter wave and terahertz frequencies. Traditional models typically rely on complex mathematical derivations and extensive geometric knowledge of the environment, leading to high computational complexity without guaranteeing accuracy in dynamic scenarios. In contrast, AI-based models, particularly Deep Learning (DL) approaches, can learn nonlinear channel characteristics directly from measurement data. As shown in Figure 6, AI models offer superior accuracy in predicting path loss and atmospheric attenuation by adapting to environmental variables that traditional equations cannot capture. However, this improved accuracy comes at the cost of higher computational requirements for training and the need for extensive datasets; this trade-off is illustrated in more detail in the comparison between DL and ML approaches in Table 7.

In the future, approaches such as federated learning and transfer learning may enable the development of more generalizable DL models across different datasets and environments. This is an important step that will increase usability, especially across different geographic regions or different communication scenarios. In addition, the integration of quantum computing and DL will provide more sophisticated and faster solutions in the channel modeling process, thus determining the direction of research in this area [67–69].

4.2 Channel Modeling with Machine Learning

High-frequency bands such as THz, mmWave and RF, despite providing high data rates and wide bandwidth, present a number of challenges in terms of signal propagation. In particular, signal attenuation, multipath propagation, and the effects of environmental factors limit the accuracy of traditional channel modeling techniques. At this point, ML stands out as an innovative approach to overcome these challenges and develop more accurate channel models [70–82].

ML develops algorithms capable of predicting future events by learning from past observations and measurements with a data-driven approach. In the context of channel modeling, machine learning algorithms understand and model the dynamic structure of the channel by analyzing complex environmental factors affecting signal propagation and the effects of these factors on the channel. These techniques have the capacity to predict the frequency, time and space-dependent changes of the channel with high accuracy by training on large data sets.

ML techniques are generally considered in two main categories: supervised and unsupervised learning. Supervised learning creates predictive models for channel modeling using labeled data sets. This approach is particularly effective when channel parameters are specific. For example, channel properties such as SNR, attenuation coefficients, and phase shift can be accurately estimated using supervised learning algorithms.

In the future, advanced ML techniques such as transfer learning and federated learning may enable the development of more generalizable and efficient channel models in different environments. These approaches can provide faster and more efficient modeling processes by enabling the transfer of information between different datasets. In addition, ML algorithms integrated with quantum computing can open new horizons in the field of channel modeling, enabling the modeling of more complex and dynamic systems [83–87].

5 Challenges and Future Research Directions

This section presents challenges and future research directions based on the current state of the art. Researchers are attempting to develop new research methods such as more effective and efficient antenna designs, better signal processing and routing techniques, more precise measurement and analysis tools, and better obstacle management in order to overcome the challenges in the development of these technologies. Furthermore, efforts are being made to create more affordable and powerful hardware designs. Table 8 presents challenges and future directions of THz, mmWave and RF.

Table 8. Operational challenges and corresponding future research directions for physical layer implementation in RF, mmWave, and THz bands.

Technology	Challenges	Future Research Directions
THz	High frequency loss, signal attenuation, difficult measurement and analysis, and high hardware costs	New materials, advanced antenna technologies, more precise measurement and analysis tools, and more cost-effective hardware designs
mmWave	Signal propagation, signal blocking, obstructions, measurement and analysis challenges	Improved routing techniques, antenna designs, measurement and analysis tools, and obstacle management
RF	Pollution, interference, spectrum splitting, as well as measurement and analysis difficulties	Improved spectrum management, filtering techniques, antenna designs, and more precise measurement and analysis tools

5.1 For THz Band Communication

6G is a technology that uses high frequency THz bands to achieve higher data rates and lower latency [7]. However, there are some obstacles and research methods to overcome in order to achieve these objectives:

- Device design: Designing devices in THz frequency bands is extremely difficult. Consequently, new techniques for designing 6G devices should be developed.
- Models of channels: Channel losses are higher in THz bands, making accurate data collection and measurements for channel models difficult. Consequently, new THz channel models must be developed.
- Antenna engineering: Antenna design and fabrication become more difficult in THz frequency bands. Thus, antenna technologies used in 6G must be specifically tailored to the THz bands.
- Spectrum management: THz frequency bands are located higher up in the RF spectrum. Hence, frequency management becomes more difficult, and appropriate spectrum management strategies must be developed.
- Physical barriers: THz frequency bands are easily blocked by physical obstacles (such as walls). This may have a negative impact on the communication link.

5.2 For mmWave Communication

6G is a technology that uses high frequency mmWave bands to achieve higher data rates and lower latency [23]. Nevertheless, there are some obstacles and research methods to overcome in order to achieve these objectives:

- Channel losses are higher in mmWave bands, resulting in lower signal strength and poor communication quality. Therefore, accurate data collection and measurements for mmWave channel models are challenging. Thus, new mmWave channel models must be created.
- Propagation losses: mmWave frequencies ensure higher data speeds compared to lower-frequency RF bands due to the availability of wider bandwidth but cause more propagation loss. Hence, communication distances for mmWave frequencies is shorter, and new techniques to reduce propagation loss must be developed.
- Shading losses: Physical barriers further obstruct mmWave signals, resulting in shading losses. To overcome these challenges, new techniques such as mmWave signal reflection and bending must be developed.
- Device design: Designing devices in the mmWave frequency bands is extremely difficult. Consequently, new techniques for designing 6G devices should be developed.
- Antenna technology: It is becoming more difficult to design and manufacture antennas in mmWave frequency bands. Hence, 6G antenna technologies must be specially adapted to mmWave bands.
- Spectrum management: mmWave bands are located higher up in the radio frequency spectrum. Therefore, frequency management becomes more difficult, and appropriate spectrum management strategies must be developed.

5.3 For RF Communication

6G is designed to provide high data rates, low latency, and expanded coverage areas [36]. Nevertheless, some RF communications challenges and future research methods may include:

- Optional frequency split access (FDD) or time split access (TDD): RF communications in 6G will need to choose between FDD and TDD. FDD is better suited to high-speed data transfer and high-capacity networks, whereas TDD is better suited to lower latency and greater flexibility.
- RF background noise reduction: RF background noise is a major issue in the high frequency RF spectrum. To reduce RF background noise in 6G, new technologies and algorithms must be developed.
- High Frequencies: Using very high frequencies in the RF spectrum, 6G aims to provide faster speeds and lower latency. These high frequencies, however, these high frequencies can cause issues such as low penetration depth and high signal loss. Hence, better antenna and signal processing techniques will be required in the future.
- Spectrum Management: The RF spectrum is limited, and an increasing number of devices and applications are utilizing it. Thus, spectrum management will become more important in the future. Various techniques, such as multiple access, spectrum sharing, and white space technology, must be developed.
- MIMO Technology: Multiple Input Multiple Output (MIMO) technology will be critical in 6G. Nevertheless, when operating in the high frequency RF spectrum, MIMO technology becomes more difficult. Therefore, more advanced MIMO algorithms will need to be developed and implemented in the future.
- Security: Security: In terms of privacy and security, RF communication is critical. Therefore, more secure and confidential RF communication technologies must be developed in the future.
- Energy Efficiency: RF devices, particularly high frequency RF devices, consume a lot of energy. Consequently, it will be necessary in the future to develop more energy efficient RF devices and systems.

5.4 Challenges in Spectrum Aggregation and Inter-Band Management

While independently optimizing RF, mmWave, and THz bands is crucial, the main operational challenge in 6G lies in aggregating these heterogeneous spectrum resources. Managing the coexistence of these bands requires overcoming significant differences in propagation characteristics, particularly the extreme differences in path loss mitigation and interference sensitivity between THz/mmWave and sub-6 GHz RF bands.

A critical area for future research is the development of seamless vertical switching mechanisms. Given the high susceptibility of THz and mmWave links to dynamic interference, the network must be able to instantly switch traffic to a lower frequency RF band to maintain session continuity and return to higher frequency bands when line of sight is restored.

Furthermore, optimized routing protocols must be developed to manage these cross-band transitions. These protocols must consider not only signal strength but also the application's specific latency and reliability requirements, and dynamically route data packets between short-range, high-capacity THz links and long-range, high-coverage RF links. Addressing these cross-band challenges is crucial to realizing 6G's vision of cell-free and ubiquitous connectivity.

5.5 AI for THz, mmWave, RF

AI-based solutions for wireless communication technologies have made significant progress in THz, mmWave, and RF bands. Nevertheless, there are still several challenges for the widespread applicability and effective use of these technologies. Furthermore, future research in these areas is critical to fully realize the potential of AI and further improve wireless communication systems. Table 9 lists the challenges and future research directions of AI in the THz, mmWave, and RF bands.

Table 9. Key challenges and future research opportunities for implementing AI-based solutions across different frequency bands.

	Challenges	Future Research Directions
THz	High dataset requirement. Model generalization issues. High computational costs.	Transfer learning and data augmentation techniques. Developing fast and energy efficient AI algorithms. Hybrid AI-physical models.
mmWave	High versatility requirement. Sensitivity to environmental changes. Device complexity.	Real-time adaptive AI models. Low power consumption AI algorithms.AI integration in multi-antenna systems.
RF	Limited bandwidth. Interference management challenges. Low data rates.	Advanced spectrum sharing algorithms. AI-based power management and interference mitigation techniques. Flexible and scalable AI models.

The success of AI-based models largely depends on the quality and scope of the datasets they are trained on. Creating large and diverse datasets for THz, mmWave, and RF bands is essential to increase the generalization ability of these models. Nevertheless, obtaining large datasets in these bands, especially at THz frequencies, is limited due to the cost and technical difficulties of data collection. In addition, creating sufficiently representative datasets for different environmental conditions and user scenarios is also a significant challenge.

AI algorithms, especially deep learning models, require high computational power to be trained on large amounts of data. In THz and mmWave communication systems, such high computational requirements for real-time applications can have a negative impact on the energy consumption of devices. Therefore, developing energy-efficient algorithms is a critical requirement to ensure the widespread applicability of AI in these bands [88, 89].

While AI has great potential in THz, mmWave, and RF communication bands, several challenges need to be overcome to fully realize these technologies. Future research should focus on critical areas such as generating large datasets, developing energy-efficient algorithms, improving the interpretability of AI models, and integrating with existing systems. These efforts will improve the performance of wireless communication systems and pave the way for next-generation communication technologies.

5.5.1 Feasibility of Hybrid AI-Physical Models

To address the limitations of purely data-driven approaches, such as high dataset requirements and poor generalization highlighted in Table 9, future research should focus on hybrid AI-physical models. These models offer a viable implementation strategy by combining the interpretability of physical channel laws with the learning capabilities of deep learning. In a practical application, a hybrid framework might utilize coarse-grained physical models to generate the basic channel prediction, while a lightweight neural network refines this prediction by learning from residual errors arising from complex environmental scattering or hardware defects. This approach significantly reduces computational cost and training data size compared to black box AI models, making it highly feasible for real-time 6G applications where energy efficiency and rapid adaptation are critical.

5.6 Research Roadmap: Prioritizing Future Directions

To provide a structured roadmap, we allocate the challenges presented in Tables 8 and 9 to a research roadmap prioritized according to urgency and feasibility of implementation:

- Accurate channel models derived from comprehensive measurement campaigns

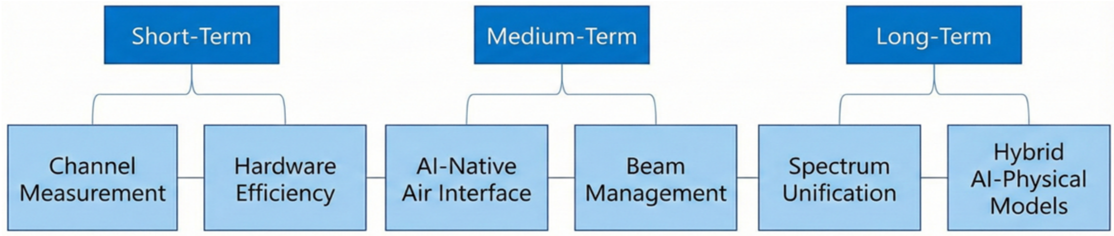

Figure 7. The Proposed Research Roadmap for 6G Spectrum Unification illustrates the transition from physical layer characterization (short term) to fully unified AI-based networks (long term).

are urgently needed before the deployment of complex networks. Simultaneously, the development of low-power RF front-ends is critical for making high-frequency devices commercially viable.

- Once the physical layer is stabilized, the focus should shift to AI-based air interfaces. This involves training deep learning models for beam management and channel estimation using datasets collected in the initial phase.
- Developing cross-layer protocols for seamless transitions between THz, mmWave, and RF bands, and creating hybrid AI-physical models capable of generalization across diverse environments, represents the long-term vision for fully realized 6G networks.

Figure 7 illustrates the proposed research roadmap for 6G spectrum coupling.

6 Conclusion

Because of their advantages such as high bandwidth and fast data transfer, THz, mmWave, and RF communication technologies in 6G have great potential in the development of future wireless communication networks. Nevertheless, each technology has its own set of benefits and drawbacks. THz and mmWave technologies have high bandwidth and data rates, but they have drawbacks such as short-range coverage and blocking issues. While RF technology has the advantages of greater coverage and lower costs, it has lower bandwidth and data rates. Therefore, the best technology for future wireless communication networks will be chosen based on the application and requirements. Future research focusing on the development of these technologies with higher performance, lower power consumption, and lower costs is expected to make a significant contribution to the development of wireless communication networks. Traditional methods in channel modeling are effective in predicting channel behavior based on physical and statistical models, but they are limited in complex environments, especially in mmWave and THz bands. In contrast, AI-based modeling has the potential to replace traditional methods in future communication systems by providing the opportunity to make more precise and dynamic channel predictions by learning from large data sets.

THz and mmWave technologies have significant advantages in terms of bandwidth and data rate, as well as low energy consumption and high security. Nevertheless, these technologies are limited to short distances and suffer from significant blocking and propagation issues. They are also not widely used commercially due to high hardware costs. Because of lower hardware costs, RF technology has a wider coverage and is more widely used. Furthermore, blocking and propagation issues are less common and easier to measure and analyze. However, due to the lower bandwidth and data rate, it has limitations.

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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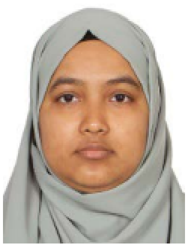

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