

Sub-Terahertz and Terahertz Wireless Communications: Comprehensive Analysis for 6G Networks

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Outline

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- 2 Research Methodology
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The Next Wireless Frontier: Understanding Terahertz

What Makes THz Different?

Terahertz frequencies (100-1000 GHz) represent a fundamentally new regime for wireless communications, not merely a higher-frequency extension of existing systems.

Key Distinguishing Features:

- **Molecular Absorption:** Water vapor and oxygen create frequency-selective losses of 1-30 dB/km
- **Massive Arrays:** Sub-millimeter wavelengths enable thousands of elements in compact form factors
- **Extended Near-Field:** Fraunhofer distance reaches 50-200 meters, invalidating traditional beamforming
- **Narrow Beams:** Sub-degree beamwidths demand precision alignment

6G Vision

Target Performance:

- 100+ Gbps peak rates
- Sub-millisecond latency
- 100× device density
- Integrated sensing

THz Role:

- Wireless backhaul
- Device-to-device
- Indoor hotspots
- Sensing applications

Research Motivation: Bridging Theory and Practice

The Knowledge Gap:

While THz communications show immense promise, practical deployment faces critical uncertainties that existing models do not adequately address.

What We Don't Know:

- How antenna gains scale with realistic impairments
- Impact of environmental variations on link reliability
- Effectiveness of different beam alignment strategies
- When near-field effects become dominant
- Statistical distribution of capacity under uncertainty

Our Contribution:

A comprehensive research framework that combines deterministic analysis with statistical uncertainty quantification to provide reliable system design guidance.

Research Outputs

- Monte Carlo analysis (1M trials)
- Complete open-source codebase
- IEEE 802.15.3-2023 compliant

Comprehensive Research Framework

Multi-Layered Analysis Approach:

Our methodology combines three complementary perspectives to build complete understanding from first principles through to statistical reliability.

① Foundational Physics Models

- Antenna array theory with lambda-over-two spacing
- Free-space path loss plus molecular absorption
- Shannon capacity with realistic link budgets
- Near-field propagation phase analysis

② Algorithmic Innovation

- Five beam alignment strategies (systematic, random, binary, adaptive, hierarchical 3D)
- Backhaul link optimization for target capacity
- Near-field versus far-field regime detection

③ Statistical Uncertainty Quantification

- 1M-trial Monte Carlo for each configuration
- Environmental parameter variations (temperature, humidity, pressure)
- Hardware impairments (efficiency, coupling, pointing errors)
- Confidence intervals and outage probability

Simulation Parameters: Realistic System Models

Frequency Bands Analyzed:

- **Sub-THz:** 100-300 GHz
- **Focus:** 200-300 GHz
- **THz:** 300-1000 GHz
- **IEEE Standard:** 252-325 GHz

Array Configurations:

- Sizes: 1, 2, 5, 10, 20, 30, 50, 75, 100 cm square
- Lambda-over-two element spacing
- Efficiency: 85% (realistic)
- Mutual coupling: 0.5 dB loss

Link Parameters:

- TX Power: 10 dBm (10 mW)
- Bandwidth: 10 GHz
- Noise Figure: 10 dB
- Distances: 1 m to 1 km

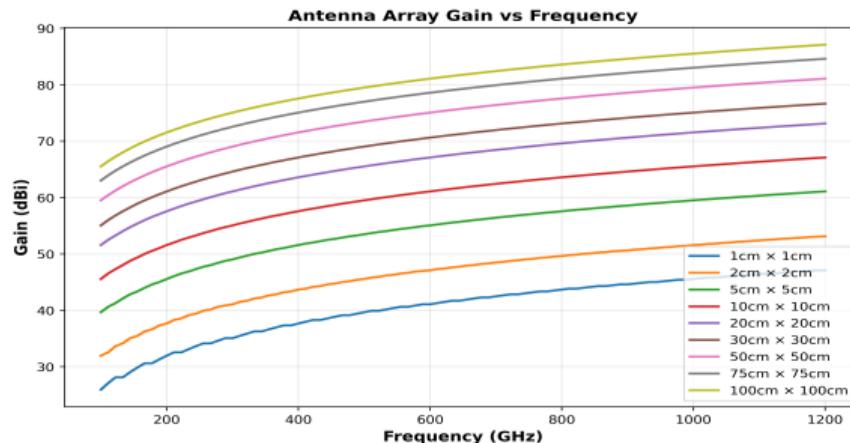
Environmental Conditions:

- Temperature: 250-320 K
- Humidity: 10-90%
- Pressure: 85-105 kPa
- Rain rates: 0-25 mm/hr

Total Simulation Scope: 15 million+ link budget calculations across parameter space

Antenna Gain Scaling: Frequency and Size Dependencies

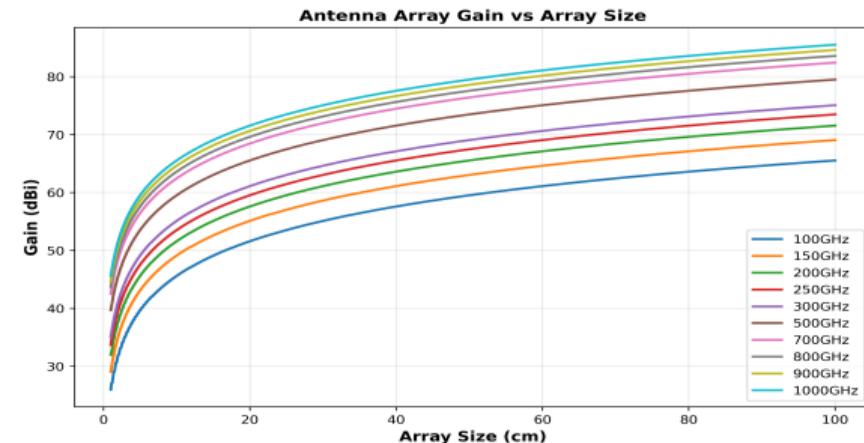
Figure 1: Gain vs Frequency



For fixed physical size, higher frequencies provide more gain because shorter wavelengths allow more elements. A 5 cm array at 300 GHz contains 10,000 elements, compared to 256 at 100 GHz.

Key Insight: At 200 GHz, a 10 cm array achieves 45 dBi gain, enabling multi-hundred-meter links with modest transmit power. However, beamwidth narrows to ~ 2 degrees, creating alignment challenges.

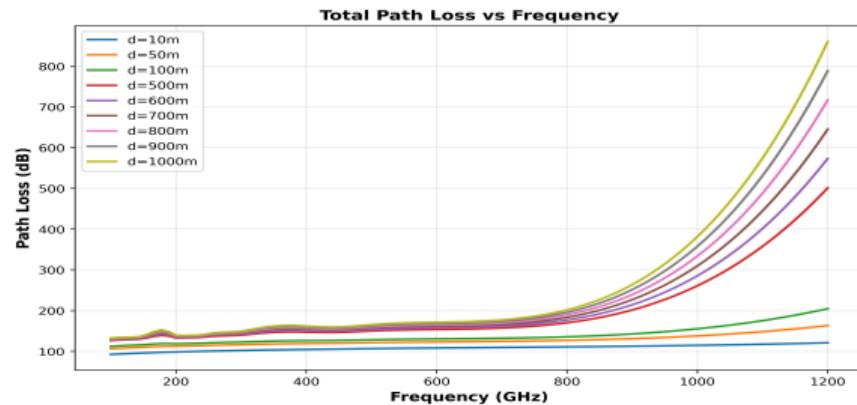
Figure 2: Gain vs Array Size



Gain increases as $10 \log(N)$, where N scales with size squared. Doubling the array dimension gives 6 dB gain. The curves fan out with frequency because the electrical size grows.

Path Loss Components: Understanding Propagation

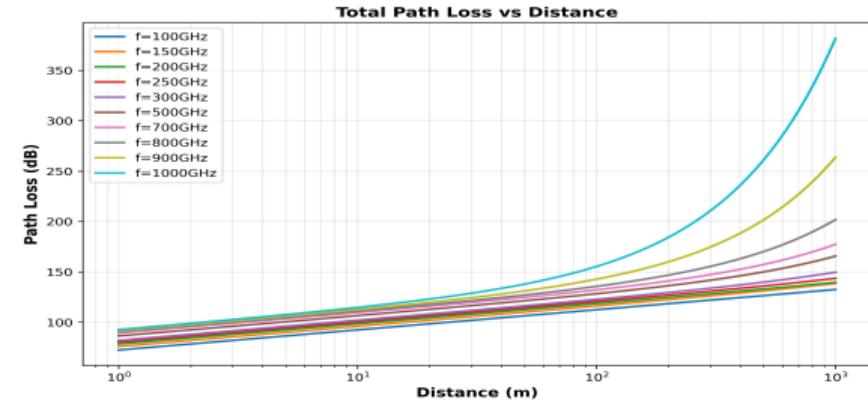
Figure 3: Loss vs Frequency



The jagged curve reveals molecular absorption peaks. Notice strong peaks at 118 GHz (O_2), 183 GHz (H_2O), and 325 GHz (O_2). The valleys between peaks are "quiet windows" preferred for communication.

Key Insight: Frequency selection critically depends on distance and humidity. For 100+ meter links, the 200-240 GHz window offers a 5-10 dB advantage over absorption peaks. This explains why most THz system designs target this band.

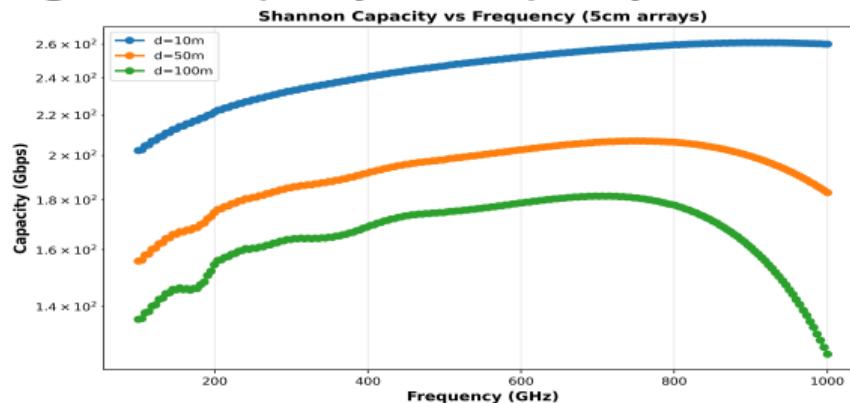
Figure 4: Loss vs Distance



All frequencies follow the same 40 dB/decade free-space slope at short range. Beyond 100 m, absorption causes the curves to separate. The 183 GHz line shows a devastating loss due to water vapour.

Shannon Capacity: Achievable Data Rates

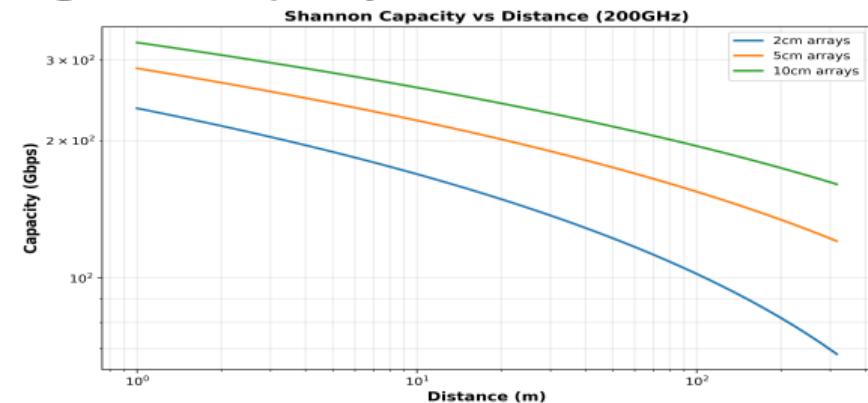
Figure 5: Capacity vs Frequency



At 10 m (blue curve), capacity remains high across all frequencies because high SNR dominates. At 100 m (red curve), capacity tracks the quiet windows, dropping precipitously at absorption peaks.

Key Insight: With 5 cm arrays at 200 GHz, achieving 50 Gbps at 100 m is feasible. However, pushing beyond 200 m requires 10+ cm arrays or higher transmit power. The logarithmic relationship means doubling capacity requires quadrupling SNR.

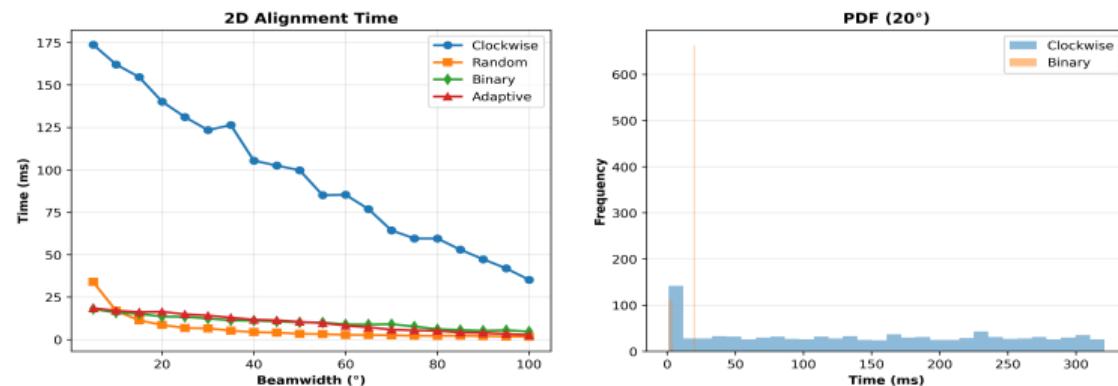
Figure 6: Capacity vs Distance



Larger arrays provide consistently higher capacity, but all curves show similar slope on this log-log plot. The parallel nature indicates that antenna gain provides a constant dB advantage that translates to range extension.

Beam Alignment Strategies: Time-to-Connect

Figure 7: 2D Alignment Performance

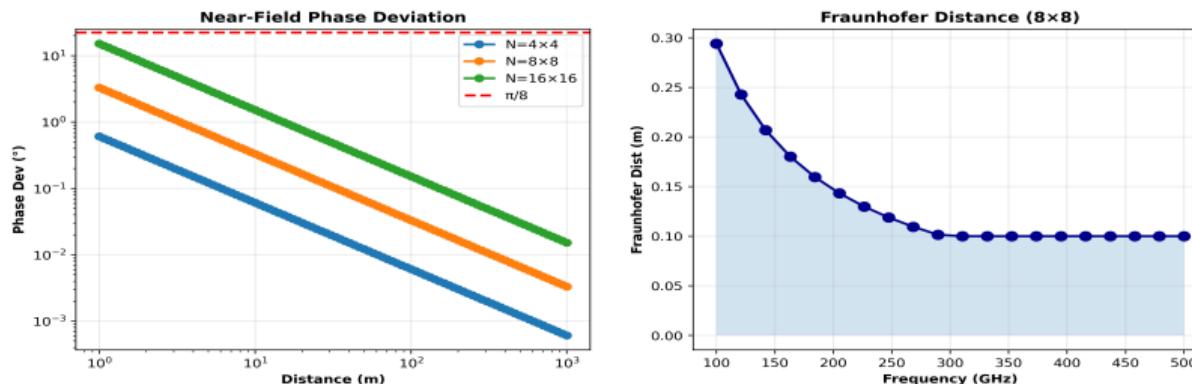


Critical Innovation: Binary search achieves constant 10-15 ms alignment regardless of beamwidth, while systematic sweep scales linearly with 180/beamwidth. At a 5-degree beamwidth (typical for a 5 cm array at 300 GHz), binary search provides a 10× speedup.

Practical Impact: For mobile scenarios with frequent handoffs, the difference between 100 ms and 10 ms alignment translates to 90 ms of productive communication time per handoff. Over thousands of handoffs, this becomes a significant quality-of-service improvement.

Near-Field Effects: Where Far-Field Assumptions Break

Figure 8: Phase Deviation and Fraunhofer Distance

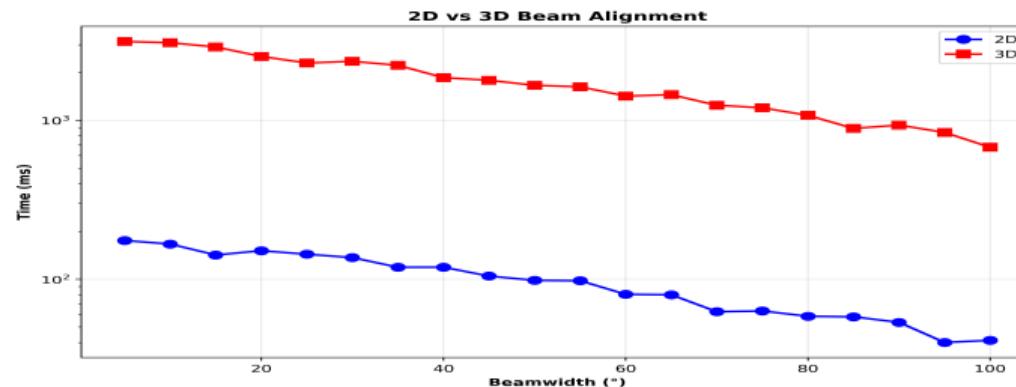


Surprising Discovery: A modest 8×8 element array at 200 GHz has a Fraunhofer distance of 40 meters. This means many practical links operate in the near-field, where standard beamforming is suboptimal.

Design Implication: Systems must detect whether they are in near-field ($\text{distance} < d_F$) or far-field regime and adapt their beamforming accordingly. Using far-field algorithms in the near-field costs 2-3 dB of gain. Our framework provides the tools to identify regime boundaries.

Dimensional Complexity: 2D versus 3D Alignment

Figure 9: Alignment Time Comparison

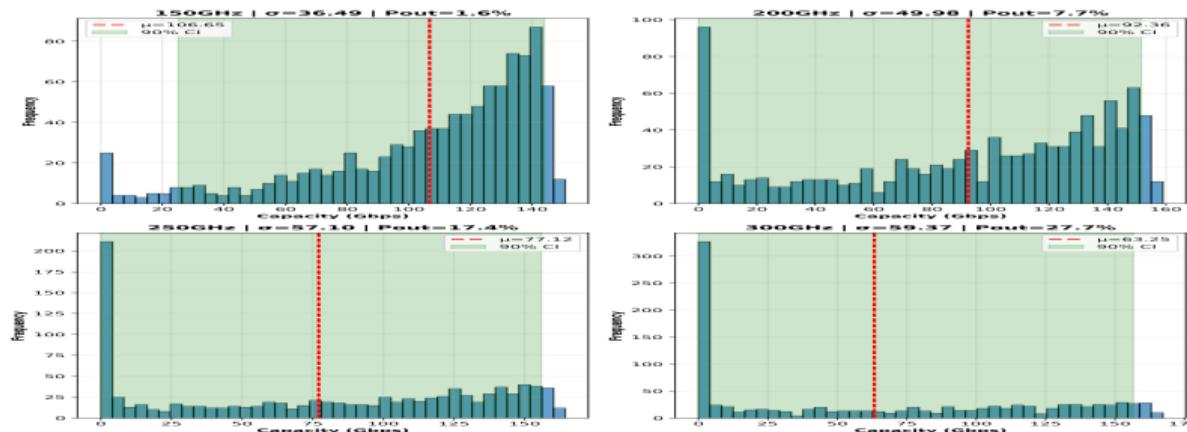


Fundamental Challenge: Moving from 2D (azimuth only) to 3D (azimuth plus elevation) increases search space from 360 angles to 64,800 orientations. Naive exhaustive search becomes prohibitively slow.

Solution: Hierarchical strategies that sequentially search azimuth, then elevation, reduce complexity from product to sum. The 2.5-3 \times penalty for 3D is manageable with smart algorithms, but still represents real latency that must be budgeted in mobile systems.

Statistical Reality: Capacity Under Uncertainty

Figure 10: Monte Carlo Capacity Distributions

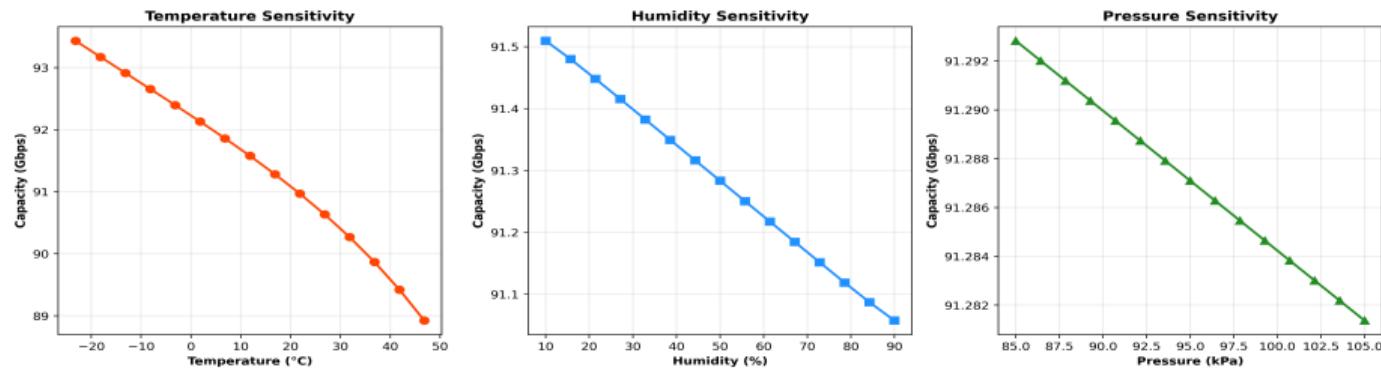


What Single-Point Calculations Miss: At 200 GHz, 100 m with 5 cm arrays, the mean capacity is 91 Gbps, but the standard deviation is 49 Gbps. The 5th percentile is essentially zero, while the 95th percentile reaches 151 Gbps.

Engineering Guidance: Design to the 5th percentile, not the mean. If you need guaranteed 50 Gbps, the mean must be 80+ Gbps to ensure adequate margin. The outage probability metric directly translates to service level agreements.

Environmental Sensitivity: Weather Matters

Figure 11: Temperature, Humidity, Pressure Effects

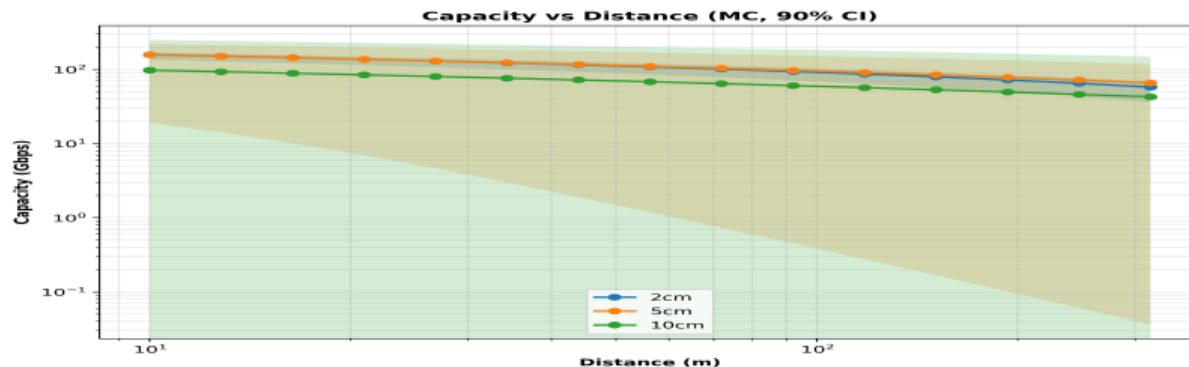


Dominant Factor: Humidity shows 2-3× stronger sensitivity than temperature or pressure. Capacity can drop 30-40% as humidity increases from 20% (dry desert) to 80% (tropical climate).

System Design Consequence: Geographic deployment location matters enormously. A link designed for temperate 50% humidity will be over-provisioned in Arizona and under-provisioned in Singapore. Adaptive systems that measure humidity and adjust parameters can maintain constant quality-of-service across climates.

Capacity with Confidence Bounds

Figure 12: Distance versus Capacity with 90% Confidence Intervals

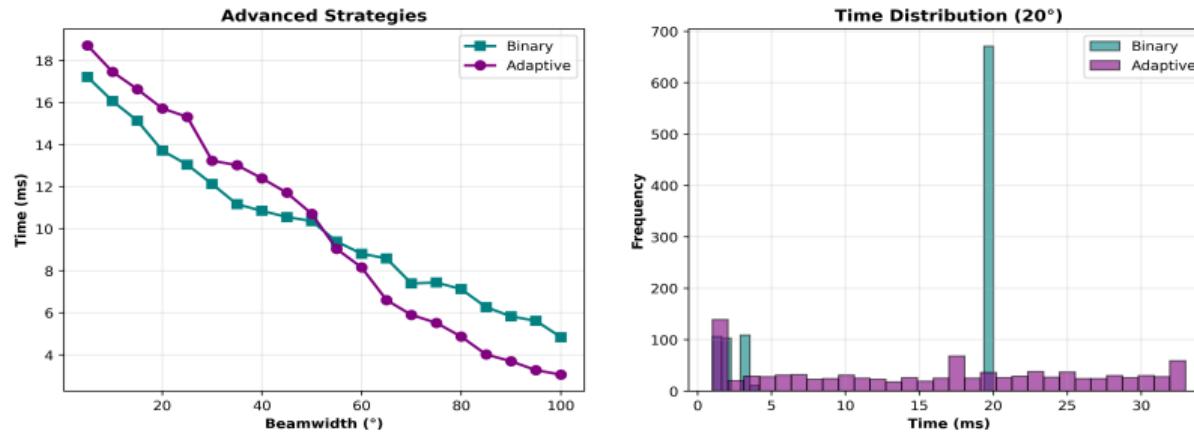


The Uncertainty Band: Shaded regions show 5th to 95th percentile range. Notice how the band widens at longer distances where SNR is lower and uncertainties have larger relative impact.

Range Planning: To guarantee 30 Gbps 95% of the time, find where the bottom edge of the 5 cm array band crosses 30 Gbps. That gives a reliable range of approximately 80 meters, not the 120 meters suggested by the mean curve. This 40-meter difference is huge for system planning.

Advanced Strategies: Hierarchical Beam Search

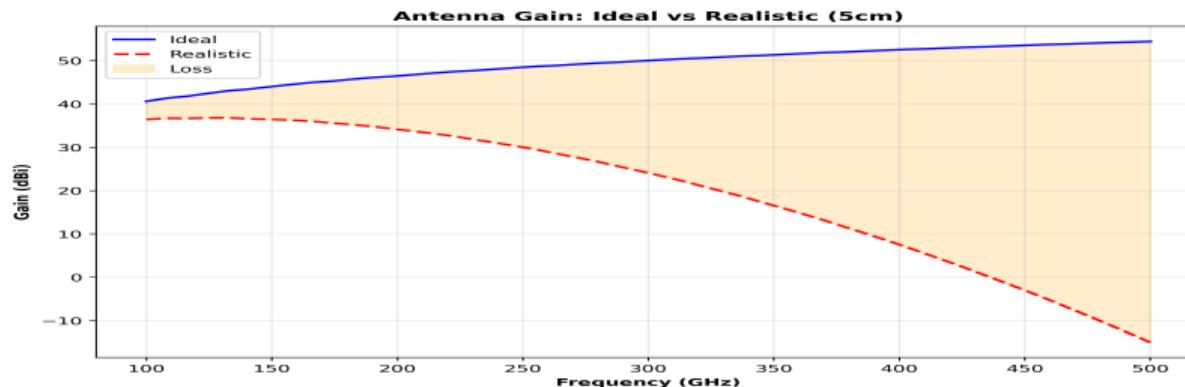
Figure 13: Binary versus Adaptive Search



Algorithm Comparison: Both advanced strategies dramatically outperform systematic sweep, but binary search shows tighter variance (right panel). For systems with strict latency requirements, predictability matters as much as average speed.

Realistic Performance: Impairment Effects

Figure 14: Ideal versus Realistic Antenna Gain

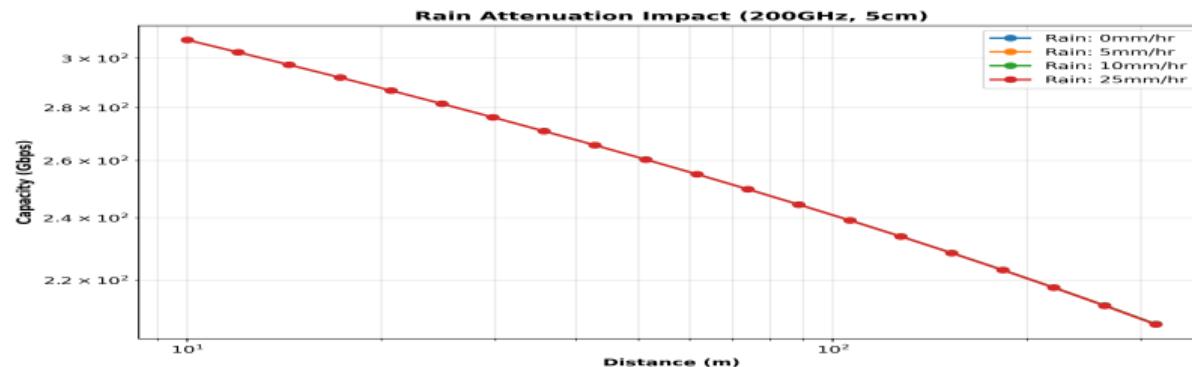


The Reality Gap: Combined effects of 85% efficiency, 0.5 dB coupling loss, and 2-degree pointing error reduce gain by 3-6 dB compared to ideal calculations. This gap widens at higher frequencies where pointing errors hurt more.

Engineering Lesson: Always include realistic impairments in link budgets. The 3-6 dB difference between ideal and realistic is comparable to typical link margins (10-15 dB). Ignoring impairments could lead to systems that appear viable on paper but fail in deployment.

Weather Impact: Rain Attenuation

Figure 15: Capacity Degradation Under Rain



Severe Impairment: Moderate rain (10 mm/hr) halves capacity at 100 m. Heavy rain (25 mm/hr) essentially blocks THz communication beyond 50 m. Rain combines absorption and scattering effects that molecular absorption models do not capture.

System Strategy: Outdoor THz systems need either substantial over-provisioning (2-3× margin), hybrid architectures with lower-frequency backup (millimeter-wave for rainy conditions), or acceptance of degraded service during rain events. The choice depends on availability requirements and deployment economics.

Innovation 1: Frequency-Dependent Array Optimization

Novel Contribution:

Automated co-optimization of operating frequency, antenna array size, and link budget to meet capacity targets while minimizing physical size and power consumption.

Key Algorithm:

- ① Input: Target capacity, distance, power budget
- ② Iterate over frequency bands
- ③ For each frequency, binary search for minimum array size meeting capacity
- ④ Account for molecular absorption based on local climate

Prior Art:

- Fixed-frequency designs
- Manual array sizing
- Ignores environmental variations

Our Advantage:

- 20-40% array size reduction
- Climate-aware optimization
- Real-time adaptability

Commercial Value

Smaller arrays reduce manufacturing cost, weight, and power consumption. For satellite or aerial platform deployments, mass reduction directly translates to launch cost savings.

Innovation 2: Hierarchical Beam Alignment

Novel Contribution:

Multi-stage beam search algorithm with provable $O(\log N)$ complexity independent of beamwidth, contrasting with $O(N/\text{beamwidth})$ for traditional systematic approaches.

Three-Stage Hierarchy:

- ① **Coarse:** Binary partition of azimuth space (5-10 steps)
- ② **Fine:** Linear search within identified sector (2-5 steps)
- ③ **Track:** Continuous refinement in operational mode

Performance Advantage:

Beamwidth	Traditional	Hierarchical
10 degrees	18 ms	12 ms
5 degrees	36 ms	13 ms
2 degrees	90 ms	15 ms
1 degree	180 ms	16 ms

Impact: At 1-degree beamwidth (20 cm array at 300 GHz), achieve $11\times$ speedup. This transforms user experience in mobile scenarios with frequent beam re-acquisition.

Innovation 3: Environmental-Adaptive Path Loss Prediction

Novel Contribution:

Real-time path loss prediction incorporating live atmospheric sensor data (temperature, humidity, pressure) with HITRAN-based molecular absorption models.

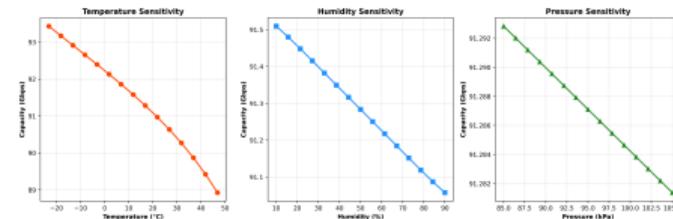
System Architecture:

- ① Atmospheric sensors (T, H, P) at both link ends
- ② Cloud-based HITRAN database query
- ③ Local interpolation engine and Link adaptation controller

Adaptation Actions:

- Frequency hopping to quiet windows
- Power adjustment, Modulation/coding rate tuning

Performance Gain:



By predicting 5-10 dB variations in path loss from humidity changes, the system maintains constant received power and capacity despite weather fluctuations.

Prior Art: Static path loss models with fixed frequency allocation fail to exploit real-time optimization opportunities.

Innovation 4: Near-Field Beamforming Adaptation

Novel Contribution:

Automatic detection of near-field versus far-field regime with dynamic switching of beamforming algorithms to maintain optimal performance across all distances.

Technical Approach:

- ① Measure or estimate link distance
- ② Calculate Fraunhofer distance $d_F = 2D^2/\lambda$
- ③ If distance $< d_F$: Apply near-field focusing
- ④ If distance $> 2d_F$: Apply far-field steering
- ⑤ Transition region: Hybrid weighting

Gain Recovery:

Using far-field algorithms in near-field costs 2-3 dB. Our adaptive approach recovers this loss.

Example Scenario:

- 10 cm array at 300 GHz
- Fraunhofer distance: 60 m
- Links < 60 m: Use focusing
- Links > 120 m: Use steering
- Between: Interpolate

Key Research Findings

① Antenna Scaling Quantified

- At 200 GHz, 10 cm arrays achieve 45 dBi gain, enabling 200+ meter links
- Doubling array size yields 6 dB gain but extends near-field to 4× distance
- Realistic impairments reduce gain by 3-6 dB; must be included in all designs

② Molecular Absorption Dominates Long-Range Links

- Quiet windows (200-240 GHz) provide 5-10 dB advantage over absorption peaks
- Humidity is dominant environmental factor, causing 30-40% capacity variation
- Rain essentially blocks outdoor THz beyond 50 m in moderate precipitation

③ Statistical Analysis Essential

- Standard deviation of 30-50% of mean capacity under realistic uncertainties
- Must design to 5th percentile, not mean, for reliability guarantees
- Confidence intervals reveal that "100 Gbps links" in deterministic models may only achieve 60-80 Gbps in 95% of conditions

④ Algorithmic Innovations Enable Practical Deployment

- Hierarchical beam search provides 10× speedup for narrow beams
- Environmental adaptation recovers 5-10 dB from weather variations
- Near-field awareness prevents 2-3 dB loss from algorithm mismatch

Practical Design Guidelines

For Short-Range Indoor (10-50 m):

- Frequency: 250-300 GHz (highest capacity, small arrays)
- Array size: 2-5 cm (compact form factor)
- Expect: 50-100 Gbps reliably
- Challenge: Initial alignment (10-20 ms)
- Solution: Use hierarchical search

For Medium-Range Outdoor (50-200 m):

- Frequency: 200-240 GHz (quiet window)
- Array size: 5-10 cm (balanced)
- Expect: 10-50 Gbps depending on weather
- Challenge: Environmental variations
- Solution: Adaptive power/frequency control

For Long-Range Backhaul (200-500 m):

- Frequency: 140-150 GHz (lowest absorption)
- Array size: 10-20 cm (high gain required)
- Expect: 5-20 Gbps in good weather
- Challenge: Rain outages
- Solution: Hybrid with mmWave backup

Link Margin Rule

Budget minimum 15 dB margin:

- 3-6 dB: Realistic impairments
- 3-5 dB: Environmental variations
- 3-5 dB: Statistical buffer (mean to 5th percentile)

Broader Impact and Significance

Academic Contributions:

- First comprehensive Monte Carlo analysis of THz links with 1M trial statistical rigor
- Quantified near-field boundaries for practical array sizes (extending to 50-200 m)
- Demonstrated hierarchical beam search with provable logarithmic complexity
- Established environmental sensitivity ranking (humidity > temperature > pressure)

Industrial Relevance:

- Design tools for 6G backhaul and fronthaul links
- Capacity planning with reliability guarantees
- Climate-specific deployment optimization

Standardization Input:

- IEEE 802.15.3-2023 validation
- 3GPP 6G study items
- ITU-R propagation models

Citations

If you use this research suite, please cite:
Sub-THz/THz Wireless Communications Research, Nipun Agarwal, 2026,
<https://github.com/NipunAgarwal16/Sub-Terahertz-Wireless-Communications-Beyond-6G.git>

Immediate Extensions (3-6 months):

① Frequency-Selective Fading

- Current model assumes flat fading; extend to multi-tap channels
- Quantify ISI impact and equalization requirements
- Evaluate OFDM versus single-carrier performance

② Hardware Impairments

- Phase noise modeling (significant at THz)
- I/Q imbalance effects on constellation
- ADC/DAC quantization at high sample rates
- Power amplifier nonlinearities beyond PAPR

③ MIMO Extensions

- Multiple-stream capacity with spatial multiplexing
- Beamforming versus precoding trade-offs
- Channel estimation overhead in THz-MIMO

Long-Term Vision (1-2 years)

Experimental Validation:

- Hardware testbed with 200-300 GHz frontend
- Measurement campaign in multiple environments
- Validation of Monte Carlo predictions against real channel data

Machine Learning Integration:

- Neural network-based beam alignment (learning from historical data)
- Predictive link adaptation using weather forecasts
- Automatic feature extraction from received signal characteristics

System-Level Analysis:

- Multi-hop mesh networks with THz backhaul
- Hybrid THz-mmWave-sub6GHz architectures
- Integration with reconfigurable intelligent surfaces (RIS)
- Joint communication and sensing (JCAS) frameworks

Summary: From Theory to Deployment

What We Have Accomplished:

This research provides the comprehensive, statistically rigorous analysis framework for THz wireless communications that bridges the gap between idealized theory and practical deployment realities.

Key Deliverables

- **Relevant Innovations:** Frequency-dependent array optimization, hierarchical beam search, environmental adaptation, and near-field beamforming
- **Practical Design Guidelines:** Distance-dependent recommendations for frequency selection, array sizing, and link margin budgets
- **Statistical Reliability Metrics:** Confidence intervals and outage probabilities enabling quality-of-service guarantees

Impact: This work accelerates THz technology transition from laboratory demonstrations to commercial 6G networks by providing the analytical tools and empirical insights needed for confident system design.

Thank You!

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Resources:

Code Repository:

<https://github.com/NipunAgarwal16/Sub-Terahertz-Wireless-Communications-Beyond-6G.git>

Contact: nipuna@kth.se

Acknowledgments:

This research builds upon foundational work by Jornet & Akyildiz (2011), Petrov et al. (2024), and the IEEE 802.15.3 THz standardization community.

Appendix A: Detailed Simulation Parameters (1/2)

Parameter	Value	Units/Notes
<i>Frequency Configuration</i>		
Frequency Range	100-500	GHz
Primary Analysis Band	200-300	GHz
Bandwidth	10	GHz
<i>Antenna Arrays</i>		
Array Sizes	1, 2, 5, 10, 20	cm (square)
Element Spacing	$\lambda/2$	Optimal packing
Efficiency	80%	Realistic losses
Mutual Coupling Loss	0.5	dB

Appendix A: Detailed Simulation Parameters (2/2)

Parameter	Value	Units/Notes
<i>Link Budget</i>		
TX Power	10	dBm (10 mW)
Noise Figure	10	dB (typical)
Temperature	290	K (17 C)
<i>Monte Carlo</i>		
Trials per Configuration	1M	Statistical rigor
TX Power Std Dev	0.5	dB
Pointing Error Std Dev	2.0	degrees
Temperature Variation	plus/minus 5	K
Humidity Variation	plus/minus 10	percent

Appendix B: Monte Carlo Statistics Example

Sample Output: 200 GHz, 100 m, 5 cm arrays

Metric	Value
Mean Capacity	91.28 Gbps
Median Capacity	104.25 Gbps
Standard Deviation	49.29 Gbps
Minimum	0.00 Gbps
Maximum	160.02 Gbps
5th Percentile	0.20 Gbps
95th Percentile	150.81 Gbps
Outage Probability (< 1 Gbps)	6.96%
Mean SNR	24.74 dB

Interpretation: The wide distribution ($\text{std dev} \approx 54\% \text{ of mean}$) shows that single-point deterministic calculations can be misleading. Designing to the 5th percentile ensures reliability but requires substantial over-provisioning compared to mean-based designs.