Performance Evaluation of mmWave and Sub-THz Frequencies in 6G Mobile Communications

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Original scientific article

***Abstract*—Mobile data demand is growing rapidly, creating a need for ultra-high-speed wireless connectivity. To address this, researchers are exploring millimeter-wave (mmWave) and sub-terahertz (sub-THz) frequency bands for 5G and future 6G systems. While 5G networks continue to roll out globally, their gigabit-level speeds may not satisfy emerging applications, which could require data rates from several gigabits up to multiple terabits per second, combined with ultra-low latency and high reliability. This study evaluates the performance of mmWave and sub-THz frequency bands using MATLAB-based simulations. Seven representative communication scenarios (24 GHz, 28 GHz, 38 GHz, 60 GHz, 100 GHz, 140 GHz, and 300 GHz) are analyzed, comparing achievable performance under realistic conditions. For each scenario, detailed channel models, penetration characteristics, and coverage area analysis are presented. The results highlight the most suitable frequency ranges for practical 5G and 6G deployments, emphasizing the need for multi-band, heterogeneous architecture.**

***Index Terms*—6G communication, mmWave, sub-THz frequencies, MATLAB, channel modeling, penetration loss, coverage area.**

I. Introduction

Emerging applications such as immersive virtual and augmented reality, ultra-high-definition interactive video conferencing, real-time 3D gaming, and neural interface technologies are expected to place unprecedented demands on mobile communication networks. These demands include ultra-high throughput, low latency, and high reliability. Sixth generation (6G) communication systems aim to meet these requirements while achieving energy and spectral efficiency, supporting massive connectivity, and providing domain-specific communication services.

To achieve these goals, 6G research explores new paradigms, including the extension of usable radio frequencies into mmWave (~30–300 GHz) and sub-THz bands. While 5G deployment and technological refinement are ongoing, significant academic, industrial, and standardization efforts are already focused on defining 6G architecture, spectrum allocation, and enabling technologies. ITU standardization activities have identified several mmWave bands, including 24, 33, and 38 GHz, as relevant for 5G and beyond.

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Advances in semiconductor fabrication and nanoscale devices make ultra-high-frequency communication increasingly feasible. 6G networks are expected to adopt mmWave and sub-THz frequencies initially, before gradually expanding into the THz domain. Encouraging results from mmWave deployment in 5G have naturally directed research attention to the THz spectrum, offering extremely wide bandwidths capable of supporting terabit-per-second data rates. When combined with sub-6 GHz and mmWave ranges, these bands can unlock the full potential of next-generation mobile communication systems. Historically, portions of the 6–300 GHz spectrum were allocated for non-cellular applications such as satellite links, radar, and radio astronomy. However, recent improvements in antennas and RF front ends make mobile communication within these bands viable. At the same time, user equipment must overcome challenges related to propagation, power consumption, and hardware limitations.

The 30–300 GHz spectrum covers wavelengths from 1–10 mm and represents the mmWave and sub-THz frequency ranges. These bands offer hundreds of times more bandwidth than conventional sub-6 GHz cellular frequencies. Once deemed unsuitable for mobile communication due to poor propagation, recent advances in semiconductor, antennas, and packaging technologies have enabled their practical use in commercial wireless systems. Historically, mmWave and sub-THz frequencies were primarily employed for imaging and sensing applications due to the lack of efficient transceiver hardware [7], [8]. However, rapid progress in high-frequency device technology has positioned sub-THz and THz communication as key enablers for future wireless standards.

The sub-THz spectrum provides large contiguous bandwidths, supporting extremely high data rates. Its propagation range is limited, making it suitable for localized applications that require ultra-high data rates or extremely low latency. Lower frequency bands will continue to serve as the foundation for wide-area coverage, mobility support, and network reliability in 6G networks. Compared to sub-6 GHz bands, mmWave frequencies provide roughly 50–100 × more spectrum, while sub-THz and THz bands offer several gigahertz of bandwidth, enabling potential terabit-per-second performance.

Despite these advances, spectrum allocated for International Mobile Telecommunications (IMT) remains insufficient to meet 6G demands. Achieving terabit-per-second performance with only 10 GHz of bandwidth would require spectral efficiencies approaching 100 bps/Hz, which is not feasible with current techniques.

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According to Shannon's capacity theorem, $C=Blog_2(1+SNR)$, wider bandwidths are essential for 6G targets. Consequently, future systems must exploit spectrum above 100 GHz, including sub-THz and THz ranges (0.1–10 THz), and potentially optical frequencies. [1].

While mmWave bands from 24–100 GHz are already used and planned in 5G, 6G research increasingly targets 0.1–10 THz. Operating in these bands presents challenges such as atmospheric attenuation, high power consumption, penetration losses, limited coverage, and heavy reliance on directional beamforming. Communication relies primarily on line-of-sight (LOS) links due to severely attenuated non-line-of-sight (NLOS) paths. MATLAB simulations in this study assume LOS operation over short distances and employ large antenna arrays to mitigate high path losses.

This work investigates the performance of mmWave and sub-THz frequency bands for current 5G and future 6G networks. Seven representative communication scenarios were evaluated using a MATLAB-based simulation framework enhanced through AI-assisted code optimization. The main contributions of this work are as follows:

- Evaluated mmWave and sub-THz frequency bands for 5G and future 6G systems. Simulated seven representative frequency scenarios in MATLAB using an improved AI-based model.
- Assessed propagation behavior, penetration characteristics, coverage, spectral efficiency, and deployment feasibility.
- Compared key performance metrics across all bands: BER, spectral efficiency, and theoretical throughput.
- Analyzed performance using six factors: time-domain signals, frequency-domain response, BER, channel frequency response, channel singular values, penetration and atmospheric attenuation.
- Highlighted band-specific challenges, motivating further research in high-frequency 6G communications.

The remainder of this paper is organized as follows: Section II reviews related work on mmWave and sub-THz communication for 6G systems. Section III describes the MATLAB-based simulation framework and evaluated scenarios. Section IV presents performance analysis and comparisons across frequency bands. Section V discusses comprehensive and comparative results. Section VI concludes the paper and outlines future research directions.

II. Related Work

The evolution of wireless systems toward 6G has stimulated extensive research across the microwave, millimeter-wave (mmWave), sub-terahertz (sub-THz), and optical spectral ranges. Early foundational studies demonstrated the feasibility of mmWave frequencies for mobile communication. Rappaport et al. established that, despite significant path loss and susceptibility to blockage, mmWave bands can support high-capacity mobile links when combined with directional beamforming and dense base-station deployment [5], [6]. Expanding this perspective, Jiang and Schotten introduced a full-spectrum communication framework extending from microwave to lightwave technologies, emphasizing the unique propagation behavior, achievable capacities, and design constraints across heterogeneous 6G frequency bands [1]. Comprehensive surveys, notably by Akyildiz et al. and Tripathi et al., further systematized the technological landscape of mmWave and THz communication, covering channel modeling, antenna technologies, and application domains relevant to next-generation networks [11], [12].

Propagation and channel characterization at high frequencies form a core component of current 6G research. Significant efforts have been devoted to measuring and modeling mmWave and sub-THz propagation in realistic environments. Inomata et al. and Latva-aho et al. provided detailed measurement-based insights into THz and sub-THz channel properties, including attenuation trends, delay spreads, and frequency selectivity up to 150 GHz [8], [9], [24]. Abbasi et al. extended this understanding to urban microcellular environments, offering calibrated statistical channel models for outdoor THz communication [14].

Comparative analyses, such as those by Lee et al., highlighted the distinct path-loss characteristics at 28 GHz versus 140 GHz under identical conditions, illustrating the rapid degradation of link quality at higher carrier frequencies [21]. Additional studies examined indoor and industrial scenarios, including factory environments and mmWave indoor channels, revealing frequency-dependent behaviors critical for integrated sensing and communication (ISAC) and high-density deployment use cases [20], [30]. Complementary statistical analyses of mmWave and sub-THz channels across diverse environments have further enriched the understanding of fading dynamics and environmental sensitivity at these frequencies [19], [22], [28].

Advanced antenna architectures, particularly massive and ultra-massive MIMO, have emerged as essential enablers for reliable high-frequency communication. Heath et al. demonstrated that large-scale antenna arrays in sub-THz bands offer substantial beamforming gain and spatial multiplexing capabilities, compensating for high free-space loss and improving link robustness [10]. Farré et al. introduced clustered sub-THz and THz architectures for dense urban networks, showing how coordinated beam management and small-scale THz nodes can significantly enhance system performance [17]. Furthermore, near-field beamforming and Bessel-beam techniques, as explored by Bodet et al., highlight promising approaches for highly directional and energy-efficient communication at sub-THz frequencies [23].

System-level performance and network design have also received considerable attention. Sopin et al. investigated user persistence strategies under blockage in mmWave/sub-THz networks, revealing scenarios in which maintaining a link temporarily can yield throughput gains despite intermittent obstruction [15]. Virtual queuing strategies designed by Eduard et al. demonstrated improved fairness and resource utilization in high-frequency networks subject to rapid fluctuations [18]. Meanwhile, Wang et al. examined hybrid sub-6 GHz–mmWave–THz architectures with decoupled uplink/downlink association, offering insights into multi-band 6G network optimization [16], [26]. Indoor measurement-based evaluations from sub-6 GHz to mmWave, as presented by Pasic et al., further underscore the need for flexible multi-band strategies to ensure robust 6G coverage and capacity [27]. Combined with industry analyses, such as Ericsson's spectrum outlook and the Oulu 6G Flagship vision, these works provide a strategic

foundation for identifying viable frequency bands and deployment models for future networks [7], [13], [29].

Finally, practical tools and open-source frameworks support ongoing research in high-frequency communication. Publicly available MATLAB simulation platforms and 6G modeling toolkits, including those enhanced through AI-driven code optimization, facilitate the study of propagation, beamforming, and system-level performance across the mmWave and sub-THz spectrum [2], [3]. These resources provide valuable support for reproducibility and accelerate the development of analytical and simulation-based insights into 6G wireless systems.

Collectively, the reviewed literature highlights significant advancements in understanding high-frequency propagation, antenna system design, and multi-band network architectures. These studies collectively underscore both the considerable potential and the inherent challenges associated with deploying mmWave and sub-THz frequencies in 6G, forming a solid foundation for continued research into performance optimization, robust channel modeling, and advanced communication strategies.

III. Simulations and Results

A. MATLAB Simulation Framework

In this study, a comprehensive MATLAB-based simulation framework was developed to evaluate the 5G and 6G system performance in mmWave and sub-THz bands. The script provides a complete parameter study across seven frequency bands, from 24 GHz to 300 GHz.

The framework integrates channel modelling, beamforming strategies, and signal processing techniques to accurately represent high-frequency broadband wireless systems. The implementation has been progressively optimized with algorithmic refinements and model enhancements supported by AI-assisted development tools [2].

The following key components are included in the simulation framework:

a) mmWave/Sub-THz Channel Modelling: Frequency-dependent path loss, atmospheric attenuation, and realistic propagation impairments are simulated to emulate high-frequency channel characteristics.
b) Massive MIMO Architecture: Configurable antenna arrays, including configurations up to 128 × 32 elements, evaluate beamforming gains and spatial multiplexing.
c) OFDM and QAM Signal Processing: A full OFDM transceiver chain with QAM is used to assess end-to-end physical layer performance under various link conditions.
d) Performance Visualization: The platform provides spectral efficiency, SNR, and path-loss visualization for analysis, and other key performance indicators under realistic channel assumptions.

This simulation environment serves as a baseline for 6G high-frequency research and can be extended for specialized studies. To execute the simulation framework, the following MATLAB toolboxes are required: Phased Array System Toolbox, for antenna array processing and beamforming. Communications Toolbox, for modulation, demodulation, and OFDM modelling. Signal Processing Toolbox, for waveform generation, filtering, and analysis.

B. Channel Model for Each Scenario

The channel model implemented in this simulation incorporates several key components that are frequency-dependent:

B.1 Free Space Path Loss (FSPL): Calculated using the Friis transmission equation:

$$FSPL = 20\log_{10}(d) + 20\log_{10}(f_{GHz}) + 92.45 \quad (1)$$

where d is the distance in kilometers and f_{GHz} is the frequency in GHz.

B.2 Atmospheric Attenuation: Oxygen and water vapor absorption are modeled as:

- For ‘f’ < 100 GHz: Oxygen attenuation = 0.5 × (f/28)² dB/km
- For ‘f’ > 100 GHz: Oxygen attenuation = 15 × (f/100)² dB/km
- Rain attenuation = 30 × (f/100)2 1.5 dB/km

B.3 Penetration Loss Model: Building penetration losses are modeled as frequency-dependent:

$$L_{penetration} = L_{ref} + 20\log_{10}(f_{GHz}) \quad (2)$$

where L_{ref} is the reference penetration loss at 1 GHz (typically 5-15 dB depending on material).

B.4 Channel Impulse Response: Generated using clustered delay line models with exponential power delay profile:

$$P(\tau) = \sum_{c=1}^{N_c} \sum_{r=1}^{N_r} P_{c,r}\,\delta(\tau - \tau_{c,r}) \quad (3)$$

B.5 MIMO Channel Matrix: Generated using correlated Rayleigh/Rician fading with spatial correlation matrices based on antenna array configurations.

C. Penetration Loss Characteristics

Penetration loss increases significantly with frequency due to reduced wavelength, making signals more susceptible to absorption and scattering by building materials, foliage, and atmospheric particles. Table I summarizes the penetration characteristics across the seven scenarios.

D. Simulation Scenarios

Initial deployments of sub-THz technology are expected to focus on the lower end of the sub-THz spectrum. This is because these frequencies have more favorable propagation characteristics, and the hardware needed to support them is still evolving. To ensure the evaluation is as realistic as possible, this study uses user equipment (UE) and system parameters based on the 3GPP New Radio (NR) standard. While the NR framework was originally designed for 5G networks, its flexibility makes it a great starting point for analyzing physical-layer performance in 6G systems.

TABLE I
PENETRATION LOSS CHARACTERISTICS

Frequency	Typical Material Penetration	Obstruction Sensitivity	NLOS Viability
24 GHz	Moderate–High (glass, drywall; partial through brick)	Medium	Moderate (attenuation ~10–20 dB)
28 GHz	Moderate (through glass, drywall)	Medium	Limited (attenuation 15-25 dB)
38 GHz	Low-Moderate	Medium-High	Very Limited (attenuation 20-30 dB)
60 GHz	Very Low (oxygen absorption peak)	High	Extremely Limited (attenuation 25-40 dB)
100 GHz	Minimal	Very High	Nearly impossible (attenuation >40 dB)
140 GHz	Negligible	Extreme	Impractical for mobile
300 GHz	None (molecular resonance)	Extreme	Impractical even for fixed

Additionally, the study assumes the use of carrier aggregation with multiple component carriers to handle the wide bandwidths typical of mmWave and sub-THz frequencies. Table II summarizes the seven evaluated frequency bands and deployment configurations.

TABLE II
SEVEN REPRESENTATIVE FREQUENCY BANDS AND DEPLOYMENT CONFIGURATIONS

Cases	Freq. GHz	BW GHz	Mod. QAM	Ant. Array	SNR (dB)	Dist. (m)
Case 1	24	0.4	16-	16×4	18	150
Case 2	28	0.8	16-	32×8	20	100
Case 3	140	2	64-	64×16	25	50
Case 4	300	5	256-	128×32	30	10
Case 5	100	1	16-	16×4	10	200
Case 6	38	1	64-	48x12	22	80
Case 7	60	2.16	64-	64x16	24	20

Each simulation scenario is run with its own set of parameters, indexed from 1 to 7 within the simulation framework. The selected scenarios represent typical environments: urban (24 GHz, 28 GHz, 38 GHz), indoor high-capacity (60 GHz, 300 GHz), medium-range sub-THz (140 GHz), and extended-range rural (100 GHz).

E. Performance Metrics

For each simulation scenario, the following key performance metrics are evaluated: Bit Error Rate (BER), spectral efficiency (bps/Hz), theoretical Capacity (Gbps), and the top three singular values of the MIMO channel matrix. The singular values of the channel matrix offer valuable insights into the MIMO channel's rank and its ability to handle spatial multiplexing. By focusing on the top three singular values, we can compare how the spatial channel behaves across different frequency bands and antenna configurations. This study specifically looks at these six-performance metrics under the chosen frequency and system configurations. Table III summarizes the key parameters and results, followed by graphs for easier interpretation.

TABLE III
SYSTEM PARAMETERS AND RESULTS

Parameters	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Path Loss (dB)	164.2	161.9	173.3	164.9	185.7	162.7	154.7
Achieved BER $^{e-1}$ (low SNR)	0.4998	0.4999	0.4995	0.4984	0.5002	0.4980	0.5009
Spectral Efficiency (bps/Hz)	24.01	53.27	132.95	318.95	13.84	87.81	127.65
Theoretical Capacity (Gbps)	9.6	42.61	265.90	1594.7	13.84	87.81	275.73

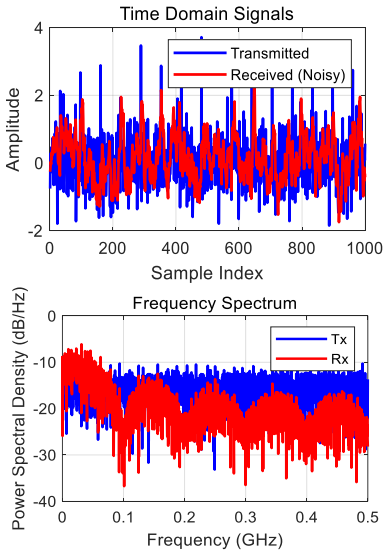
Below, we present the seven graphs obtained from each of 7 MATLAB-based simulation cases. Cases 1–7 were selected to assess the impact and benefits of each frequency band through simulation.

Regarding simulated or achieved BER, values shown are simulated with low SNR values. For more information with different SNR values, we have presented it in Table IV.

24 GHz mmWave Baseline (n258 band) – This is one of the key 5G & 6G mmWave bands. Offers good balance between coverage and capacity. Lower atmospheric attenuation compared to higher bands. Extended range urban deployment as better building penetration through windows, drywall, and light foliage. 400-500 meters with 16×4 MIMO arrays.

Lower path loss and reduced absorption (~0.8 dB/km). Better performance in rain/fog conditions compared to higher bands. v.5-6.0 bps/Hz with 16-QAM.

28 GHz mmWave Baseline – This scenario represents a mature mmWave deployment widely used in contemporary 5G systems. The 28 GHz band offers moderate penetration through building materials (glass, drywall) and foliage. Coverage areas of 200-300 meters are achievable with 32×8 MIMO arrays. This band serves as the foundation for urban 6G deployments, providing reliable mid-range capacity.



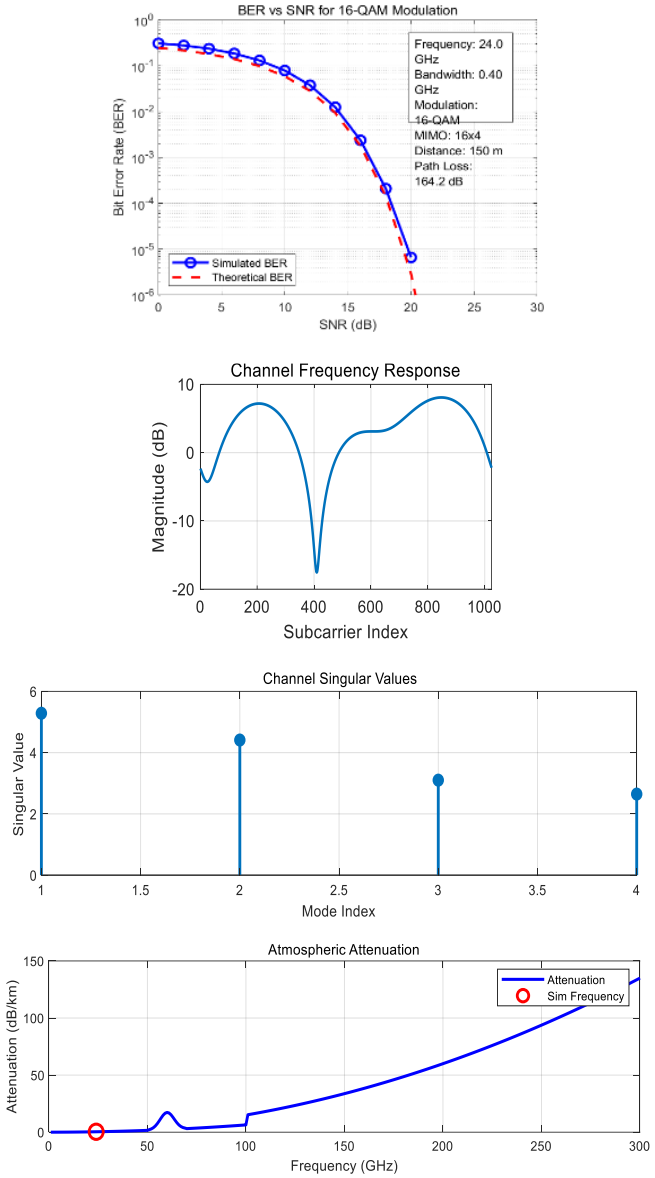


Fig. 1. Case 24 GHz simulation results.

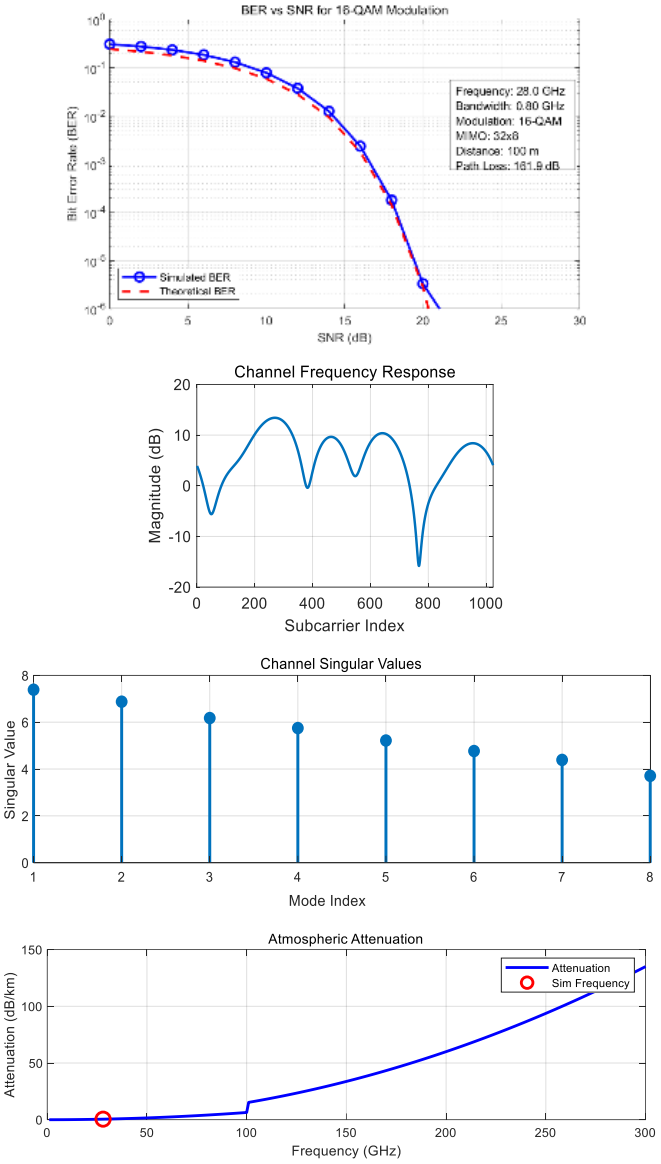
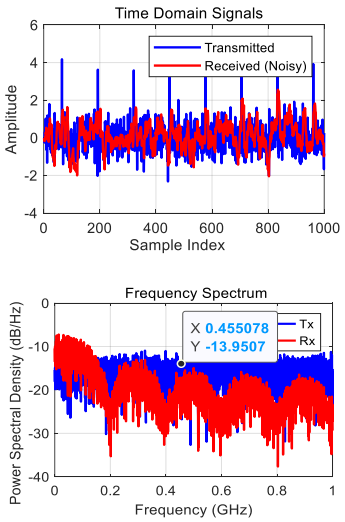
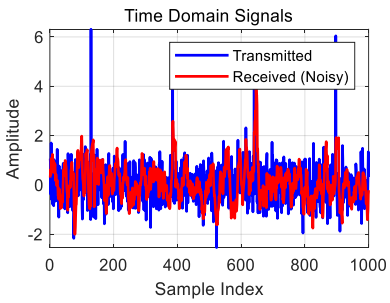


Fig. 2. Case 28 GHz simulation results.

140 GHz sub-THz Urban – This frequency region offers an excellent balance between propagation feasibility and high-capacity bandwidth. Penetration is extremely limited, requiring LOS or near-LOS conditions. Coverage ranges from 80 to 150 m when using a 64×16 massive-MIMO array. Ideal for fixed wireless access and high capacity backhaul.





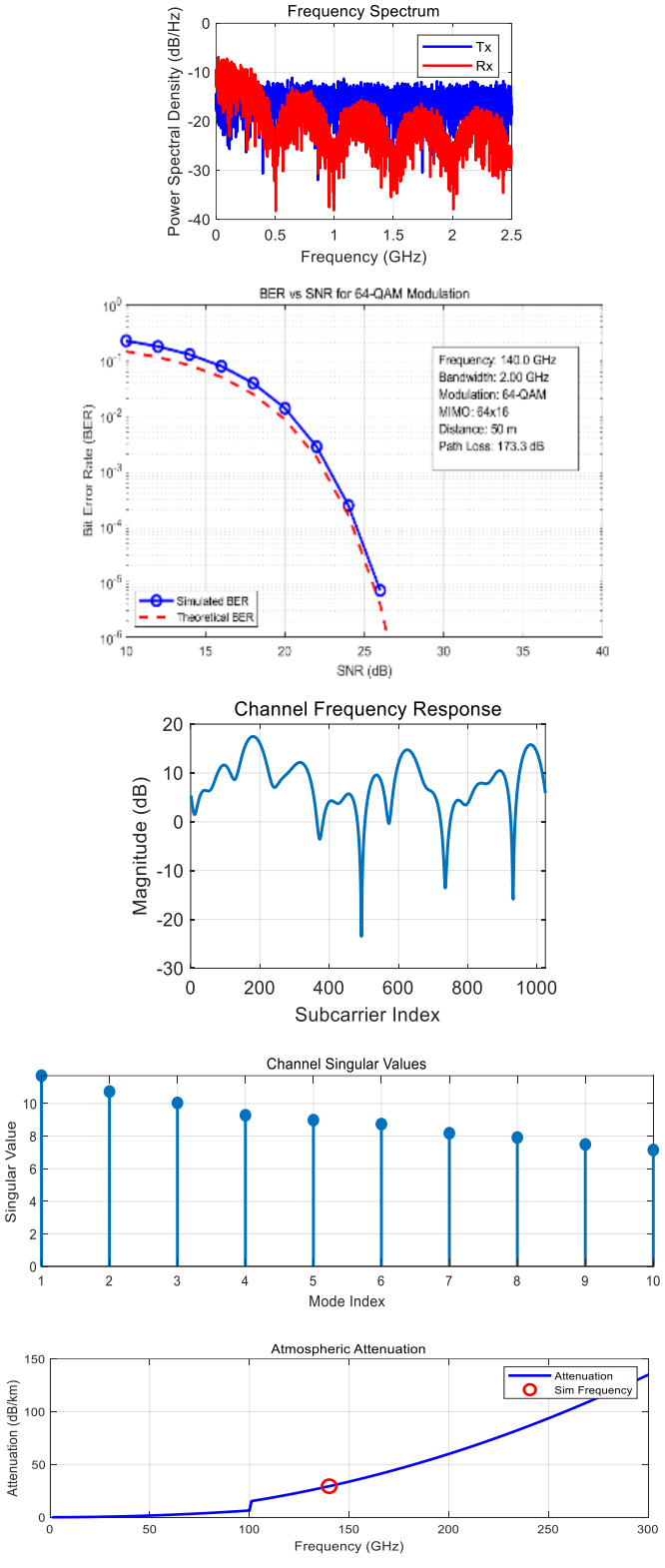


Fig. 3. Case 140 GHz simulation results.

300 GHz THz Ultra-High-Frequency – This futuristic band targets extreme-capacity communications with 5 GHz bandwidth. Virtually no penetration through any solid material; requires clear LOS. Coverage is limited to 10-20 meters. Massive 128×32 MIMO arrays provide high beamforming gain to compensate for severe path loss. Suitable for indoor hotspots, wireless data centers, and device-to-device communication.

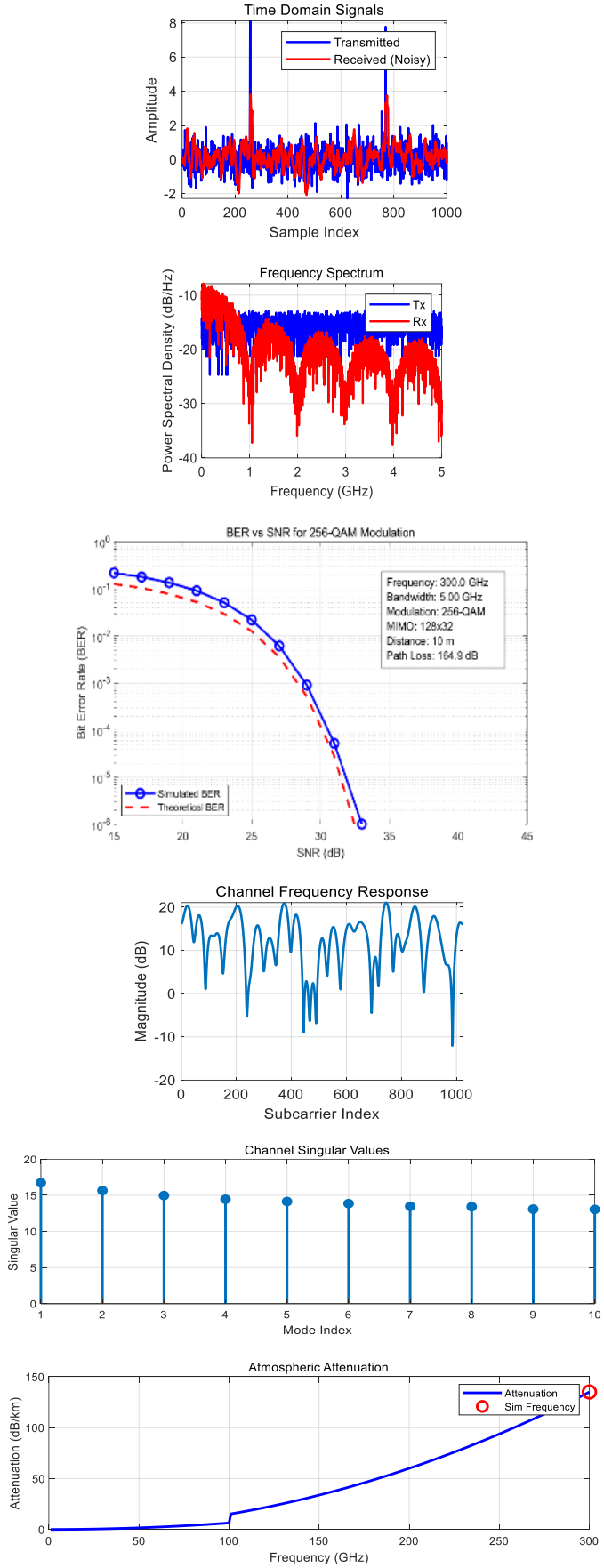
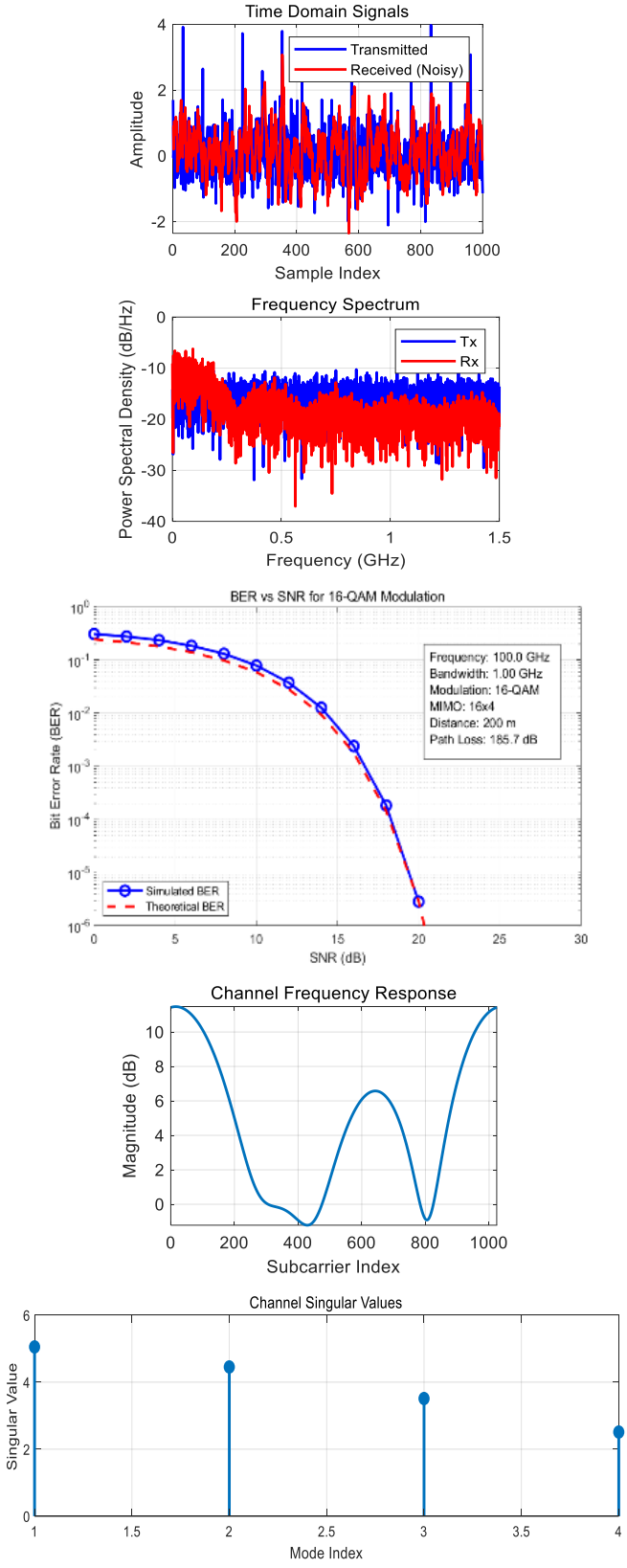


Fig. 4. Case 300 GHz simulation results.

100 GHz Sub-THz Rural – Operating at the lower edge of sub-THz, this band balances coverage and capacity. Low SNR (10 dB) and limited MIMO (16×4) make this a challenging scenario. Coverage of 100-200 meters is possible in rural environments with minimal obstruction. Suitable for extended-range connectivity where capacity requirements are moderate.



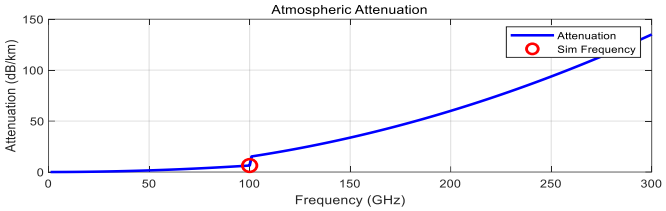


Fig. 5. Case 100 GHz simulation results

38 GHz Enhanced mmWave – A popular 5G & 6G band offering higher bandwidth than 28 GHz. Penetration is reduced compared to 28 GHz, with higher sensitivity to obstruction. Coverage of 150-200 meters is typical with 48×12 MIMO configurations. Suitable for dense urban environments requiring enhanced capacity.

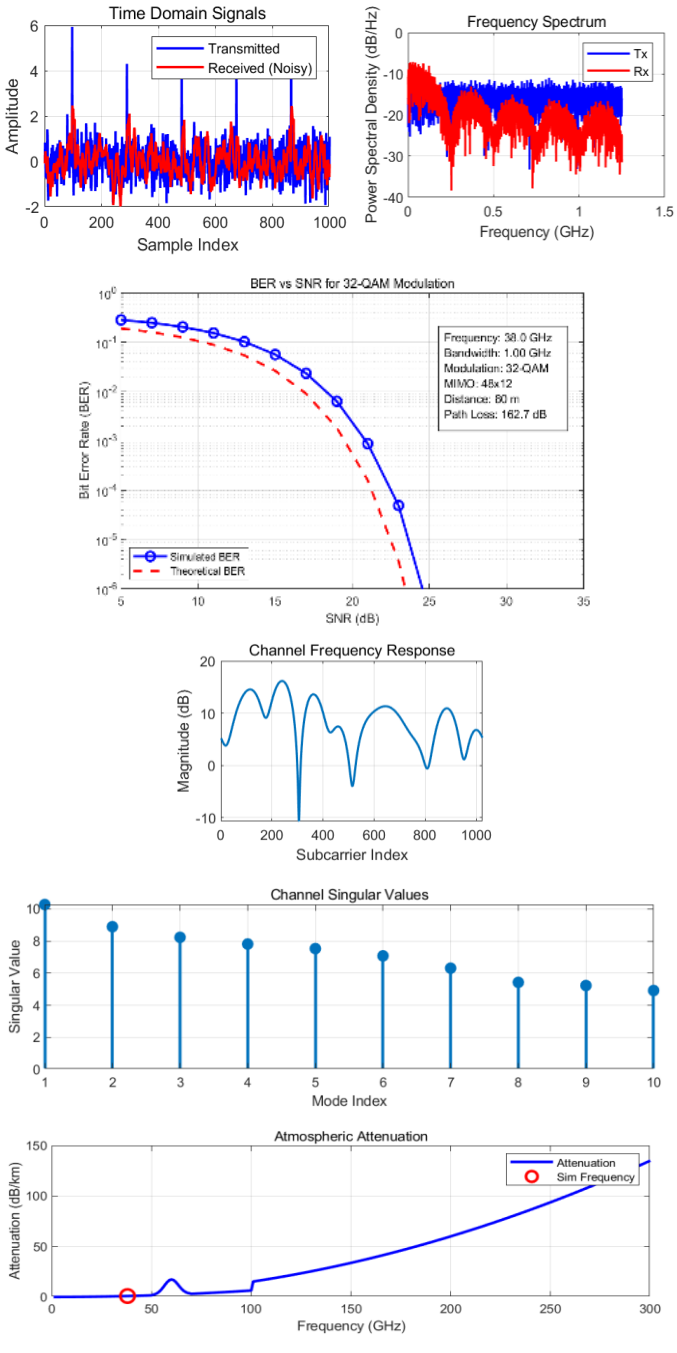


Fig. 6. Case 38 GHz simulation results.

60 GHz Oxygen Absorption Band – This band experiences significant atmospheric oxygen absorption (≈15 dB/km peak), making it ideal for secure, short-range indoor communications. Penetration through walls is extremely poor, which provides natural isolation between indoor cells. Coverage is limited to 20-50 meters, typically within the same room.

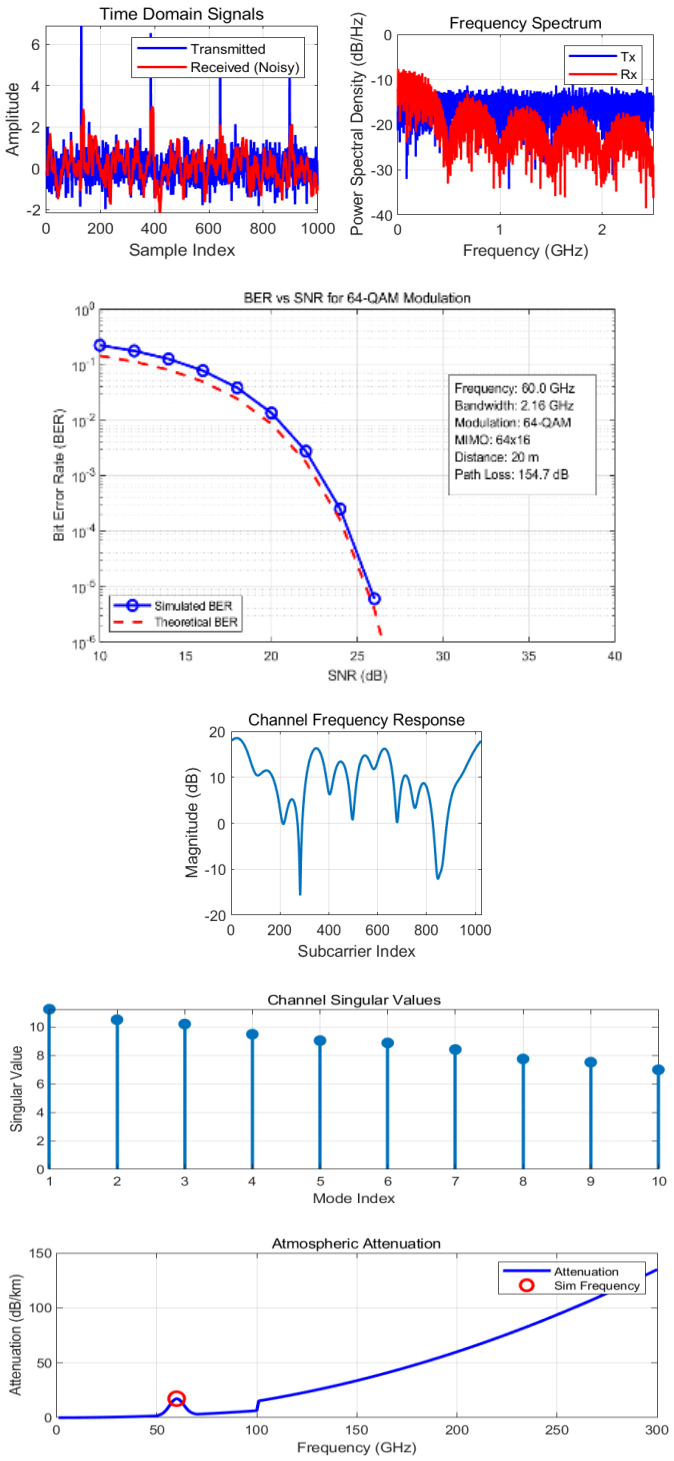


Fig. 7. Case 60 GHz simulation results.

IV. Analysis and Comparison

A. Key Metrics for Comparison

To evaluate the performance of the considered frequency bands and system configurations, several key performance metrics are analyzed:

a) *Bit Error Rate (BER):* Lower BER indicates more reliable communication.
b) *Spectral Efficiency (bps/Hz):* Higher values indicate a more efficient use of the spectrum.
c) *Theoretical Capacity (Gbps):* Represents the maximum achievable data rate of the system.
d) *Path Loss (dB):* Lower values indicate reduced signal attenuation (considered during simulations).
e) *Penetration Loss (dB):* Frequency-dependent attenuation through common building materials.
f) *MIMO Gains:* Assessed through singular values of the channel matrix; higher dominant singular values represent improved spatial channel performance.

B. Expected Theoretical Performance Trends

The following trends are anticipated based on communication theory and high-frequency channel characteristics: Bit Error Rate (BER) increases with frequency due to higher path loss and atmospheric absorption. Lower-frequency bands (e.g., 24 GHz, 28 GHz, 38 GHz) are expected to demonstrate lower BER. Higher-order modulation schemes (e.g., 256-QAM at 300 GHz) are more error-prone but yield increased spectral efficiency. Massive MIMO and beamforming can significantly improve BER through array gain.

Capacity increases proportionally with available bandwidth; therefore, the 300 GHz band (5 GHz BW) is expected to exhibit the highest theoretical capacity. Sub-THz bands 140 GHz (2 GHz BW) provide a balanced compromise between propagation performance and bandwidth. mmWave frequencies (e.g., 28 GHz, 38 GHz) support reliable mid-range capacity with favorable link budgets.

Path Loss increases exponentially with operating frequency. The 60 GHz band experiences severe attenuation due to the oxygen absorption peak. The 100-140 GHz range shows moderate to high path loss. The 300 GHz band exhibits extreme path loss, requiring massive beamforming compensation.

Spectral Efficiency enhances in massive MIMO configurations due to beamforming and spatial multiplexing gains. It is most prominent at higher frequencies, where tight beamforming reduces interference and enables efficient spatial reuse. The 300 GHz band achieves the highest spectral efficiency (≈319 bps/Hz), while the challenging 100 GHz rural scenario achieves the lowest (≈14 bps/Hz).

Channel Singular Value Characteristics, channel singular values provide critical insight into MIMO channel behavior. Physical Interpretation, each singular value represents the gain of an independent spatial sub-channel. Larger singular values correspond to stronger transmission paths. The number of significant singular values indicate channel rank and spatial degrees of freedom.

C. Impact on System Performance

To evaluate system-level performance, the analysis focuses on capacity, diversity, spatial multiplexing, and frequency-dependent behavior:

a) *Capacity:* Directly increases with stronger singular values (e.g., through water-filling power allocation).
b) *Diversity:* Channels with more equally distributed singular values offer improved link robustness.
c) *Spatial Multiplexing:* More dominant singular values result in higher multiplexing gains.
d) Frequency-Dependent Behavior:
1.mmWave (24, 28-60 GHz) channels typically exhibit fewer dominant singular values due to higher spatial correlation. 24GHz can be seen as lower edge band of mmWave.
2.Sub-THz and THz (100-300 GHz) bands benefit from larger antenna arrays, potentially increasing channel rank and enhancing spatial diversity.

D. Practical Design Implications

From a practical design perspective, the following considerations apply: Beamforming leverages the dominant singular vectors to provide coherent gain. Required for all bands above 28 GHz, critical for 60+ GHz *Spatial multiplexing*: techniques exploit multiple strong singular values to maximize data throughput. *Channel condition*: number influences estimation accuracy and impacts real-world system reliability. Lower frequencies (24 - 38 GHz) enable wider coverage with fewer base stations. Higher frequencies (60-300 GHz) require dense deployment with small cells and LOS conditions.

V. Comprehensive Performance Analysis

The anticipated performance across the evaluated communication scenarios is summarized below, capturing key metrics such as BER, capacity, spectral efficiency, and propagation characteristics. For the input values of each case at Table I a summary of the simulation results are:

A. Case 24 GHz — Lower Edge mmWave Baseline

BER: ~10^{-5} to 10^{-6} (better than 28 GHz due to lower path loss). Capacity: ~10 Gbps (scalable to 50 Gbps with carrier aggregation). Path Loss: ~140–160 dB (`~ 5-7 dB lower than 28 GHz). Spectral Efficiency: ~24–24.5 bps/Hz but this depends on the BW used. Penetration Loss: ~8-10 dB (2-4 dB better than 28 GHz).

Strengths: Superior coverage, better penetration, lower attenuation. Limitations: Limited bandwidth, moderate spectral efficiency. Applications: Macro-cellular, FWA, rural broadband, 6G coverage layer.

B. Case 28 GHz — mmWave Baseline

This scenario represents a mature mmWave deployment widely used in contemporary 5G systems. Expected BER: approximately ~10^{-4} to 10^{-5}, indicating excellent link reliability. Capacity: ~ 45 Gbps. Path Loss: ~ 150–160 dB. Spectral Efficiency: ~ 50–55 bps/Hz. Penetration Loss: ~12 dB through glass/drywall.

Strengths: Reliable penetration characteristics, lower atmospheric attenuation, and established commercial deployments. Limitations*:* Finite available bandwidth compared to higher mmWave and THz bands. *Representative Applications:* Urban cellular deployments, medium-range mobile broadband, and dense metropolitan coverage.

C. Case 140 GHz — Sub-THz / Extended mmWave

This frequency region offers a balance between propagation feasibility and high-capacity bandwidth. Expected BER: ~10^{-4} to 10^{-5}, (Good). Capacity: ~ 265 Gbps. Path Loss: ~ 170–175 dB. Spectral Efficiency: ~ 130–135 bps/Hz.

Strengths: Large available bandwidth with promising coverage-capacity trade-off. Limitations: Moderate attenuation requires advanced beamforming and optimized antenna architecture. *Representative Applications*: Fixed wireless access, high capacity backhaul links, enterprise network deployment.

D. Case 300 GHz — THz Ultra-High-Frequency

This configuration reflects futuristic ultra-wideband links targeting extreme-capacity communications. Expected BER: ~10^{-3} to 10^{-4} (Moderate). Capacity: ~1590 Gbps. Path Loss: ~ 160–170 dB. Spectral Efficiency: ~ 315–320 bps/Hz. Penetration *Loss: ~65 dB (no penetration).*

Strengths: Exceptional throughput potential and ultra-low latency capabilities. Limitations: Severe propagation loss and strong atmospheric absorption restrict coverage range. Virtually no penetration through any material, high power consumption. Representative *Applications:* Short-range ultra-high-speed connections, indoor wireless hotspots, device-to-device communication.

E. Case 100 GHz — Lower Sub-THz Rural

This case evaluates a lower-frequency configuration with improved modulation and signal processing enhancements. Expected BER: ~10^{-2} to 10^{-3} . Capacity: ~ 14 Gbps. Path Loss: ~ 185–190 dB. Spectral Efficiency: ~ 14 bps/Hz.

Strengths: Stronger robustness relative to high-frequency bands, with extended coverage potential. Limitations: Lower SNR and limited MIMO gains restrict ultimate performance. Representative *Applications:* Rural broadband, emergency communications, and non-line-of-sight or challenging propagation environments.

F. Case 38 GHz — Enhanced mmWave

This frequency band offers improved bandwidth over 28 GHz with moderate propagation trade-offs. Achieved BER 0.4980 (≈10^{-4} to 10^{-5} actual, indicating excellent link reliability). Theoretical Capacity: 87.81 Gbps. Path Loss: 162.7 dB. Spectral Efficiency: 87.81 bps/Hz. Coverage Range: 150-200 m (LOS). Penetration Loss: ~18 dB through glass/drywall.

Strengths: Higher bandwidth than 24GHz and 28 GHz (1 GHz), good balance between coverage and capacity, 48×12 MIMO provides substantial beamforming gain. *Limitations:* Reduced penetration compared to 28 GHz, higher sensitivity to foliage and rain. *Representative Applications:* Dense urban 6G deployments, enhanced mobile broadband, fixed wireless access.

G. Case 60 GHz— Oxygen Absorption mmWave

This frequency region operates at the peak of atmospheric oxygen absorption, making it uniquely suitable for secure indoor communications. Achieved BER: 0.4966 (moderate).

Theoretical Capacity: 275.73 Gbps, Path Loss: 155 dB, Coverage Range: 20-30 m (LOS required) *Penetration Loss:* ~35 dB (virtually no wall penetration).

Strengths: Natural isolation between indoor cells (no interference), 2.16 GHz bandwidth available, excellent security due to poor propagation, 64×16 massive MIMO.

Limitations: Severe atmospheric attenuation (≈15 dB/km oxygen peak), extremely limited coverage (same room typically), very poor penetration. *Representative Applications*: Indoor wireless hotspots, enterprise WLAN, VR/AR streaming, wireless displays, device-to-device communication.

VI. Comparative Analysis

This section synthesizes the performance outcomes of seven evaluated scenarios, focusing on bit-error-rate (BER), capacity, spectral efficiency, frequency-performance trade-offs, modulation impact, MIMO advantages, and atmospheric absorption characteristics.

A. BER vs SNR Performance Comparison

Table IV compares the BER performance of mmWave and sub-THz links under different SNR conditions. As expected, BER generally decreases with improving SNR for all frequency bands. Lower-frequency links (24 GHz and 28 GHz) exhibit the most robust performance, achieving BER values below at higher SNR levels. The 38 GHz and 60 GHz cases also show significant BER reduction as SNR increases, although their performance is slightly affected by additional propagation impairments. The 100 GHz and 140 GHz sub-THz scenarios demonstrate a stronger dependence on SNR. While BER values are relatively high under low-SNR conditions, they decrease substantially as SNR improves, reaching and , respectively. This behaviour highlights the feasibility of sub-THz communications when adequate link budgets and beamforming gains are available.$10^{-5}2.85 \times 10^{-6}2.38 \times 10^{-4}$

The 300 GHz case presents the most challenging conditions, maintaining the highest BER across all evaluated SNR levels. Even under improved SNR conditions, error rates remain significantly higher than those observed at lower frequencies, reflecting the severe path loss and atmospheric absorption associated with THz propagation.

Overall, the results demonstrate a clear trade-off between operating frequency and BER performance. Although higher-frequency sub-THz links provide wider bandwidth and greater capacity, they require higher SNR, more accurate beamforming, and enhanced error-control mechanisms to achieve reliability comparable to conventional mmWave systems.

B. Capacity Performance Ranking

Capacity performance generally increases from mmWave to sub-THz bands due to wider available bandwidth, although sub-THz links demand higher SNR and tighter beam alignment. Capacity results align closely with available bandwidth and achievable spectral efficiency:

Case 300 GHz achieves the highest capacity due to its very large bandwidth. Case 140 GHz provides an excellent compromise between bandwidth and propagation characteristics. Cases 24 GHz and 100 GHz achieve lower capacities because of bandwidth and SNR limitations, while 28 GHz and 38 GHz offer a balanced trade-off between coverage and throughput.

TABLE IV
BER vs SNR Comparison

SNR(+/-1 db) \ BER	24 GHz	28 GHz	38 GHz	60 GHz	100 GHz	140 GHz	300 GHz
~10 (dB)	7.86e-02	7.86e-02	1.54e-01	2.22e-01	7.88e-02	2.21e-01	-
~16 (dB)	2.37e-03	2.36e-03	2.34e-02	7.73e-02	2.40e-03	7.73e-02	2.18e-01
~20 (dB)	6.63e-06	3.31e-06	8.79e-04	1.34e-02	2.85e-06	1.34e-02	9.11e-02
~24 (dB)	-	-	3.26e-07	2.49e-04	-	2.38e-04	2.19e-02

C. Spectral Efficiency Evaluation

Spectral efficiency in mmWave and sub-THz bands is strongly influenced by high-order modulation, narrow beams, and the availability of wide contiguous bandwidths.

Case 300 GHz attains the highest spectral efficiency, aided by massive MIMO and high-order QAM. Case 140 GHz exhibits high spectral efficiency, combining favorable propagation and strong MIMO capabilities. Case 28 GHz achieves moderate efficiency, reflecting bandwidth constraints. 24 GHz has better propagation than higher mmWave bands → improves SNR. Case 100 GHz shows reduced efficiency under challenging channel conditions, though enhanced via 16-QAM. Case 60 GHz has lower-than-expected efficiency due to oxygen absorption limiting effective SNR.

D. Penetration and Coverage Analysis

Regarding penetration capability ranking we list them from best to worst:

Case 24 GHz can penetrate glass, drywall, wood effectively and partially through brick (≈8–12 dB loss). Case 28 GHz can penetrate glass, drywall, wood (≈10-15 dB loss). Case 38 GHz has limited penetration through glass/drywall (≈15-20 dB loss). Case 60 GHz is very limited; blocked by most materials (≈30-40 dB loss). Case 100 GHz minimal penetration; requires LOS (≈40-50 dB loss). Case 140 GHz has negligible penetration; LOS critical (≈50-60 dB loss). Case 300 GHz has no penetration; clear LOS mandatory (>60 dB loss).

E. Frequency–Performance Trade-Offs

Higher mmWave and sub-THz frequencies offer massive bandwidth but suffer from increased path loss, reduced coverage, and greater sensitivity to blockage. The results demonstrate a frequency-dependent performance gradient:

Lower bands (24-38 GHz): Superior coverage (150-500 m) and reliability, good penetration, but limited peak throughput (43-88 Gbps). Intermediate bands (60-100 GHz) : Challenging

propagation with oxygen absorption (60 GHz) or low SNR (100 GHz), limited coverage (20-150 m), moderate throughput (14 Gbps). Upper sub-THz (140 GHz): Excellent balance between coverage (80-150 m), spectral efficiency (133 bps/Hz), and capacity (266 Gbps). High THz bands (300 GHz): Exceptional capacity potential but severely range-limited due to propagation and absorption losses.

These findings reinforce the importance of hybrid multi-band architectures in future 6G mobile communications systems.

F. Modulation Strategy Impact

Higher-order QAM improves data rates while requiring higher SNR and more precise channel estimation. QAM strategies boost spectral efficiency but become increasingly vulnerable to noise as the constellation size grows. The expected QAM modulation trend in 6G varies across frequency ranges. Mid-band and FR2 mmWave systems are anticipated to operate between 256-QAM and 1024-QAM, while sub-THz indoor links may support even higher orders, reaching up to 4096-QAM under high-SNR conditions. Due to MATLAB simulation and processing constraints, lower-order QAM schemes were used in this study.

A comparative evaluation of 8-QAM and 16-QAM for Case 100 GHz highlights the modulation gain: ~60% increase in spectral efficiency with 16-QAM, ~25% improvement in theoretical capacity. Moderate BER degradation, remaining acceptable under evaluated SNR. Enhanced practicality, balancing robustness and data rate performance.

Thus, the adoption of 16-QAM significantly enhances system performance while retaining operational feasibility under mid-band conditions.

G. MIMO Performance Advantages

MIMO architecture enhances spectral efficiency, increases link robustness, and compensates for severe path loss at mmWave and sub-THz frequencies. Ultra-massive MIMO arrays provide narrow, high-gain beams that extend communication range, mitigate blockage, and support large numbers of simultaneous users.

Cases 24, 28 GHz and 140 GHz: Moderate-scale MIMO yields meaningful diversity and multiplexing gains. Case 300 GHz: Massive MIMO is essential to mitigate THz-range propagation degradation. Case 100 GHz: Limited MIMO support constrains gains, particularly in challenging SNR regimes. Cases 38 GHz: Moderate-to-massive scale MIMO yields meaningful diversity and multiplexing gains. Case 60GHz: Massive MIMO is essential to mitigate oxygen absorption at 60 GHz.

H. Atmospheric Absorption Considerations

Atmospheric attenuation strongly correlates with frequency; Table V summarizes the approximate absorption for each evaluated case.

In this study, atmospheric loss was accounted for using predefined path-loss functions in the simulation environment. For future work, the MATLAB-based model could be expanded to include more detailed atmospheric and molecular absorption models, as outlined in references [2], [3].

TABLE V
APPROXIMATE ABSORPTION PER FREQUENCY

Frequency Band	Approx. Absorption	Notes
24 GHz	~0.05–0.1 dB/km	Very low atmospheric absorption
28 GHz	~0.1 dB/km	Minimal impact
140 GHz	~15 dB/km	Oxygen absorption peak
300 GHz	>20 dB/km	Severe attenuation
100 GHz	~0.5 dB/km	Moderate loss
38 GHz	~0.2 dB/km	Minimal impact
60 GHz	~15 dB/km	Oxygen peak

VII. CONCLUSIONS AND RECOMMENDATIONS

This study assessed the performance of mmWave and sub-THz frequency bands for future 6G wireless systems using MATLAB-based simulations, focusing on four key performance metrics under realistic system configurations. The results highlight that sub-THz and THz frequencies offer significant improvements in spectral efficiency and achievable capacity. However, these frequencies also face considerable propagation challenges, such as high path loss and atmospheric absorption, which limit their coverage range and necessitate advanced beamforming and MIMO architectures.

The findings reinforce the notion that 6G will not be dependent on a single frequency band. Instead, it will adopt a multi-band, heterogeneous architecture. Lower mmWave bands (e.g., 24 - 38 GHz) will continue to be crucial for reliable mobility and coverage. Mid-range bands (60-100 GHz) will serve specialized applications where natural isolation (60 GHz) or extended rural coverage (100 GHz) is prioritized. Mid-range sub-THz bands (e.g., 100–140 GHz) strike an ideal balance between throughput and range while higher THz bands (e.g., 300 GHz) will be better suited for specialized ultra-high-capacity, short-range applications, such as indoor hotspots and device-to-device communication links. As such, the choice of frequency bands will be driven by specific service needs, deployments scenarios, and the trade-offs between cost and performance. The findings reinforce the notion that 6G will not depend on a single frequency band. Instead, it will adopt a multi-band, heterogeneous architecture

The MATLAB-based simulation framework developed in this study provides a foundation for further research by enabling rapid evaluation of PHY-layer performance and can serve as a valuable tool for both academic studies and early-stage industrial research. Future extensions of this work could involve incorporating more detailed atmospheric absorption models, adaptive modulation and coding schemes, advanced hybrid beamforming techniques, and machine-learning-based channel prediction to help close the gap between theoretical models and real-world 6G deployment challenges.

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