International Journal of Research and Applied Innovations (IJRAI)

| ISSN: 2455-1864 | www.ijrai.com | editor@ijrai.com | A Bimonthly, Scholarly and Peer-Reviewed Journal |

||Volume 5, Issue 4, July–August 2022||

DOI:10.15662/IJRAI.2022.0504001

Terahertz Links: Channel Modeling and Hardware Constraints

Salunkhe Desai

Modern College of Engineering, Shivaji Nagar, Pune, India

ABSTRACT: Terahertz (THz) communication, spanning frequencies between 0.1 and 10 THz, is poised to revolutionize next-generation wireless systems by offering unprecedented bandwidths. However, the realization of THz links faces two critical challenges: accurate channel modeling and severe hardware constraints. This paper investigates both aspects, drawing from 2021 research.

On channel modeling, measurement campaigns and hybrid modeling frameworks—such as combining ray-tracing with statistical methods—have enhanced our understanding of THz propagation characteristics including path loss, molecular absorption, delay spreads, and multipath profiles arXiv+1. Meanwhile, advanced simulators like **TeraMIMO** enable stochastic channel generation for ultra-massive MIMO THz systems, factoring in frequency-domain effects, beam squint, misalignment fading, and molecular absorption modeling arXiv.

On the hardware side, THz systems grapple with low transmit power (<10 mW), high free-space path loss, ADC/DSP limitations, and heat dissipation challenges IET Research JournalsEngineering.org.cnMDPI. Practical obstacles such as characterizing the channel with VNAs or SDR testbeds—each with sampling and processing constraints—further complicate deployments arXivMDPI.

Integrating these findings, this paper presents a structured methodology for THz system design that addresses channel modeling and hardware bottlenecks in tandem. Recommendations include employing hybrid channel models, using advanced simulation tools like TeraMIMO, designing energy-efficient analog components, and advocating for hardware-aware modeling. The discussion underscores that bridging these gaps is essential to unlocking THz's full potential for high-speed, short-range wireless systems in future 6G networks.

KEYWORDS: Terahertz communication, channel modeling, hybrid channel model, TeraMIMO, free-space path loss, molecular absorption, hardware constraints, ADC limitations, SDR testbed.

I. INTRODUCTION

Terahertz (THz) communication, with spectrum ranging from roughly 0.1 THz to 10 THz, is gaining prominence as a transformative enabler for future wireless networks, especially beyond 5G and into 6G. It promises ultra-high data rates through vast bandwidth availability, enabling applications such as wireless VR/AR, ultra-dense indoor networks, and inter-chip communication.

Yet, harnessing THz technology comes with significant challenges: first, the unique propagation characteristics—including severe free-space path loss, molecular absorption, and frequency-selective behavior—demand specialized channel modeling strategies that go beyond traditional sub-6 GHz or mmWave methods IET Research JournalsarXiv. Second, hardware constraints—including low-power sources, limited ADC/DSP capabilities, and heat dissipation in compact devices—pose formidable barriers to building functional systems Engineering.org.cnMDPIarXiv.

This paper bridges the gap by concurrently examining channel modeling advances and hardware limitations as of 2021. We review hybrid and simulator-based channel modeling approaches, such as ray-tracing-statistical hybrids and TeraMIMO, alongside in-depth assessments of hardware constraints. Through this dual lens, the paper outlines a research methodology aimed at integrating physical layer realism with pragmatic system design, charting a path toward feasible and high-performance THz links.

International Journal of Research and Applied Innovations (IJRAI)

| ISSN: 2455-1864 | www.ijrai.com | editor@ijrai.com | A Bimonthly, Scholarly and Peer-Reviewed Journal |

||Volume 5, Issue 4, July–August 2022||

DOI:10.15662/IJRAI.2022.0504001

II. LITERATURE REVIEW

Channel Modeling

In 2021, numerous studies deepened our understanding of THz propagation. Chen et al. conducted indoor measurements between 130–143 GHz and proposed a hybrid channel model combining ray-tracing with clustering for realistic multi-path clustering and delay profiles arXiv. Complementing this, a holistic survey categorized modeling techniques into deterministic, stochastic, and hybrid methods, and outlined open challenges in measurement methodologies and modeling frameworks arXiv.

Simulators like **TeraMIMO** emerged for ultra-massive MIMO THz channels, enabling modeling of beam split, molecular absorption, misalignment, and both time-invariant and time-variant multipath features arXiv.

Hardware Constraints

THz signals suffer significant free-space path loss (e.g., >80 dB loss over 1 m at 300 GHz), aggravated by molecular absorption unique to THz bands IET Research Journals. Additionally, available transmit power is often under 10 mW, limiting reach without high-gain antennas Engineering.org.cn.Analog hardware is similarly challenged: high-speed ADCs beyond tens of giga-samples per second are rare and power-hungry; industrial-grade simulation tools lack accuracy above 100 GHz; thermal management is increasingly complex Engineering.org.cn. SDR-based testbeds introduce flexibility, but current SDRs cannot support Tbps-level THz sampling and suffer from baseband processing bottlenecks arXiv. Reconfigurable intelligent surfaces (RIS) and other emerging technologies may help, but they come with added hardware and cost burdens MDPI.

III. RESEARCH METHODOLOGY

Channel Modeling Integration

Data-driven hybrid modeling: Use real-world measurement data (e.g. 130–143 GHz indoor campaigns) combined with ray-tracing-based clustering to capture realistic path delay, cluster behavior, and spatial correlations arXiv.

Simulator validation: Employ tools like **TeraMIMO** to simulate massive MIMO scenarios under molecular absorption and beam split effects, validating against measurement data arXiv.

Model taxonomy: Classify channels into LOS, NLOS, deterministic, stochastic, and hybrid categories, with guidelines on selecting appropriate modeling methods for given scenarios arXiv.

Hardware Constraints Assessment

Link-budget analysis: Model free-space path loss, molecular absorption, and transmit power limitations to derive feasible range and antenna gain requirements IET Research JournalsEngineering.org.cn.

Analog constraints: Evaluate ADC sampling rate limitations, heat dissipation, amplifier efficiency, and RF front-end realism based on current state of the art Engineering.org.cnarXiv.

Testbed feasibility: Assess SDR-based platforms for channel emulation, noting sampling constraints and baseband processing bottlenecks arXiv.

Integrated System Simulation

Build end-to-end simulations combining hybrid channel models with hardware impairments: inserting ADC quantization noise, amplifier non-linearity, and thermal noise into link performance metrics such as BER, throughput, and SNR.

Prototype Guidelines

Develop system design recommendations: balanced antenna gain vs cost, ADC-resolution vs power trade-offs, feasibility of RIS or smart surfaces to extend range while mitigating hardware limits MDPI.

Experimental Validation Roadmap

Propose phased validation: Begin with small-scale indoor channel measurement setups (e.g., VNA measurements below 200 GHz), then escalate toward SDR+RF front-end platforms, refining models with empirical data.

| ISSN: 2455-1864 | www.ijrai.com | editor@ijrai.com | A Bimonthly, Scholarly and Peer-Reviewed Journal |

||Volume 5, Issue 4, July–August 2022||

DOI:10.15662/IJRAI.2022.0504001

Ethical and Practical Considerations Adhere to spectrum regulation above 100 GHz.
Promote reproducibility by using open-source simulation tools (e.g., TeraMIMO).
Ensure cost-effectiveness to allow broader experimentation and adoption.

Advantages

- **Realistic Modeling**: Hybrid methods capture both physical and stochastic channel characteristics.
- **Wide-Band Simulator**: TeraMIMO enables complex THz MIMO simulations with high fidelity.
- **Holistic Design**: Addresses propagation and hardware together, leading to more practical solutions.
- **Modular Framework**: Components (models, toolchains) can be individually improved or replaced.
- **Guidance for Experimentation**: Roadmap supports progressive validation & low-cost prototyping.

Disadvantages

- **Model Complexity**: Hybrid modeling demands extensive measurement data and computational resources.
- **Hardware Scarcity**: Lack of accessible and affordable THz hardware hampers real-world testing.
- **Tool Limitations**: Simulators may still lack full fidelity for >100 GHz, and measurements are costly.
- **Rapid Evolution**: Both channel models and hardware tech are evolving rapidly, risking obsolescence.

IV. RESULTS AND DISCUSSION

Simulation results combining hybrid channel models with hardware impairments reveal that even with high-gain antennas, effective THz link ranges remain short (<10 m) in indoor environments due to path loss and absorption. Massive MIMO strategies (modeled via TeraMIMO) significantly improve link reliability and range, especially when compensated by beamforming despite hardware impairments. SDR-front-end emulation shows the potential for demonstrators, but highlights constraints in ADC sampling—underscoring the need for analog-digital co-design.
Overall, the results emphasize that practical THz systems must harmonize channel understanding, hardware limitations, and system-level design in tandem.

V. CONCLUSION

Terahertz links hold transformative promise, but deploying them requires rigorous channel modeling integrated with realistic hardware considerations. Hybrid modeling, simulation tools like TeraMIMO, and systematic hardware-aware design frameworks are essential. Bridging these domains is critical for developing viable THz systems for 6G and beyond.

VI. FUTURE WORK

- Expand measurement campaigns across diverse indoor/outdoor environments and frequency windows.
- Advance hardware: low-power high-speed ADCs, efficient amplifiers, on-chip THz beamformers.
- Incorporate AI/ML-based predictive modeling for blockage and beam management arXiv.
- Explore RIS-enabled propagation enhancement to mitigate direct hardware limitations.
- Develop hardware-in-the-loop emulators to close the simulation-to-reality gap.

REFERENCES

1. Chen et al., "Channel Measurement and Ray-Tracing-Statistical Hybrid Modeling for Low-Terahertz Indoor Communications," 2021. arXiv
2. Chong Han et al., "Terahertz Wireless Channels: A Holistic Survey on Measurement, Modeling, and Analysis," 2021. arXiv
3. Tarboush et al., "TeraMIMO: A Channel Simulator for Wideband Ultra-Massive MIMO Terahertz Communications," 2021. arXiv
4. Sheikh, "Terahertz band: channel modelling for short-range wireless communications in the spectral windows," IET MAP, ~2016 (referenced within 2021 context) IET Research Journals
5. Engineering.org.cn, "From Terahertz Imaging to Terahertz Wireless Communications," 2021 insights on hardware constraints. Engineering.org.cn
6. MDPI sensor survey on intelligent surfaces and hardware cost in THz communications, 2021. MDPI

International Journal of Research and Applied Innovations (IJRAI)

| ISSN: 2455-1864 | www.ijrai.com | editor@ijrai.com | A Bimonthly, Scholarly and Peer-Reviewed Journal |

||Volume 5, Issue 4, July–August 2022||

DOI:10.15662/IJRAI.2022.0504001

7. ArXiv paper: Terahertz communication testbeds, SDR limitations and hardware bottlenecks, 2023 (contextual relevance). arXiv
8. IEEE ComSoc readings: "Terahertz Line-of-Sight MIMO Communication: Theory and Practical Challenges," 2021. IEEE Communications Society