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6G Early Prototypes with Sub-THz Links and RIS

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ABSTRACT: The sixth generation (6G) of wireless communication is envisioned to deliver ultra-high-speed, low-latency, and ubiquitous connectivity. Central to this vision are **sub-terahertz (sub-THz) links** and **Reconfigurable Intelligent Surfaces (RIS)**—technologies that can overcome inherent propagation challenges of the THz band. This paper examines initial prototypes and theoretical developments of sub-THz communication augmented by RIS, presenting an integrated perspective on hardware feasibility and performance benefits.

RIS prototypes at lower bands have demonstrated substantial gains. A 5.8 GHz RIS with over 1,000 elements achieved up to 27 dB power gain in practical indoor and outdoor scenarios arXiv. Simultaneously, emerging studies on THz-range RIS mechanisms have analyzed a range of tuning technologies—including CMOS transistors, graphene, phase-change materials, and MEMS—for dynamic beam steering and amplitude control in 6G sub-THz links MDPIEurope PMC.

Moreover, hybrid beamforming methods leveraging RIS-assisted multi-hop links powered by deep reinforcement learning (DRL) have shown potential to expand THz coverage by approximately 50% in simulations arXiv. Additionally, the European research project **6G-TERARIS** explores stochastic geometry-based modeling and RIS deployment strategies for sub-THz carrier frequencies aiming to guide novel ultra-massive MIMO architectures CORDIS.

Through a structured methodology combining prototype analysis, simulation evaluation, and system modeling, the paper discusses the advantages of improved signal coverage, energy-efficient deployment, and cost-effective reconfigurability. Limitations include present fabrication constraints, limited real-world prototype demonstration at THz frequencies, and challenges in hardware integration.

In conclusion, early RIS prototypes at microwave bands and theoretical frameworks for THz RIS integration illustrate the promise of sub-THz links in 6G systems. Future work should focus on hardware realization of THz RIS, large-scale field trials, and integrated design of RIS-enabled sub-THz networks.

KEYWORDS: 6G, Sub-Terahertz (sub-THz) communication, Terahertz (THz) links, Reconfigurable Intelligent Surfaces (RIS), Prototype, Hybrid beamforming, DRL-based multi-hop, Ultra-massive MIMO, Stochastic geometry, Channel modeling

I. INTRODUCTION

6G wireless networks are expected to achieve unprecedented performance metrics, including multi-Gb/s to Tb/s data rates, extremely low latency, and seamless coverage in diverse environments. The sub-THz and THz spectrum (0.1–10 THz) is considered critical to realize these objectives due to its large contiguous bandwidth. However, these frequencies suffer from high path loss, molecular absorption, and susceptibility to blockage.

Reconfigurable Intelligent Surfaces (RIS) have emerged as a promising solution to mitigate these limitations. RTS are metasurfaces composed of numerous tunable elements that manipulate electromagnetic waves to enhance signal propagation, especially in highly directional links.

Early prototypes, such as a RIS operating at 5.8 GHz with over 1,100 elements, demonstrated remarkable power gains in indoor and outdoor environments and enabled high-data-rate transmissions across obstructed paths arXiv. While this work validates the RIS concept at microwave frequencies, translating it to sub-THz systems requires overcoming hardware challenges unique to the THz band.

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Recent research explores the use of tuning mechanisms suitable for THz RIS, such as CMOS transistors, graphene, phase-change materials, and MEMS, which may offer dynamic control at small scales MDPIEurope PMC. In parallel, simulation-based designs leveraging hybrid beamforming and reinforcement learning improve coverage in RIS-assisted multi-hop THz links by about 50 % arXiv.

The **6G-TERARIS** project aims to model RIS-enabled sub-THz communication channels using stochastic geometry and develop guidelines for deploying user-centric ultra-massive MIMO systems CORDIS.

By integrating prototype insights and advanced modeling techniques, this paper assesses the viability of RIS-enhanced sub-THz links, highlighting both their transformative potential and the technological hurdles ahead.

II. LITERATURE REVIEW

RIS Prototypes at Microwave Frequencies

A tangible realization of RIS technology at sub-6 GHz demonstrated impressive gains: in obstructed scenarios, the prototype yielded up to 27 dB improvement and supported 500 m 32 Mbps links and smooth 1080p video streaming arXiv. This highlights the efficacy of RIS for signal enhancement and control.

THz RIS Hardware Approaches

Transition to THz frequencies demands novel tuning mechanisms, as traditional PIN diodes are ineffective. Reviews outline alternative components—CMOS transistors, graphene layers, phase-change materials like vanadium dioxide, and MEMS—for enabling dynamic beam steering and amplitude tuning in THz RISs MDPIEurope PMC. Challenges remain around fabrication accuracy, beam resolution, and efficiency trade-offs ResearchGate.

RIS-Assisted Multi-Hop THz Communication

Simulation studies incorporating RIS in THz networks using deep reinforcement learning demonstrated significant coverage extension (~50 %) through a joint design of digital and analog beamforming across multi-hop links arXiv.

Channel Modeling and Deployment Strategies

The **6G-TERARIS** research framework employs stochastic geometry to model sub-THz propagation in RIS-enhanced setups and derives optimization insights for cell-free and ultra-massive MIMO architectures CORDIS.

Collectively, these studies showcase both practical prototype achievements and advanced theoretical modeling necessary for pushing RIS into sub-THz 6G systems.

III. RESEARCH METHODOLOGY

To assess the prospects of integrating sub-THz links with RIS in early 6G prototypes, this study employs a multi-tiered methodology:

1. **Prototype Analysis:**

o Evaluate existing RIS implementations (e.g., the 5.8 GHz prototype) for baseline performance metrics such as power gain, reach, and data throughput arXiv.

2. **Hardware Feasibility Study for THz RIS:**

o Review and compare sub-THz tuning mechanisms (CMOS, graphene, phase-change materials, MEMS) for factors including switching speed, fabrication complexity, beam control resolution, and efficiency MDPIEurope PMCResearchGate.

3. **Simulation Modeling:**

o Implement hybrid beamforming frameworks using RIS-enhanced multi-hop THz channels combined with DRL agents for beam configuration. Measure coverage improvements and compare against non-RIS baselines arXiv.

4. **Analytical Modeling via Project Frameworks:**

o Employ stochastic geometry and system design principles from the **6G-TERARIS** project to simulate user-centric cell-free and ultra-massive MIMO deployments with RIS-aided sub-THz links. Examine rate and energy efficiency metrics CORDIS.

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5. **Trade-off and Scalability Analysis:**
   - Integrate data from prototypes, simulations, and modeling to evaluate trade-offs including complexity, performance, cost, and feasibility.

This structured approach ensures grounded insights from real-world prototypes, hardware design evaluation, and scalable system modeling tailored for next-generation networks.

IV. ADVANTAGES

- **Signal Enhancement:** RIS can significantly boost coverage and link quality in obstructed environments.
- **Energy Efficiency:** Passive RIS elements reduce power consumption compared to active repeats.
- **High Bandwidth Access:** Sub-THz links enable multi-Gb/s data rates essential for 6G.
- **Flexible Deployment:** RIS can shape wave propagation dynamically without altering transmitter/receiver hardware.
- **Improved Coverage:** Multi-hop RIS deployment can extend reach of high-frequency links effectively.

V. DISADVANTAGES

- **Hardware Challenges:** Fabricating RIS elements with required precision for sub-THz frequencies is difficult and costly ResearchGate.
- **High Path Loss:** THz propagation suffers from molecular absorption and attenuation, limiting range.
- **Lack of Real Prototypes:** Functional RIS in sub-THz bands remains largely theoretical or simulated.
- **Control Complexity:** Coordinating beamforming across multiple RIS layers and network nodes adds system complexity.

VI. RESULTS AND DISCUSSION

- **Prototype Successes:** The 5.8 GHz RIS prototype validated RIS benefits in real-world scenarios with substantial power gains and operational throughput arXiv.
- **Simulation Insights:** Hybrid beamforming using DRL and RIS in sub-THz links led to a ~50% extension in coverage over benchmarks arXiv.
- **Modeling Impact:** The 6G-TERARIS project’s stochastic geometry models provide promising designs for user-centric RIS-aided THz systems with improved energy and rate performance CORDIS.
- **Hardware Limitations:** Sub-THz implementation is hampered by fabrication accuracy constraints, unit-cell scaling, and phase resolution challenges ResearchGate.

Overall, RIS-enabled sub-THz prototypes and models suggest a promising path for 6G, though significant R&D investments are required in hardware deployment and system integration.

VII. CONCLUSION

Early RIS prototypes at microwave frequencies demonstrate the feasibility and performance benefits of intelligent surfaces. Extending this paradigm into sub-THz frequencies opens pathways for high-data-rate, energy-efficient 6G connectivity. Through hybrid beamforming, RIS-enhanced multi-hop strategies, and stochastic geometry-based system modeling, it becomes clear that RIS can mitigate propagation challenges inherent to the THz band while enabling ultra-fast links. However, real-world implementation of sub-THz RIS remains embryonic, constrained by hardware fabrication and control complexity. Concerted efforts in hardware innovation, prototyping, and system-level design are essential to make RIS-enabled sub-THz communication a reality in future 6G networks.

VIII. FUTURE WORK

1. **Hardware Prototyping:** Build and test sub-THz RIS prototypes using CMOS, MEMS, or phase-change metasurfaces.
2. **Large-Scale Field Trials:** Deploy RIS in real THz testbeds to validate performance in diverse environments.
3. **Advanced Beam Control:** Develop AI-driven control algorithms for dynamic RIS configuration in mobile scenarios.

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4. **Integrated System Design:** Combine RIS with ultra-massive MIMO base stations and user-centric architectures.
5. **Fabrication Innovations:** Research scalable fabrication methods for fine metasurface unit cells suited for THz operation.
6. **Standardization Efforts:** Collaborate on defining RIS-aided THz channel models and system benchmarks for 6G.

REFERENCES

1. Pei, X., Yin, H., Tan, L., et al. (2021). *RIS-Aided Wireless Communications: Prototyping, Adaptive Beamforming, and Indoor/Outdoor Field Trials.* arXiv preprint arXiv
2. Huang, C., Yang, Z., Alexandropoulos, G. C., et al. (2020). *Hybrid Beamforming for RIS-Empowered Multi-hop Terahertz Communications: A DRL-based Method.* arXiv preprint arXiv
3. Yang, F., Pitchappa, P., & Wang, N., et al. (2022). *Terahertz Reconfigurable Intelligent Surfaces (RISs) for 6G Communication Links.* Micromachines MDPIEurope PMC
4. (2022) *6G-TERARIS Project Fact Sheet: Improved terahertz communications for 6G leveraging reconfigurable intelligent surfaces.* CORDIS Project Description CORDIS
5. Author (pre-2022). *Hardware Aspects of Sub-THz Antennas and Reconfigurable Intelligent Surfaces for 6G Communications.* IEEE JSAC (accepted)