Channel Capacity in the Terahertz Band: Analytical Assessment for 6G Deployment

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Abstract— **While 5G networks are still being constructed in many parts of the world, the conversation has already shifted toward sixth-generation (6G) wireless systems, a leap that promises unprecedented speed, responsiveness, and connectivity. To meet the demands of sub-millisecond latency, multi-terabit-per-second (Tbps) data rates, and ultra-dense device deployments, existing spectrum resources are no longer sufficient. This has turned global attention to the terahertz (THz) band (0.1–10 THz), a largely unexploited spectral frontier with the potential to unlock vast bandwidths. Yet, the THz band is not without its constraints. Severe free-space path loss, high molecular absorption, and limited transmission range pose significant challenges to its practical deployment. This paper presents an analytical estimate of the channel capacity of THz communication systems under the high-humidity, tropical conditions of Southern Nigeria (27°C, 88% RH). The findings reveal a trade-off between bandwidth and range, severely exacerbated by molecular absorption. The analysis demonstrates that while the 1.5 THz band is rendered practically unusable beyond 10 meters, the 300 GHz band deliver up to 56.6 Gbps at 10 meters and maintains a viable link greater than 1 Gbps up to 60 meters. A key finding of this work is the quantification of extreme SNR decay, measured at 28.8 dB/decade for 300 GHz and a prohibitive 130.7 dB/decade for 1.5 THz, confirming that molecular absorption is the dominant impairment beyond free-space loss. The study concludes that the 300-600 GHz spectrum is the most viable window for short-range, high-density 6G applications in tropical climates. To overcome the inherent limitations, it is strongly recommended that 6G deployments in such environments integrate advanced beamforming with Ultra-Massive MIMO (UM-MIMO), Reconfigurable Intelligent Surfaces (RIS) for path loss mitigation, and hybrid network architectures that synergise THz small cells with robust fibre and mmWave backhaul.**

Keywords— Terahertz communications, 6G networks, channel capacity, molecular absorption, and high-density applications

1. Introduction

Living in a time where digital experiences are evolving faster than ever, from holographic telepresence that brings distant people into the same room, to extended reality (XR) that blurs the line between the physical and the virtual worlds, and the ever-expanding Internet of Everything (IoE) that will connect billions of devices in real time [1]. These innovations aren't just futuristic dreams anymore; they seem to be knocking on our door. With expectations of delivering peak data rates beyond one terabit per second (Tbps) [2], near-instantaneous latency measured in fractions of a millisecond, and the ability to support ultra-dense device ecosystems, 6G is poised to redefine connectivity as we know it. Achieving these ambitious goals, however, means venturing into new spectral territory, beyond the familiar millimetre wave (mmWave) bands.

That's where the terahertz (THz) band comes into play. Stretching from 0.1 to 10 THz, it is believed that this spectrum will offer vast, contiguous bandwidths that could unlock the kind of data rates 6G demands. But it's not all smooth sailing. THz signals are said to face steep hurdles: intense free-space path loss, significant atmospheric molecular absorption, and the current limitations of transceiver hardware [3].

To truly understand whether THz can rise to the occasion, we need a deep dive into its channel capacity, how much data it can realistically carry under real-world conditions. This paper takes on that challenge, laying the groundwork for assessing THz's potential in powering the high-density, high-performance future of 6G.

2. Review of Related Works

Analytical modelling of channel capacity in the terahertz band has emerged as a critical research area as 6G networks push towards terabit-per-second (Tbps) data rates. Classical Shannon capacity models, while foundational, require adaptation to account for THz-specific impairments such as molecular absorption, frequency-dependent path loss, and non-Gaussian noise [4] and [5], Reference [6] emphasized that THz channels exhibit unique noise characteristics due to absorption-induced fluctuations, which must be integrated into capacity calculations to avoid overestimation.

Several studies have proposed modified capacity formulas that incorporate stochastic fading models tailored to THz propagation. Authors in [7] validated the fluctuating two-ray (FTR) model for indoor THz environments, showing improved accuracy over Rayleigh or Rician assumptions. Reference [8] introduced hybrid statistical models that combined deterministic path loss with probabilistic fading, offering a more realistic basis for capacity estimation. These models are particularly relevant for short-range indoor deployments, where multipath effects and material interactions dominate.

Molecular absorption not only attenuates signal strength but also introduces absorption-induced noise, which can degrade spectral efficiency if not properly modelled [4] and [9]. Accurate atmospheric modelling is therefore essential. Comparative assessments by [9] and [10] revealed that small deviations in environmental parameters such as humidity and temperature can significantly affect capacity predictions, underscoring the need for precise simulation tools and real-time environmental sensing.

Advanced modelling frameworks now incorporate multi-antenna systems and spatial multiplexing. [11] explored MIMO configurations in THz bands, showing that large antenna arrays can partially compensate for path loss and improve ergodic capacity. [12] extended this by proposing adaptive beamforming algorithms that dynamically optimize link capacity in mobile THz environments. These techniques are particularly promising for high-density urban deployments, where spatial diversity can be exploited. Simulation-based studies have also contributed to analytical assessments. For example, [13] modelled near-field THz propagation and highlighted the limitations of far-field assumptions in mobile scenarios. While [14] integrated RIS and UAV platforms into their models, showing that intelligent surfaces can reshape channel conditions and enhance capacity under blockage and mobility constraints. Reference [15] demonstrated that large-area programmable metasurfaces can dynamically manipulate THz wavefronts, improving ergodic and outage capacity in realistic environments.

In addition to propagation and hardware challenges, waveform design is said to play a role in capacity optimisation. Traditional schemes like OFDM are said to struggle with Doppler shifts and frequency selectivity in THz channels. Emerging formats such as orthogonal time frequency space (OTFS), orthogonal delay-Doppler division multiplexing (ODDM), and affine frequency division multiplexing (AFDM) offer improved robustness in high-mobility scenarios [16] and [17]. These innovations complement analytical models by enabling more efficient use of available spectrum.

The literature converges on the need for hybrid analytical models that combine empirical channel measurements, stochastic fading distributions, and deterministic absorption profiles. These models will form the basis for accurate capacity estimation and system-level optimisation in THz-operated 6G networks. However, gaps remain in large-scale dataset availability, unified simulation frameworks, and scalable deployment strategies, all of which must be addressed to unlock the full potential of THz communications. This work analytically evaluates a realistic, non-technology-enhanced channel capacity of the terahertz frequency band vis-à-vis the tropical terrain-specific weather conditions.

3. Methodology.

To analytically assess the channel capacity in the terahertz band for 6G high-density applications. The following steps were deployed for selected frequencies of 300 GHz, 600 GHz, 1 THz, 1.2 THz and 1.5 THz.

3.1Computation of Parameters

The pathloss at different distances is generally calculated using the model given in (1) [18], [19], [20] and [21].

$$PL_{CI}(d) = PL(d_o) + n10log_{10}\left(\frac{d}{d_o}\right) + X_\sigma \quad (1)$$

Where $PL_{CI}(d)$ is the pathloss at distance d (dB), $PL(d_o)$ is the pathloss at a reference distance d_o (dB), X_σ is the log-normal shadow fading term, n is the path loss exponent, and
d_o is the reference distance taken as one meter in this work. For easy analytical evaluation, (2) was considered.

3.1.1. Determination of pathloss at a distance (d).

Pathloss can be represented conveniently by a stochastic large-scale model of (2), which compensates for shadowing and molecular absorption [6] and [22]. (2) was deployed in this analysis.

$$PL_{dB}(d) = 20log_{10}(f) + 20log_{10}(d) + 32.4 + K_{abs}(f).d + X_\sigma \quad (2)$$

where,
$PL_{dB}(d)$ Pathloss from transmitter to receiver at the distance d in dB.
d is the distance from the transmitter in metres.
f is the frequency of transmission in Hertz.
$K_{abs}(f).d$ is the absorption loss and
X_σ is the shadow fading.

3.1.2. Computation of the absorption loss for the terahertz frequencies.

Taking into consideration the respective frequencies (300 GHz, 600 GHz, 1 THz, 1.2 THz and 1.5 THz), at distances from ten meters to two hundred meters, at temperature of 27 degrees centigrade, relative humidity (RH) (%) of 88% [23] as reported by NIMET [24], and sea level pressure of 1013.25 hPa [24], the molecular absorption, using the ITU-R P.676-13 [26] updated line-by-line model of oxygen and water vapour absorption was developed for the horizontal path.

3.1.3. Computation of the log-normal fading coefficient for the 6G frequencies.

Many articles, such as 3GPP [27], [28], [29] and [30] have recommended fading constants (σ) of between 4 dB and 12 dB for frequencies greater than 100 GHz. 8 dB happens to be the median value for urban microcells computations. This work, therefore, adopted +8 dB as the worst-case shadow fading coefficient and added ±8 dB variability at all distances and frequencies using (2).

3.1.4. Computation of Signal-to-Noise-Ratio (SNR) (dB).

To understand the channel capacity, it was necessary to calculate the signal-to-noise ratio. This can be done using equation (3) [31], [32] or by following steps 1-3 of (4) to (6) [33].

$$SNR\ (dB) = P_t(dBm) - PL(dB) - N(dBm)] \quad (3)$$

Step 1: Calculate the received power using

$$P_r(dBm) = P_t(dBm) - PL(dB) \quad (4)$$

Step 2: Calculate the total noise power $N(dBm) =$

$$N_o + 10log_{10}(B) \quad (5)$$

Step 3: Compute the $SNR(dB) = P_r(dBm) - N(dBm)]$ (6)

Where:
N_o is the thermal noise.
B is the bandwidth. Here, we will use a 10 GHz bandwidth for the THz band.
SNR is the signal-to-noise ratio.
P_t is the transmit power.
P_r is the received power.

3.1.5. Computation of Channel Capacity (bps).

The channel capacity was computed using the Shannon channel capacity (7);

$$C_{bps} = Blog_2(1 + SNR_{linear}) \quad (7)$$

RESULTS

This work assessed the feasibility of the Terahertz (THz) band communication (300 GHz–1.5 THz) for 6G networks, especially as regards its use for high-density applications like mixed reality, holographic telepresence, telemedicine, brain computer interface and smart cities. The assessment focused on the path loss, SNR, and capacity across distances of 10m to 200 m, for the selected frequencies.

Figure 1 shows the relationship between the pathloss and the distance at the respective frequencies. It could be seen that there is a quadratic increase in the pathloss with the frequencies and also a linear relationship between the pathloss and the distance, as expected.

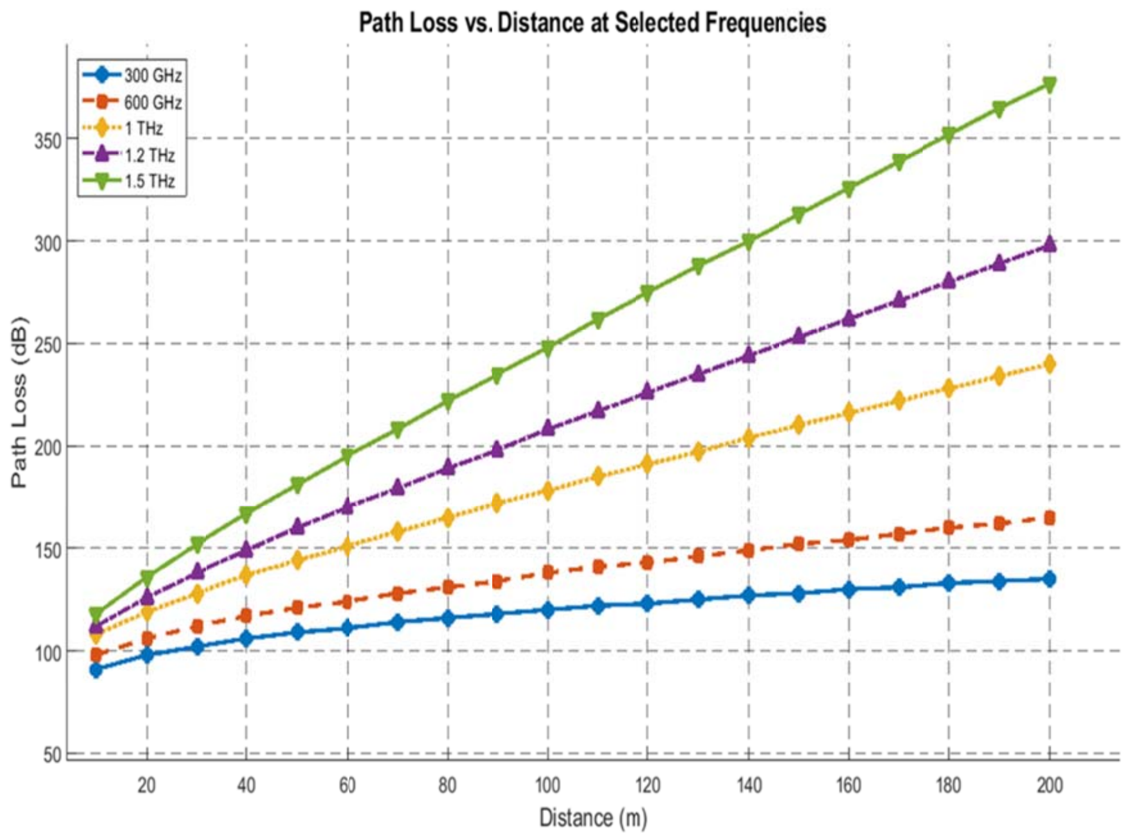

Figure 1: Plot of Pathloss per Distance at Respective Frequencies

The 1.5 THz frequency looks completely unusable above 10 metres, even though the pathloss was at 117.7 dB. So it is deducible that higher frequencies suffer from extreme attenuation and this might limit the practical use of the spectrum to less than 50 metres. It is better to target the 300 GHz to 600 GHz range for short-range applications while the regulators look downward the spectrum for lower frequencies for instance the 700 GHz band now proposed by the 3GPP. Technologies that improve the services, such as the use of relays, and intelligent reflecting surfaces, must be developed for use from initial deployment.

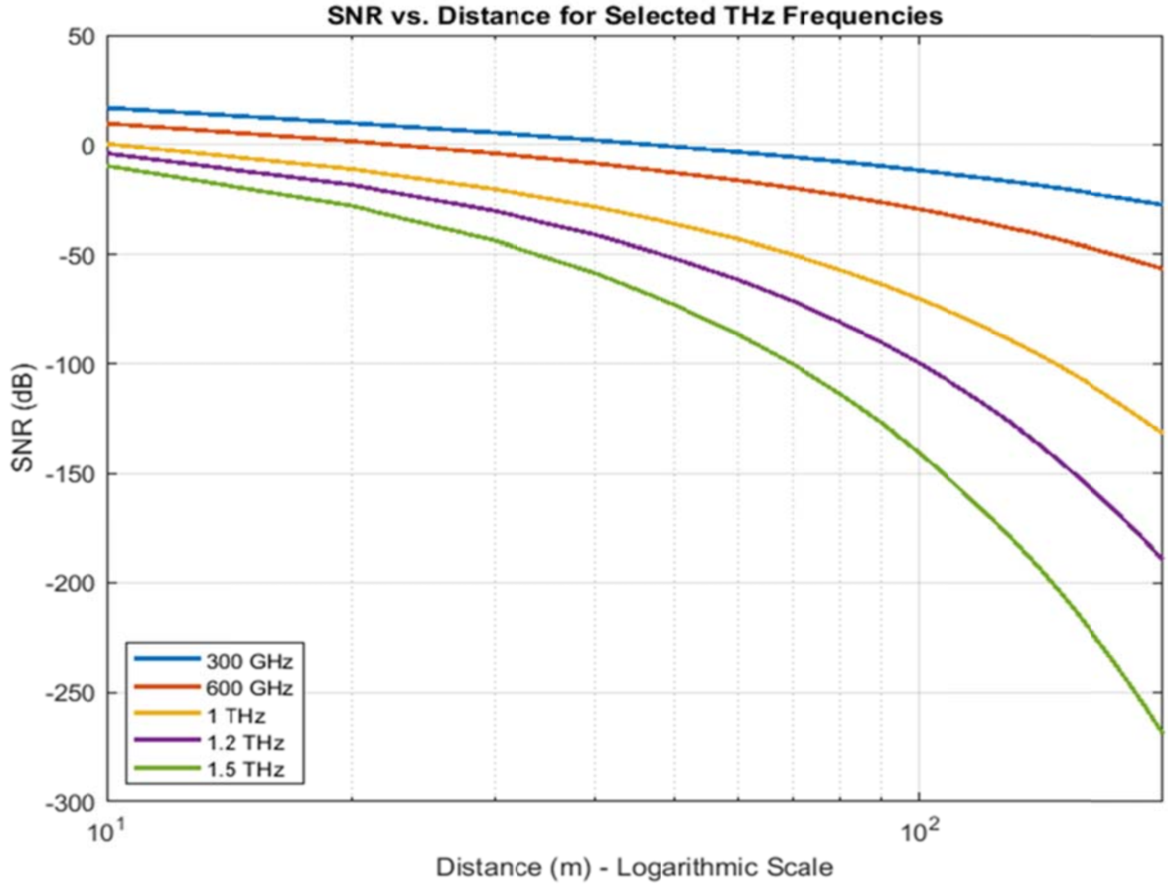

Figure 2: Plot of SNR with Respect to Distance at chosen Frequencies

Figure 2 plots the SNR in dB against distance on a logarithmic scale. A logarithmic x-axis is used to better visualize the exponential decay of the signal as the distance increases up to the point that the signal strength compared to the noise strength at 1 THz dropped below 0 dB at 10 metres. This shows that THz signals are noise-limited beyond short ranges, and technologies like beamforming, ultra-massive multiple-input multiple-output (MIMO) antennas technology and adaptive modulation will be mandatory to boost gain and manage SNR variations. From Table 1, the SNR decay per decade can be seen for all the frequencies and the higher the frequency the higher the decay rate.

Table 1: SNR Decay per Decade

Frequency	SNR at 10 m (dB)	SNR at 100 m (dB)	Decay per Decade (dB/decade)
300 GHz	+17.0	-11.8	28.8 dB/decade
600 GHz	+9.8	-29.5	39.3 dB/decade
1 THz	+0.4	-70.2	70.6 dB/decade
1.5 THz	-9.7	-140.4	130.7 dB/decade

The free space pathloss contributes 20 dB/decade decay while the molecular absorption is responsible to the 10 -50 dB decays as the frequency increases. The absorption losses of the 1.5 THz frequency is so very high that it renders it unusable at -100 dB/decade unless within a dense microcell arrangement.

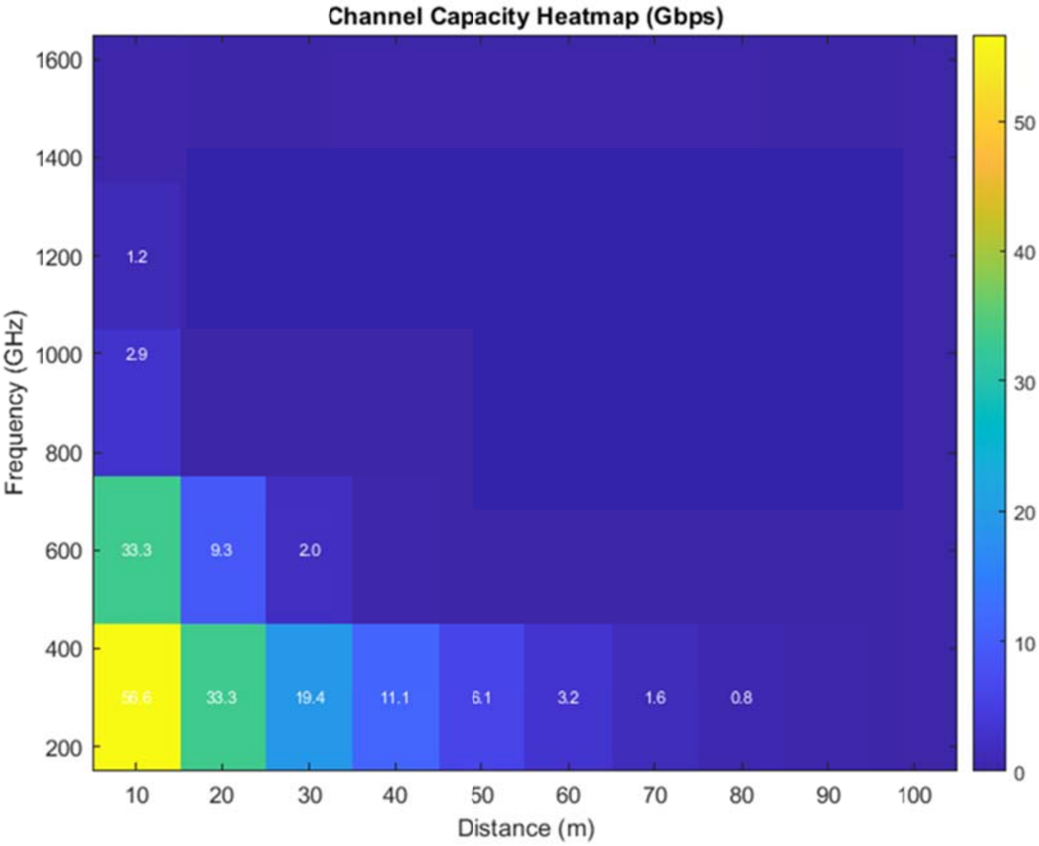

Figure 3: Capacity Heatmap

Figure 3 shows the capacity heatmap. The viable capacities (greater than 1 Gbps) were below 60 m for 0.3 THz frequency and below 20 m from the transmitter for the 0.6 GHz band. The 1-15 THz had very poor capacities beyond 10 m. This implies that fiber cables and mmWaves will remain highly vital for backhauling activities and ways of hybridising them should be considered from the design stages.

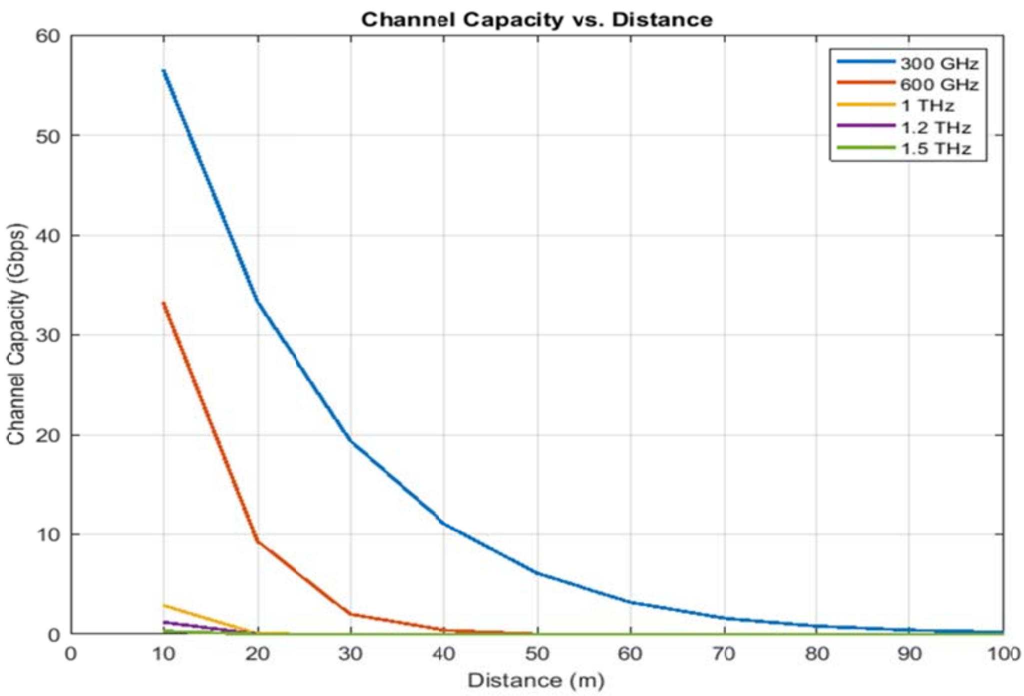

Figure 4: Plot of Channel Capacity against Distance for Selected Frequencies.

Figure 4 discusses the capacity in a graph. It plots the achievable data rate (Gbps) against distance for each frequency. This translates the physical layer impairments like path loss, and SNR into a tangible metric for network planners (data rates). It is possible to understand the operational range for each frequency band. For example, it shows that a 300 GHz link can provide a more than 10 Gbps connection for up to about 40 meters, which is perfect for a dense indoor hotspot like airport halls, and malls or a small cell backhaul link. Figure 5 present the relationship in a clear and easy to relate 3-dimensional view.

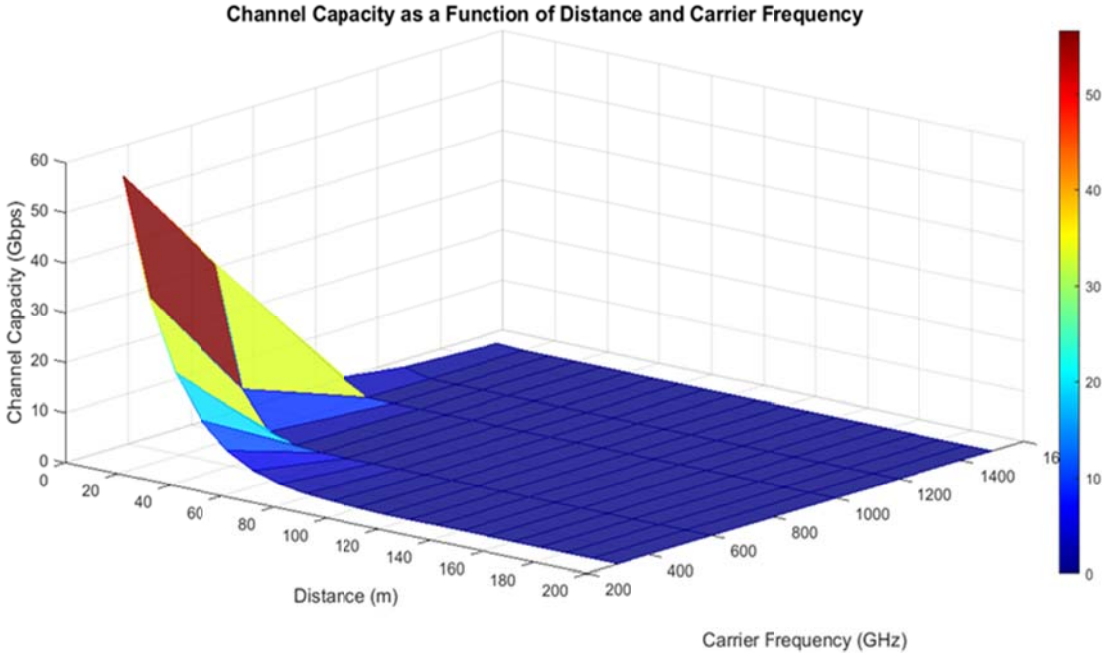

Figure 5: 3-D Channel Capacity relationship with Distance and Frequency.

Discussion of Results

The results from the analytical model and the generated graphs lead to several critical discussions:

1. The Dominance of Molecular Absorption: The results confirm that molecular absorption, not just free-space path loss, is the primary impediment in the THz band, especially in high-humidity tropical environments. The calculated SNR decay per decade far exceeds the 20 dB/decade from free-space loss alone. The 130.7 dB/decade decay for 1.5 THz is prohibitive, rendering it useless for any practical communication link beyond a few meters. This underscores the necessity of accurate, environment-based channel modelling.

2. The Viable Spectrum Window: The analysis successfully identifies the 300-600 GHz sub-band as the most practical spectrum for 6G THz deployments. Within this window, systems can achieve the multi-Gbps rates required for 6G applications over usable distances (20-60 meters). This finding is crucial for regulators and standards bodies allocating spectrum and for engineers designing early THz systems.

3. The Short-Range, High-Density Paradigm: The results force a paradigm shift. THz technology will not provide wide-area coverage. Instead, its value lies in creating extremely high-capacity "bubbles" or hotspots. This aligns perfectly with 6G use cases like immersive XR in a conference room, ultra-fast kiosks in airports, wireless backhaul between closely spaced buildings, and chip-to-chip communication.

4. The Non-Negotiable Need for Advanced Technologies: The steep performance decay shown in the graphs means that simple, omnidirectional THz communication is not feasible. The results directly justify the need for the technologies mentioned in the abstract like UM-MIMO, RIS and Hybrid Networks.

Conclusion

This research presented an analytical assessment of THz channel capacity under the specific and challenging conditions of a tropical climate. The findings are unequivocal: while the THz band offers unparalleled bandwidth, its practical utility is critically constrained by molecular absorption, limiting its effective use to short ranges.

The key conclusion is that the lower sub-THz spectrum (300-600 GHz) represents the most viable window for deploying high-density 6G applications in tropical regions. However, realising this potential is contingent upon the integration of advanced antenna systems like UM-MIMO and RIS to form and steer high-gain beams, thereby mitigating the severe path loss and absorption.

Therefore, THz communications will not replace existing technologies but will instead become a vital component of a heterogeneous 6G network architecture, providing the ultimate solution for localised, ultra-high-speed connectivity. Future work must focus on experimental validation of these models in real-world tropical settings and the development of efficient resource allocation algorithms for THz-based ultra-dense networks.

This study provides essential foundation and a clear set of design guidelines for network engineers and policymakers aiming to harness the terahertz spectrum for the future of wireless communication in Nigeria and similar tropical regions.

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