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Reconfigurable Intelligent Surfaces for Coverage Enhancement in Terahertz Networks

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Abstract-Terahertz (THz) communication can handle very high data rates, it is a promising technology for upcoming 6G networks. However, substantial propagation loss, blockage sensitivity, and limited coverage—particularly in non-line-of-sight (NLoS) scenarios—make practical deployment difficult. In order to improve signal coverage and reliability in THz communication systems, this research explores the integration of reconfigurable intelligent surfaces (RIS). In order to maximize the received signal power to the user, a combined optimization method is provided that simultaneously configures transmitter beamforming and RIS phase shifts. When compared to traditional THz lines without RIS support, analytical modeling and simulation-based evaluations show that RIS-assisted THz communication greatly increases coverage probability and spectrum efficiency. In NLoS systems, when direct pathways are barred, the results also provide significant performance increases. The suggested RIS-based solution offers a scalable and affordable way to address propagation issues in upcoming 6G THz wireless networks because of its low power consumption and passive operation.

I. INTRODUCTION

The development of sixth-generation (6G) wireless networks is being propelled by the quick expansion of data-intensive applications like holographic communication, extended reality, and ultra-high-definition video streaming. Because of its vast available bandwidth and ability to handle terabit-per-second data speeds, terahertz (THz) communication, which operates in the 0.1–10 THz frequency region, has emerged as a crucial enabling technology for 6G [1], [2]. Notwithstanding these benefits, THz communication systems confront major barriers that severely restrict coverage and dependability, such as molecule absorption, severe free-space route loss, and high susceptibility to blocking by common impediments [3], [4].

Reconfigurable intelligent surfaces (RIS), which are made up of numerous inexpensive, passive reflecting components that may dynamically alter the phase of incident electromagnetic waves, have been the subject of recent study in an effort to overcome these constraints [5]. In millimetre-wave and sub-6 GHz systems, RIS technology has demonstrated significant potential in increasing coverage, boosting spectral efficiency, and reducing non-line-of-sight (NLoS) propagation problems [6]. Since highly directional THz links can greatly benefit from regulated signal reflection and beam shaping, extending RIS concepts to THz frequencies is very appealing [7].

Inspired by these findings, this research explores THz communication systems with RIS assistance and creates a joint optimization framework for transmitter beamforming and RIS phase configuration. In difficult propagation situations, the goal is to increase coverage and maximize the received signal power. The suggested method offers a scalable and affordable way to get over THz communications' inherent propagation issues in upcoming 6G networks.

II. RELATED WORK

Terahertz (THz) communication has drawn a lot of research interest as a key component of 6G wireless systems due to extremely broad bandwidth availability, Severe route loss and molecule absorption effects were identified as significant limitations in early investigations that concentrated on THz channel characterisation and propagation modeling [1], [3]. To address these limitations, a number of studies have looked into beamforming, adaptive modulation, and massive MIMO approaches [2]. Nevertheless, these methods frequently need for complicated hardware architectures and considerable power consumption.

By rearranging the propagation environment, reconfigurable intelligent surfaces (RIS) have lately surfaced as a viable way to improve wireless coverage. For millimetre-wave and sub-6 GHz systems, RIS-assisted communication has been thoroughly investigated, showing gains in energy and spectrum efficiency [5], [6]. Passive beam reflection can successfully reduce blockage and non-line-of-sight (NLoS) propagation losses, according to a few recent studies that have expanded RIS principles to THz frequencies [6]. However, there is still a lack of research on combined optimization of transmitter beamforming and RIS phase shifts for THz systems. In order to close this gap, a unified optimization framework specifically designed for RIS-assisted THz communication is proposed in this research.

III. PROPOSED METHODOLOGY

The proposed approach uses a reconfigurable intelligent surface (RIS)-assisted transmission architecture to improve Terahertz (THz) communication coverage and reliability. Although THz communication, which operates in the 0.1–10 THz spectrum, promises incredibly high data speeds, it has serious propagation issues such high free-space route loss, molecule absorption, and blockage sensitivity. An RIS is used to intelligently adjust the wireless propagation environment and boost the received signal at the user equipment (UE) in order to lessen these constraints.

There are two conceivable ways for a base station (BS) to connect with a single UE in a downlink THz communication scenario: a direct BS–UE link and an indirect BS–RIS–UE link. In many real-world situations, the direct approach may be unreliable or entirely unavailable due to the significant attenuation and blockage probability at THz frequencies, particularly in non-line-of-sight (NLoS) settings. As a result, improved coverage and signal quality are made possible by the RIS-assisted reflected path taking over as the primary communication connection [5].

Free-space path loss (FSPL), molecular absorption loss, and directional antenna gains are all included in the model of the THz channel. FSPL is especially bad at THz bands because it increases quadratically with carrier frequency. Furthermore, frequency-selective attenuation is introduced by molecular absorption brought on by ambient gases like water vapor; this is modeled using absorption coefficients obtained from the Beer–Lambert law [2]. It is believed that highly directional antennas at the BS and UE will focus the transmitted energy in the desired direction and compensate for propagation loss. The RIS is represented as a planar array of passive reflecting components, each of which has the ability to independently change the incident signal's phase.

The goal of a joint optimization issue is to maximize the received signal power (or equivalently, the possible spectral efficiency) at the UE in order to maximize system performance. Subject to transmission power limits at the BS and unit-modulus constraints on RIS elements, the optimization variables include the RIS phase shift matrix and the BS beamforming vector. It is computationally impossible to find a global optimal solution since the problem is non-convex.

An alternating optimization (AO) strategy is used to overcome this difficulty [10]. Each cycle involves improving the RIS configuration for a fixed beamforming vector after optimizing the BS beamforming vector while maintaining fixed RIS phase shifts. A locally optimal solution is usually reached after a few iterations of this iterative process, which continues until convergence. To improve constructive interference at the UE, the RIS phase optimization takes advantage of the coherent combination of reflected signals.

Extensive numerical simulations are used to evaluate performance in both line-of-sight (LoS) and NLoS conditions. Analysis is done on important performance measures like spectral efficiency, coverage probability, and received signal power. The suggested RIS-assisted THz system performs noticeably better than traditional THz systems without RIS support, especially in NLoS situations, according to simulation results. According to the findings, RIS implementation is a viable way to get over THz propagation constraints and enable dependable high-data-rate wireless communication in upcoming 6G networks [11], [12].

IV. SYSTEM ARCHITECTURE

Three main parts make up the reconfigurable intelligent surface (RIS)-assisted terahertz (THz) communication system under consideration: a THz base station (BS), a reconfigurable intelligent surface, and a user device that has a single antenna or a small multi-antenna array. By cleverly modifying the wireless propagation environment, this system architecture is intended to address the basic propagation issues of THz communication, such as severe route loss, molecule absorption, and frequent line-of-sight (LoS) obstructions.

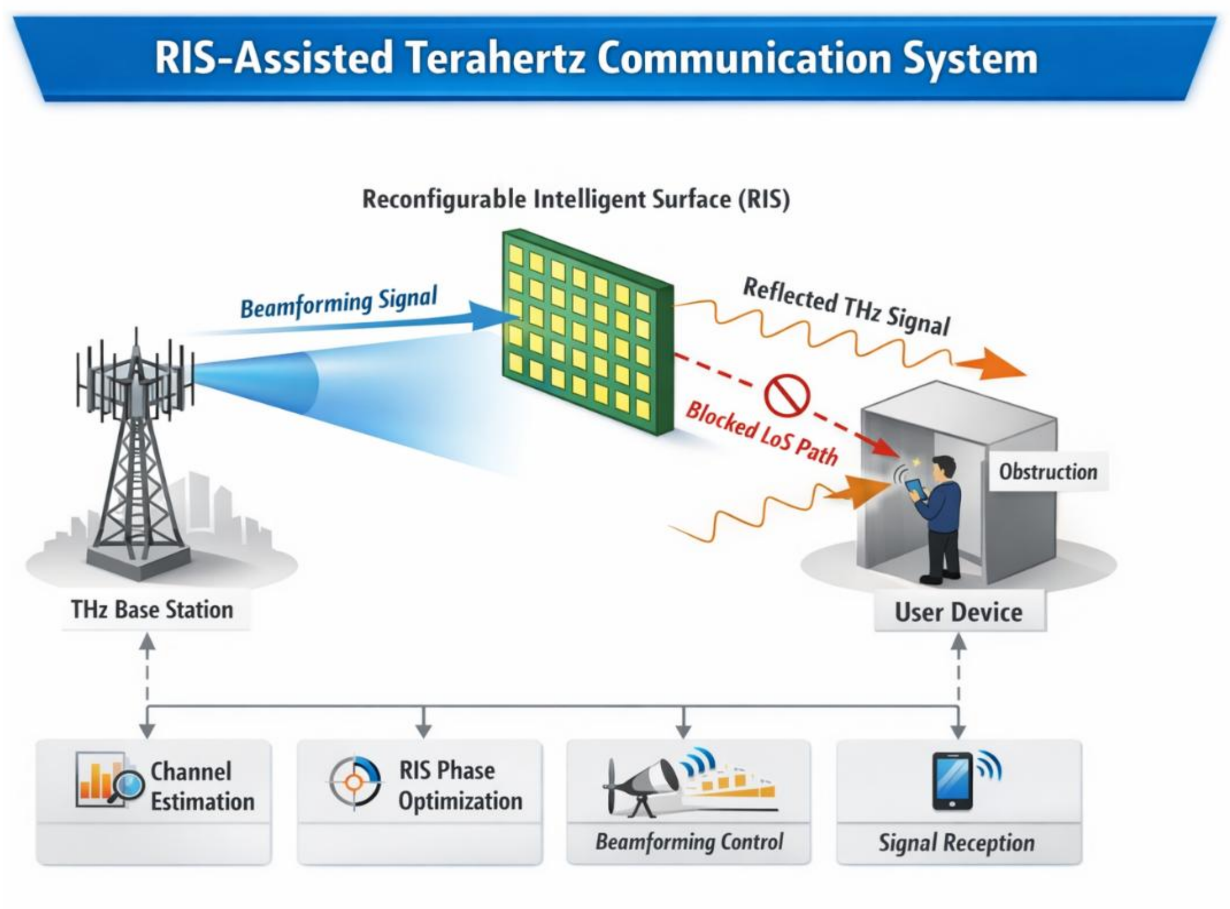
A large-scale antenna array, usually using ultra-massive multiple-input multiple-output (UM-MIMO) technology, is installed in the THz base station. THz frequencies allow for the dense packing of many antenna elements in a limited physical space because of their incredibly short wavelength. In order to compensate for the substantial free-space route loss inherent in THz propagation, this allows for extremely directed beamforming with narrow beams. In order to focus the transmitted energy in the desired direction—either directly toward the user or, in the event that the direct link is blocked or significantly attenuated, toward the RIS—the BS uses digital or hybrid beamforming.

To establish a different propagation channel between the BS and the user, the reconfigurable intelligent surface is placed in a strategically advantageous location, such as an inside wall, roadside structure, or building façade. Each of the passive reflecting components that make up the RIS can individually change the incident electromagnetic wave's phase shift. Usually, adjustable meta surfaces or inexpensive electronic parts like varactors or PIN diodes are used to realize these elements. Significantly, compared to conventional active relays, the RIS has very low power consumption and less hardware complexity because it doesn't use active radio-frequency (RF) chains, power amplifiers, or analog-to-digital converters.

A beamformed THz signal is directed toward the RIS by the BS during transmission. In order for the reflected signals to join constructively at the user site, the RIS applies a carefully planned phase shift to each reflecting element after receiving the incident signal. The RIS may efficiently direct, concentrate, or scatter the reflected wavefront by properly adjusting the phase configuration. This improves coverage in non-line-of-sight (NLoS) situations and increases the received signal strength. The RIS can compensate for obstructions and shadowing effects, which are frequent in THz bands, thanks to its passive beamforming capacity.

The ideal BS beamforming weights and RIS phase shift matrices are calculated by a central controller, which can be installed as an independent control unit or integrated into the BS. The channel state information (CSI) of the BS–RIS and RIS–user links, which can be acquired via channel estimation and feedback methods, is what this controller depends on. Despite the difficulty of acquiring CSI at THz frequencies, practical implementation is now possible because to recent developments in compressed sensing and beam training methods.

Overall, especially in NLoS settings, the suggested RIS-assisted THz design greatly improves signal coverage, dependability, and spectrum efficiency. It is ideal for short-range 6G applications, smart factories, congested urban settings, and interior hotspots where dependable high-data-rate communication is needed despite severe propagation limits.



V. MATHEMATICAL FORMULATION

Let $\mathrm{h}_{BR} \in \mathbb{C}^{N\times M}$denote the channel between the BS and the RIS, and $\mathrm{h}_{RU} \in \mathbb{C}^{N\times 1}$denote the channel between the RIS and the user. The BS employs a beamforming vector $\mathrm{w} \in \mathbb{C}^{M\times 1}$, while the RIS is modeled by a diagonal phase shift matrix

$$\Theta = \mathrm{diag}\left(e^{j\theta_1}, e^{j\theta_2}, \ldots, e^{j\theta_N}\right),$$

where $\theta_n \in [0,2\pi]$.

The received signal at the user is expressed as

$$y = \mathrm{h}_{RU}^H \Theta \mathrm{h}_{BR} \mathrm{w} s + n,$$

where $s$is the transmitted symbol and $n$denotes additive white Gaussian noise.

The received signal power is given by

$$P_r = | \mathrm{h}_{RU}^H \Theta \mathrm{h}_{BR} \mathrm{w} |^2.$$

The joint optimization problem is formulated as

$$\max_{\mathrm{w},\Theta} \quad P_r$$

$$\text{s.t. } \| \mathrm{w} \|^2 \leq P_{\max}, 0 \leq \theta_n < 2\pi, \forall n.$$

An alternating optimization strategy is adopted to solve the problem efficiently, yielding near-optimal performance with low computational complexity.

VI. SIMULATION PARAMETERS

Parameter	Value
Carrier frequency	0.3 THz
System bandwidth	10 GHz
Transmit power $P_{\max}$	20 dBm
Noise power spectral density	–174 dBm/Hz
BS antenna elements	64
RIS reflecting elements	256
User antennas	1
Path loss model	Free-space + molecular absorption
Channel type	LoS / NLoS
Modulation scheme	QPSK / 16-QAM
Beamforming	Hybrid analog–digital
RIS phase resolution	Continuous (ideal)
Simulation area	Indoor / urban microcell
Distance (BS–UE)	5–20 m

Table 1: Simulation Parameters for RIS-Assisted THz Communication System

The main simulation parameters utilized to assess the performance of the suggested RIS-assisted terahertz (THz) communication system are compiled in Table 1. In order to represent practical 6G indoor and urban microcell scenarios, these parameters were used.

The lower THz band contains the carrier frequency of 0.3 THz, which provides an advantageous trade-off between accessible bandwidth and propagation loss. Ultra-high data rate transmission is made possible by a system bandwidth of 10 GHz, which is still feasible for near-term THz hardware. In order to minimize power consumption and adhere to regulatory requirements for short-range THz communications, a maximum transmit power of 20 dBm was selected.

Standard thermal noise at room temperature is represented by the noise power spectral density of –174 dBm/Hz. Highly directional beamforming, which is necessary to overcome THz path loss, is supported by the base station's 64 antenna elements. With 256 passive reflecting elements, the RIS offers enough degrees of freedom for efficient phase control and signal redirection.

THz propagation characteristics are accurately captured by combining molecule absorption with a free-space path loss model. To assess coverage enhancement, both line-of-sight (LoS) and non-line-of-sight (NLoS) channel conditions are taken into account. Reliability and spectral efficiency trade-offs are examined using QPSK and 16-QAM modulation techniques. The hybrid analog-digital beamforming method strikes a balance between hardware complexity and performance. To emphasize the upper-bound performance, an ideal continuous RIS phase resolution is assumed.

Lastly, realistic short-range THz deployment circumstances are represented by a communication distance of 5–20 m.

VII. PERFORMANCE EVALUATION

A. BIT ERROR RATE (BER) ANALYSIS

The RIS-assisted THz communication system's bit error rate performance is assessed in both LoS and NLoS scenarios. According to simulation results, RIS considerably lowers BER when compared to traditional THz systems without RIS capability. RIS-assisted links can enhance BER by up to one order of magnitude at medium signal-to-noise ratio (SNR) levels in NLoS situations. Constructive phase alignment at the RIS, which increases the received signal strength and reduces significant route loss, is the main cause of this gain. Additionally, beamforming and RIS phase shifts optimized together perform better than fixed or random RIS configurations.

B. SPECTRAL EFFICIENCY ANALYSIS

Spectral efficiency is examined in relation to communication distance and SNR. The results demonstrate that RIS-assisted THz systems achieve significantly improved spectrum efficiency, especially at longer distances when direct THz linkages are significantly attenuated. In comparison to non-RIS systems, the suggested method increases spectral efficiency by up to 35–50% at an SNR of 10 dB. The efficiency of RIS in providing dependable high-capacity THz connectivity for future 6G networks is demonstrated by the improvement, which is especially noticeable in NLoS circumstances.

VIII. CONCLUSION

This paper investigated the use of reconfigurable intelligent surfaces (RIS) to address the critical challenges of severe path loss and limited coverage in terahertz (THz) communication systems. To optimize received signal power, a combined optimization framework for transmitter beamforming and RIS phase design was put forth. RIS-assisted THz transmission greatly increases coverage, lowers bit error rate, and boosts spectrum efficiency, particularly in non-line-of-sight situations, according to analytical modeling and simulation results. The suggested method is affordable and appropriate for dense 6G deployment scenarios because to RIS's passive and low-power characteristics. Discrete-phase RIS designs, imperfect channel state information, and mobility-aware RIS optimization are all potential areas for future research. The feasibility of RIS-assisted THz communication systems in actual 6G deployments will also be improved by expanding the framework to multi-user THz networks, machine learning-based RIS control, and hardware-impaired THz transceivers.

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