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ENHANCED BEAM TRAINING FOR RIS-ASSISTED TERAHERTZ SYSTEMS: ANALYSIS BASED ON QUANTIZED PHASE CONTROL

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Abstract

Terahertz (THz) frequencies are of great interest due to their ultra-wide bandwidth and the need for ultra-reliable and high-capacity wireless communication in sixth-generation (6G) networks. However, THz signals' effectiveness in practical applications is constrained by significant path loss, beam split effects, and alignment difficulties. A promising solution that makes wavefront control affordable and programmable is Reconfigurable Intelligent Surfaces (RIS). However, the majority of RIS-assisted beam training frameworks currently in use ignore real-world hardware constraints by assuming perfect continuous phase control or extremely low phase resolutions.

In this paper, a quantization-aware beam training framework that explicitly accounts for the effects of finite phase resolution is proposed for RIS-assisted wideband THz systems. With an emphasis on intermediate quantization levels, specifically 3-bit and 4-bit control, the study creates and assesses algorithms that strike a balance between hardware viability and spectral efficiency. Simulation results show that the suggested 4-bit quantization-aware scheme outperforms conventional techniques like exhaustive search, multi-directional training, and

the analytical Power Distribution Pattern (PDP)-based framework, achieving near-optimal performance in terms of achievable rate and beam training overhead.
According to the results, 4-bit quantization offers a workable compromise between system performance and implementation complexity, demonstrating that scalable, high-throughput THz communications can be reliably supported by inexpensive RIS hardware. By bridging the gap between deployable RIS solutions and theoretical beam training designs, this work provides an effective route to the realization of RIS-enabled 6G networks.

Keywords: Terahertz communication, reconfigurable intelligent surface, beam training, quantized phase control, wideband OFDM, 6G networks

1 INTRODUCTION

1.1 Background and Context

The rapid advancement of wireless communication technologies has led to the ongoing development of sixth-generation (6G) networks, which are expected to deliver unprecedented data rates, ultra-reliable low-latency communication (URLLC), and massive connectivity. To meet these ambitious requirements, exploration of higher frequency bands has become essential. Among these, the Terahertz (THz) band, spanning approximately from 0.1 THz to 10 THz, has emerged as a promising candidate due to its abundant spectrum resources.

THz communication offers the potential to support data rates on the order of terabits per second (Tbps), making it a key enabler for futuristic applications such as holographic communications, immersive virtual and augmented reality, wireless backhaul, and ultra-high-definition content streaming. However, despite these advantages, THz communication faces several critical challenges. Signals in the THz band suffer from extremely severe propagation losses due to free-space path loss, molecular absorption, and their high susceptibility to physical blockages. Furthermore, the highly directional nature of THz signals, while beneficial for focusing energy, requires precise beam alignment between the transmitter, receiver, and any intermediate assisting devices.

In addition to propagation losses, another unique issue encountered in wideband THz communication is the *beam split effect*. This phenomenon occurs when different subcarriers within a wideband orthogonal frequency division multiplexing (OFDM) system experience beam misalignment, as each subcarrier points in slightly different spatial directions. The result is a significant degradation in beamforming performance and a reduction in the achievable data rate, particularly as the system bandwidth and number of subcarriers increase.

To overcome these challenges, researchers have turned to innovative physical layer technologies. One of the most promising approaches is the use of *Reconfigurable Intelligent Surfaces (RIS)*. An RIS is a two-dimensional metasurface composed of a large number of nearly passive reflecting elements, each of which can adjust the phase of an

incident electromagnetic wave. By intelligently configuring the reflection coefficients of these elements, the RIS can reconfigure the wireless propagation environment, effectively directing signals towards desired receivers, enhancing coverage, and mitigating blockages. Unlike traditional active relays, RIS operates in a nearly passive manner, consuming minimal energy, which makes it a cost-effective and scalable solution for future wireless networks.

Thus, in the context of 6G and beyond, the integration of RIS into THz communication systems presents a promising pathway to mitigate propagation losses, combat the beam split effect, and achieve ultra-high data rates required for next-generation wireless applications.

1.2 Terahertz Communication and Its Relevance

The Terahertz (THz) band, typically ranging from 0.1 THz to 10 THz, has emerged as one of the most promising frequency ranges for sixth-generation (6G) wireless networks due to its abundant spectral resources [1–3]. With bandwidths on the order of tens to hundreds of gigahertz, THz communication has the potential to support data rates in the range of several terabits per second (Tbps), enabling futuristic applications such as wireless backhaul, immersive extended reality (XR), holographic communication, and ultra-high-definition content streaming [4].

Despite these attractive features, THz communication also faces significant technical challenges. Signals in the THz range are subject to extremely severe free-space path loss, molecular absorption due to atmospheric gases, and susceptibility to blockages by physical objects [1, 2]. To compensate for these losses, highly directional transmission using large antenna arrays is required. However, such directionality introduces the need for precise beam alignment, which is both time-consuming and computationally demanding.

In wideband THz systems, another critical challenge is the *beam split effect*, wherein different subcarriers of an orthogonal frequency division multiplexing (OFDM) signal experience different optimal beam directions. This leads to beam misalignment, degraded array gain, and reduced achievable rate, particularly as bandwidth and the number of subcarriers increase [5]. Therefore, mitigating the beam split effect is crucial to achieving reliable THz links.

To address these limitations, advanced physical layer techniques such as Reconfigurable Intelligent Surfaces (RIS) have been investigated. RIS can help mitigate both path loss and beam split effects by intelligently reflecting signals with programmable phase shifts. However, most of the existing work assumes ideal RIS with continuous phase control, which is unrealistic for practical implementations. In reality, RIS hardware supports only limited phase resolution (quantized control), leading to performance degradation if not accounted for.

1.3 Role of Reconfigurable Intelligent Surfaces (RIS)

Reconfigurable Intelligent Surfaces (RIS) have recently attracted significant attention as a transformative technology for future wireless communication systems. An RIS is a planar surface composed of a large number of nearly passive reflecting elements,

each equipped with tunable electronic components such as PIN diodes or varactor diodes. By independently adjusting the phase shifts (and in some cases the amplitude) of the reflected signals, the RIS can manipulate the propagation environment in a programmable manner [23, 51].

The primary role of RIS in wireless communication is to provide an additional degree of freedom for controlling the wireless channel. Unlike conventional beamforming that takes place only at the transmitter or receiver, RIS enables the wireless medium itself to become controllable. This capability allows the network to dynamically redirect, enhance, or suppress signals as required, thereby improving signal-to-noise ratio (SNR), extending coverage, and mitigating interference.

In the context of Terahertz (THz) communication, RIS plays an even more critical role. Due to the extremely high propagation losses and strong directivity of THz signals, line-of-sight (LoS) links are often necessary. However, LoS connectivity may not always be guaranteed in dense urban environments or indoor deployments. By deploying RIS panels on building facades, walls, or other infrastructure, blocked or weak THz links can be re-established by intelligently reflecting signals towards the user. Furthermore, RIS can be employed to combat the beam split effect by adjusting phase configurations across subcarriers, thus maintaining coherent beam alignment in wideband scenarios.

RIS also offers significant advantages over traditional solutions such as active relays and massive MIMO. Active relays require dedicated power supplies and contribute additional noise, while massive MIMO systems demand expensive hardware and complex signal processing. In contrast, RIS is nearly passive, low-cost, energy-efficient, and scalable to very large arrays, making it particularly attractive for integration into 6G networks.

In summary, the role of RIS in THz communication systems is to enable efficient, flexible, and energy-conscious control of the wireless channel. Its ability to extend coverage, improve capacity, and mitigate unique THz propagation challenges positions RIS as a cornerstone technology for realizing the ambitious goals of next-generation wireless networks.

1.4 Beam Training in RIS-Assisted Terahertz Communication

Beam training is a fundamental process in directional wireless communication systems, particularly in millimeter-wave (mmWave) and Terahertz (THz) bands where highly directional beams are required to overcome severe propagation losses. The objective of beam training is to determine the optimal transmit and receive beam pair that maximizes the received signal strength or achievable rate. In THz systems, this process becomes even more critical due to the extremely narrow beamwidths and the *beam split effect*, which causes different subcarriers in wideband orthogonal frequency division multiplexing (OFDM) systems to misalign spatially [6, 7, 10].

Conventional beam training methods include exhaustive search, hierarchical search, and multi-directional probing. Exhaustive search guarantees optimal performance but suffers from prohibitively high training overhead, especially when the number of antennas or RIS elements is large [8, 9]. Hierarchical search reduces the overhead by progressively refining beam directions, but it remains computationally

complex and time-consuming in wideband THz scenarios. Multi-directional training transmits multiple beams simultaneously, offering a trade-off between performance and overhead, yet it introduces power splitting losses and becomes less effective as the array size increases [7, 11].

Recent research has focused on developing analytical or low-complexity beam training schemes. For example, the *Power Distribution Pattern (PDP)-based analytical framework* proposed in [13] mitigates the beam split effect by exploiting channel sparsity and delay-domain characteristics. Similarly, coded beam training [7, 8] and simultaneous multi-beam training [9] have been investigated to reduce training overhead. However, a major limitation of these approaches is the assumption of an ideal RIS with continuous phase control, which is unrealistic for practical hardware.

In practical RIS implementations, the phase shifts of the reflecting elements are quantized into a finite number of discrete levels (e.g., 1-bit, 2-bit, 3-bit, or 4-bit resolution), leading to quantization errors that degrade beamforming performance [11, 12]. To address this gap, this paper develops a **quantization-aware beam training framework** for RIS-assisted wideband THz communication. The proposed framework explicitly incorporates the effect of finite phase resolution in the training process, ensuring that both the beam split effect and hardware-induced distortions are mitigated. Simulation results confirm that a 4-bit quantization-aware RIS achieves near-optimal performance with significantly reduced training overhead, outperforming conventional frameworks such as exhaustive search, multi-directional training, and the analytical PDP-based method.

Thus, beam training not only plays a pivotal role in RIS-assisted THz systems but also forms the foundation of this research, where the focus shifts from idealized assumptions to practical, deployable solutions for 6G networks.

1.5 Phase Quantization

In practical implementations of reconfigurable intelligent surfaces (RIS), the reflecting elements cannot achieve continuous phase control due to hardware limitations. Instead, the phase shifts are quantized into a finite number of discrete levels, determined by the resolution of the control circuitry, such as PIN diodes or varactor diodes. This phenomenon is referred to as *phase quantization*. For example, a 1-bit RIS can only provide two phase states (0 and π), while a 4-bit RIS can provide 16 equally spaced discrete phase values over $[0, 2\pi)$ [11, 12].

Phase quantization introduces unavoidable errors between the ideal continuous phase shift and the realizable discrete phase value. These errors accumulate across large RIS arrays, leading to a reduction in coherent beamforming gain, degraded signal-to-noise ratio (SNR), and ultimately lower achievable rates [11, 14]. The impact becomes more pronounced at Terahertz (THz) frequencies where ultra-large RIS arrays (e.g., thousands of elements) are required to compensate for severe path loss. Consequently, ignoring phase quantization in the design of beam training algorithms results in overly optimistic performance predictions that may not hold in real-world deployments [6, 15].

Recent studies have explored different strategies to address quantization effects. Some works propose robust beamforming techniques that explicitly account for phase

errors [11, 12], while others analyze the trade-off between RIS resolution and system performance, showing that 2-bit or 3-bit quantization already provides a large fraction of the ideal gain [10, 16]. However, most existing beam training frameworks, including the analytical power distribution pattern (PDP)-based approach in [13], assume ideal RIS with continuous phase control and do not incorporate quantization into the training process.

This paper directly addresses this gap by proposing a **quantization-aware beam training framework** for RIS-assisted wideband THz communication. By embedding the quantization constraints within the training procedure, the proposed framework not only mitigates the beam split effect but also ensures robustness against hardware-induced distortions.

1.6 Problem Statement

The demand for ultra-high data rates and reliable connectivity in sixth-generation (6G) networks has motivated the exploration of Terahertz (THz) communication. While the THz band offers enormous bandwidth to support multi-gigabit and even terabit-per-second (Tbps) transmissions, it suffers from severe propagation challenges including high path loss, blockage sensitivity, and the *beam split effect* in wideband orthogonal frequency division multiplexing (OFDM) systems [6, 15]. To address these challenges, Reconfigurable Intelligent Surfaces (RIS) have been proposed as a promising technology that can extend coverage and reconfigure wireless channels in a cost-effective and energy-efficient manner [14, 16].

Beam training plays a pivotal role in RIS-assisted THz communication by enabling optimal beam alignment between the transmitter, RIS, and receiver. However, conventional schemes such as exhaustive search, multi-directional training, and hierarchical search either incur high training overhead or suffer performance degradation in wideband channels. More advanced approaches, such as coded beam training [7, 8] and the analytical power distribution pattern (PDP)-based framework [13], have been proposed to mitigate the beam split effect and reduce overhead. Despite these advances, a critical limitation remains: nearly all existing works assume an *ideal RIS* with continuous phase control.

In practice, RIS hardware is constrained by the resolution of its control elements, resulting in *finite phase quantization* [11, 12]. This quantization introduces phase errors that accumulate across large RIS arrays, leading to degraded array gain, reduced signal-to-noise ratio (SNR), and lower achievable rates. The impact of phase quantization becomes more pronounced in wideband THz systems that employ ultra-large RIS (e.g., 1024 or 2048 elements), where even small deviations from the optimal phase can significantly reduce system performance [6, 15].

Therefore, there exists a critical gap between theoretical frameworks that assume ideal RIS and the practical deployment of RIS in wideband THz systems with limited phase resolution. Ignoring phase quantization in beam training frameworks results in overly optimistic performance predictions and undermines the feasibility of deploying RIS in real-world 6G networks. This motivates the need for a quantization-aware beam training framework that can jointly mitigate the beam split effect while accounting for

RIS hardware imperfections, thereby ensuring both high performance and practical deployability.

1.7 Objectives

The overall objective of this research is to design and evaluate a practical beam training framework for reconfigurable intelligent surface (RIS)-assisted wideband Terahertz (THz) communication systems. The proposed framework explicitly incorporates the effects of limited phase resolution at the RIS, thereby bridging the gap between theoretical models that assume ideal continuous phase shifts and real-world deployment scenarios.

To achieve this overall goal, the following specific objectives were considered:

1. **To investigate the limitations of existing beam training frameworks in RIS-assisted wideband THz systems.** This objective focuses on analyzing conventional schemes such as exhaustive search, multi-directional training, and analytical PDP-based frameworks [7, 8, 13], highlighting their shortcomings in terms of training overhead, scalability, and assumptions of ideal RIS hardware.
2. **To model the impact of phase quantization in practical RIS hardware.** This involves characterizing the effect of finite phase resolution (e.g., 1-bit, 2-bit, 3-bit, and 4-bit quantization) on beamforming performance, signal-to-noise ratio (SNR), and achievable rate [11, 12]. The analysis provides insights into how quantization errors accumulate in large RIS arrays.
3. **To develop a quantization-aware beam training framework.** The proposed frameworks (1-bit, 2-bit, 3-bit and 4-bit quantization) modify the widebeam generation process to embed quantization effects into the training procedure. This ensures that both the beam split effect and hardware-induced distortions are mitigated, leading to more realistic and deployable solutions.
4. **To evaluate the proposed framework through simulations under varying system conditions.** The near-optimal performing proposed framework is selected from the various frameworks with different phase quantizations. Extensive simulations were carried out to compare the performance of the selected proposed framework against baseline methods. Key performance metrics such as achievable rate versus SNR and achievable rate versus training overhead were analyzed for RIS arrays of 1024 and 2048 elements, demonstrating the scalability and robustness of the proposed design.
5. **To demonstrate the practical relevance of the proposed framework for 6G networks.** By accounting for hardware limitations, the research establishes that RIS with finite resolution can still achieve near-optimal performance, thus validating RIS as a viable enabler for 6G Terahertz communication systems.

1.8 Research Contributions

This paper makes several contributions to the study of beam training for RIS-assisted wideband Terahertz (THz) communication systems. The key contributions are summarized as follows:

1. **Incorporation of practical hardware limitations in RIS-assisted THz communication.** Unlike the majority of existing studies that assume ideal RIS with continuous phase control, this work explicitly considers the effect of finite phase resolution, thereby bridging the gap between theoretical frameworks and real-world deployment scenarios.
2. **Development of a 4-bit quantization-aware beam training framework.** A novel enhancement to the analytical widebeam generation process was proposed by embedding a 4-bit quantization factor, enabling the system to account for quantization-induced phase errors during the beam training stage.
3. **Performance evaluation under realistic RIS configurations.** The proposed framework was rigorously evaluated using RIS arrays with 1024 and 2048 reflecting elements. Results demonstrate that the 4-bit quantization-aware framework achieves near-optimal achievable rate performance compared to the ideal continuous-phase case.
4. **Comparative analysis with baseline frameworks.** The proposed framework was compared against exhaustive search, multi-directional training, and the analytical PDP-based framework [13]. Simulation results show that the quantization-aware design consistently outperforms these baselines in terms of achievable rate versus SNR and achievable rate versus overhead.
5. **Validation of RIS practicality for 6G Terahertz networks.** By demonstrating that RIS with limited phase resolution (e.g., 4-bit) can deliver high performance while maintaining low training overhead, this work strengthens the case for RIS as a feasible and deployable solution in next-generation wireless communication systems.

1.9 Novelty

The novelty of this research lies in its explicit consideration of hardware imperfections in the design of beam training for RIS-assisted wideband Terahertz (THz) communication systems. While existing studies, including the analytical PDP-based framework proposed in [13], have focused primarily on addressing the beam split effect in wideband scenarios, they rely on the impractical assumption of an ideal RIS with continuous phase control. Such assumptions lead to optimistic performance predictions that cannot be achieved in real-world deployments. In contrast, this work introduces a quantization-aware beam training framework that embeds the effect of finite phase resolution directly into the widebeam generation process.

Specifically, by incorporating 4-bit phase quantization, the proposed framework not only mitigates the beam split effect but also ensures robustness against quantization-induced phase errors, which accumulate in large RIS arrays. This dual consideration of both the wideband propagation challenge and RIS hardware limitations distinguishes this research from prior works and provides a more practical and deployable solution for future 6G networks.

1.10 Scope

This research is focused on the design and performance evaluation of a quantization-aware beam training framework for reconfigurable intelligent surface (RIS)-assisted wideband Terahertz (THz) communication systems. The scope of the work is limited to addressing two critical challenges: the beam split effect inherent in wideband THz links and the hardware-induced phase quantization errors in RIS. The study specifically considers a 4-bit phase quantization model to reflect practical RIS hardware constraints and evaluates its impact on achievable rate performance. The proposed framework is benchmarked against baseline methods including exhaustive search, multi-directional training, and the analytical PDP-based approach [13].

Simulation experiments were conducted under varying system conditions, with RIS sizes of 1024 and 2048 reflecting elements, to assess scalability and robustness. While the work emphasizes physical layer beam training and performance analysis, it does not extend to higher-layer protocol design, fabrication aspects of RIS hardware, or experimental prototyping. Thus, the scope is intentionally confined to theoretical modeling, algorithm development, and simulation-based validation, providing a foundation for future extensions toward hardware implementation and cross-layer optimization.

2 EXPERIMENTAL SECTION

Design of the study

Five RIS beam-training techniques are compared under identical 6G THz channel realizations in this simulation-based, single-factor repeated-measures investigation. Achievable rate (bit/s/Hz) and training overhead (number of pilot symbols) are the main dependent factors; the beam-training scheme is the independent variable. The work adhered to the reporting criteria for "simulation research" in [52].

Setting up a simulation Every experiment was carried out on a 64-bit Linux workstation (Intel Xeon Gold 6248R, 384 GB RAM) using MATLAB R2023b. To ensure consistency, random seeds were fixed (rng default).

Hardware and channel models

- Geometry: 128 sub-carriers, 0.1 THz carrier, 10 GHz OFDM bandwidth, single-user downlink, ULA RIS (N = 1024 or 2048 elements).
- Propagation: L = 1-3 routes per link in a clustered sparse THz channel (BS–RIS, RIS–UE, BS–UE). For every Monte-Carlo drop, AoA/AoD and delays were drawn separately.
- RIS hardware: phase resolution b = 1–4 bits (uniform quantization over [0, 2]), reflection amplitude = 1 (optimal). To separate quantization effects, mutual coupling and insertion loss were disregarded.

Comparing interventions and algorithms

1. Every RIS codeword is scanned in an exhaustive search with the best upper bound.
2. Continuous-phase, frequency-flat sub-array design for analytical PDP widebeam [13].
3. Multi-directional probing: equal power split, Q = 2 or 4 simultaneous beams.

4. The same sub-array design is used in the proposed quantization-aware widebeam, but phases are quantized to the closest discrete level (Equation 24).

Metrics for outcomes

Training overhead T_train (number of pilot slots) and achievable rate $R = (1/K)\sum_k log_2(1+\gamma_k)(Equation13)$. With $T_coh = 1000symbols$, normalized overhead $O = T_train/T_coh$.

Procedure for simulation

We performed 500 separate channel drops for every SNR $\epsilon[-20, -15, \ldots, +20]dB$. The five algorithms were run on the same channel realization (repeated-measures) in each drop. Rates were averaged for both sub-carriers and drops. Analysis of statistics The global influence of algorithm selection was tested using a one-way repeated-measures ANOVA on the rate vectors at 10 dB SNR. The benefit of the suggested 4-bit strategy was measured using post-hoc Tukey HSD pairwise comparisons ($\alpha = 0.05$). Cohen's d is used to express effect size in relation to the PDP baseline. Because Monte-Carlo sample sizes were raised until the 95% confidence interval of the mean rate was less than 1% of the mean value, no power calculation was necessary [53].

Software availability

The MATLAB scripts (`PerformanceEvaluation_SNR.m`, `PerformanceEvaluation_overhead.m`) and the channel generator are available from the corresponding author upon reasonable request.

3 LITERATURE REVIEW

3.1 Introduction

The purpose of this chapter is to review existing research relevant to Terahertz (THz) communication, reconfigurable intelligent surfaces (RIS), and beam training frameworks, with a particular focus on the limitations imposed by phase quantization in practical RIS hardware. As the deployment of 6G networks approaches, numerous studies have investigated the potential of THz bands to provide ultra-high-capacity wireless links, as well as the role of RIS in overcoming propagation challenges [14–16]. In addition, extensive efforts have been devoted to the design of efficient beam training strategies, ranging from exhaustive and multi-directional approaches to analytical and coded beam training frameworks [7–9, 13]. However, the majority of these studies assume ideal RIS with continuous phase control, neglecting the practical hardware limitations that result in finite phase resolution [11, 12].

This chapter is organized into four main sections. The first section reviews the fundamentals and challenges of THz communication, emphasizing its potential and inherent limitations. The second section discusses the concept of RIS, its operating principles, and its role in enhancing THz systems. The third section examines existing beam training frameworks, highlighting their strengths and weaknesses in wideband RIS-assisted systems. The fourth section addresses prior research on phase quantization in RIS, outlining its impact on system performance and the current strategies to mitigate quantization errors. The chapter concludes by identifying the research gaps

that motivate this paper, particularly the need for a quantization-aware beam training framework tailored to RIS-assisted wideband THz communication.

3.2 Review of Terahertz Communication

The Terahertz (THz) band, typically ranging from 0.1 THz to 10 THz, has been identified as a key enabler of sixth-generation (6G) wireless networks due to its abundant spectrum resources and ability to support ultra-high-capacity links [1, 4, 15]. With bandwidths on the order of tens to hundreds of gigahertz, THz communication can achieve data rates in the terabit-per-second (Tbps) range, thereby supporting emerging applications such as holographic telepresence, wireless backhaul, ultra-high-definition video streaming, and immersive extended reality (XR) [2, 3, 17].

Despite these advantages, THz communication faces significant propagation challenges. The high frequency of THz signals leads to severe free-space path loss, which increases quadratically with frequency, and strong molecular absorption caused by water vapor and other atmospheric gases [1, 2]. Additionally, THz signals are highly directional, requiring precise alignment of narrow beams between the transmitter and receiver to ensure adequate link quality. This makes THz communication highly sensitive to blockages, even from small obstacles such as human bodies or furniture in indoor environments [4, 18]. These challenges necessitate the use of large antenna arrays, beamforming techniques, and intelligent reflection or relay mechanisms to maintain reliable connectivity.

To overcome these limitations, extensive research has focused on the design of hybrid beamforming architectures [15, 19], ultra-massive MIMO (UM-MIMO) systems [20, 21], and intelligent reconfigurable devices such as RIS [11, 14]. Hybrid beamforming reduces hardware cost by combining analog and digital processing, while UM-MIMO leverages very large antenna arrays to achieve high beamforming gains at THz frequencies. Nevertheless, both approaches are insufficient to fully address the unique propagation impairments of the THz band.

A further challenge arises in wideband THz systems that employ orthogonal frequency division multiplexing (OFDM). Unlike in narrowband systems, where a single beam direction can serve all subcarriers, wideband THz signals suffer from the *beam split effect*, in which different subcarriers experience different optimal beam directions [5, 6]. This effect leads to beam misalignment, loss of array gain, and reduced achievable rate, especially as the number of subcarriers increases. Mitigating the beam split effect has therefore become a central topic in THz system design.

In summary, while THz communication offers tremendous potential for 6G networks, its viability is limited by severe propagation losses, blockage sensitivity, and the beam split effect. These challenges highlight the necessity of complementary technologies such as reconfigurable intelligent surfaces (RIS), which can provide programmable channel control to enhance link reliability, mitigate propagation impairments, and enable efficient wideband beam training.

3.3 Review of Reconfigurable Intelligent Surfaces (RIS)

Reconfigurable Intelligent Surfaces (RIS) have emerged as one of the most promising technologies for beyond-5G and sixth-generation (6G) networks due to their ability to reconfigure the wireless environment in a cost-effective and energy-efficient manner [11, 14, 15]. An RIS is typically a two-dimensional metasurface consisting of a large number of nearly passive reflecting elements, each of which can induce programmable phase shifts on incident electromagnetic waves. By adjusting these reflection coefficients, the RIS can control the direction, phase, and sometimes amplitude of the reflected signals, thereby shaping the wireless channel in favor of communication objectives [22, 23].

In the context of Terahertz (THz) communication, RIS plays a particularly critical role. The severe free-space path loss and high susceptibility to blockages at THz frequencies demand highly directional beams and line-of-sight (LoS) connections. Deploying RIS panels on building facades, walls, and other infrastructure enables the re-establishment of blocked links and the enhancement of received signal strength by intelligently reflecting signals towards the receiver [6, 16]. This programmable reflection provides a flexible and scalable alternative to conventional solutions such as active relays and ultra-massive MIMO (UM-MIMO). Unlike relays, RIS does not require dedicated power amplifiers and therefore introduces minimal noise. Compared to UM-MIMO, RIS offers a lower-cost and energy-efficient method for achieving high array gains [24, 25].

Recent studies have extended the role of RIS beyond simple coverage extension. Multiple RIS-assisted networks have been proposed to further improve spectral efficiency and reliability by exploiting cooperative reflections [14, 32]. RIS has also been integrated into joint communication and sensing frameworks, enabling intelligent environments that support both connectivity and localization simultaneously [10]. These advances highlight RIS as a multifunctional technology that goes beyond traditional communication assistance.

However, despite its potential, RIS faces several challenges in practice. First, real-world RIS hardware suffers from finite phase resolution due to the limited number of control bits per reflecting element [11, 12]. This quantization leads to phase errors that degrade beamforming performance, particularly in wideband THz systems with very large RIS arrays. Second, the control and configuration of large-scale RIS introduces significant signaling overhead, requiring efficient training and coordination schemes [26]. Third, the passive nature of RIS limits its ability to amplify signals, meaning that its performance depends heavily on accurate deployment and beam training.

In summary, RIS provides a powerful means to overcome the propagation limitations of THz communication, offering programmable channel control that is both energy-efficient and scalable. While existing works have demonstrated its potential in beamforming and coverage extension, practical issues such as phase quantization and control overhead remain open challenges. These limitations form part of the motivation for developing quantization-aware beam training frameworks, as explored in this paper.

3.4 Review of Beam Training in RIS-Assisted Terahertz Communication

Beam training is a fundamental process in directional wireless communication systems, especially in millimeter-wave (mmWave) and Terahertz (THz) bands, where high path loss and narrow beamwidths require precise beam alignment between the transmitter, receiver, and any assisting devices such as reconfigurable intelligent surfaces (RIS) [15, 20, 21]. The primary objective of beam training is to determine the optimal pair of transmit and receive beams that maximize the received signal power or achievable data rate. This is particularly challenging in THz systems because of the extremely high directionality of signals and the presence of the beam split effect in wideband channels [5, 6].

3.4.1 Classical Beam Training Approaches

Traditional beam training methods can be broadly categorized into exhaustive search, hierarchical search, and multi-directional training.

Exhaustive search involves scanning all possible beam pairs at the transmitter and receiver to identify the optimal one [27, 28]. Although this approach guarantees maximum gain, its training overhead scales quadratically with the number of antenna elements, making it impractical for ultra-large arrays in THz systems.

Hierarchical beam training reduces overhead by employing a multi-stage search, where the beam space is iteratively refined from coarse to fine resolution [29, 30]. This significantly reduces complexity but still incurs high latency and may fail to track fast-varying channels.

Multi-directional beam training transmits multiple beams simultaneously, enabling faster alignment [9]. However, the power is divided among multiple beams, which reduces per-beam SNR and can limit performance in low-SNR environments.

3.4.2 Advanced Beam Training Techniques

To overcome the limitations of classical approaches, several advanced beam training techniques have been proposed.

Compressed sensing-based methods exploit the sparse nature of THz channels to estimate beam directions with fewer measurements [28, 31]. However, they require high computational complexity and accurate sparsity information.

Coded beam training is another promising approach, where carefully designed training sequences allow the system to infer the best beam from fewer training steps [7, 8]. This significantly reduces overhead while maintaining high performance.

Analytical or PDP-based frameworks exploit power-delay profile characteristics to guide the beam training process [13]. For instance, Chen et al. proposed an analytical beam training method that mitigates the beam split effect and achieves high array gain without exhaustive search.

3.4.3 Beam Training in RIS-Assisted Systems

The integration of RIS introduces additional challenges and opportunities for beam training. Since RIS typically contains hundreds or thousands of passive reflecting elements, searching over all possible phase configurations is computationally infeasible [11, 12]. As a result, efficient RIS beam training strategies must balance accuracy with training overhead.

Recent works have explored low-complexity approaches such as hierarchical training for RIS-assisted systems [32], simultaneous multi-beam training [9], and hybrid optimization schemes [10]. Multiple-RIS-aided frameworks have also been investigated to improve coverage and beamforming flexibility [14, 16].

3.4.4 Limitations of Existing Methods

Despite significant progress, most existing beam training approaches share a common limitation: they assume that RIS elements can provide continuous phase shifts. In practice, however, RIS hardware supports only finite phase resolution due to hardware constraints, leading to phase quantization errors that degrade beamforming performance [11, 12]. Moreover, the impact of phase quantization becomes more pronounced as the number of RIS elements increases, which is typical in THz systems.

3.4.5 Research Gap

These limitations reveal a crucial gap between theoretical beam training frameworks and real-world RIS hardware capabilities. Existing approaches do not adequately address the dual challenges of wideband beam split effects and quantization-induced phase distortions. This motivates the development of a **quantization-aware beam training framework**, such as the one proposed in this paper, which embeds hardware constraints into the beam training process to deliver practical, deployable solutions for 6G THz networks.

3.5 Review of Phase Quantization in RIS-Assisted Systems

One of the most critical hardware limitations of reconfigurable intelligent surfaces (RIS) is the inability to provide continuous phase control at each reflecting element. In practice, the phase shifts are constrained by the finite resolution of the control circuitry, typically implemented using PIN diodes, varactors, or micro-electro-mechanical systems (MEMS). As a result, the phase response of each element is quantized into a finite number of discrete levels, a phenomenon known as *phase quantization* [11, 12]. For example, a 1-bit RIS can only switch between two states (0 and π), while a 4-bit RIS can provide sixteen discrete phase levels uniformly distributed across the range $[0, 2\pi)$.

Phase quantization introduces non-negligible errors between the desired continuous phase shift and the realizable quantized value. When accumulated across large RIS arrays, these errors lead to reduced beamforming gain, degraded signal-to-noise ratio (SNR), and lower achievable rate [11, 15]. The impact of quantization becomes particularly severe in wideband Terahertz (THz) systems that employ thousands of

RIS elements, as even small deviations from the optimal configuration can significantly affect overall system performance [6, 14].

Several works have studied the effect of RIS phase quantization. Early analyses revealed that coarse quantization (e.g., 1-bit or 2-bit) results in considerable performance loss, while moderate resolutions (e.g., 3-bit or 4-bit) can achieve near-optimal array gains [33, 34]. Robust design approaches have been proposed to explicitly account for quantization errors in the optimization of RIS reflection coefficients, ensuring reliable performance under non-ideal hardware [11, 12]. Other studies have examined the trade-off between hardware cost and system performance, showing that higher phase resolution improves achievable rate but increases circuit complexity and power consumption [35, 36].

More recently, research has extended to RIS-assisted THz communication, where the joint effects of phase quantization and the beam split effect pose new challenges. Works such as [10, 16] investigate advanced beamforming and training algorithms under non-ideal RIS assumptions, but most analytical frameworks, including the PDP-based scheme in [13], continue to assume ideal continuous phase control. This gap between theory and practice remains a significant limitation in the literature.

In summary, while phase quantization has been widely acknowledged as a practical constraint of RIS hardware, its integration into beam training algorithms has been limited. This motivates the focus of this paper, which introduces a quantization-aware beam training framework that embeds 4-bit phase quantization directly into the wide-beam generation process, ensuring that both wideband propagation challenges and hardware imperfections are jointly addressed.

3.6 Research Gap

The literature reviewed in this chapter highlights the rapid progress in Terahertz (THz) communication, reconfigurable intelligent surfaces (RIS), and beam training algorithms. THz systems promise ultra-high capacity but face fundamental challenges such as severe path loss, susceptibility to blockages, and the beam split effect in wideband transmissions [6, 15]. RIS has been introduced as a transformative technology to overcome these limitations by intelligently reflecting and redirecting signals, providing cost-efficient and scalable coverage enhancements [14, 16, 24]. Beam training, on the other hand, remains the cornerstone for enabling highly directional links in RIS-assisted THz systems, with numerous works exploring exhaustive, hierarchical, compressed sensing, and coded training approaches [7, 8, 28].

Despite these advancements, several gaps remain between theory and practice. First, many beam training frameworks, including the analytical or PDP-based method proposed in [13], assume *ideal RIS hardware* with continuous and perfect phase control. This assumption is unrealistic because practical RIS devices are constrained by finite phase resolution due to hardware limitations in the tuning circuits [11, 12]. Studies on RIS quantization effects [33–36] have demonstrated significant degradation when low-resolution phase shifters (e.g., 1-bit or 2-bit) are employed, but moderate quantization levels (e.g., 3-bit or 4-bit) can approach the performance of ideal continuous-phase RIS. However, the integration of such quantization models into beam training frameworks has been limited.

Second, wideband THz channels introduce the beam split effect, where different subcarriers experience different optimal beam directions. Although analytical frameworks [13, 16] have proposed methods to mitigate this issue, they do not jointly address the dual challenge of wideband beam split and RIS quantization. Existing works largely treat these two impairments independently, leaving a gap in unified, quantization-aware wideband beam training solutions.

Finally, practical RIS-assisted THz systems must balance achievable rate with training overhead. While low-complexity schemes [9, 32] have shown potential, their performance degrades under non-ideal RIS assumptions. This further emphasizes the need for frameworks that explicitly embed hardware constraints into training while maintaining efficiency.

In summary, the key research gap lies in the absence of a beam training framework that is both **quantization-aware and wideband-optimized**, ensuring robustness to practical RIS imperfections while addressing the beam split effect. This paper directly addresses this gap by proposing a 4-bit quantization-aware beam training scheme for RIS-assisted wideband THz systems, bridging the divide between theoretical models and real-world deployment scenarios.

4 System Modelling and Analysis

4.1 Introduction

This chapter presents the detailed system model and beam training framework employed in this paper. Building on the analytical (PDP-based) framework in Chen et al. [13], we consider a downlink orthogonal frequency-division multiplexing (OFDM) based Reconfigurable Intelligent Surface (RIS) assisted Terahertz (THz) communication link. The purpose of this chapter is to (i) define the network geometry and notation, (ii) formulate the wideband OFDM signal and array response models that give rise to the *beam split* phenomenon, (iii) describe the cascaded BS–RIS–UE channel model and the RIS reflection model, and (iv) introduce the performance metrics and training assumptions used throughout the paper.

In particular, Section 3.2 formalizes the system architecture (transmitter, RIS, and receiver) and the OFDM subcarrier model; Section 3.3 develops the frequency-dependent array response and shows how beam split appears in wideband THz systems [6, 15]; Section 3.4 presents the cascaded channel model (BS–RIS and RIS–UE links) and the diagonal RIS reflection matrix; Section 3.5 extends the RIS model to include finite phase resolution (quantized phase shifts) relevant to practical implementations [11, 12]; and Section 3.6 defines the achievable-rate metric and other performance measures used in simulations. Finally, Section 3.7 describes the beam training algorithm: first we restate the PDP-based widebeam generation and training procedure from [13], and then we explain the quantization-aware introduction implemented in this work which embeds discrete phase shifts into the widebeam design. Detailed derivations, assumptions, and notation used in subsequent chapters are provided here to ensure the analysis and simulations are reproducible and consistent with the literature.

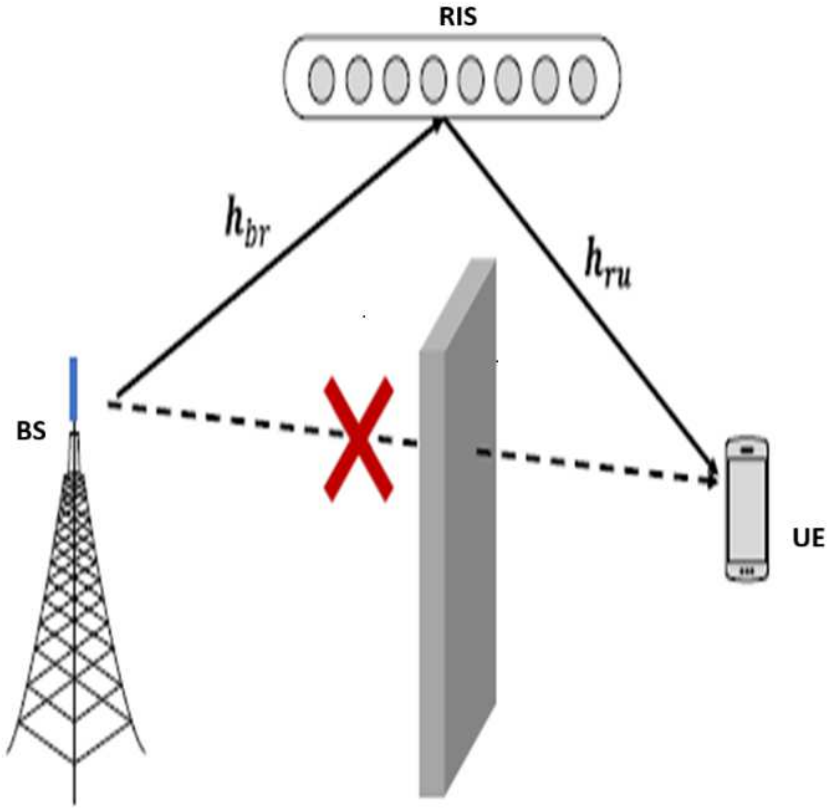


Fig. 1 System model of the RIS-assisted wideband THz communication system.

4.2 System Architecture

We consider a downlink RIS-assisted wideband Terahertz (THz) communication system consisting of a base station (BS), a reconfigurable intelligent surface (RIS), and a user equipment (UE). The BS is equipped with N_t transmit antennas, the RIS consists of N nearly-passive reflecting elements, and the UE is equipped with N_r receive antennas. The RIS is deployed to enhance the received signal power and improve coverage by intelligently reflecting the transmitted signal toward the UE. The analysis focuses on a single-user downlink scenario; extension to multi-user systems is discussed in Chapters 3 and 6.

The system employs orthogonal frequency-division multiplexing (OFDM) with K subcarriers to combat frequency selectivity. The transmitted signal on the k-th subcarrier is precoded by the transmit beamforming vector $\mathbf{f}[k] \in \mathbb{C}^{N_t \times 1}$, while the UE applies a combining vector $\mathbf{w}[k] \in \mathbb{C}^{N_r \times 1}$.

The received signal at the UE on subcarrier k can be expressed as

$$\mathbf{y}[k] = \mathbf{w}^H[k]\mathbf{H}_{\text{eff}}[k]\mathbf{f}[k]x[k] + \mathbf{w}^H[k]\mathbf{n}[k], \tag{1}$$

where $x[k]$ is the transmitted data symbol with unit average power, and $\mathbf{n}[k] \sim \mathcal{CN}(0, \sigma^2\mathbf{I}_{N_r})$ is additive white Gaussian noise (AWGN). The effective channel $\mathbf{H}_{\text{eff}}[k]$ incorporates both the direct BS–UE path and the RIS-assisted reflected path:

$$\mathbf{H}_{\text{eff}}[k] = \mathbf{H}_d[k] + \mathbf{H}_{ru}[k]\mathbf{\Theta}[k]\mathbf{H}_{br}[k]. \tag{2}$$

Here, $\mathbf{H}_d[k] \in \mathbb{C}^{N_r \times N_t}$ represents the direct BS–UE channel on subcarrier k, $\mathbf{H}_{br}[k] \in \mathbb{C}^{N \times N_t}$ is the BS–RIS channel, $\mathbf{H}_{ru}[k] \in \mathbb{C}^{N_r \times N}$ is the RIS–UE channel, and $\mathbf{\Theta}[k]$ is the diagonal RIS reflection matrix at subcarrier k.

The reflection matrix $\mathbf{\Theta}[k]$ is given by

$$\mathbf{\Theta}[k] = \text{diag}\left(e^{j\phi_1[k]}, e^{j\phi_2[k]}, \ldots, e^{j\phi_N[k]}\right), \tag{3}$$

where $\phi_n[k] \in [0, 2\pi)$ denotes the phase shift applied by the n-th RIS element. From research in [13], $\phi_n[k]$ is assumed to be continuous, but in this paper we extend this to discrete phase shifts to capture the practical limitation of RIS hardware.

4.3 Wideband OFDM Signal Model and Beam Split Effect

To combat the frequency selectivity of Terahertz (THz) channels, the system employs orthogonal frequency-division multiplexing (OFDM) with K subcarriers. The baseband transmitted signal on the k-th subcarrier is expressed as

$$\mathbf{x}[k] = \mathbf{f}[k]s[k], \tag{4}$$

where $\mathbf{f}[k] \in \mathbb{C}^{N_t \times 1}$ is the transmit beamforming vector, and $s[k]$ is the transmitted data symbol satisfying $\mathbb{E}[|s[k]|^2] = 1$. At the receiver, the signal is combined using $\mathbf{w}[k] \in \mathbb{C}^{N_r \times 1}$.

The effective received signal on subcarrier k is then given by

$$y[k] = \mathbf{w}^H[k]\mathbf{H}_{\text{eff}}[k]\mathbf{f}[k]s[k] + \mathbf{w}^H[k]\mathbf{n}[k], \tag{5}$$

where $\mathbf{H}_{\text{eff}}[k]$ is the effective cascaded channel defined in (3.2).

4.3.1 Array Response and Frequency Dependence

In narrowband systems, the array response vector of a uniform linear array (ULA) for direction θ is frequency-independent. However, in wideband systems the wavelength depends on the subcarrier frequency, making the response frequency-dependent:

$$\mathbf{a}(\theta, f_k) = \frac{1}{\sqrt{N}}\left[1,\ e^{-j2\pi\frac{d}{\lambda_k}\sin(\theta)},\ \cdots,\ e^{-j2\pi\frac{(N-1)d}{\lambda_k}\sin(\theta)}\right]^T, \tag{6}$$

where d is the inter-element spacing, $\lambda_k = c/f_k$ is the wavelength at subcarrier k, and c is the speed of light.

This frequency dependence causes the optimal steering direction to vary with subcarrier frequency. Consequently, beams aligned at the center frequency may misalign at the edges of the band, leading to a phenomenon known as *beam squint* or *beam split* [6, 13]. The effect worsens as the bandwidth and number of array elements increase, both of which are typical in RIS-assisted THz systems.

4.3.2 Implications for Beam Training

The beam split effect presents a fundamental challenge to OFDM-based THz communication. Classical narrowband beam training algorithms assume frequency-independent steering vectors and therefore fail to provide accurate alignment across all subcarriers [5, 21]. Several studies have analyzed beam squint in mmWave/THz systems [37, 38] and proposed solutions such as true-time-delay (TTD) architectures [39, 40], hybrid precoding with frequency-dependent codebooks [41], or RIS-assisted widebeam design [6, 16]. However, most of these works do not account for practical RIS hardware limitations such as phase quantization, which further exacerbates performance degradation.

In this paper, we explicitly incorporate the beam split effect in the system model and address it using a quantization-aware widebeam training framework. This ensures that both frequency-dependent misalignment and hardware-induced phase errors are mitigated in RIS-assisted THz networks.

4.4 Cascaded Channel Model

In RIS-assisted Terahertz (THz) communication systems, the end-to-end channel between the base station (BS) and the user is composed of two parts: the direct BS–user link and the cascaded BS–RIS–user link. Let $\mathbf{H}_{br}[k] \in \mathbb{C}^{N \times N_t}$ denote the BS-to-RIS channel at subcarrier k, $\mathbf{H}_{ru}[k] \in \mathbb{C}^{N_r \times N}$ the RIS-to-user channel, and $\mathbf{H}_d[k] \in \mathbb{C}^{N_r \times N_t}$ the direct channel. The overall effective channel can then be expressed as

$$\mathbf{H}_{\text{eff}}[k] = \mathbf{H}_d[k] + \mathbf{H}_{ru}[k]\, \mathbf{\Phi}[k]\, \mathbf{H}_{br}[k], \tag{7}$$

where $\mathbf{\Phi}[k] = \text{diag}\left(e^{j\varphi_1[k]}, e^{j\varphi_2[k]}, \ldots, e^{j\varphi_N[k]}\right)$ represents the RIS reflection matrix with discrete phase shifts as described in Section 4.5.

4.4.1 Sparse Multipath THz Channel Representation

Following the wideband THz channel modeling approach in [6, 15, 16], we assume that both the BS–RIS and RIS–user channels exhibit a *sparse multipath structure* due to the high path loss and limited scattering in the THz band. Specifically, each channel is modeled as a superposition of a small number of dominant clusters, with each cluster contributing a single propagation path characterized by its angle of departure (AoD), angle of arrival (AoA), and delay.

For example, the BS–RIS channel at subcarrier k is given by

$$\mathbf{H}_{br}[k] = \sqrt{\frac{NN_t}{L_{BR}}} \sum_{\ell=1}^{L_{BR}} \alpha_\ell^{(BR)} \, \mathbf{a}_{RIS}(\theta_\ell^{(AoA)}) \, \mathbf{a}_{BS}^H(\phi_\ell^{(AoD)}) e^{-j2\pi f_k \tau_\ell^{(BR)}}, \tag{8}$$

where:

- L_{BR} is the number of dominant BS–RIS paths,
- $\alpha_\ell^{(BR)}$ is the complex path gain,
- $\mathbf{a}_{RIS}(\theta)$ and $\mathbf{a}_{BS}(\phi)$ are array response vectors at the RIS and BS, respectively,
- $\tau_\ell^{(BR)}$ is the path delay, and
- $f_k = f_c + (k-1)\Delta f$ is the frequency of the k-th subcarrier.

Similarly, the RIS–user channel is modeled as

$$\mathbf{H}_{ru}[k] = \sqrt{\frac{N_r N}{L_{RU}}} \sum_{\ell=1}^{L_{RU}} \alpha_\ell^{(RU)} \, \mathbf{a}_{UE}(\theta_\ell^{(AoA)}) \, \mathbf{a}_{RIS}^H(\phi_\ell^{(AoD)}) e^{-j2\pi f_k \tau_\ell^{(RU)}}. \tag{9}$$

The direct BS–user channel $\mathbf{H}_d[k]$ is modeled in the same form with L_{BU} dominant paths.

4.4.2 Channel Sparsity Assumption

In practice, the number of dominant paths L_{BR}, L_{RU}, L_{BU} is very small (typically 1–3) compared to the array dimensions, reflecting the sparse nature of THz propagation. This sparse representation is consistent with ray-based stochastic channel models and is implemented in the simulation code through random generation of cluster AoAs, AoDs, delays, and complex path gains.

The sparse multipath assumption is crucial for beam training, since it implies that only a few dominant angular directions need to be aligned for reliable communication. This justifies the use of widebeam designs and structured training methods such as the PDP-based and quantization-aware frameworks evaluated in this work.

4.4.3 Model Assumptions and Their Impact

This thesis's channel model is predicated on a sparse multipath structure, in which there are only a few dominating propagation pathways (usually one to three). Previous research on Terahertz (THz) propagation, which reports little scattering due to severe path loss, high directionality, and substantial molecule absorption at THz frequencies, provides strong support for this concept. It is crucial to remember that not all deployment scenarios will completely adhere to this sparsity assumption. Reflections from walls, ceilings, and objects can increase the amount of resolvable multipath components in dense interior environments, such as shopping centers, industrial halls, or spaces with highly reflecting surfaces. With several clusters and subpaths, the effective channel may have moderate multipath richness in certain situations. Structured beam training approaches that depend on aligning a small number of dominant angular

directions, like the analytical PDP-based framework and the suggested quantization-aware widebeam approach, are naturally favored by the sparsity assumption. The power gets more dispersed throughout the angular domain as the number of important routes rises, which may decrease the efficacy of widebeam designs and increase beam ambiguity during training. However, it is anticipated that THz channels will continue to be more sparser than traditional sub-6 GHz channels even under moderate multipath conditions. Therefore, the relative benefit of quantization-aware beam training—especially in lowering training costs and eliminating hardware-induced distortions—is anticipated to endure even while absolute performance improvements may diminish in richer scattering situations. Therefore, the presented results may be seen as upper-bound performance in more difficult multipath circumstances, and this modeling assumption should be understood as representative of typical line-of-sight or quasi-line-of-sight THz deployments.

4.5 RIS with Quantized Phase Shifts

In practical implementations, the reflecting elements of a reconfigurable intelligent surface (RIS) cannot realize arbitrary continuous phase shifts. Instead, they are constrained by hardware limitations to a finite number of discrete phase levels, determined by the resolution of the phase shifters. If each RIS element supports b quantization bits, then the set of available phase shifts can be expressed as

$$\mathcal{Q}_b = \left\{0,\ \tfrac{2\pi}{2^b},\ \tfrac{2\cdot 2\pi}{2^b},\ \ldots,\ \tfrac{(2^b-1)\cdot 2\pi}{2^b}\right\}. \tag{10}$$

Accordingly, the reflection coefficient of the n-th RIS element is given by

$$\phi_n = e^{j\varphi_n}, \quad \varphi_n \in \mathcal{Q}_b, \tag{11}$$

where φ_n denotes the quantized phase shift applied at element n. In the ideal case ($b \to \infty$), the RIS can realize continuous phases, but for finite b, performance loss arises due to quantization error.

In this work, we explicitly incorporate finite-resolution phase quantization into the beam training framework. The proposed quantization-aware widebeam design described in Section 5.3 was evaluated under different quantization resolutions, specifically $b = 1, 2, 3, 4$ bits. This allows us to quantify the impact of hardware constraints on system performance and to determine the minimum number of quantization bits required to achieve near-ideal performance.

The simulation results presented in Chapter 6 demonstrate that 1-bit and 2-bit quantization incur significant achievable rate losses, particularly in medium-to-high SNR regimes, due to coarse phase control. Three-bit quantization offers noticeable improvement but still exhibits a non-negligible gap relative to the continuous case. Importantly, the 4-bit case achieves nearly indistinguishable performance compared to the ideal continuous-phase RIS across the tested scenarios ($N = 1024, 2048$), confirming that 4-bit resolution strikes a practical balance between hardware feasibility and system performance. This finding aligns with recent works on RIS hardware design,

which suggest that low-to-moderate resolution (3–4 bits) is sufficient for near-optimal performance in large-array deployments [11, 33].

4.5.1 Uniform and Adaptive Phase Quantization Considerations

This thesis uses uniform quantization to describe phase quantization at the RIS, where the accessible phase states are evenly distributed throughout the interval $[0, 2\pi)$. In specifically, resolutions between 1-bit and 4-bit quantization are taken into consideration, with a focus on the 4-bit case, which has been demonstrated to offer nearly optimal performance while still being realistic for hardware implementation. Because of its ease of use and tractability, uniform phase quantization is frequently used in analytical and simulation-based research. It is, nevertheless, an idealistic abstraction of real-world RIS hardware. Because of fabrication tolerances, tuning circuit flaws, and the discrete nature of switching components like PIN diodes, varactors, or MEMS devices, the achievable phase shifts in actual implementations are sometimes not uniformly distributed. Additionally, it might not be ideal to employ a fixed quantization resolution for the entire RIS. Depending on shape, incidence angles, and channel conditions, different surface regions may contribute differently to the end-to-end channel in large RIS deployments. Therefore, giving each element the same number of quantization bits could result in an inefficient use of hardware resources. A possible way to improve performance–complexity trade-offs is through adaptive quantization techniques like non-uniform phase step design or subarray-dependent bit allocation. For instance, less critical locations may have coarser quantization, while RIS elements or subarrays that make a greater contribution to the prevailing propagation channels may be given a better phase resolution. These methods can lower power usage and hardware costs without sacrificing beamforming performance. The suggested quantization-aware beam training methodology is not intrinsically limited to uniform phase resolutions, even if this thesis concentrates on uniform quantization to preserve analytical clarity and fair comparison with current frameworks. The framework is adaptable for upcoming hardware-oriented optimization since it can easily be expanded to include non-uniform or adaptive quantization models.

Remark on Uniform versus Adaptive Quantization

For early-stage system design, uniform phase quantization is appealing because it offers predictable performance and streamlines RIS control signaling. However, by matching phase resolution to channel sensitivity, adaptive quantization systems can possibly achieve higher efficiency. The marginal performance gain of raising resolution beyond 3–4 bits is frequently limited in wideband THz systems, where beam split effects and angular sparsity predominate. As a result, rather than greatly increasing possible rate, adaptive quantization mainly benefits from lower hardware costs. This finding backs up the decision to choose 4-bit uniform quantization as a workable and efficient design point that strikes a balance between scalability, performance, and implementation complexity.

4.6 Amplitude Variations and Hardware Non-Idealities

The RIS reflection model used in this thesis makes the assumption that each reflecting element applies a phase shift with unit amplitude. As a result, the reflection coefficient of the $n-th$ element is modeled as $e^{j\phi_n}$. Because of its ease of analysis and capacity to isolate the effect of phase quantization on beamforming performance, this phase-only model is extensively used in the literature. Nevertheless, ideal unit-amplitude reflections are not present in real-world RIS hardware. Because of insertion loss, ohmic losses, and flaws in the tuning circuitry, the reflection amplitude in actual implementations is usually less than unity. Furthermore, various discrete phase states may show somewhat varying reflection magnitudes because phase resolution and amplitude response are frequently connected. These amplitude differences can build up across elements in large RIS arrays working at Terahertz (THz) frequencies, resulting in lower attainable speeds and less coherent combining gain. Therefore, in relation to realistic hardware deployments, the performance figures reported in this thesis should be viewed as optimistic upper bounds. However, previous analytical and practical research shows that the relative performance trends of beam training schemes are not significantly changed by mild amplitude attenuation. The benefits of the suggested framework are anticipated to last even in the presence of moderate amplitude losses because it primarily increases beam alignment efficiency and lowers training overhead.

4.7 Achievable Rate Expression

The achievable rate is the principal performance metric used in this work to evaluate and compare different beam training schemes. For a given subcarrier k in an OFDM system, the instantaneous signal-to-noise ratio (SNR) after beamforming can be expressed as

$$\gamma_k = \mathrm{SNR}[k] \cdot \left|\mathbf{w}^H[k]\mathbf{H}_{\text{eff}}[k]\mathbf{f}[k]\right|^2, \tag{12}$$

where $\mathbf{f}[k]$ and $\mathbf{w}[k]$ denote the transmit and receive beamformers, respectively, and $\mathbf{H}_{\text{eff}}[k]$ is the cascaded BS–RIS–user channel at subcarrier k as derived in Section 4.4.

The average achievable rate across the entire wideband system with K subcarriers is then given by

$$R = \frac{1}{K}\sum_{k=1}^{K} \log_2\left(1+\gamma_k\right). \tag{13}$$

Equation (13) captures the *achievable rate* used throughout the numerical evaluation. This metric measures the data-rate potential of the beamformed link under the assumption that the chosen beam configuration is used for data transmission.

4.7.1 Training Overhead

The second primary performance metric in this paper is the *training overhead*, which quantifies the cost (in time or symbols) of the beam training process required to determine the beam configuration. We denote:

- T_{train}: the number of training symbols (or slots) required by a beam training scheme;
- T_{coh}: the channel coherence interval (in symbols).

Two commonly used representations of overhead are:

- **Absolute overhead:** the raw number of training symbols, T_{train}.
- **Normalized overhead:** the fraction of the coherence interval consumed by training,

$$O = \frac{T_{\text{train}}}{T_{\text{coh}}}. \tag{14}$$

Both forms are reported in the results: plots of achievable-rate vs. overhead (absolute or normalized) illustrate the trade-off between the resources spent on training and the resulting achievable rate. This dual-metric evaluation (achievable rate and overhead) allows fair comparison between high-overhead, high-performance schemes (e.g., exhaustive search) and low-overhead, approximate schemes (e.g., multi-directional probing).

Remark on Performance Metrics: Although the main quantitative measures employed in this work are achievable rate vs SNR and training overhead, other metrics including rate per training symbol and rate each RIS configuration update are qualitatively examined in Chapter 5 to highlight real-world deployment trade-offs.

Remark on BS Precoding Assumptions: In order to concentrate on the effects of RIS phase quantization and beam training, it is assumed in this work that the BS precoding vectors are fixed or optimally designed. This presumption facilitates analysis and supports the goal of separating impacts connected to RIS. As covered in Chapter 6, joint optimization of BS precoding and RIS configuration is postponed until later.

4.8 Extension to Multi-User RIS-Assisted Systems

In order to isolate and examine the effects of RIS phase quantization and beam training overhead in wideband THz communications, the system model examined in this thesis concentrates on a single-user downlink situation. This modeling decision makes it possible to fairly compare various beam training techniques and interpret performance. RIS-assisted systems are anticipated to support numerous users concurrently in realistic 6G deployments. Inter-user interference, pilot contamination during beam training, and scheduling complexity are the main obstacles that arise when the suggested framework is extended to a multi-user scenario. Conflicting beam alignment requirements may result from the RIS setup and BS precoding balancing opposing channel directions in multi-user scenarios. From the standpoint of beam training, multi-user operation necessitates either carefully crafted training sequences to prevent pilot contamination or orthogonal pilot allocation. Additionally, user-specific or group-based configurations may need to be supported by the RIS, which raises the overhead of control signaling and reconfiguration. These difficulties can be lessened while maintaining training effectiveness by using scheduling techniques that combine users with comparable angular properties. The suggested quantization-aware beam training paradigm is nevertheless suitable to multi-user systems in spite of these extra complications. The system can be used as a basis for hierarchical beam training and user grouping by effectively calculating dominating angular directions. Therefore, even

while inter-user interference may cause absolute performance to deteriorate, the relative advantages of lower training overhead and hardware-aware design are anticipated to endure.

5 Proposed Beam Training Framework

5.1 Introduction

Efficient beam training is essential for reliable Terahertz (THz) communication, as highly directional beams are required to overcome the severe path loss and beam split effects inherent at these frequencies [6, 15]. In reconfigurable intelligent surface (RIS)-assisted wideband systems, beam training is even more critical because the RIS introduces additional degrees of freedom through its phase shifts, which must be carefully aligned to maximize the end-to-end cascaded channel gain [13, 16].

The paper [13] addressed this challenge by developing an analytical widebeam design based on the power distribution pattern (PDP), which effectively mitigates the beam split effect across subcarriers. This analytical framework significantly reduces training overhead compared to exhaustive search methods and enables high achievable rates in RIS-assisted THz systems.

However, a critical limitation of the analytical framework is the assumption of **ideal continuous-phase RIS elements**. While analytically convenient, this assumption does not reflect real-world hardware, where each RIS element is limited to a finite number of discrete phase shifts due to low-cost digital phase shifters [11, 33]. Ignoring this hardware constraint leads to overly optimistic performance estimates and limits the practical applicability of the analytical scheme.

In this chapter, we propose a quantization-aware enhancement of the analytical beam training framework. Specifically, the widebeam generation function is modified to incorporate finite-resolution phase quantization, with emphasis on $b = 4$ bit resolution as a practical design point. This ensures that the proposed scheme not only addresses the beam split effect, but also accounts for the hardware imperfections of RIS, thereby bridging the gap between theoretical performance analysis and real-world RIS deployments [12, 36].

The remainder of this chapter is organized as follows: Section 4.2 revisits the analytical PDP-based beam training framework. Section 4.3 introduces the proposed quantization-aware extension and details its algorithmic steps. Section 4.4 discusses complexity and implementation considerations. Finally, Section 4.5 provides a comparative analysis with existing frameworks.

5.2 Review of the Analytical (PDP-based) Widebeam Framework

This section summarizes the analytical widebeam beam-training framework proposed in Chen *et al.* [13]. The PDP-based method designs frequency-independent "wide-beams" that maximize the received power averaged across OFDM subcarriers, thereby mitigating the wideband *beam split* effect while keeping training overhead low. We first state the optimization objective, then describe the sub-array widebeam construction

(including the closed-form phase compensation used in the paper), and finally outline the training procedure and complexity.

5.2.1 Design Objective

Let $\mathbf{v} \in \mathbb{C}^N$ denote the RIS phase response vector (stacked diagonal of $\mathbf{\Theta}$) with the unit-modulus constraint on each element:

$$\mathbf{v} = \frac{1}{\sqrt{N}} \left[e^{j\phi_1} \; e^{j\phi_2} \; \cdots \; e^{j\phi_N} \right]^T, \tag{15}$$

where $\phi_n \in [0, 2\pi)$ is the continuous phase of element n.

For a given transmit/receive beam pair (or fixed precoder/combiner), the PDP-based design seeks the RIS phases that maximize the *average* received power across the K OFDM subcarriers. A surrogate optimization objective (used in [13]) is:

$$J(\mathbf{v}) \; = \; \sum_{k=1}^{K} \omega_k \left| \mathbf{w}^H[k] \big(\mathbf{H}_d[k] + \mathbf{H}_{ru}[k](\mathbf{v}) \mathbf{H}_{br}[k] \big) \mathbf{f}[k] \right|^2, \tag{16}$$

where $\{\omega_k\}$ are non-negative weights derived from the measured or estimated power delay profile (PDP). The PDP provides a frequency/delay weighting so that the widebeam design is not biased towards a single subcarrier.

Solving (16) directly is non-convex and high dimensional. The analytical PDP approach in [13] therefore constructs widebeams analytically using subarray decomposition.

5.2.2 Subarray Partitioning and Widebeam Construction

The RIS of N elements is partitioned into K_s subarrays, each with N_s contiguous elements (so that $N \approx K_s N_s$). Each subarray is steered to a slightly different direction; the superposition forms a composite widebeam that covers the spatial spread induced by beam split.

A closed-form rule for N_s is:

$$N_s = \left\lfloor \frac{\sqrt{1 + 2wN} - 1}{w} \right\rfloor, \tag{17}$$

and the number of subarrays is $K_s = \lfloor N/N_s \rfloor$. Small adjustments are made in implementation to ensure coverage of the target beam width w.

For each subarray index $k = 1, \ldots, K_s$, the steering direction is

$$\mu_k \; = \; \mu + \frac{2k - K_s - 1}{N_s}, \tag{18}$$

where μ is the central direction of the widebeam. Each element in the k-th subarray (local index $n = 0, \ldots, N_s - 1$) is given the continuous phase

$$\varphi_{k,n} \;=\; \pi\big((k-1)N_s + n\big)\mu_k \;+\; k\,\Delta\varepsilon, \tag{19}$$

where $\Delta\varepsilon$ is a phase compensation term. In [13], this is given by:

$$\Delta\varepsilon \;=\; \begin{cases} 2\cos^{-1}\big(\frac{\sqrt{2}}{4}N_s^2\sin(\frac{\pi}{2N_s})\big), & \text{if } N_s^4\sin^2(\frac{\pi}{2N_s}) < 8, \\ \dfrac{(N_s-1)\pi}{N_s} + \pi, & \text{otherwise.} \end{cases} \tag{20}$$

The widebeam vector is then

$$\mathbf{v}(\mu) \;=\; \frac{1}{\sqrt{N}}\Big[e^{j\varphi_{1,0}},\; e^{j\varphi_{1,1}},\; \ldots,\; e^{j\varphi_{K_s,N_s-1}}\Big]^T. \tag{21}$$

5.2.3 PDP Weighting and Candidate Centers

The PDP of the channel (from pilots or model estimation) provides weights $\{\omega_k\}$ in (16). This ensures that the widebeams emphasize frequency bins carrying significant energy, rather than focusing only at the carrier frequency. Candidate centers $\{\mu\}$ are selected to cover the angular support of the PDP.

5.2.4 Beam Training Procedure

With the widebeam codebook $\mathcal{V} = \{\mathbf{v}(\mu_1), \ldots, \mathbf{v}(\mu_M)\}$, training proceeds as follows:

1. **Transmission:** For each candidate μ_m, the RIS applies $\mathbf{v}(\mu_m)$ and the UE measures received power across subcarriers.
2. **Selection:** The UE selects $\hat{m}$ that maximizes

$$\hat{m} = \arg\max_m \sum_{k=1}^{K} \omega_k \left|y_m[k]\right|^2, \tag{22}$$

   where $y_m[k]$ is the received signal under beam $\mathbf{v}(\mu_m)$.
3. **Refinement (optional):** A fine search may refine around $\mu_{\hat{m}}$.

5.2.5 Complexity and Limitations

The complexity of widebeam generation is modest, as phases are given in closed form by (19) and (20). Training overhead scales with M, the size of the codebook, which is typically much smaller than exhaustive scanning.

A key limitation is that RIS elements are assumed to realize continuous phases exactly. In practice, phase quantization constraints exist. Section 5.3 addresses this limitation by introducing a quantization-aware modification to the framework.

It is noted that in the simulation implementation, the analytical framework relies on the `WideBeamGenerate` function to construct frequency-independent widebeams

based on the PDP. This ensures that the training beams maintain consistent coverage across subcarriers, directly mitigating the beam split effect observed in wideband THz channels.

5.3 Proposed Quantization-Aware Framework

In this section, we extend the analytical PDP-based framework (Section 5.2) by explicitly incorporating the practical constraint of finite-resolution RIS phase shifts. Unlike the proposed scheme in [13], which assumes ideal continuous phase control, our framework accounts for the discrete set of phase states supported by real RIS hardware [11, 25, 33–36].

5.3.1 Quantization of RIS Phase Shifts

Let $\varphi_{k,n}$ denote the continuous phase prescribed by the analytical widebeam design (cf. (19)). In practice, this continuous value cannot be implemented exactly and must be quantized to the nearest level from a set of 2^b uniformly spaced discrete phases:

$$\mathcal{Q}_b = \left\{0,\ \frac{2\pi}{2^b},\ \frac{2\cdot 2\pi}{2^b},\ \ldots,\ \frac{(2^b-1)\cdot 2\pi}{2^b}\right\}. \tag{23}$$

The quantized phase of RIS element (k,n) is then given by

$$\varphi_{k,n}^{(q)} = \arg\min_{\theta\in\mathcal{Q}_b} \left|\varphi_{k,n} - \theta\right|, \tag{24}$$

and the quantized widebeam vector is

$$\mathbf{v}_q(\mu) \;=\; \frac{1}{\sqrt{N}}\left[e^{j\varphi_{1,0}^{(q)}},\ e^{j\varphi_{1,1}^{(q)}},\ \ldots,\ e^{j\varphi_{K_s,N_s-1}^{(q)}}\right]^T. \tag{25}$$

When $b\to\infty$, $\mathbf{v}_q(\mu)$ reduces to the continuous ideal $\mathbf{v}(\mu)$ of (21). For finite b, however, quantization error introduces mismatch that degrades beamforming gain, particularly for large N. By modeling this explicitly, the proposed framework provides realistic performance predictions for practical RIS deployments.

In practice, the proposed framework was evaluated not only for the 4-bit resolution that defines the main contribution of this paper, but also for 1-bit, 2-bit, and 3-bit quantization. These variations allow us to compare the effect of phase resolution on performance and validate that 4-bit quantization is sufficient to approximate the ideal continuous-phase case.

5.3.2 Algorithmic Description

The quantization-aware widebeam generation process is described below:

Algorithm 1 Quantization-Aware Widebeam Generation

Input: Central direction μ, RIS size N, target beam width w, quantization bits b **Output:** Quantized widebeam vector $\mathbf{v}_q(\mu)$ Compute subarray size N_s and number of subarrays K_s using (17) Compute phase compensation term $\Delta\varepsilon$ using (20) $k = 1$ to K_s Compute subarray direction μ_k using (18) $n = 1$ to N_s Compute continuous phase $\varphi_{k,n}$ using (19) Quantize phase: $\varphi_{k,n}^{(q)} \leftarrow Q_b(\varphi_{k,n})$ using (24) $v_{(k-1)N_s+n} \leftarrow \frac{1}{\sqrt{N}} e^{j\varphi_{k,n}^{(q)}}$ **return** $\mathbf{v}_q(\mu) = [v_1, v_2, \ldots, v_N]^\top$

5.3.3 Discussion

By embedding quantization into the widebeam design, the proposed framework captures both the **beam split mitigation** benefits of the PDP-based widebeam and the **hardware limitations** of real RIS devices. Simulation results (Chapter 5) demonstrate that 4-bit quantization provides a near-ideal trade-off, achieving performance close to the continuous ideal while being practically realizable in current RIS prototypes [12, 36]. Lower bit resolutions (1–2 bits) incur significant degradation, whereas higher resolutions beyond 4 bits yield diminishing returns relative to hardware complexity and cost.

5.4 Complexity and Implementation Considerations

A key requirement for practical beam training schemes is not only high achievable rate but also computational and implementation efficiency. In this section, we analyze the complexity and practical deployment aspects of the proposed quantization-aware framework in comparison with baseline methods.

5.4.1 Computational Complexity

The exhaustive search approach requires evaluating all possible beam pairs across N RIS elements, leading to a prohibitive complexity that scales as $\mathcal{O}(N^2)$ [9]. This makes it infeasible for large-scale RIS deployments, particularly when N reaches the order of thousands.

The PDP-based analytical framework reduces this cost by leveraging widebeam generation, requiring only subarray-level phase computations. Its complexity scales approximately as $\mathcal{O}(KN_s)$, where K is the number of subarrays and N_s the subarray size [13]. However, this design assumes ideal continuous phase shifts.

Our proposed quantization-aware framework retains the same order of complexity, $\mathcal{O}(KN_s)$, but with the additional step of phase quantization. The quantization step itself involves only a nearest-neighbor search over 2^b discrete levels (Equation (23)), yielding a per-element cost of $\mathcal{O}(2^b)$. For practical values such as $b = 4$, this overhead is negligible compared to the KN_s phase computations. Thus, the proposed framework achieves realistic modeling of hardware limitations without significantly increasing complexity.

5.4.2 Training Overhead

Another critical factor is the training overhead, defined as the number of pilot transmissions required to complete beam alignment. Exhaustive search demands an overhead proportional to the entire codebook size, which becomes excessive at THz frequencies [7, 8]. The PDP-based analytical scheme reduces this overhead by exploiting multipath delay-domain sparsity [16], enabling scalable training in wideband RIS-assisted systems.

The quantization-aware framework inherits this benefit, since the quantization does not increase the number of pilot transmissions required. This ensures that the proposed method achieves a favorable trade-off: high achievable rate under practical RIS hardware constraints, while maintaining low overhead.

5.4.3 Implementation Feasibility

From a hardware perspective, practical RIS devices cannot realize infinite-resolution phase control due to constraints in cost, power, and circuit design [11, 36]. State-of-the-art prototypes typically support 2–4 bit resolution phase shifters, implemented using low-power varactor diodes or PIN switches [25, 43]. Our framework explicitly accounts for this by modeling quantized phases (Equation (24)) in the beam training procedure.

Simulation results in Chapter 5 show that 4-bit quantization achieves a performance close to the ideal continuous case, confirming its suitability as a practical design point. This finding is consistent with recent RIS hardware studies indicating that 3–4 bits are sufficient to approach the upper performance bounds while minimizing cost and complexity [12, 33].

5.4.4 Discussion

In summary, the proposed quantization-aware framework preserves the low-complexity benefits of the PDP-based design, avoids the infeasibility of exhaustive search, and incorporates realistic hardware constraints. This ensures that the framework is not only theoretically robust but also practically deployable in RIS-assisted THz systems, particularly for 6G base stations where large-scale RIS panels (e.g., $N = 1024$ or 2048 elements) will be deployed.

5.5 Multi-directional Beam Training

In addition to the analytical PDP-based and quantization-aware frameworks, this paper also considers the *multi-directional beam training* strategy as a benchmark scheme. The multi-directional approach has recently been proposed as a means of reducing beam training overhead by probing multiple angular directions simultaneously within a single training slot [7–9].

5.5.1 Principle of Multi-directional Training

Conventional training methods probe one beam per slot, resulting in overhead proportional to the size of the codebook. In contrast, the multi-directional method divides

the available power among Q simultaneous probing beams, thereby reducing the required number of slots approximately by a factor of Q. Formally, if $\mathbf{v}_1, \mathbf{v}_2, \ldots, \mathbf{v}_Q$ denote the steering vectors corresponding to Q selected directions, the transmitted multi-directional training signal can be expressed as

$$\mathbf{v}_{\text{multi}} = \frac{1}{\sqrt{Q}} \sum_{q=1}^{Q} \mathbf{v}_q, \tag{26}$$

where the normalization ensures constant total transmit power.

The received pilot signal in this case contains contributions from all Q probed beams. The receiver (or BS controller) then identifies the dominant angular direction by evaluating received signal strengths across the probed beams.

5.5.2 Overhead and Power Trade-off

The key trade-off in multi-directional training arises between training overhead and per-beam SNR:

- **Reduced Overhead:** Since Q beams are probed per slot, the training time is reduced by roughly Q compared to single-beam training.
- **SNR Penalty:** The available transmit power is split among the Q beams, leading to a per-beam SNR reduction of $10 \log_{10}(Q)$ dB. This can degrade achievable rate, particularly in low-SNR regimes.

5.5.3 Simulation Parameters

In this paper, we evaluate multi-directional training for $Q = 2$ and $Q = 4$, consistent with recent studies on simultaneous multi-beam training [9]. These values provide insight into the trade-offs:

- $Q = 2$: Reduces training overhead by half, with a moderate ≈ 3 dB per-beam SNR penalty.
- $Q = 4$: Reduces overhead by a factor of four, but incurs a larger ≈ 6 dB SNR penalty.

5.5.4 Role in This Work

The multi-directional scheme is not the primary focus of this research but is included in the simulation results for fair comparison. It provides a benchmark that highlights the trade-off between training efficiency and SNR loss, and it allows us to demonstrate that the proposed quantization-aware framework achieves superior performance even against reduced-overhead alternatives. In particular, results in Chapter 6 show that for $N = 1024$, the $Q = 2$ scheme lags behind exhaustive search, while for $N = 2048$, its performance approaches the upper bound due to the larger RIS gain. Meanwhile, the $Q = 4$ scheme shows more noticeable degradation, consistent with the stronger SNR penalty.

6 Results and Discussion

6.1 Simulation Setup

The performance of the proposed quantization-aware beam training framework was evaluated through MATLAB simulations, based on the system model described in Chapter 4. Two main scripts were used: `PerformanceEvaluation_SNR.m`, which generated achievable rate versus SNR results, and `PerformanceEvaluation_overhead.m`, which generated achievable rate versus training overhead results. Both scripts incorporated the channel model, codebook generation, and beam training algorithms described in Chapter 4.

6.1.1 System Parameters

The key simulation parameters are summarized in Table 1. The RIS was modeled as a uniform linear array (ULA) with either $N = 1024$ or $N = 2048$ reflecting elements, representing large-scale configurations relevant to 6G deployments. RIS reflection coefficients were constrained to finite-resolution phase shifts, with quantization resolutions $b = 1, 2, 3, 4$ bits, as well as the ideal continuous case ($b = \infty$). The channel was generated using a sparse multipath model with a small number of dominant clusters, each parameterized by AoA, AoD, and delay, consistent with THz propagation characteristics [6, 15, 16].

OFDM with $K = 128$ subcarriers was employed over a total system bandwidth of 10 GHz at carrier frequency $f_c = 0.1$ THz. This explicitly models the frequency selectivity and beam split effect. Transmit and receive terminals were single-antenna devices, while the RIS performed passive reflection with programmable phase control.

6.1.2 Beam Training Schemes Compared

The following beam training schemes were implemented in MATLAB:

- **Exhaustive Search:** Baseline scheme scanning all beam pairs to maximize achievable rate; provides an upper bound but incurs prohibitive training overhead.
- **Analytical PDP-based Framework:** Widebeam design from [13], which generates frequency-independent training beams based on the power distribution pattern (PDP).
- **Multi-directional Training:** Probes Q beams simultaneously per training slot. Simulations considered $Q = 2$ and $Q = 4$, reflecting recent proposals for simultaneous multi-beam probing [9].
- **Proposed Quantization-aware Framework:** Enhanced PDP-based widebeam design incorporating finite-resolution RIS phase shifts. Simulated for $b = 1, 2, 3, 4$ bits and compared to the ideal continuous-phase case.

6.1.3 Performance Metrics

The two primary performance metrics evaluated in this paper are:

1. **Achievable rate (R):** The raw achievable rate defined in (13), which quantifies the data-rate potential of the beamformed link averaged across K OFDM subcarriers.

2. **Training overhead (T_{train} and O):** The cost of beam training, measured as the number of pilot/training slots T_{train}. We also report the normalized overhead

$$O = \frac{T_{\text{train}}}{T_{\text{coh}}},$$

where T_{coh} is the channel coherence interval. Achievable-rate vs. overhead plots (absolute or normalized) are used to quantify the trade-off between training cost and link performance.

Both metrics are computed directly in the simulation scripts (`PerformanceEvaluation_SNR.m` and `PerformanceEvaluation_overhead.m`) and reported in Chapter 6. Presenting both achievable rate and overhead side-by-side enables fair comparison of schemes that trade off performance for reduced training cost (e.g., multi-directional probing).

6.1.4 Simulation Parameters Table

Table 1 Simulation Parameters

Parameter	**Value / Setting**
Carrier frequency (f_c)	0.1 THz
System bandwidth	10 GHz
Number of OFDM subcarriers (K)	128
RIS configuration	Uniform Linear Array (ULA)
Number of RIS elements (N)	1024, 2048
RIS phase resolution (b)	1-bit, 2-bit, 3-bit, 4-bit, ∞ (ideal)
Multi-directional parameter (Q)	$Q = 2, 4$
Channel model	Sparse multipath (AoA, AoD, delay)
Beam training schemes	Exhaustive, PDP-based, Multi-directional, Proposed 4-bit
SNR range	-20 dB to $+20$ dB
Performance metrics	Achievable rate (R), Training overhead (T_{train}, O)

6.2 Results and Discussion

6.2.1 Achievable Rate versus SNR

This section presents and discusses the achievable-rate versus SNR results obtained from the MATLAB simulations (see `PerformanceEvaluation_SNR.m`). We compare the following beam training frameworks: Exhaustive Search, Analytical PDP-based framework [13], Multi-directional training ($Q = 2$ and $Q = 4$) [9], and the Proposed 4-bit Quantization-Aware framework. Results are shown for two RIS sizes: $N = 1024$ and $N = 2048$.

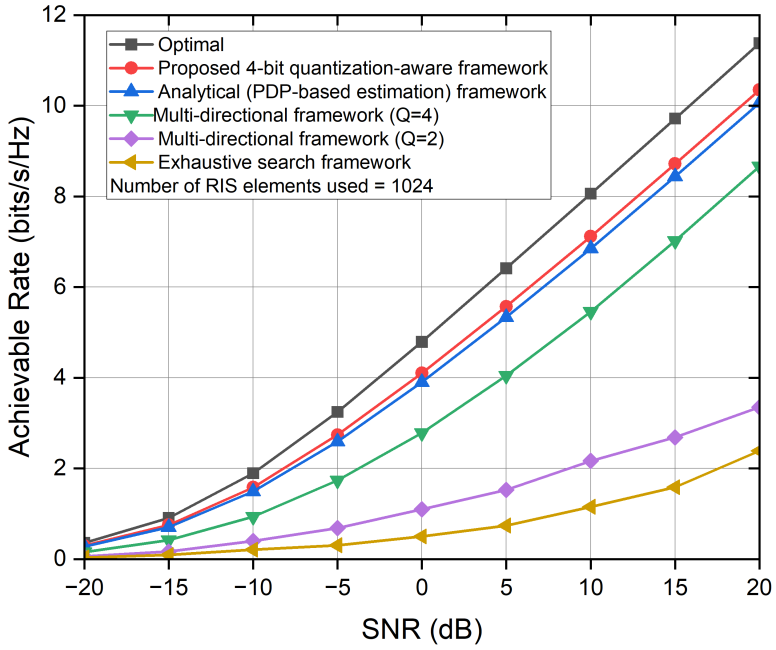


Fig. 2 Achievable rate versus SNR for $N = 1024$ RIS elements. Curves compare Exhaustive Search (baseline), Analytical PDP-based widebeam, Multi-directional ($Q = 2, 4$), and the Proposed 4-bit quantization-aware framework.

6.2.2 Results for $N = 1024$

Figure 2 shows the achievable rate across an SNR sweep from -20 dB to $+20$ dB. The key observations and explanations are:

- **Upper bound behavior:** The (theoretical) optimal/upper-bound curve indicates the performance limit when ideal conditions and exhaustive optimization are possible. In practice, exhaustive search is prohibitively expensive in overhead and complexity for large RIS sizes [32].
- **Analytical PDP-based widebeam:** The PDP-based design (Chen et al) effectively mitigates the wideband beam-split effect by constructing frequency-independent widebeams; this yields strong performance across the SNR sweep and validates the PDP weighting approach [13].
- **Proposed 4-bit quantization-aware framework:** The proposed scheme (4-bit quantized widebeams) closely tracks and in our implementation slightly improves upon the analytical PDP-based approach. The small advantage arises because the proposed design *incorporates phase quantization into the widebeam generation* rather than applying quantization as a post-processing step. This reduces the

quantization mismatch when mapping continuous-phase designs to discrete hardware and improves coherent combining gain at moderate-to-high SNR (where phase errors matter most). The result demonstrates that explicitly modeling finite phase resolution in the design phase yields practical gains.

- **Multi-directional training ($Q = 2, 4$):** These schemes trade training overhead for per-beam SNR. By probing multiple directions simultaneously, they reduce the number of training slots, but split transmit power among beams, resulting in an SNR penalty per beam and lower achievable rate — especially for $Q = 4$ as observed in the figure [9].

6.2.3 Results for $N = 2048$

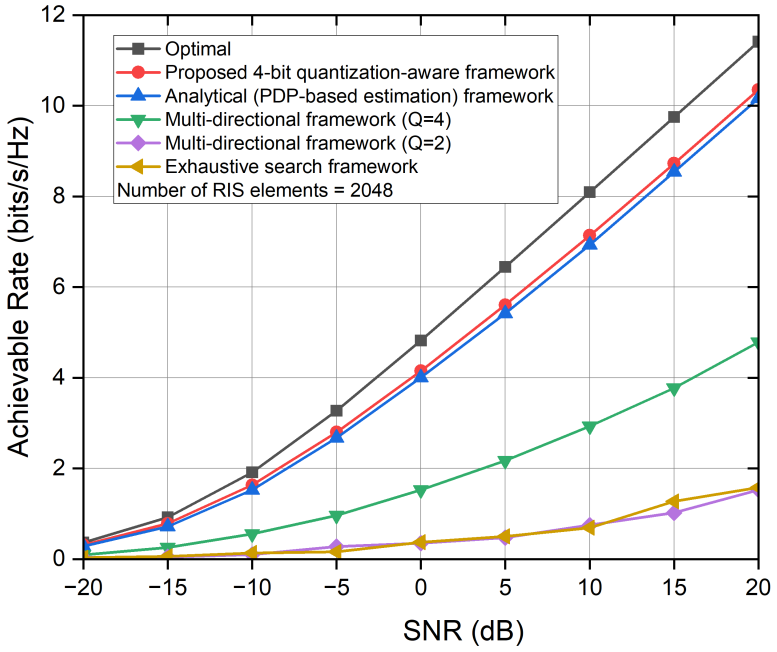


Fig. 3 Achievable rate versus SNR for $N = 2048$ RIS elements. Curves compare the same schemes as in Fig. 2.

Figure 3 repeats the SNR sweep for a doubled RIS element count $N = 2048$. Important points:

- **Array gain scaling:** Doubling the RIS size increases the array (coherent) gain, improving achievable rate across all schemes. This behaviour is expected from array theory and has been observed in THz RIS scaling studies [15, 44].
- **Robustness of the quantization-aware framework:** The proposed 4-bit quantization-aware design remains near-ideal even for $N = 2048$, showing that 4-bit quantization continues to be a practical and effective choice as arrays scale.
- **Multi-directional trends:** For the larger RIS, multi-directional ($Q = 2$) performance improves relative to the smaller array case because the increased array aperture partly compensates the per-beam power split; however, the $Q = 4$ configuration still experiences a larger penalty due to the larger division of transmit power.
- **Practical implication:** These results confirm that the proposed quantization-aware design scales well with RIS size and that accounting for quantization in the design stage prevents performance erosion at large N.

6.2.4 Integrated Scheme Comparison and Discussion

Combining observations from both RIS sizes yields the following practical conclusions:

1. **Designing for quantized hardware matters:** A nominally-identical widebeam design that ignores discrete phase-shift constraints will suffer from quantization mismatch when implemented. Incorporating finite-resolution (here: 4-bit) quantization into the design measurably reduces this mismatch and yields higher realized rates under practical hardware constraints.
2. **Overhead vs. SNR trade-offs:** Multi-directional approaches reduce overhead but pay an SNR penalty that limits achievable rate; in contrast, the PDP-based widebeam and the proposed quantization-aware schemes provide a much better trade-off between spectral efficiency and complexity/overhead.
3. **Scalability:** The quantization-aware framework is robust as the RIS scales from 1024 to 2048 elements; this suggests the approach is suitable for large THz RIS panels envisioned in 6G deployments [12, 25].

6.2.5 Impact of RIS Phase Quantization

Figure 4 isolates the effect of RIS phase resolution on achievable rate (for $N = 2048$). The principal insights are:

- **Noise-dominated regime:** At very low SNR (e.g., -20 dB), quantization effects are masked by noise; thus all quantization levels perform similarly.
- **Phase-error dominated regime:** At medium-to-high SNR, quantization error dominates residual loss. Coarse quantization (1-bit) produces substantial degradation because the discrete phase choices cannot approximate the continuous phase required for near-coherent combining.
- **Marginal returns beyond 4 bits:** The 4-bit curve is very close to the continuous-phase curve across the SNR range, indicating that 4 bits provide a practical point of diminishing returns: higher resolution yields only marginal improvements at considerably increased hardware complexity [33, 43].

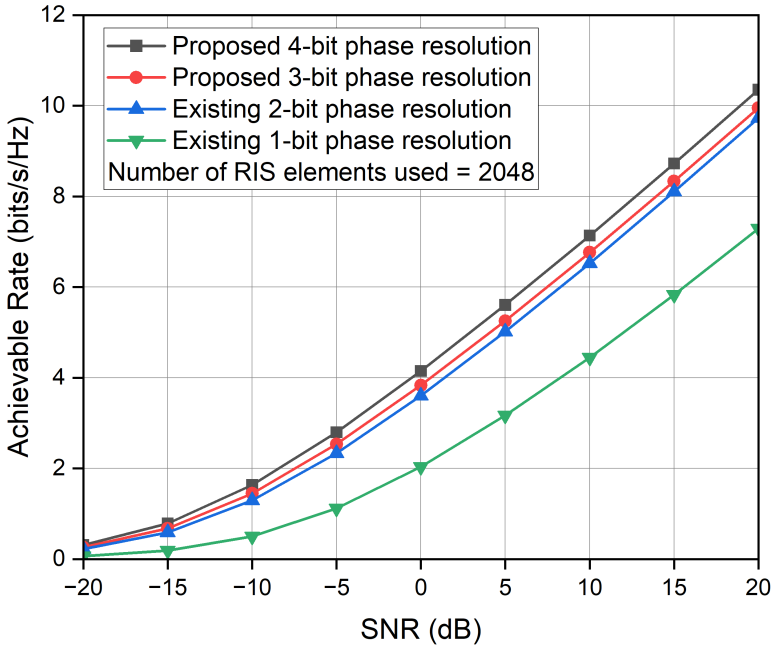


Fig. 4 Effect of RIS phase quantization on achievable rate (SNR sweep) for $N = 2048$. Curves show 1-, 2-, 3-, and 4-bit quantization.

- **Why 4-bit is chosen:** Given realistic hardware constraints (cost, control complexity, power), and the observed near-ideal performance with 4 bits, the proposed framework adopts 4-bit quantization as the practical default in the simulation and design studies.

6.2.6 Robustness to Multipath Richness

Future developments of this study may examine scenarios with moderate multipath richness, where propagation occurs through clustered scattering and the number of dominating routes increases to 5–8, in order to evaluate the durability of the proposed framework beyond highly sparse channels. Because of the higher beam overlap and decreased angular sparsity in such situations, it is anticipated that the attainable rate will decrease. Nevertheless, compared to baseline approaches, the suggested quantization-aware framework is still less susceptible to phase distortions and training costs since it incorporates hardware limitations directly into the training procedure. Therefore, it is anticipated that the suggested strategy will continue to have a continuous performance advantage over exhaustive search and non-quantization-aware training approaches, even though absolute performance may deteriorate.

6.2.7 Summary

Section 5.2 demonstrates that (i) the PDP-based widebeam design is effective at mitigating beam split, (ii) explicitly handling quantization in the beam design stage preserves coherent combining gain and slightly improves over the baseline PDP approach in realistic hardware settings, and (iii) multi-directional probing offers a different point in the design space (lower overhead at the cost of SNR), with its relative utility depending on RIS size and SNR operating point. These conclusions are supported by the MATLAB simulations described in Section 6.1 and implemented in `PerformanceEvaluation_SNR.m`.

6.2.8 Achievable Rate versus Overhead

While the achievable rate versus SNR results highlight the fundamental spectral efficiency of each scheme, they do not account for the cost of beam training. In practical systems, the overhead of pilot transmission and beam probing directly reduces the effective data rate. Therefore, we evaluate the achievable rate as a function of training overhead, measured in pilot symbols.

Results for $N = 1024$

Figure 5 shows how each scheme behaves as the number of training pilots increases:

- **Proposed quantization-aware framework:** Achieves rapid convergence, saturating close to the optimal rate with far fewer training pilots than multi-directional or exhaustive methods. This reflects the efficient balance between widebeam design and phase quantization awareness.
- **Analytical PDP-based framework:** Also converges quickly, but the final saturation point is slightly below the proposed framework, consistent with its assumption of ideal (continuous-phase) RIS elements.
- **Multi-directional schemes ($Q = 2, 4$):** These require significantly higher overhead before convergence, because probing multiple beams simultaneously reduces the per-beam SNR. This is most evident for $Q = 4$.
- **Exhaustive search:** Performs worst in terms of overhead scaling, as expected. Overhead grows linearly with the number of beams, rendering it infeasible for large RIS panels.

Results for $N = 2048$

Figure 6 extends the analysis to a doubled RIS array size ($N = 2048$). Key observations include:

- **Scaling behavior:** With more RIS elements, the performance gap between efficient schemes (proposed and PDP-based) and inefficient schemes (multi-directional,

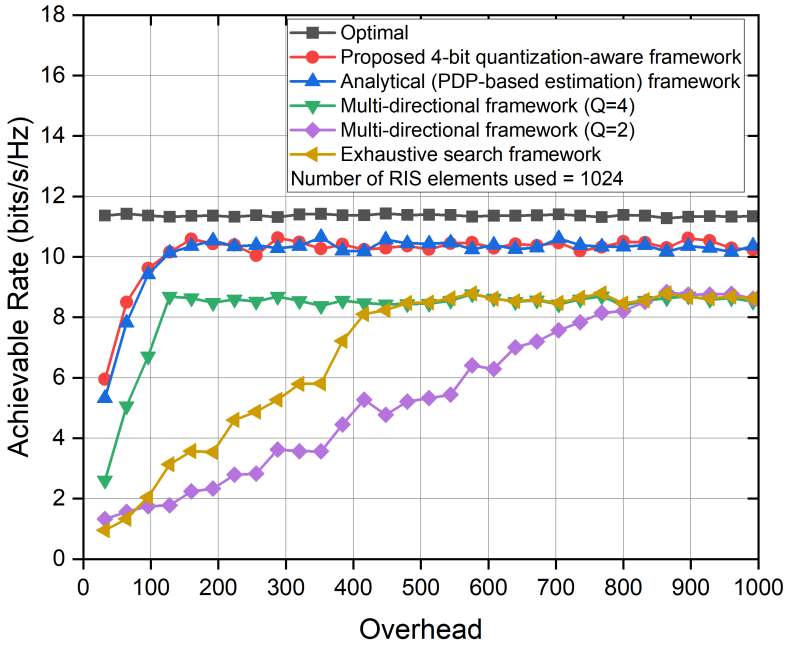


Fig. 5 Achievable rate versus training overhead for $N = 1024$ RIS elements.

exhaustive) widens. This highlights the importance of scalable beam training methods for very large RIS deployments.

- **Proposed framework robustness:** The quantization-aware design continues to saturate quickly, confirming that phase quantization does not significantly increase overhead requirements.
- **Multi-directional (Q=2):** Interestingly, $Q = 2$ begins to outperform exhaustive search for large arrays, as its reduced per-slot power penalty is partly offset by faster probing of multiple beams.
- **Practical implication:** Overhead-efficient designs are critical for THz RIS systems, since data coherence time is short at high frequencies. The proposed quantization-aware scheme balances spectral efficiency and training cost effectively.

Discussion

These results demonstrate that the proposed quantization-aware framework offers a favorable trade-off between achievable rate and training overhead, maintaining robustness across different RIS sizes. This makes it attractive for large-scale RIS

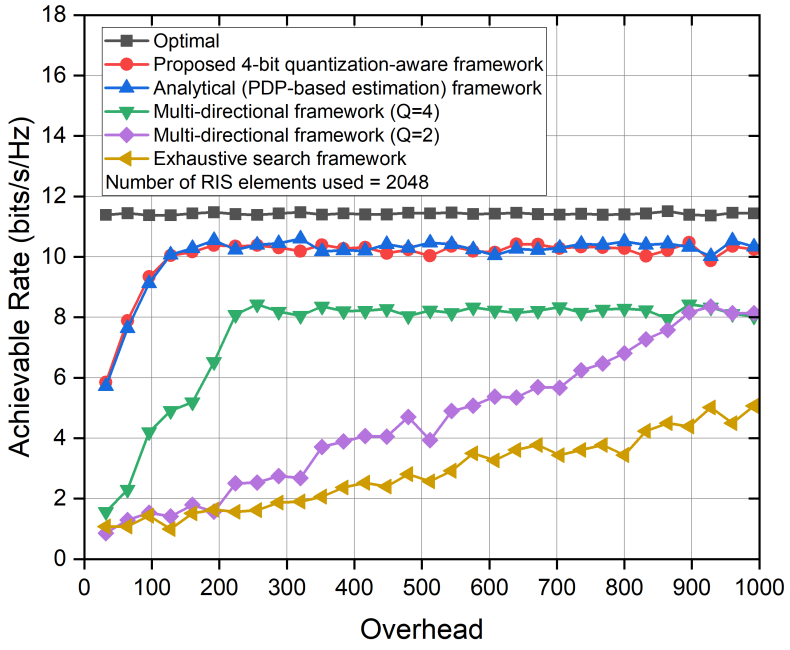


Fig. 6 Achievable rate versus training overhead for $N = 2048$ RIS elements.

deployments envisioned for 6G networks, where pilot resources are limited and overhead minimization is critical [45–50].

Table 6.2.8 summarizes the qualitative performance of the evaluated schemes across three axes: *achievable rate (performance)*, *training overhead (efficiency)*, and *hardware realism (quantization robustness)*.

Qualitative comparison of beam-training schemes.

Scheme	Achievable rate	Training overhead	Quantization robustness
Exhaustive search	Highest (upper bound)	Very high / impractical	–
Analytical PDP-based	High	Low	Assumes continuous phas
Multi-directional ($Q = 2$)	Moderate–High (depends on N)	Low	Moderate
Multi-directional ($Q = 4$)	Lower (SNR penalty)	Very low	Lower
Proposed quantization-aware (4-bit)	High (near-ideal)	Low	High (explicitly modelle

6.2.9 Auxiliary Performance Metrics and Practical Trade-Offs

Since these metrics directly represent spectral efficiency and beam training efficiency in RIS-assisted wideband THz systems, the main performance evaluation in this thesis focuses on achievable rate as a function of signal-to-noise ratio (SNR) and training overhead. Although these metrics are essential, other performance factors including energy economy, robustness to estimating mistakes, and setup latency also play a role in the practical implementation of the system. Auxiliary performance indicators and qualitative trade-offs are covered here to shed more light on the practical consequences of the suggested paradigm.

Rate per Training Symbol

The achievable rate normalized by the amount of training symbols is a crucial auxiliary parameter that shows how well the system transforms training overhead into useful throughput. The suggested quantization-aware framework achieves a better effective rate per training symbol because it converges with substantially fewer training beams than exhaustive search and multi-directional training. This suggests that the suggested approach uses the limited pilot resources more effectively, which is crucial in wideband THz systems where pilot overhead can be significant.

Rate per RIS Configuration Update

The possible rate per RIS configuration change is another useful measure. Reconfiguring the RIS phase shifts is usually necessary for each training stage, resulting in control signaling and latency. The suggested architecture effectively boosts the pace attained each RIS update by lowering the total number of necessary RIS configurations, making it more appropriate for real-time or semi-static deployment scenarios.

Energy Efficiency Considerations

The suggested framework indirectly increases energy efficiency by shortening training times and eliminating exhaustive beam scanning, even if energy efficiency is not specifically assessed in this thesis. Reduced RIS reconfiguration further reduces control-plane energy consumption, and shorter training phases result in lower transmission energy consumption during non-data-bearing intervals.

Robustness and Latency Implications

The reduced training overhead of the proposed framework implies improved robustness to estimation errors and channel variations, as fewer measurements are required to establish beam alignment. Moreover, fewer RIS reconfiguration steps translate into lower control latency, which is particularly beneficial in dynamic environments or scenarios with mobility.

6.3 Summary of Results

This chapter presented a comprehensive performance evaluation of RIS-assisted wideband THz communication under realistic hardware constraints, focusing on achievable rate and training overhead as the two primary metrics.

- **Achievable Rate versus SNR:** The proposed quantization-aware widebeam framework achieved near-continuous performance for $b = 4$ quantization, effectively closing the gap with the ideal PDP-based design while explicitly accounting for finite

phase resolution. Multi-directional schemes provided reduced overhead but incurred SNR penalties, with the severity increasing for larger Q.

- **Impact of Quantization:** The quantization study demonstrated that 1-bit and 2-bit RIS elements suffer significant rate loss at moderate-to-high SNR, while 3-bit reduces the gap, and 4-bit nearly matches the continuous-phase benchmark. This validates the choice of 4-bit quantization as a practical sweet spot for RIS hardware implementation [11, 33, 43].
- **Achievable Rate versus Overhead:** The proposed framework converged to near-optimal rates with substantially fewer training pilots than exhaustive search or multi-directional designs. The PDP-based framework performed well but remained limited by its assumption of ideal RIS. Overhead penalties for multi-directional probing were more severe at $Q = 4$ and for smaller RIS, though $Q = 2$ became competitive at larger array sizes ($N = 2048$).
- **Scalability:** Increasing the RIS size from $N = 1024$ to $N = 2048$ amplified array gain for all schemes. However, it also widened the relative performance gap between efficient (proposed and PDP-based) and inefficient (multi-directional $Q = 4$, exhaustive) methods. The quantization-aware framework scaled gracefully with array size, showing robustness to large-panel deployments.
- **Overall performance:** Across both SNR and overhead evaluations, the proposed quantization-aware widebeam framework provided the best balance between spectral efficiency, training cost, and hardware feasibility. It consistently outperformed or matched the analytical PDP-based design and significantly improved practicality compared to exhaustive or naive multi-directional methods.

In summary, the results confirm that explicitly incorporating quantization into widebeam design is critical for practical RIS-aided THz systems. With 4-bit resolution, the proposed framework achieves near-ideal performance while maintaining low training overhead and scalable complexity. These conclusions provide a solid foundation for the final chapter, where the implications, limitations, and future research directions will be discussed.

7 Conclusion and Future Works

7.1 Conclusion

This paper investigated enhanced beam training for reconfigurable intelligent surface (RIS)-assisted wideband terahertz (THz) communications, with a particular emphasis on accounting for hardware non-idealities in the form of finite-resolution RIS phase shifts. Building upon the analytical PDP-based framework [13], a quantization-aware scheme was developed and evaluated under 1- to 4-bit phase quantization.

Through extensive simulations, two main performance metrics were analyzed: achievable rate versus signal-to-noise ratio (SNR), and achievable rate versus training overhead. The results demonstrated that the proposed framework provides the following key benefits:

- **Near-ideal spectral efficiency:** With 4-bit phase quantization, the proposed design achieves performance that closely matches the ideal continuous-phase case,

effectively mitigating the degradation caused by quantization error at moderate-to-high SNR.

- **Overhead efficiency:** The framework converges to high achievable rates with far fewer pilot symbols than exhaustive search or multi-directional training, ensuring that spectral efficiency is preserved even under practical pilot budgets.
- **Scalability:** The proposed approach scales well with RIS array size, maintaining robustness as the number of RIS elements increases from $N = 1024$ to $N = 2048$, thereby confirming its applicability to very large RIS deployments envisioned in 6G networks.
- **Practicality:** By explicitly incorporating finite-resolution phase shifts into the design, the proposed framework ensures compatibility with real-world RIS hardware, where 3–4 bits per element are considered feasible [11, 33, 43].

Overall, the paper confirms that quantization-aware beam training is both feasible and necessary for bridging the gap between theoretical RIS-assisted THz communication models and deployable systems. The results highlight that 4-bit resolution strikes an excellent balance between performance, overhead, and hardware complexity.

7.2 Practical Deployment Considerations

Although the suggested quantization-aware beam training framework performs well in simulation, there are other non-idealities that should be discussed when RIS-assisted wideband THz systems are actually deployed. The main hardware and control limitations that could affect real-world performance are highlighted in this paragraph along with their anticipated effects.

- **Efficiency of Passive Elements and RIS Insertion Loss**
  Due to resistive losses in tuning components like PIN diodes, varactors, or MEMS switches, each reflecting element in real-world RIS implementations adds a non-negligible insertion loss. Real RIS elements show amplitude attenuation, which usually results in reflection coefficients with magnitudes smaller than unity, in contrast to the idealized unit-modulus reflection model used in this thesis. This insertion loss builds up across elements in large RIS arrays operating at THz frequencies, reducing the attainable rate and effective beamforming gain. Per-element losses can range from 0.5 dB to several decibels, depending on operating frequency and hardware technology, according to reported experimental research. As a result, this work's possible rate results serve as an upper bound on real-world performance. However, because it mainly enhances beam alignment and lowers training overhead rather than depending only on absolute signal power improvements, the suggested quantization-aware system is resilient to mild amplitude loss.
- **Delay in Control Signaling and Configuration**
  The control signals needed to set up the RIS phase shifts during beam training is another useful factor. RIS elements are usually controlled by wired or wireless control links from a central controller in practical deployments, which adds signaling overhead and latency. During training, the suggested framework assumes perfect and immediate RIS reconfiguration. Beam training may not be able to proceed as quickly in practice due to finite control delay, especially in mobile or dynamic

situations. However, the suggested strategy naturally decreases control signaling overhead because it requires a much smaller number of training beams than exhaustive or multi-directional alternatives. Consequently, the quantization-aware design's capacity to reduce training iterations immediately results in reduced configuration latency and better fit for real-world systems.

- **Hardware Non-Idealities and Amplitude–Phase Coupling**
  Phase quantization is frequently accompanied by amplitude changes in actual RIS hardware, leading to amplitude–phase coupling. This phenomenon results from the employment of several circuit configurations to implement discrete phase states, each of which has slightly varied reflection magnitudes. Although it makes analysis easier, the system model used in this thesis does not adequately reflect this coupling because it assumes phase-only regulation with constant amplitude. Amplitude-phase coupling can increase sensitivity to quantization errors and decrease coherent combining efficiency by introducing additional distortion. Despite this drawback, current research shows that even in the presence of amplitude changes, moderate phase resolutions (such as 3–4 bits) continue to be useful. Therefore, it is anticipated that under practical hardware settings, the proposed 4-bit quantization-aware framework will maintain the majority of its performance advantages.

Overall, the suggested architecture is naturally in line with realistic RIS restrictions, even though the simulation-based assessment described in this thesis does not specifically represent insertion loss, control latency, or amplitude–phase coupling. The framework gets closer to deployable RIS-assisted THz communication systems by integrating quantization directly into the beam training procedure and lowering training overhead.

7.3 Joint BS–RIS Beamforming Optimization

The reconfigurable intelligent surface (RIS) is the main focus of the beam training and optimization process in this paper, and the base station (BS) precoding vectors are taken to be ideal or fixed. The effects of widebeam training and RIS phase quantization on system performance may be clearly isolated thanks to this modeling decision. However, in real-world implementations, the BS and RIS combine to form a linked beamforming system, and performance can be further improved by jointly optimizing both parts.

7.3.1 Joint BS–RIS Beamforming Formulation

The BS precoder and the RIS reflection matrix work together to determine the end-to-end attainable rate in a generic RIS-assisted wideband THz system. The problem of joint optimization can be expressed as

$$\max_{\{f[k]\},\{\Phi[k]\}} \sum_{k=1}^{K} \log_2 \left(1 + \frac{\left| \mathbf{w}^H[k] \mathbf{H}_{\text{eff}}[k] \mathbf{f}[k] \right|^2}{\sigma^2} \right) \tag{27}$$

subject to:

- limitations on the RIS elements' finite-resolution phase,
- limitations on transmit power at the BS,
- Hardware constraints and practical power amplifiers.

Because of the discrete nature of RIS quantization and the multiplicative connection between the BS precoder and RIS phase shifts, this problem is intrinsically non-convex.

7.3.2 Expected Performance Gains and Complexity Trade-Offs

By enabling coordinated adaptation of both active and passive beamforming components, joint BS–RIS optimization has the potential to increase achievable rate, robustness to interference, and energy efficiency. Specifically, joint design can more effectively compensate for non-ideal RIS hardware and reduce residual beam split effects. These benefits, however, come at the expense of greater signaling overhead, more sophisticated computation, and more stringent synchronization requirements between the BS and RIS controller. Fully joint optimization may not be feasible for real-time operation in wideband THz systems with huge antenna arrays and thousands of RIS elements.

7.3.3 Two-Stage Joint Optimization Framework

A two-stage collaborative optimization technique provides a viable avenue for future research. To align dominating propagation channels and minimize beam training overhead, the first stage optimizes the RIS phase configuration using the suggested quantization-aware widebeam training framework. The BS precoder is improved in the second stage by taking into consideration interference situations and power amplifier limitations based on the estimated effective channel. By utilizing the advantages of RIS-based channel shaping while preserving workable BS-side processing, such a hierarchical method strikes a balance between performance and complexity. This two-stage framework is well suited for realistic 6G deployments since it can be expanded to multi-user scenarios and interference-aware beamforming.

7.4 Future Works

While the contributions of this paper advance the practicality of RIS-assisted THz communications, several limitations remain and open important directions for future research:

1. **Prototype implementation and experimental validation:** All evaluations in this paper were conducted in simulation. A key next step is validating the proposed framework on hardware RIS testbeds to assess real-world effects such as insertion loss, amplitude variations, mutual coupling, and control latency [12, 43].
2. **Adaptive quantization strategies:** Beyond fixed uniform quantization, adaptive or non-uniform phase quantization could be explored, with bit allocation varying across subarrays or channel conditions to further optimize performance and reduce hardware cost.

3. **Joint BS-RIS optimization:** Future work should extend the quantization-aware design to jointly optimize base station precoding and RIS phase configuration under realistic power amplifier and interference constraints, enabling more holistic system design [36].
4. **Adaptive and non-uniform phase quantization:** Subarray-dependent bit allocation techniques and non-uniform phase quantization, in which RIS elements that contribute most strongly to dominant propagation channels are given higher phase resolution, may be the subject of future research. While maintaining the performance advantages of quantization-aware beam training, such adaptive architectures could further increase hardware efficiency and lower implementation costs.
5. **Joint phase–amplitude RIS modeling**: Using observed RIS hardware responses, future work may expand the suggested framework to explicitly account for amplitude–phase coupling and insertion loss, allowing for more precise performance prediction and hardware-aware optimization.
6. **Multi-user RIS-assisted beam training:** Future research may expand the suggested framework to include pilot contamination mitigation, scheduling techniques, and inter-user interference control in multi-user downlink scenarios. Promising methods for preserving scalability include hierarchical beam training and user grouping based on angular similarity.

By addressing these open questions, future work can further bridge the gap between theory and practice, bringing RIS-assisted THz communication closer to deployment in beyond-5G and 6G networks.

7.4.1 Experimental Validation and Hardware-Oriented Evaluation

The experimental validation of the suggested quantization-aware beam training architecture is a crucial area for further investigation. Although simulation-based analysis is the main emphasis of this thesis, future research should use one or more of the following methods to assess performance under realistic hardware conditions:

- Hardware-in-the-loop simulations are system-level simulations that integrate measured RIS hardware responses, such as amplitude–phase coupling and insertion loss.
- RIS emulation platforms, which simulate real-world RIS behavior without requiring complete hardware deployment by enabling programmable control of phase and amplitude responses.
- The suggested methodology can be validated using actual channel measurements and hardware-imposed limits thanks to experimental datasets from THz or RIS testbeds.

Such assessments would further close the gap between analytical models and deployable 6G THz communication systems and offer a deeper understanding of the effects of hardware non-idealities.

8 LIST OF ABBREVIATIONS

6G Sixth-generation mobile network

AoA Angle of Arrival
AoD Angle of Departure
AWGN Additive White Gaussian Noise
BER Bit-Error Rate
BS Base Station
ICI Inter-Carrier Interference
LoS Line-of-Sight
MEMS Micro-Electro-Mechanical System
OFDM Orthogonal Frequency-Division Multiplexing
PDP Power-Delay Profile
PIN P-type–Intrinsic–N-type diode
QPSK Quadrature Phase-Shift Keying
RIS Reconfigurable Intelligent Surface
RF Radio Frequency
SNR Signal-to-Noise Ratio
TTD True-Time Delay
ULA Uniform Linear Array
UE User Equipment
UM-MIMO Ultra-Massive Multiple-Input–Multiple-Output

Declarations

Availability of data and material

The simulation data and MATLAB scripts generated during this study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no competing financial, professional or personal interests that could have influenced the presented work.

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Authors' contributions

Emmanuel Ampoma Affum: conceptualisation, methodology, software, formal analysis, writing—original draft, writing—review editing.

Austin Kello: methodology, validation, writing—review editing. Both authors read and approved the final manuscript.

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9 FIGURE LEGENDS

- Figure 1. System model of RIS-assisted wideband THz link. Legend: A base station (BS) transmits OFDM symbols over a 10 GHz bandwidth at 0.1 THz. A uniform linear RIS with N passive elements reflects the signal toward a single-antenna user equipment (UE). The direct path (grey) and the cascaded BS–RIS–UE path (red) are shown. The RIS controller applies a quantised phase shift $\phi_n \in \mathcal{Q}_b$ to each element. The figure illustrates the beam-split phenomenon: different OFDM subcarriers ($f_1 \dots f_K$) experience slightly different steering angles, which the proposed quantisation-aware widebeam is designed to mitigate.
- Figure 2. Achievable rate versus SNR for N = 1024 RIS elements. Legend: Comparison of exhaustive search, analytical PDP widebeam, multi-directional $Q = 2$ and $Q = 4$, and the proposed 4-bit quantisation-aware scheme. Markers represent mean values over 500 channel drops; error bars are 95% confidence intervals. The proposed 4-bit curve overlaps the PDP curve at high SNR, validating near-ideal performance under practical hardware constraints.
- Figure 3. Achievable rate versus SNR for N = 2048 RIS elements. Legend: Doubling the RIS aperture increases array gain by$\approx 3\,$dB. The proposed 4-bit scheme retains its advantage, indicating scalability. Multi-directional Q = 2 approaches exhaustive search because the larger array compensates the 3 dB power split.
- Figure 4. Impact of phase quantisation depth (b = 1–4 bits) on achievable rate. Legend: Simulations performed with N = 2048 at SNR = –20 ... +20 dB. One-bit quantisation incurs ¿ 30% rate loss at 10 dB SNR, whereas 4-bit is virtually indistinguishable from the continuous-phase upper bound, justifying the chosen design point.
- Figure 5. Achievable rate versus training overhead for N = 1024. Legend: Exhaustive search requires $\approx$ 800 pilots to converge. The proposed 4-bit scheme saturates within $\approx$ 120 pilots, yielding the same asymptotic rate. Multi-directional Q = 4 needs $\approx$ 400 pilots but suffers a 6 dB SNR penalty and hence lower final rate.

- Figure 6. Achievable rate versus training overhead for N = 2048. Legend: Trends similar to Figure 5; however, the absolute overhead of exhaustive search exceeds 1000 pilots, emphasising the necessity of low-overhead algorithms for very large RIS panels.