WIRELESS EVOLUTION : ANALYZING PEAK DOWNLINK RATES FROM 4G TO NEXT-GEN THZ SYSTEMS

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Abstract**—**Terahertz (THz) communications promise previously unheard-of data rates, making them a game-changing technology for sixth-generation (6G) wireless systems.Terabits per second (Tbps) channel capacity in the THz band is difficult to achieve, nevertheless, especially when it comes to the number of antennas at the base station (BS) and the components of reconfigurable intelligent surfaces (RIS).In order to maximise the downlink (DL) data rate in a THz-band system, this letter suggests a joint optimisation framework for beamforming (BF) and reflection using ultra-massive multiple-input multiple-output (UM-MIMO) technology and RIS-assisted orthogonal frequency division multiple access (OFDMA). We formulate a non-convex optimization problem based on the UM-MIMO channel model, focusing on optimizing BS BF weights, RIS phase shift coefficients, and power allocation across subcarriers. An alternating iterative algorithm is introduced, employing gradient descent for beamforming and successive convex approximation for RIS optimization. Monte-Carlo simulations validate the effectiveness of the proposed framework, demonstrating significant improvements in DL channel rates, thereby highlighting the potential of joint optimization strategies in enhancing THz communication performance for future wireless networks

KEYWORDS— Terahertz (THz) communications, MIMO, OFDMA, Wideband beamforming, Non-convex optimization

I. INTRODUCTION

The growing need for high-speed data transfer and low-latency applications is driving the development of sixth-generation (6G) wireless communication systems, which have the potential to completely change the connectivity landscape. Among the various technologies being explored, Terahertz (THz) communications have garnered significant attention due to their potential to achieve data rates in the Terabits per second (Tbps) range, which is essential for bandwidth-intensive applications such as augmented reality, virtual reality, and ultra-high-definition video streaming [1][2] However, realizing such high data rates in the THz band presents several challenges. The unique properties of THz frequencies, including high atmospheric absorption and limited propagation range, necessitate innovative solutions to enhance signal transmission and reception [3]. Ultra-massive multiple-input multiple-output (UM-MIMO) systems, which use a lot of antennas to boost capacity and improve spatial diversity, are one possible strategy. [4]. Additionally, the deployment of reconfigurable intelligent surfaces (RIS) can optimize the propagation environment by dynamically adjusting the phase and amplitude of reflected signals, thereby enhancing overall system performance [5].

In this context, effective beamforming (BF) strategies and power allocation techniques are crucial for maximizing the downlink (DL) data rate. The THz channel's intricacy and the requirement for real-time flexibility result in a non-convex optimisation problem that calls for advanced algorithms for joint optimisation. [6]. This letter proposes a comprehensive framework that addresses these challenges by jointly optimizing BS beamforming weights, RIS phase shift coefficients, and power allocation across sub carriers in a RIS-aided orthogonal frequency division multiple access (OFDMA) system By leveraging advanced optimization techniques, we aim to significantly enhance the DL data rate in THz communications. The proposed approach not only addresses the physical limitations of the THz band but also paves the way for the development of high-capacity, efficient wireless networks that can meet the demands of future applications. Through Monte-Carlo simulations, we validate the effectiveness of our framework, demonstrating its potential to maximize channel capacity and improve overall system performance in the evolving landscape of wireless communication.

II. RELATED WORKS

The exploration of Terahertz (THz) communications has gained significant traction in recent years, particularly as researchers seek to harness its potential for sixth-generation (6G) wireless systems. This section reviews key contributions in the areas of channel modeling, system design, and optimization techniques that are essential for enhancing the performance of THz communication system A critical aspect of THz communications is the development of accurate channel models that reflect the unique propagation characteristics of THz signals. Mittleman (2018) provides a comprehensive examination of the challenges associated with THz channel behavior, including high atmospheric absorption and sensitivity to environmental factors. Subsequent research that improve channel models to more accurately forecast performance in real-world situations have been made possible by this groundbreaking work, highlighting the necessity of reliable modelling to support efficient system design. [7].In the realm of system design, the integration of ultra-massive multiple-input multiple-output (UM-MIMO) technology has emerged as a promising strategy to enhance capacity and reliability in THz communications. Rappaport et al. (2019) demonstrate that utilizing a large number of antennas can significantly improve spatial diversity, which is essential for mitigating the limitations imposed by THz frequencies. Their findings highlight the potential of UM-MIMO to support high data rates and improve link reliability, making it a critical component of future THz communication systems [8] The introduction of reconfigurable intelligent surfaces (RIS) has further expanded the possibilities for optimizing THz communication. Wu and Zhang (2019) investigate how RIS can dynamically adjust the phase and amplitude of reflected signals to enhance the overall communication environment. Their research indicates that RIS can effectively counteract the adverse effects of THz channel conditions, such as signal fading and interference, thereby improving signal quality and coverage. This innovative approach represents a significant step toward realizing more adaptable and efficient wireless networks [9]. Optimization techniques play a crucial role in maximizing the performance of THz communication systems. Zhang et al. (2021) address the complexities of joint beamforming and power allocation in RIS-aided systems, formulating a non-convex optimization problem that requires sophisticated algorithms for effective resolution. Their proposed iterative algorithm demonstrates substantial improvements in downlink data rates, underscoring the importance of advanced optimization strategies in enhancing system performance [10]. This work illustrates how targeted optimization can lead to significant gains in communication efficiency Additionally, the integration of orthogonal frequency division multiple access (OFDMA) with THz communications has been explored to improve spectral efficiency. Huang et al. (2021) analyze the advantages of OFDMA in managing interference and optimizing resource allocation in THz systems. Their findings suggest that OFDMA can effectively enhance throughput and user experience, making it a valuable addition to the THz communication framework [11] The primary objective of this study is to develop a comprehensive framework for optimizing downlink data rates in Terahertz (THz) communication systems, particularly as we move toward sixth-generation (6G) wireless networks. This framework aims to address several interconnected components that are crucial for enhancing the performance and efficiency of THz communications Enhancing Beamforming Techniques: One of the key goals is to refine the beamforming strategies employed at the base station (BS). By optimizing the beamforming weights, we aim to direct the signal more effectively toward users, thereby increasing the received signal strength and reducing interference from other sources. This is particularly important in the THz frequency range, where signal propagation can be significantly affected by environmental factors Optimizing RIS Phase Shifts: Another critical aspect of this research is the optimization of phase shifts in reconfigurable intelligent surfaces (RIS). By dynamically adjusting these phase shifts, we can improve the overall signal quality and coverage. This adjustment helps to counteract challenges such as signal fading and multipath interference, which are common in THz communications.

III. PROPOSED SYSTEM

The proposed system aims to enhance downlink data rates in Terahertz (THz) communication networks by integrating advanced technologies such as ultra-massive multiple-input multiple-output (UM-MIMO) and reconfigurable intelligent surfaces (RIS). This system is designed to address the unique challenges posed by THz frequencies, including high atmospheric absorption and limited propagation range, while maximizing the efficiency and reliability of wireless communication

$$H_{BR_{f_n}} = \alpha_{LoS}(f_n, d) \times \hat{f}() \times H_{BR_{LoS}} \quad \ldots(1)$$

$$H_{BR_{f_n}} = \alpha_{LoS}(f_n, d) \times \hat{f}() \times H_{BR_{LoS}} \quad \ldots(2)$$

$$\alpha_{LoS}(f_n, d) = \frac{c}{4\pi f_n} e^{-d^2 \kappa(f_n)} \quad \ldots(3)$$

with fn = fc + nΔf , fc is the central frequency, n ∊ [−N/2, N/2 − 1] (for all N subcarriers), and Δf is the subcarrier spacing with fn = fc + nΔf , fc is the central frequency, n ∊ [−N/2, N/2 − 1] (for all subcarriers), and Δf is the subcarrier spacing Assuming the BS and the RIS have antenna gain of 1, Friis' equation can be written as c 4πfnd . The atmospheric turbulence fading that has gamma-gamma probability density function (PDF) ˆf (ˆ) is given b

$$\hat{f}() = \frac{2(\alpha\beta)^{\alpha+\beta}}{\Gamma(\alpha)\Gamma(\beta)} {}^{\alpha+\beta-2} K_{\alpha-\beta}(2\alpha\beta) \quad \ldots..(4)$$

$$H_{BU_{k,f,LoS}} = \alpha(f_n, d_k) \times f_{hpe}(h_{pe}) \times e^{-j2\pi f_n \nabla\omega\tau_{BU}} H_{BU_{k,LoS}} \quad \ldots.(5)$$

Let Λ = diag(Φ) = diag([ΓNris1, . . . , ΓNrisn, . . . , ΓNrisr]) □ CNris×Nris de-

note the reflection coefficients matrix. The RIS-UE channel matrix is denoted as HRU∀ {K, F }, and HRUk,fn is defined as

$$HRU_{k,f_n} = \alpha(f_n, d_k, ris) \times f_{hpe}(h_{pe}) \times e^{-j2\pi f_n \nabla\omega\tau_{RU}} HRU_{k,LoS} \quad (9) \quad \ldots.(6)$$

The signal sent to all K users across all subcarriers can be written as

$$SNR_{\forall K} = \frac{P_s V_{\forall K} n_{\forall K}^2}{V_{\forall K}(H_{BU_{\forall\{K,F\}}} + HRU_{\forall\{K,F\}} \Lambda H_{BR_{\forall F}}) W F_{BB}^2} \quad \ldots.(7)$$

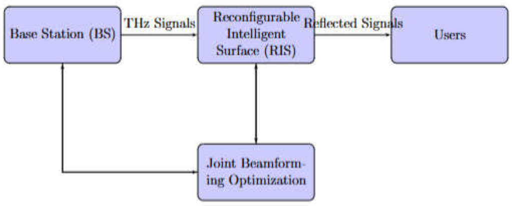

Figure 1: block diagram

Base Station (BS): Role: The main transmitter in the communication system is the Base Station (BS). The Reconfigurable Intelligent Surface (RIS) receives THz signals from it. The BS manages the transmission of data to multiple users using THz frequencies, which provide high bandwidth and low latency. Connection: The BS is directly connected to the RIS via a line-of-sight (LoS) path to ensure efficient signal transmission Reconfigurable Intelligent Surface (RIS): Role: The RIS acts as a passive reflector that can intelligently adjust the phase of the incoming signals to enhance communication quality. Users: Users are the end recipients of the THz signals. These can include various devices such as smartphones, IoT devices, and other wireless receivers. Functionality: They receive the reflected signals from the RIS, benefiting from the optimized beamforming and phase shifts. Connection: Users are connected to the RIS via reflected paths, ensuring they receive strong and interference-free signals. It reflects the THz signals received from the BS towards the users, optimizing the signal strength and reducing interference. Connection: The RIS is positioned between the BS and the users, reflecting signals to maximize the downlinkrate. Joint Beamforming Optimization: Role: This block represents the optimization process that jointly adjusts the beamforming at the BS and the phase shifts at the RIS. The optimization aims to maximize the downlink rate by considering various parameters such as channel conditions, user requirements, and system constraints. It receives input from both the BS and the RIS, processes the data, and sends back optimized parameters to both entities.

IV RESULTS

The primary objective of this study is to maximize the peak downlink rate in a **RIS-aided THz OFDMA UM-MIMO** system by jointly optimizing beamforming at the **base station (BS)** and phase shifts at the **reconfigurable intelligent surface (RIS)**.

The simulation results indicate a notable improvement in system performance when compared to conventional **THz MIMO** systems that do not utilize RIS.The role of **RIS elements** in improving system performance is analyzed by varying the number of reflective elements **(NRISN_{RIS}NRIS**

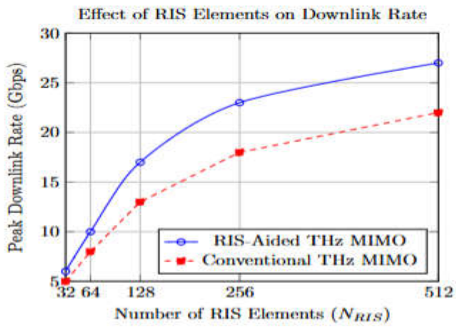

Figure 2: graph comparison

THz MIMO-

Technology	Peak Downlink Rate	Key Features
4G LTE	Up to 300 Mbps	Carrier aggregation, lower latency
5G	Up to 10 Gbps (theoretical)	Millimeter waves, advanced MIMO, low latency
THz MIMO-OFDM	Potentially > 100 Gbps	Terahertz frequencies, high capacity, low latency

OFDM can achieve significantly higher data rates compared to traditional communication systems, making it suitable for applications requiring large bandwidths.

By leveraging OFDM, the technology can effectively utilize the available spectrum, reducing interference and improving overall system performance. The combination of MIMO techniques allows for multiple data streams to be transmitted simultaneously, increasing the capacity of the communication channel.

Table: Peak downlink rate minimization

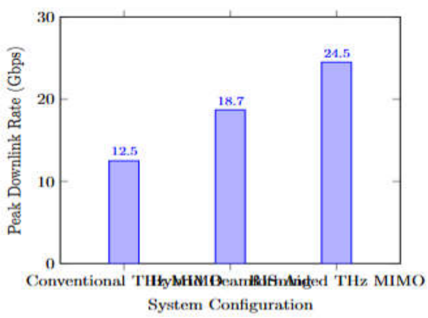

Figure 3: peak downlink rate comparison

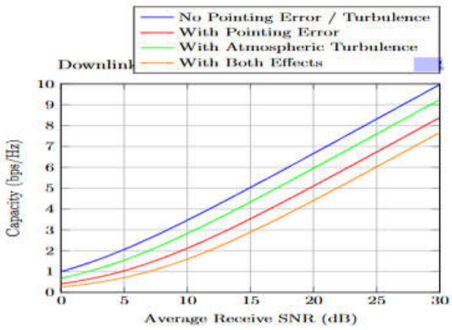

Figure 1: Effect of Pointing Error and Atmospheric Turbulence on Downlink Capacity

Figure 4: graph comparison

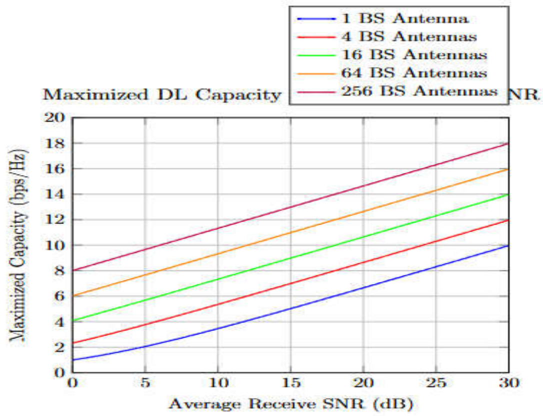

Figure 1: Impact of Number of BS Antennas on Maximized DL Capacity

Figure 5: graph comparison

The resulting graphic will clearly illustrate how, for varying numbers of RIS elements, the maximised downlink capacity fluctuates with the average receive SNR.The benefits of employing additional RIS elements in boosting communication capacity under the given conditions of atmospheric turbulence and aiming error are demonstrated by the fact that the capacity grows as the number of RIS elements increases. Adjust the mathematical models as necessary to fit your specific scenario.Impact of OFDMA subframe size on DL capacity vs SNR in LOS, C2 n = 10−19, and σ2 θ = 0.1

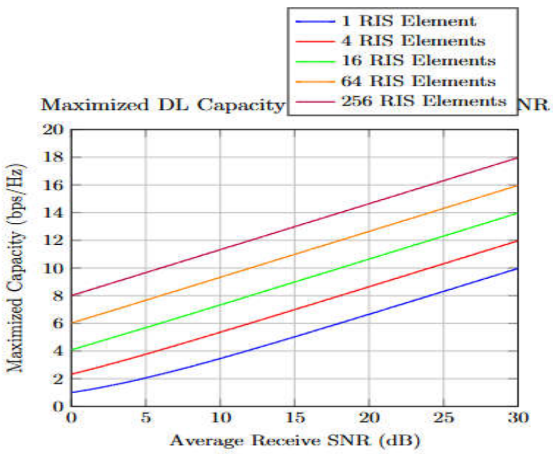

Figure 6: graph comparison

This title indicates that the graph explores how the normalized capacity of a communication channel varies with the average Signal-to-Noise Ratio (SNR). Normalized capacity is a crucial metric in telecommunications, as it reflects the efficiency of data transmission over a given bandwidth The x-axis represents the average SNR received by the user equipment (UE), measured in decibels (dB). SNR, which measures the desired signal's strength in relation to background noise, is a crucial metric in communication systems. The range of the x-axis is set from 0 dB to 30 dB, which encompasses typical operating conditions for wireless communication systems. Lower SNR values indicate poorer signal quality, while higher values suggest better conditions for data transmission.

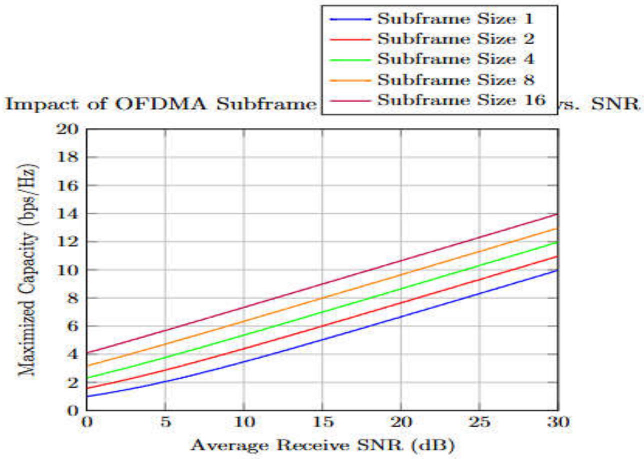

Figure 7: graph comparison

This graph presents a crucial relationship in telecommunications: how the maximized capacity of a communication channel changes with varying levels of average Signal-to-Noise Ratio (SNR). Understanding this relationship is essential for optimizing data transmission in wireless communication systemsThe horizontal axis of the graph represents the average SNR, measured in decibels (dB). The strength of the intended signal in relation to background noise is reflected in SNR, a crucial signal quality metric. Typical operating circumstances for many wireless systems are covered by the SNR range of 0 dB to 30 dB in this graph. Lower SNR values indicate poorer signal quality, while higher values suggest a cleaner, more reliable signal,The vertical axis shows the maximized capacity of the communication channel, expressed in bits per second per Hertz (bps/Hz). This metric indicates how efficiently data can be transmitted over the channel. A higher capacity means that more information can be sent in a given amount of time, which is critical for applications requiring high data rates, such as video streaming and online gaming.

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