

PERFORMANCE IMPROVEMENT OF WIRELESS COMMUNICATION USING RECONFIGURABLE INTELLIGENT SURFACES

A THESIS SUBMITTED TO AUCKLAND UNIVERSITY OF TECHNOLOGY
IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

By

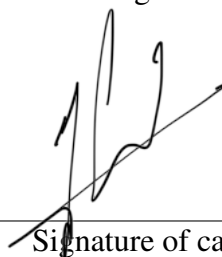
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September 2024

Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the qualification of any other degree or diploma of a university or other institution of higher learning.

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Signature of candidate

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Abstract

Wireless communication systems are rapidly evolving to meet the ever-increasing demands for enhanced capacity and ubiquitous connectivity. As we progress towards Sixth-Generation networks, novel technologies are essential to overcome the limitations of traditional communication paradigms. Reconfigurable Intelligent Surfaces (RISs) have emerged as a promising solution, offering a wide range of applications to improve signal quality, extend coverage, and mitigate interference in wireless environments. These metasurface-based structures can dynamically manipulate electromagnetic waves, providing unprecedented control over the propagation environment. This thesis focuses on three critical aspects of RIS technology: (i) unit cell design; (ii) phase distribution optimization; and (iii) propagation modeling using ray tracing (RT) techniques.

The thesis begins with a comprehensive literature review of state-of-the-art RIS structures, followed by an examination of optimization approaches for RIS-based communications. Additionally, a thorough review of RT-based propagation modeling platforms and methods for wireless communication systems, including those involving RIS structures, is presented. Following the literature review, the thesis delves into a detailed RIS design procedure, proposing a novel, dual-polarized RIS unit cell with an operating center frequency of 5.2 GHz. The study then presents an efficient optimization method for space-time-coding RIS structures, followed by the optimization of the proposed RIS's phase distribution based on the transmission power of two antennas interacting with

the RIS, utilizing a genetic algorithm. Finally, the focus shifts to RT-based propagation modeling of RIS-assisted wireless communications, proposing a novel approximation method for simulation speed enhancement. This is complemented by the introduction of a comprehensive simulation platform, WiPy-RT, developed entirely in Python.

This study makes a concerted effort to examine RIS technology from multiple perspectives, encompassing both hardware and system development. By addressing the challenges in RIS design, optimization, and propagation modeling, this thesis contributes to the advancement of RIS-assisted wireless communications. The proposed methods and tools provide valuable insights for researchers and engineers working towards the realization of efficient and reliable RIS-enhanced wireless networks, paving the way for future innovations in this rapidly evolving field.

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Glossary and Notations

Glossary

3D	Three Dimensional
3GPP	3rd Generation Partnership Project
5G	Fifth Generation
6G	Sixth Generation
AF	Amplify and Forward
AI	Artificial Intelligence
AoA	Angle of Arrival
AP	Access Point
BER	Bit Error Rate
BPSO	Binary Particle Swarm Optimization
CSI	Channel State Information
DF	Decode and Forward
eMBB	Enhanced Mobile Broadband
EM	Electromagnetic
FPGA	Field-Programmable Gate Array
IFFT	Inverse Fast Fourier Transform
IRS	Intelligent Reflecting Surface
LIS	Large Intelligent Surface

LoS	Line of Sight
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
MU-MIMO	Multi-User Multiple-Input Multiple-Output
NOMA	Non-Orthogonal Multiple Access
NSGA-II	Non-dominated Sorting Genetic Algorithm II
OFDM	Orthogonal Frequency Division Multiplexing
PEC	Perfect Electric Conductor
PDP	Power Delay Profile
PIN	Positive-Intrinsic-Negative (Diode)
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency
RIS	Reconfigurable Intelligent Surface
RT	Ray Tracing
SISO	Single-Input Single-Output
SNR	Signal-to-Noise Ratio
STC-RIS	Space-Time-Coding Reconfigurable Intelligent Surface
TDMA	Time Division Multiple Access
THz	Terahertz
UE	User Equipment
URLLC	Ultra-Reliable Low-Latency Communications
VNA	Vector Network Analyzer
Wi-Fi	Wireless Fidelity

Notation

A	Area of a sphere
A_{bend}	Amplitude of the bending sinusoidal curve
α	Attenuation constant or bending angle
β	Reflection coefficient
Γ_{pq}	Reflection coefficient at unit cell U_{pq}
$\vec{B}$	Magnetic flux density vector
$E(\theta, \phi)$	Far-field pattern of reflected electromagnetic waves
θ	Phase shift
$\vec{E}(r)$	Electric field vector
f	Frequency
g	Channel matrix from AP to RIS
h_r	Channel matrix from RIS to receiver
λ	Wavelength
L	Number of time sequences in phase distribution
m	Harmonic order
n	Refractive index
$\vec{r}$	Position vector in 3D space
ϕ	Phase angle
$S(r)$	Eikonal function representing optical path length
S_{21}	Transmission coefficient
Φ_n	Phase change in a unit cell
P_{tx}	Transmit power
R_n	Reflection loss
η	Intrinsic impedance
L_{LoS}	Line-of-Sight path loss

Chapter 1

Introduction

Wireless technology has profoundly transformed the landscape of communication, driving innovation and connectivity across the globe. From the early days of radio communication to the advent of modern 5G networks, the evolution of wireless telecommunications has been marked by significant milestones that have reshaped how we interact, work, and live.

1.1 Background

The history of wireless technology begins in the late 19th century with the pioneering work of Guglielmo Marconi, who successfully demonstrated the transmission of radio signals over long distances [19]. This breakthrough laid the foundation for the first wireless communication systems, primarily used for maritime communication. The mid-20th century saw the development of television broadcasting, further advancing wireless technology and expanding its applications beyond voice communication [20–22].

The launch of mobile telephony in the 1980s marked the beginning of a new era. The first generation (1G) of mobile networks utilized analog signals and was limited to voice-only services. The subsequent introduction of second-generation (2G) networks

in the 1990s brought about a digital revolution, offering enhanced security through digital encryption and the ability to send SMS text messages. This era also saw the emergence of basic data services, setting the stage for more advanced mobile internet capabilities [23–26].

The early 2000s witnessed the rollout of third-generation (3G) networks, which significantly improved data transmission speeds and enabled mobile broadband [27]. This development allowed for more sophisticated internet applications on mobile devices, such as video calling and online gaming [28]. The advent of fourth-generation (4G) Long Term Evolution (LTE) networks in the late 2000s further revolutionized mobile communication by providing high-speed internet access capable of supporting high-definition video streaming and large data transfers [29–32]. Today, the deployment of fifth-generation (5G) networks promises even greater advancements, with ultra-high-speed connectivity, low latency, and the capacity to support a massive number of connected devices [33–35]. This technological leap is expected to drive innovations in the Internet of Things (IoT) [36–38], autonomous vehicles, and smart cities [39–41].

Wi-Fi technology, based on the IEEE 802.11 standards, has also become ubiquitous in providing wireless local area networking solutions [21, 42, 43]. Since its introduction, Wi-Fi has evolved to support faster speeds and more reliable connections, making it an essential component of modern communication infrastructure. Similarly, Bluetooth technology, standardized as IEEE 802.15.1, has become widely used for short-range communication between devices such as smartphones, computers, and various peripherals [44, 45].

Satellite communication represents another critical aspect of wireless technology, enabling global broadcasting, navigation, and long-distance telecommunication. The deployment of communication satellites has facilitated the transmission of data across vast distances, connecting remote areas and supporting various applications, including global positioning systems (GPS) and satellite television [46–48].

The current state of wireless technology is characterized by rapid advancements and increasing demand for connectivity. The proliferation of smart devices and the growing importance of IoT have driven the development of more sophisticated and efficient wireless communication systems. The latest Wi-Fi standard, Wi-Fi 6 (802.11ax), offers higher data rates, increased capacity, and improved performance in dense environments, reflecting the continuous evolution of wireless networking [49–51].

Looking ahead, the future of wireless technology promises to bring transformative changes across various sectors. Early research into sixth-generation (6G) networks suggests they will offer even higher speeds, enhanced security, and support for advanced applications such as holographic communication. The integration of artificial intelligence (AI) and machine learning (ML) into wireless networks is expected to optimize performance, manage traffic more effectively, and enhance security measures. Additionally, the exploration of quantum communication holds the potential to create ultra-secure communication systems, leveraging the principles of quantum mechanics to protect data transmission [52–56].

As the future of wireless communication evolves, one of the most promising innovations on the horizon is the RIS (Figure 1.1). These structures have the potential to revolutionize the way electromagnetic waves are manipulated, enhancing signal propagation and network performance. RIS technology, underpinned by advancements in materials science, nanotechnology, and artificial intelligence, is poised to play a crucial role in the development of next-generation wireless systems, including the highly anticipated 6G networks [57, 58].

Reconfigurable Intelligent Surfaces are engineered surfaces composed of a vast array of sub-wavelength elements known as meta-atoms. Each meta-atom can independently control various properties of the electromagnetic waves, such as phase, amplitude, and polarization. By dynamically adjusting these properties, RIS can intelligently direct, reflect, or focus signals to improve the quality and efficiency of wireless communication.

1.1 BACKGROUND

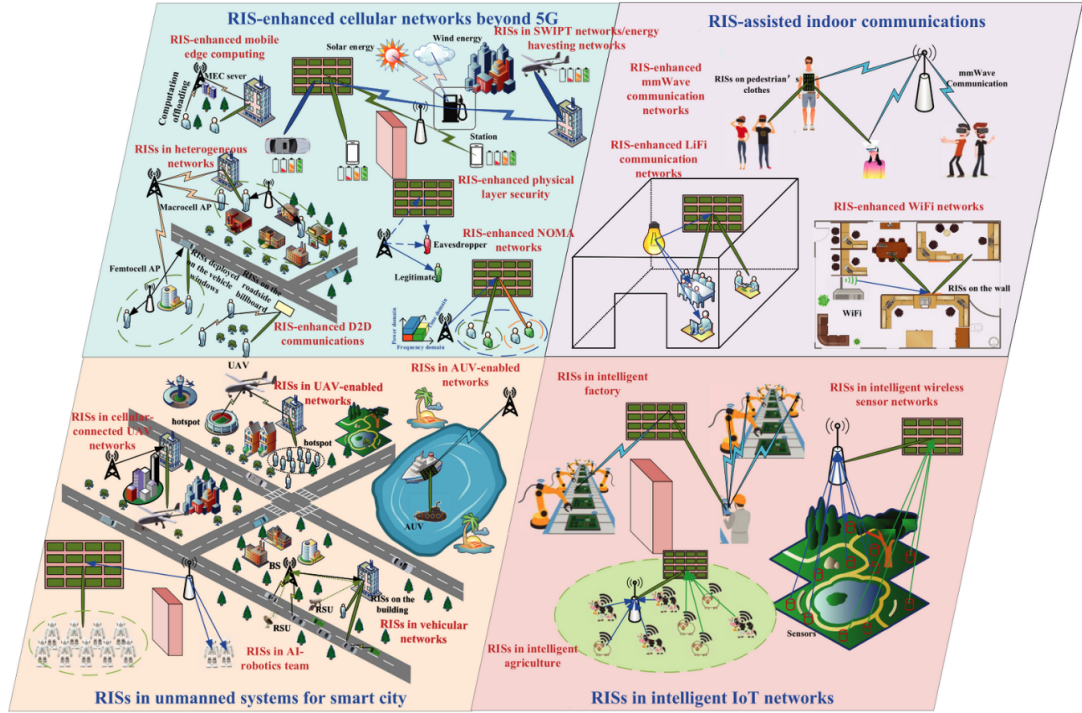


Figure 1.1: RISs in modern wireless communication systems [1].

Unlike traditional passive surfaces, RIS can actively adapt to changing environmental conditions, providing a highly flexible and responsive approach to signal management [59, 60].

The core functionality of RIS is managed by an external controller that uses advanced algorithms to configure the meta-atoms in real time. This controller can optimize the settings of the RIS based on the current wireless channel conditions, ensuring optimal signal strength and minimizing interference. This capability is particularly beneficial in environments where signal quality is typically compromised, such as urban areas with numerous obstacles or indoor settings with complex layouts. By enhancing signal propagation, RIS can significantly improve coverage and capacity in these challenging environments [1].

One of the key advantages of RIS technology is its potential to reduce the energy consumption of wireless networks. Traditional methods of boosting signal strength,

1.1 BACKGROUND

such as increasing transmission power, can be energy-intensive [61]. In contrast, RIS can achieve similar improvements in signal quality with minimal energy use by intelligently directing signals where they are needed most. This makes RIS a sustainable solution for enhancing wireless communication, aligning with the growing emphasis on energy efficiency and green technologies [62–64].

Despite its promising benefits, the practical implementation of RIS presents several technical challenges. Designing and fabricating meta-atoms that provide precise control over electromagnetic waves requires significant advancements in materials science and engineering [65]. Additionally, developing the algorithms needed for real-time control of RIS is a complex task that involves significant computational resources and sophisticated modeling techniques [66, 67]. Integrating RIS into existing wireless infrastructure also necessitates careful planning to ensure compatibility and seamless operation. Ongoing research in these areas is crucial for overcoming these challenges and unlocking the full potential of RIS technology.

The future of Reconfigurable Intelligent Surfaces in wireless communication looks exceedingly bright. As materials science, nanotechnology, and artificial intelligence continue to advance, RIS will become more capable and versatile, driving significant improvements in wireless network performance. In the context of 6G and beyond, RIS is expected to facilitate ultra-high-speed connectivity, support advanced applications like holographic communication, and enhance the security of wireless transmissions [68]. With continued research and development, RIS is set to become a cornerstone of next-generation wireless communication systems, offering smarter, more efficient, and more secure wireless environments [1].

1.2 Motivation

The unprecedented demands for high-quality and ubiquitous wireless services impose enormous challenges on existing cellular networks. While current 5G systems aim to support enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC), the goals for 6G are expected to be transformative and revolutionary. These include data-driven, instantaneous, ultra-massive, and ubiquitous wireless connectivity, as well as connected intelligence. To support these new applications and services, novel transmission technologies are essential. Reconfigurable intelligent surfaces (RISs), also known as intelligent reflecting surfaces (IRSs) or large intelligent surfaces (LISs), have emerged as a promising solution to address the challenges in diverse wireless networks. RISs comprise an array of reflecting elements capable of reconfiguring incident signals, offering the ability to proactively modify the wireless propagation environment. This capability allows RISs to mitigate a wide range of challenges encountered in various wireless scenarios, making them a focal point of research in wireless communications. The advantages of RISs are manifold. Firstly, they are easy to deploy due to their nearly-passive nature and low-cost implementation. RISs can be installed on various structures, including building facades, indoor walls, aerial platforms, roadside billboards, highway polls, vehicle windows, and even pedestrians' clothes. Secondly, RISs enhance spectral efficiency by reconfiguring the wireless propagation environment, compensating for power loss over long distances, and forming virtual line-of-sight (LoS) links between base stations and mobile users. This is particularly beneficial when the LoS link is blocked by obstacles such as high-rise buildings. RISs are also environmentally friendly compared to conventional relaying systems. Unlike amplify-and-forward (AF) and decode-and-forward (DF) relays, RISs shape incoming signals by controlling the phase shift of each reflecting element without employing power amplifiers. This passive nature

makes RISs more energy-efficient and environmentally friendly. Additionally, RISs support full-duplex and full-band transmission due to their purely reflective properties, making them compatible with existing wireless network standards and hardware.

From system design perspective, realistic channel modeling is increasingly relevant for 5G and future 6G mobile radio networks utilizing mmWave and THz bands. In these higher frequency ranges, the number of relevant multipath components may be smaller, resulting in sparse channels that can be modeled deterministically, as opposed to the rich multipath assumptions at lower frequencies. However, practical channel measurements at mmWave or THz bands are expensive and challenging. Stochastic channel modeling based on sounding channels in different environments may thereby be either infeasible or unnecessary. Several envisioned 6G technologies, such as pencil beamforming or RISs, could exploit this deterministic sparse multipath structure when the channel is known. RT simulators are proving useful in supplementing real-time channel measurements, particularly in conjunction with machine learning and localization algorithms. The emerging 6G systems with new technologies such as joint combinations and radar sensing require efficient channel modeling tools using ray tracing.

While many novel and exciting unit cell designs for RIS utilization have been proposed, there is still room for improvement. Most existing designs are sensitive to incident polarization, limiting their effectiveness in real-world scenarios where signal polarization can vary. Proposed dual-polarized structures, while addressing this issue, often appear complex and rely on numerous active elements, potentially increasing cost and energy consumption. This highlights the need for simpler, more efficient dual-polarized RIS designs that maintain performance across varied incident polarizations.

Furthermore, aside from hardware considerations, there seems to be a lack of propagation modeling platforms that are both fast and efficient while capable of analyzing RIS-assisted wireless communication systems. Current modeling approaches often

struggle to balance computational efficiency with accuracy when simulating the complex interactions between RISs and the wireless environment. This gap in modeling capabilities hinders the comprehensive evaluation and optimization of RIS-enhanced networks, emphasizing the need for advanced simulation tools that can accurately and efficiently model RIS-assisted propagation scenarios.

1.3 Original Contribution and Objectives

The main contribution of this thesis includes:

- **Development of a dual-polarized RIS with Enhanced Performance**

The proposed RIS, which is reported in Chapter 3, follows several key objectives to advance RIS technology. The design aims to create a unit-cell that maintains consistent performance regardless of signal polarization, addressing a critical limitation in current RIS designs. To ensure practicality and efficiency, the unit cell design is kept simple by using only one active element, balancing performance with cost-effectiveness and energy efficiency. The project involves designing and implementing a control circuit board to efficiently manage the RIS elements, enabling dynamic reconfiguration. To validate the design, comprehensive measurements of the proposed RIS under various conditions is conducted.

- **A Method for Fast Phase Distribution Calculation of Space-Time-Coding RIS**

This method, presented in Chapter 3, follows several key objectives. This approach provides an efficient and fast method to optimize phase shifts of each unit cell in a space-time-coding RIS. The proposed method is designed to calculate the reflection phase distribution for RISs, to reflect impinging electromagnetic EM waves towards a desired angle at different harmonic frequencies shifted from

the central frequency. Exploiting the strengths of two techniques, namely 2D Inverse Fast Fourier Transform (IFFT) and an evolutionary optimization approach based on Non-dominated Sorting Genetic Algorithm II (NSGA-II), the method achieves efficiency in calculating phase distribution of RIS structures. Results demonstrate that the proposed method can reduce the time of optimal phase distribution calculation for a 10×10 metasurface by 98.02%, compared to traditional approaches.

- **Development of a Python-based Propagation Modeling Platform for RIS-assisted Communication Systems**

The proposed propagation modeling platform, which is reported in Chapter 5, follows several key objectives to enhance the simulation and analysis of RIS-assisted wireless communication systems. Initially, a foundational propagation modeling framework is designed and implemented in the MATLAB environment, serving as a basis for further development. To address the computational challenges in RIS-assisted systems, an RT approximation method is proposed to enhance channel modeling speed while maintaining accuracy. The core of the platform, named WiPy-RT, is developed as an RT-based propagation modeling tool in Python, leveraging the language's efficiency and extensive libraries for scientific computing. To improve the performance of the RT engine within the platform, a ray launching method is proposed and implemented, enhancing its capability to model complex RIS-assisted scenarios. Finally, comprehensive benchmarking of WiPy-RT's performance against WITH-Ray, an existing, recently-proposed solution, is conducted to validate its efficiency and accuracy in modeling RIS-assisted wireless communication systems. These objectives collectively aim to create a powerful and efficient simulation tool for advancing RIS technology research and development.

1.4 Publications

Publications of the author are listed in chronological order as below [69–71]:

1.4.1 Journal Papers

1. M. Farashahi, B.-C. Seet, and X. Li., "Framework for propagation modeling of IRS-assisted communication based on ray tracing." *Physical Communication*, vol. 63, p. 102301, 2024.
2. M. Farashahi, B.-C. Seet, and X. Li., "WiPy-RT: A Fast Ray Tracing Modeling Platform for RIS-assisted Wireless Channels." Submitted to IEEE Access, in review.
3. M. Farashahi, B.-C. Seet, and X. Li., "Dual-Polarized Reconfigurable Intelligent Surface (RIS) with Quasi-Continuous Phase Shift Control." Unpublished manuscript, In submission.

1.4.2 Conference Papers

1. M. Farashahi, B.-C. Seet, and X. Li., "Fast Phase Distribution Calculation for Space-Time Coding Intelligent Reflecting Surfaces." *IEEE Conference on Antenna Measurements & Applications (CAMA)*, 2021.
2. M. Farashahi, B.-C. Seet, and X. Li., "Dual-Polarized Reconfigurable Intelligent Surface Unit Cell with Single Varactor Diode." *IEEE International Mediterranean Conference on Communications and Networking (MeditCom)*, 2024.

1.5 Outline of the Thesis

The rest of this thesis is organised as follows:

Chapter 2 Begins with a comprehensive review of RIS structures proposed in the literature. This is followed by an examination of optimization techniques developed

for RIS-assisted wireless systems. The chapter concludes with an extensive review of various approaches and techniques proposed for RT-based propagation modeling in RIS-based communications.

Chapter 3 Presents a detailed procedure for developing a fully-functional RIS from conception to implementation. This includes the design of the RIS's unit cell, unit cell parameter measurements, design of the RIS control board, and the establishment of a measurement test bed for the proposed RIS.

Chapter 4 explores optimization methods applicable to RIS structures. This chapter introduces a method for rapid optimization of space-time-coding RIS structures, followed by the optimization of the proposed RIS based on signal transmission power between the transmitter and receiver, with the RIS mediating their communication.

Chapter 5 Focuses on propagation modeling for RIS-assisted wireless systems. This chapter introduces a framework, Initially developed in MATLAB, specifically tailored for propagation modeling in RIS-assisted communication systems. The discussion then extends to a more comprehensive simulator, WiPy-RT, completely implemented in Python.

Chapter 6 Concludes the thesis and provides recommendations for future research directions in the field of RIS-assisted wireless communications.

Chapter 2

Literature Review

This chapter explores the current state of research on RIS and their applications in wireless communication systems. The review is divided into two main sections. section 2.1 aims to provide an overview of the various RIS unit cell designs, configurations, and performance parameters proposed in recent literature. Key aspects covered include reflection phase control, polarization sensitivity, biasing networks, and potential applications such as space-time coding, backscatter communication, and cloaking.

Section 2.2, on the other hand, delves into the software side of RIS technology, focusing on techniques for optimizing the RIS reflection coefficients and acquiring Channel State Information (CSI) to enhance wireless communication performance. This part of the review examines RIS-assisted wireless systems with varying complexities, ranging from Single-Input Single-Output (SISO) to Multi-User Multiple-Input Multiple-Output (MU-MIMO) configurations. Special attention is given to the problem formulations and optimization methods employed to maximize key performance indicators such as Signal-to-Noise Ratio (SNR), achievable rate, and energy efficiency.

Section 2.3 focuses on channel modeling of RIS-assisted wireless networks using ray-tracing techniques. Ray-tracing simulations provide valuable insights into the

propagation characteristics and performance of RIS-assisted channels in complex environments. This section explores the recent advancements in ray-tracing-based channel modeling, including path loss analysis, spatial and temporal correlation studies, and the impact of RIS configurations on channel properties.

Through a comprehensive analysis of the literature, several overarching trends and research gaps emerge. First, there is a clear evolution from passive metasurfaces to increasingly intelligent, adaptive RIS structures that can respond to changing environmental conditions. Second, a trade-off exists between design complexity and functional versatility, with more complex designs offering greater control but presenting fabrication and implementation challenges. Third, while significant progress has been made in hardware design and optimization techniques, the integration of these two aspects remains underdeveloped. These insights inform the research direction of this thesis, which aims to bridge the gap between theoretical RIS capabilities and practical implementation considerations for real-world wireless communication systems.

By providing a comprehensive survey of the latest advancements in RIS hardware design and communication theory, this literature review aims to identify the current state-of-the-art, highlight the potential of RIS technology in future wireless networks, and outline open research challenges to be addressed.

2.1 RIS Unit Cell Designs and Configurations

Metasurfaces, the two-dimensional counterparts of metamaterials, have emerged as a powerful tool for manipulating electromagnetic waves in a compact and efficient manner. These artificially engineered structures consist of unit cells, or meta-atoms, arranged in a periodic or quasi-periodic fashion on a flat surface. By carefully designing the geometry, size, and arrangement of these meta-atoms, researchers can tailor the electromagnetic properties of the metasurface to achieve various functionalities, such

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as anomalous reflection, perfect absorption, and polarization conversion [72–74]. The ability to control the phase, amplitude, and polarization of the reflected or transmitted waves has opened up a wide range of applications, including beam steering, focusing, and holography.

A critical analysis of the literature reveals that RIS designs can be categorized along several dimensions: (1) control mechanism (passive vs. active), (2) tuning resolution (discrete vs. continuous phase shifts), (3) operational functionality (phase-only vs. phase-and-amplitude control), and (4) polarization sensitivity (polarization-dependent vs. polarization-agnostic). These categorizations provide a framework for understanding the evolution of RIS technology and identifying areas for future development.

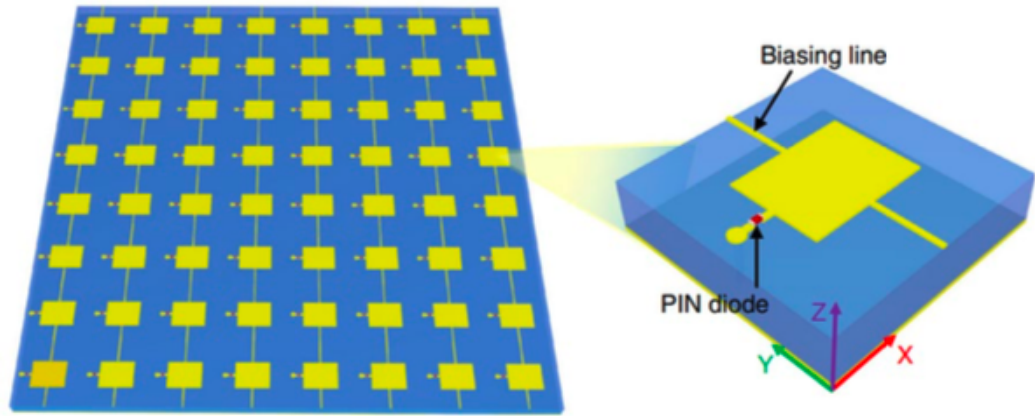


Figure 2.1: 3D perspective of an 8×8 metasurface and one of its unit cells in magnified mode [2].

In [2], the authors introduce a novel approach to control electromagnetic (EM) waves in both space and frequency domains simultaneously using digital coding metasurfaces. The key idea is to apply time-dependent coding sequences to each element of the metasurface, resulting in a space-time-coding digital metasurface. This approach enables the manipulation of the propagation direction and harmonic power distribution of the scattered EM waves.

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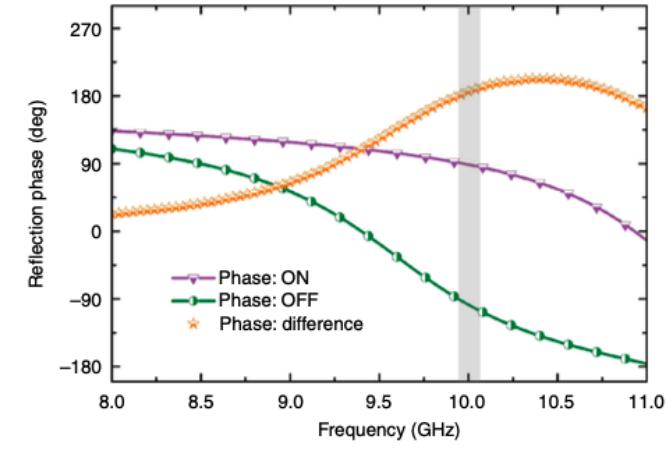
The authors propose a general theory of space-time modulated digital coding metasurfaces based on the Fourier transform method. They demonstrate the potential of their approach through several proof-of-principle examples, including harmonic beam steering, beam shaping, and scattering-signature control. A binary particle swarm optimization (BPSO) algorithm is used to design the space-time coding sequences for harmonic beam steering.

The unit cell, shown in Figure 2.1, consists of a rectangular metal patch printed on a grounded substrate (F4B with a thickness of 2 mm). A Positive-Intrinsic-Negative (PIN) diode connects the patch to the ground through a metal stub and via. By applying different voltages to the PIN diode, the reflection phase of the unit cell can be switched between two states (0° and 180°) at the operating frequency of 10 GHz.

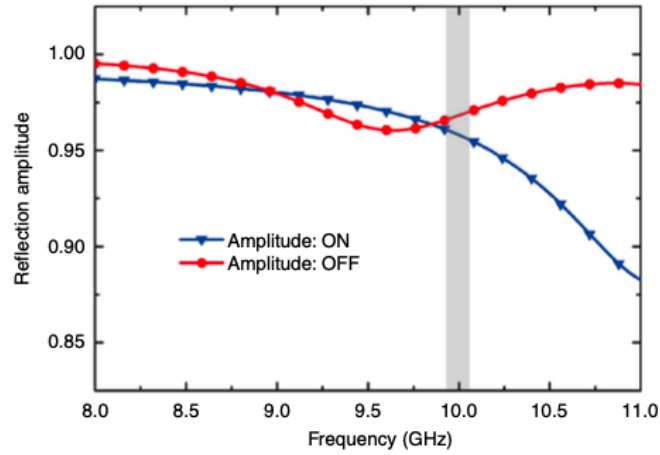
The simulated reflection phase and amplitude of the unit cell for the two diode states (ON and OFF) is shown in Figs 2.2 (a) and 2(b), respectively. When illuminated by EM waves at around 10 GHz, the unit cell can create a 180° phase shift between the ON and OFF states of the PIN diode. Additionally, at this frequency, approximately 90% of the impinging wave is reflected by the unit cell. It is worth noting that the design is sensitive to the polarization of the incident EM waves and operates within a narrow frequency band. The metasurface is controlled by an FPGA and designed to shift the frequency of the EM waves incident on its surface by switching between different diode states with a local frequency. This simple yet effective unit cell design enables the realization of the space-time-coding scheme proposed in the paper.

The space-time coding approach represents a significant advancement in RIS technology by introducing the temporal dimension to control electromagnetic waves. This enables new functionalities beyond conventional spatial-only control, such as frequency conversion and dynamic scattering pattern manipulation. However, the 1-bit phase resolution (limited to 0° and 180° states) restricts the precision of wavefront shaping, which may be insufficient for applications requiring fine-grained control. This limitation motivates

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(a)



(b)

Figure 2.2: (a) Reflection phase, and (b) reflection amplitude of the designed unit cell [2].

the development of unit cells with higher bit resolutions or continuous phase control, as seen in subsequent research.

In [3], the authors propose a metasurface design that uses a supercell instead of a single unit cell. As shown in the Figure 2.3, each unit cell consists of two patches connected by a chip with tunable resistance and capacitance values. By grouping N unit cells with different R and C values, a supercell is formed.

The main advantage of introducing the supercell concept is that it increases the number

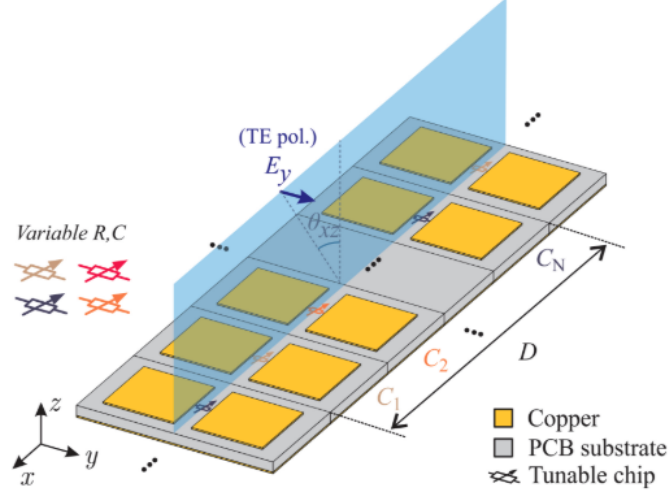


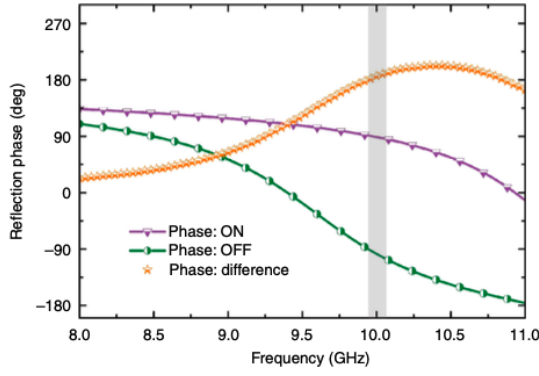
Figure 2.3: Schematic view of the supercell proposed in [3].

of tunable parameters (i.e., the capacitor values) compared to a single unit cell. This allows for a more continuously distributed phase shift across the unit cells, enabling the metasurface to act as a tunable anomalous reflector. The supercell design provides a wider tuning range for the operating frequency and incident angle. Figure 2.4 depicts the values of capacitors ($C_1, C_2, \dots, C_8$) optimized to anomalously steer the reflecting EM waves towards $\theta = 45^\circ$.

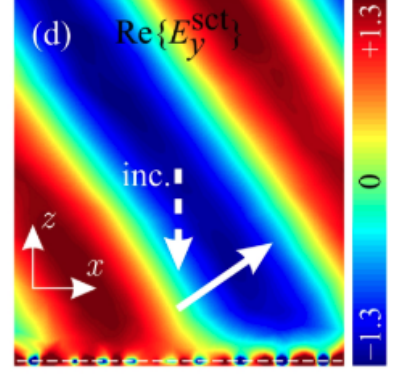
However, it is worth noting that the proposed metasurface structure is still sensitive to the polarization of the incident EM waves, which is a common limitation in many metasurface designs. Despite this drawback, the supercell approach presented in this paper offers a promising solution to achieve more versatile and reconfigurable metasurfaces by leveraging the increased number of tunable elements within each supercell.

The supercell concept represents an important architectural evolution in RIS design, addressing the limitations of binary-state unit cells by effectively creating a system with continuous phase control. This approach trades off individual unit cell simplicity for increased system-level flexibility and performance. The continuous phase control

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(a)



(b)

Figure 2.4: (a) capacitor values for a supercell with $N=8$ unit cells optimized for (b) the reflection of perpendicular incident waves towards $\theta = 0^\circ$ [3].

enabled by supercells allows for more precise wavefront shaping and beam steering capabilities, which are crucial for applications requiring high directivity or complex wave manipulation. However, this increased functionality comes at the cost of greater design complexity, more sophisticated control circuitry, and potentially higher power consumption. These trade-offs highlight a fundamental tension in RIS design between performance and practicality that persists throughout the literature.

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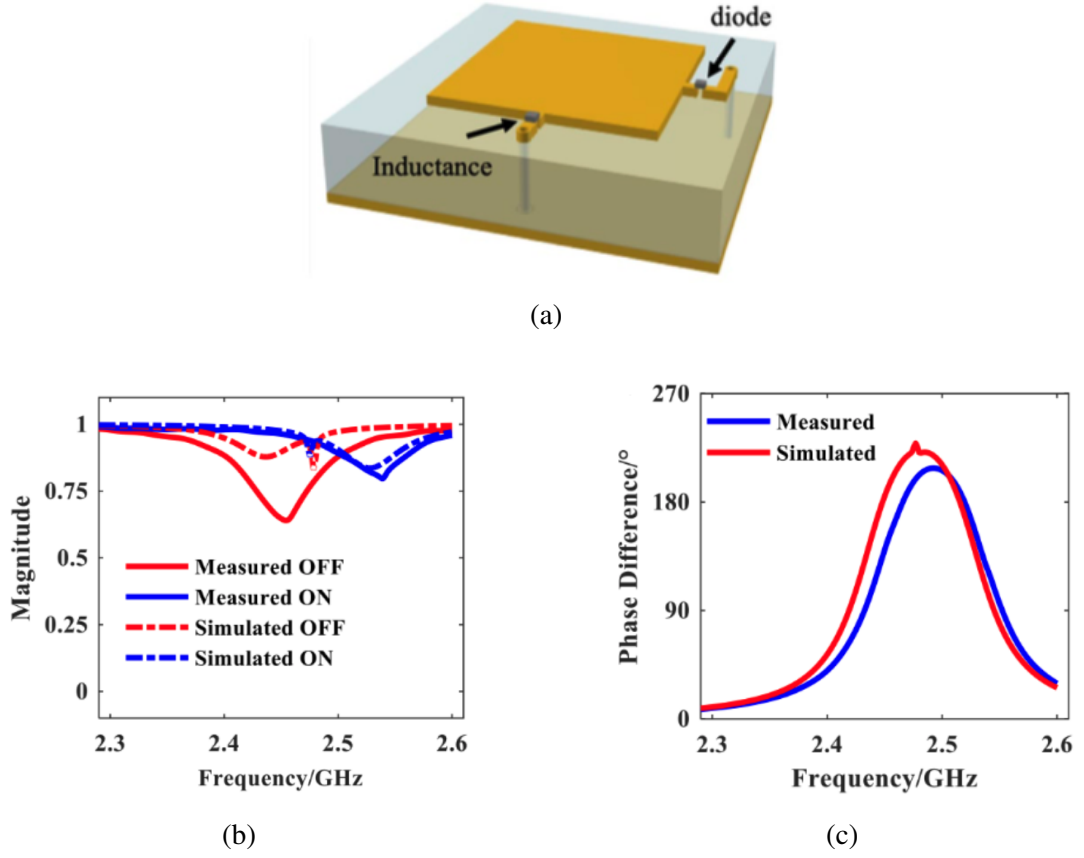


Figure 2.5: (a) Perspective view of the proposed unit cell [4], (b), (c) reflection amplitude and phase difference of the unit cell considering ON and OFF states for the integrated PIN diode.

The authors of [4] investigate the application of a metasurface in a backscatter communication system. The designed unit cell, as shown in the 3D view in Figure 2.5 (a), features a rectangular waveguide terminated with the unit cell at one end for measuring the reflection coefficients ($|S_{11}|$ and $\angle S_{11}$). When the unit cell is illuminated with normally incident EM waves at around 2.5 GHz, it can achieve a reflection phase shift of nearly 180° by switching the integrated PIN diodes between different states. These measured parameters provide insights into the reflection loss and phase delay introduced by the unit cell when set to either the ON or OFF state.

This research represents a significant shift in RIS application, moving beyond conventional reflective surfaces to enable backscatter communication. By repurposing ambient

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RF signals instead of generating new signals, this approach offers substantial energy efficiency benefits—a critical consideration for future sustainable wireless systems and IoT applications. The integration of RIS with backscatter principles demonstrates how intelligent surfaces can serve not just as passive reflectors but as active communication elements in the wireless ecosystem. This application exemplifies the versatility of RIS technology and its potential to fundamentally transform wireless network architectures.

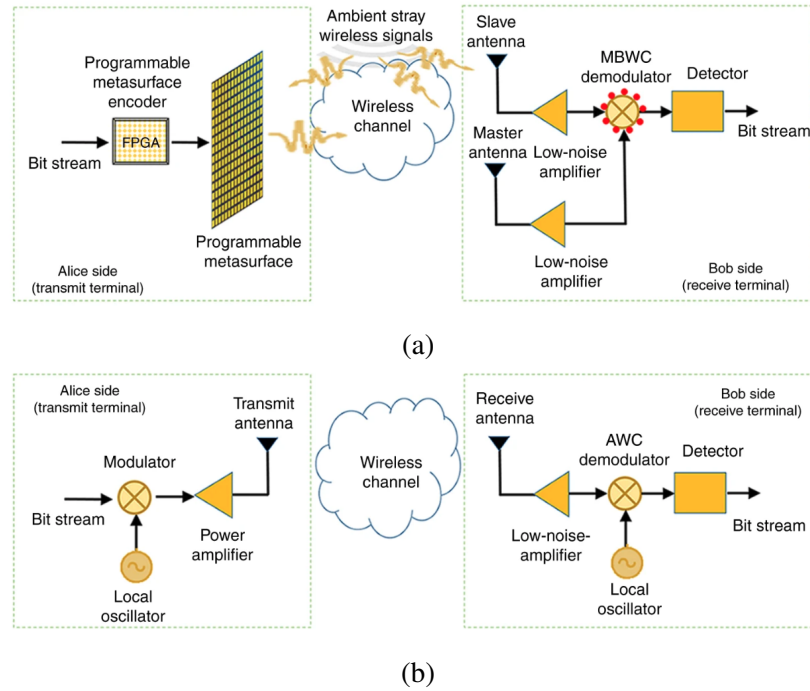


Figure 2.6: Comparison between two communication systems where in (a), a block diagram for an RIS-assisted backscatter communication, and in (b) a block diagram for an active wireless communication is illustrated [4].

The authors compare their proposed RIS-assisted backscatter communication system with a conventional active wireless communication system, as illustrated in Figure 2.6. In the RIS-based system, the metasurface is used to focus and re-modulate ambient stray signals in the environment. To send information to the receiver, the RIS must solve an optimization problem to find coding patterns that are both distinguishable at the demodulator (considering binary information quantization) and maximize the energy focused towards the receiver's location.

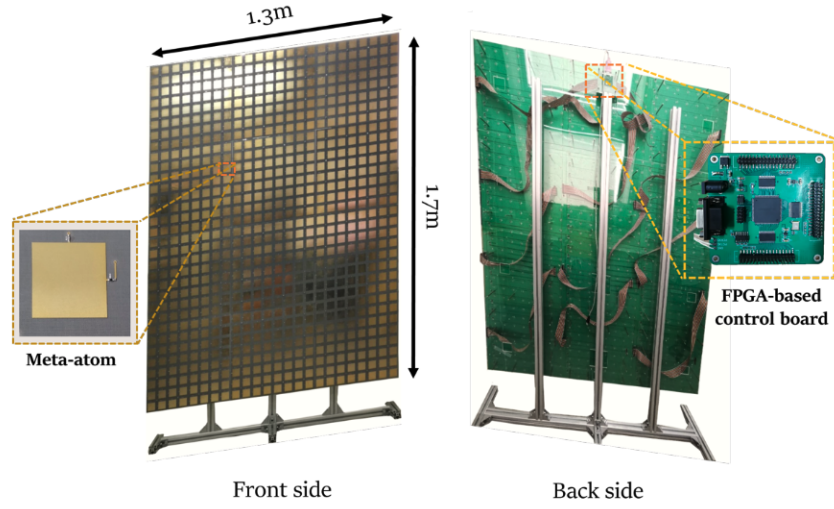


Figure 2.7: The picture of the fabricated metasurface [4].

The fabricated RIS prototype, shown in Figure 2.7, consists of 32×24 meta-atoms, each occupying an area of $54 \times 54 \text{ mm}^2$. Due to fabrication constraints, the entire metasurface is composed of 3×4 identical panels. An FPGA is used to control the metasurface by distributing commands to the individual unit cells.

This work demonstrates the potential of using RIS-assisted backscatter communication as an energy-efficient alternative to active wireless communication systems. By leveraging the ability of the RIS to modulate and focus ambient signals, the proposed system can transmit information without the need for a dedicated power amplifier, as required in conventional systems.

The work in [5] presents an RIS-assisted wireless communication system designed for the first time, using a novel unit cell for the utilized metasurface. The metasurface has 256 elements, each containing 5 PIN diodes, making it a 2-bit phase shifter. The unit cell structure (Figure 2.8) consists of two 1-mm thick FR-4 substrate layers positioned 6 mm apart in the z-axis, with two conductor layers: an upper patch and a slot-loaded plane. The ground plane is made of an aluminum sheet placed 12 mm below the slot-loaded plane.

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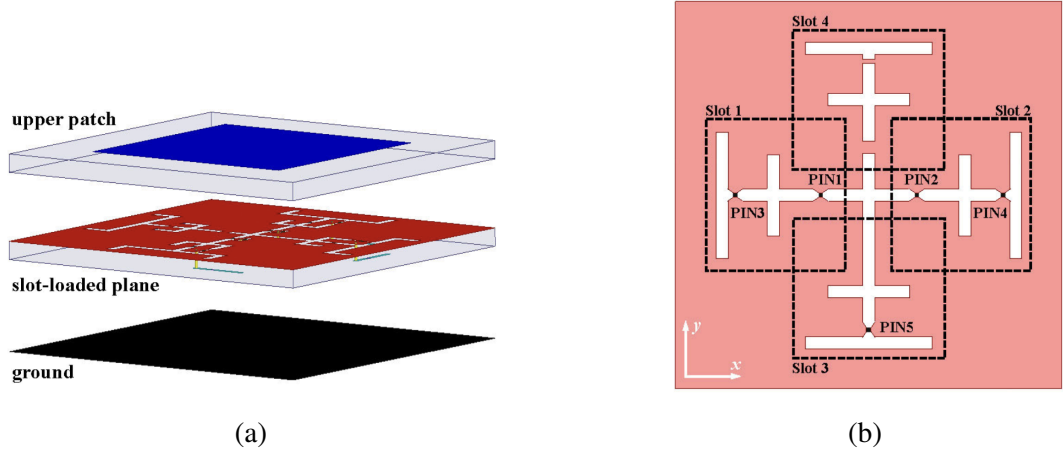


Figure 2.8: The unit cell structure proposed in [5]: (a) exploded view, (b) view of the middle layer slot-loaded plane.

The unit cell works by illuminating the upper patch with EM planar waves at a resonant frequency of 2.4 GHz, inducing currents on the slot-loaded conductor that propagate through the 4 slots based on different PIN diode configurations. These current propagation paths, as shown in Figure 2.9, produce a focused high-gain beam deviating within a two-dimensional $\pm 60^\circ$ angular range.

This implementation represents one of the first complete end-to-end demonstrations of an RIS-assisted wireless communication system, bridging the gap between theoretical RIS capabilities and practical deployment. The 2-bit phase resolution (four distinct phase states) offers a significant improvement over 1-bit designs, enabling more precise beam steering and focusing. The experimental validation of actual communication performance gains provides crucial evidence of RIS viability in real-world systems. However, the bulky multi-layer structure highlights persistent challenges in creating compact, aesthetically acceptable RIS designs suitable for indoor deployment—an important consideration for widespread adoption in consumer applications.

As depicted in Figure 2.10, the RIS-aided wireless communication model transmits data from the transmitter to the receiver as follows:

1. The signal is generated using software installed on the transmitter host.

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Configuration	PIN1/PIN2	PIN3	PIN4	PIN5
1	ON/OFF		ON	
2	OFF/ON			
3	ON/OFF		OFF	
4	OFF/ON			

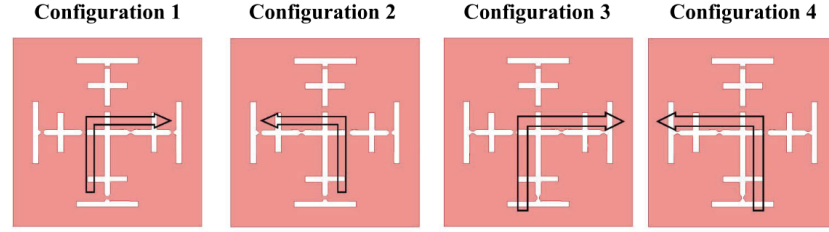


Figure 2.9: Illustration of current paths associated with different configurations for PIN diodes [5]

2. The signal is handed to the USRP, where the signal is transferred into a suitable form for propagation through a wireless channel.
3. The RIS, with its illuminated 256 elements, will generate a focused beam that can be directed towards different angles.
4. The pass-band signal is received at the user side and decoded.

The authors state that substituting the RIS for conventional phased-array antennas has led to a 58.6% reduction in power consumption. However, the RIS proposed lacks a seamless structural form due to the comprising layers being placed at a certain distance from each other, making the structure hefty and useless for indoor environments. The RIS is only useful when the transmitter is positioned in a fixed area, like in front of the surface. Designing RIS structures that can improve wireless communications quality regardless of the transmitter and receivers' positions is suggested.

Authors in [6] introduce a reconfigurable metasurface that can adapt its functionality, such as the direction of the reflected beam, based on its position and orientation (Figure 2.11). The metasurface incorporates sensors to gather information about its

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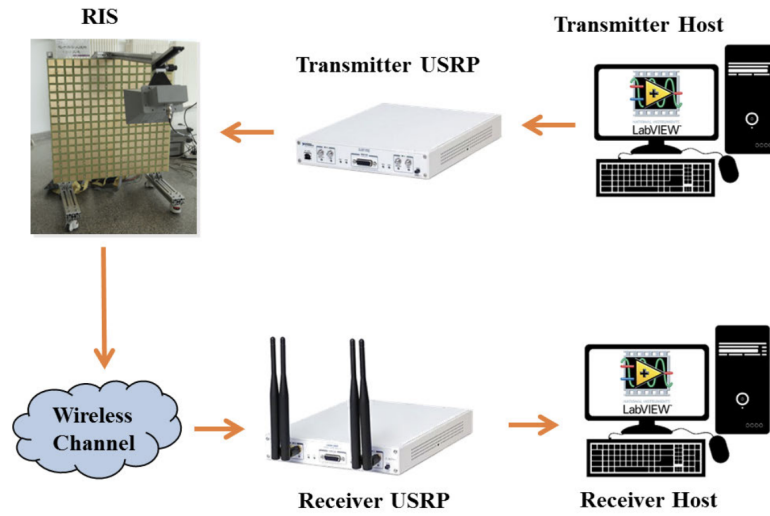


Figure 2.10: The RIS-assisted wireless communication model [5].

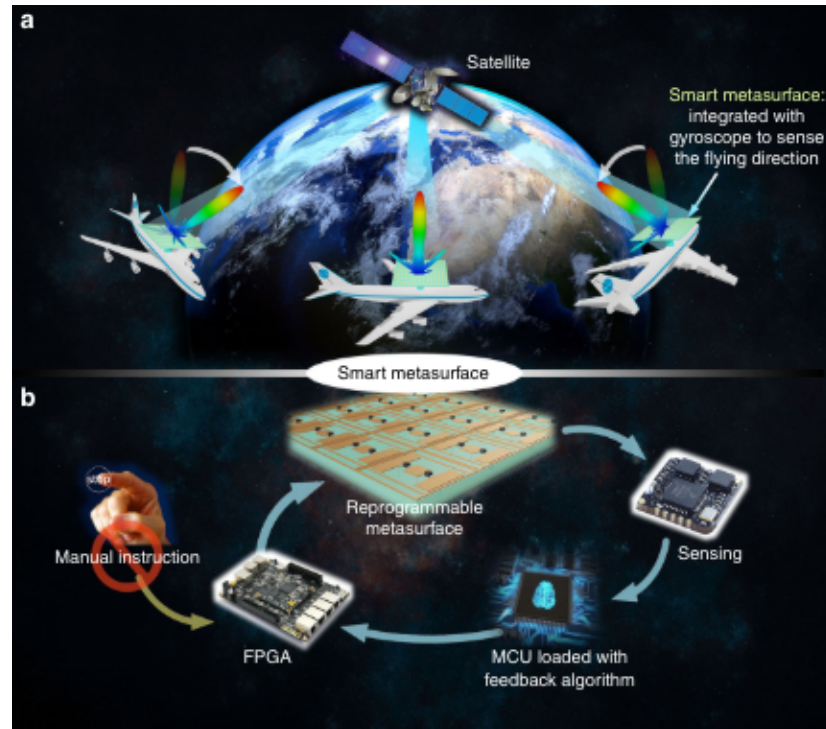


Figure 2.11: (a) Depicts the smart metasurface with self-adaptive reprogrammable functions that operate without manual intervention [6]. (b) Shows the closed-loop system of the smart metasurface, comprising a digital-coding metasurface, an FPGA, a sensor, and an MCU equipped with a fast feedback algorithm [6].

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spatial attitude, movement status, and temperature. This data is sent to a microcontroller unit (MCU) which processes it and instructs a field-programmable gate array (FPGA) to adjust the phase distribution of the metasurface elements. This enables the metasurface to maintain a consistent reflection pattern regardless of its position or orientation.

One potential application for this self-adaptive metasurface is in airplane positioning systems. Traditionally, complex devices like phased arrays and beam steering units are used to maintain constant communication between airplanes and satellites. However, the proposed intelligent metasurface could achieve the same goal more efficiently and with less complexity.

The self-adaptive metasurface concept represents a significant advancement toward truly intelligent surfaces that can autonomously respond to changing conditions. By incorporating sensing and feedback capabilities, this design moves beyond pre-programmed behavior to create a closed-loop system capable of maintaining performance under dynamic conditions. This evolution toward environmental awareness and autonomous adaptation addresses a key limitation of earlier RIS designs—their dependence on external control systems with perfect environmental knowledge. Such autonomous capability is essential for practical deployments in mobile scenarios like vehicular communications, where orientation and position constantly change.

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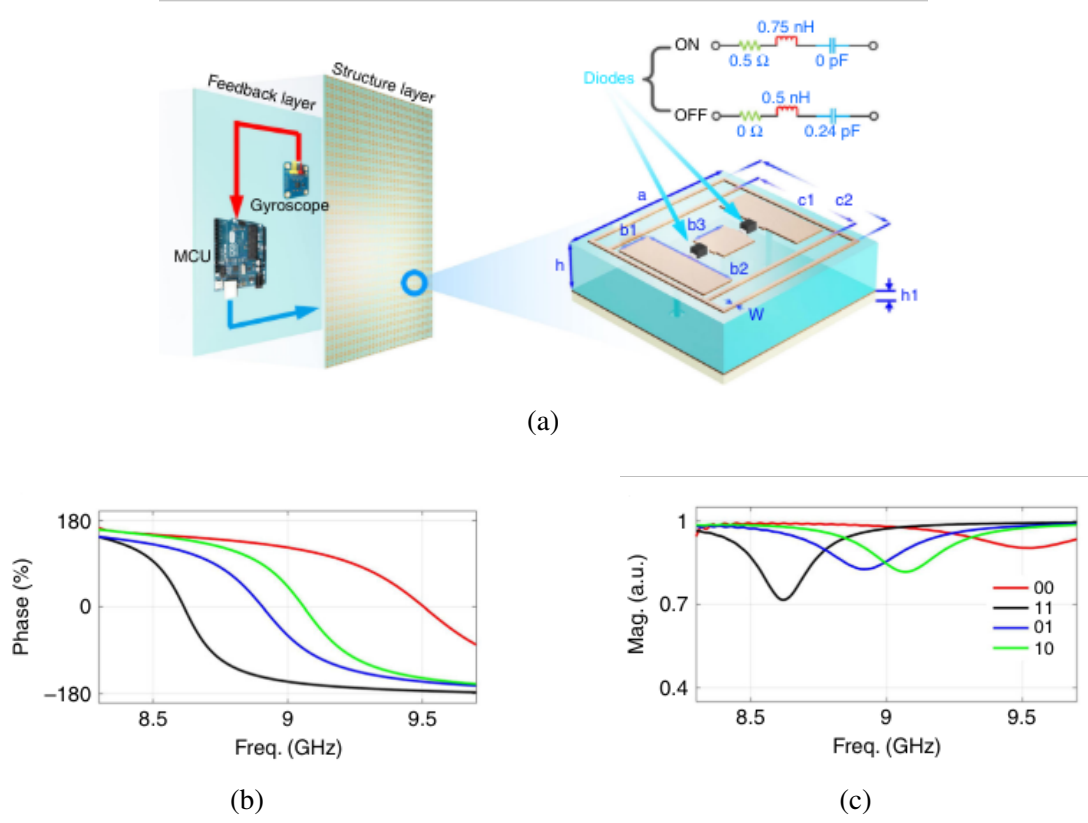


Figure 2.12: (a) Illustration of the metasurface design, (b) the phase response, and (c) the magnitude response of the unit cell for various states of the PIN diodes [6].

The unit cell of the metasurface consists of two substrate layers (a 1.6mm-thick F4B upper layer and a 0.5mm-thick FR4 lower layer) and two PIN diodes embedded in the upper patch. The unit cell designed has been depicted in Figure 2.12. At an operating frequency of 9 GHz, switching between different PIN diode states produces four distinct phase and amplitude values for the reflected waves. While this design enables some degree of self-adaptability, it requires the illuminating EM waves to come from a fixed source positioned in front of the metasurface, such as a horn antenna. Additionally, the unit cell is sensitive to the polarization of the incident waves, and the bandwidth over which the phase shifts remain linear appears to be limited.

Work in [7] presents a programmable metasurface cloak that utilizes deep learning to adapt to changing incident waves and surrounding environments in milliseconds. The

2.1 RIS UNIT CELL DESIGNS AND CONFIGURATIONS

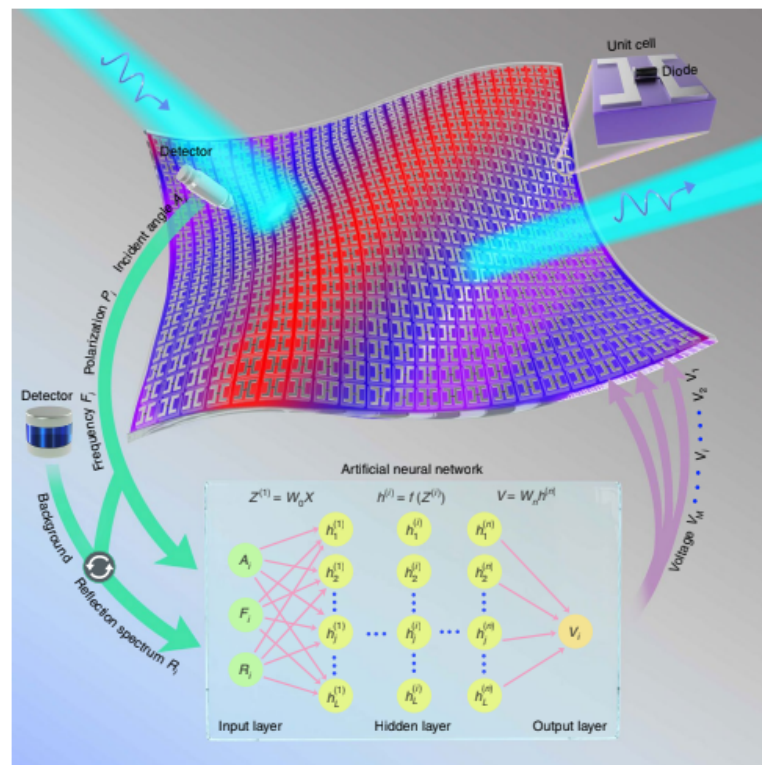


Figure 2.13: Illustration of a self-adaptive metasurface cloak enabled by deep learning [7].

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system takes three input parameters (frequency, polarization, and incident angle of the impinging EM waves) and feeds them into an artificial neural network (Figure 2.13). The network then determines the necessary phase distribution to render the metasurface invisible under the incident EM waves. In other words, the deep-learning-enabled metasurface interacts with the incident waves in such a way that an observer perceives a reflection pattern identical to one without the metasurface present.

The integration of deep learning with RIS technology represents a paradigm shift in how these surfaces are controlled. Rather than relying on traditional optimization algorithms that may struggle with complex, non-linear electromagnetic interactions, neural networks can learn these relationships directly from data. This approach enables rapid adaptation to changing conditions—reducing response time from seconds to milliseconds—and potentially overcomes the need for perfect channel state information that plagues many RIS optimization methods. The cloaking application demonstrates how RIS can not only enhance signals but also suppress them when needed, expanding the functionality spectrum to include selective signal management. This convergence of artificial intelligence and metamaterials points toward a future where surfaces can learn optimal configurations for different scenarios without explicit programming.

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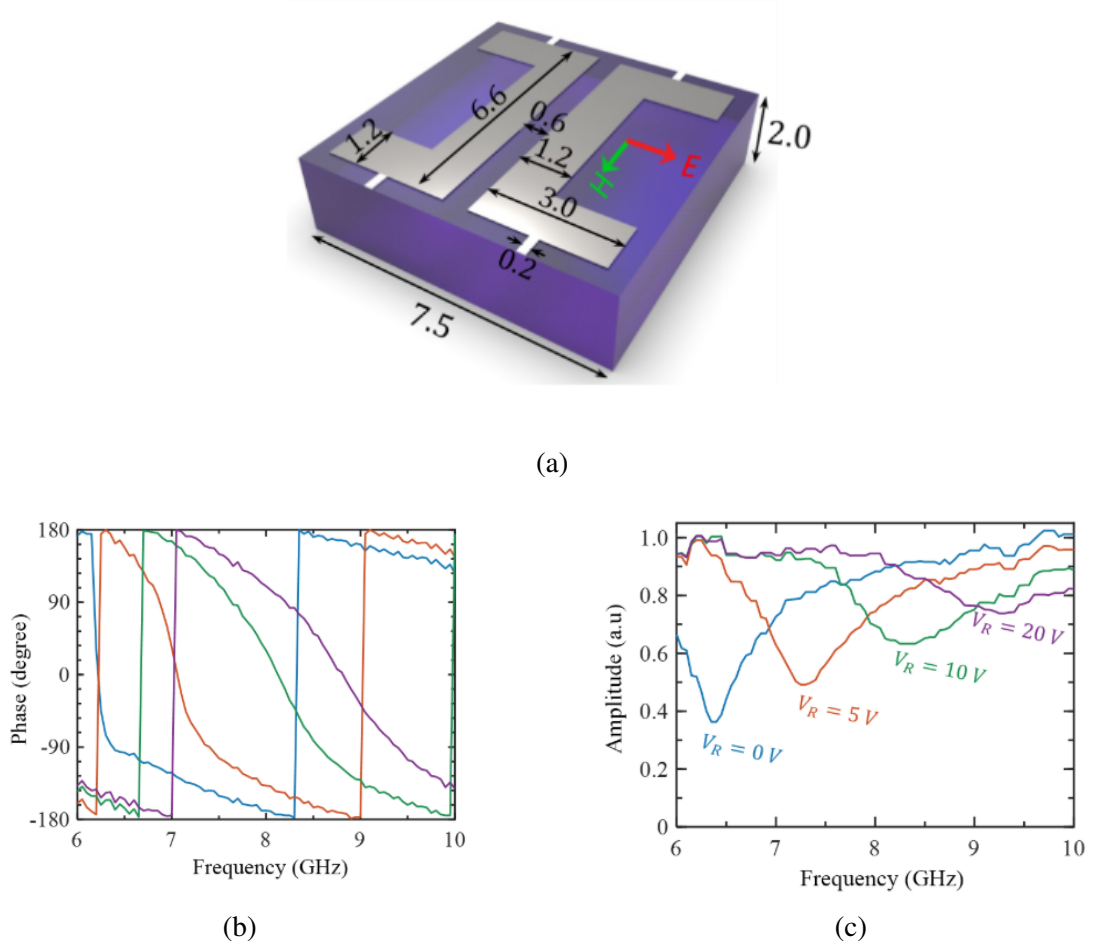


Figure 2.14: (a) The perspective view, (b), (c) measured reflection phase and amplitude of the unit cell proposed in [7].

The unit cell design in this work consists of three layers: a top copper pattern, a dielectric substrate, and a bottom ground plane. By adjusting the geometry of the top copper pattern, the phase and amplitude of the reflected waves can be controlled (Figure 2.14). The deep learning model is trained using a dataset of simulated reflection coefficients corresponding to different geometric parameters of the unit cell. Once trained, the model can predict the appropriate unit cell geometry for any given set of input parameters, enabling the metasurface to adapt its cloaking functionality in real-time.

Both research works [6, 7] demonstrate significant advancements in the development

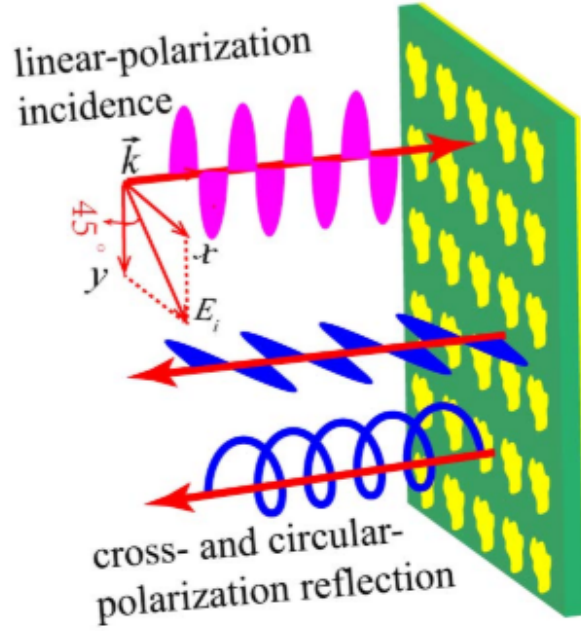


Figure 2.15: The schematic model of a reflect polarization active converter [8]

of self-adaptive metasurfaces. The ability of these surfaces to dynamically adjust their electromagnetic properties in response to changing conditions opens up new possibilities for applications in wireless communication, sensing, and cloaking. However, challenges remain in terms of improving the bandwidth, reducing the sensitivity to polarization, and extending the adaptability to scenarios where the illuminating source is not fixed relative to the metasurface. Future research could explore novel unit cell designs, advanced control algorithms, and the integration of more sophisticated sensing and learning capabilities to further enhance the performance and practicality of self-adaptive metasurfaces.

In the literature reviewed thus far, the primary focus of metasurface structures has been on their ability to modify the reflection phase and amplitude. However, there is another critical functionality that metasurfaces can provide: polarization conversion. This functionality allows the metasurface to receive electromagnetic (EM) waves with one polarization and reflect them with a different polarization, such as converting linearly polarized waves to circularly polarized waves or enabling cross-polarization conversion.

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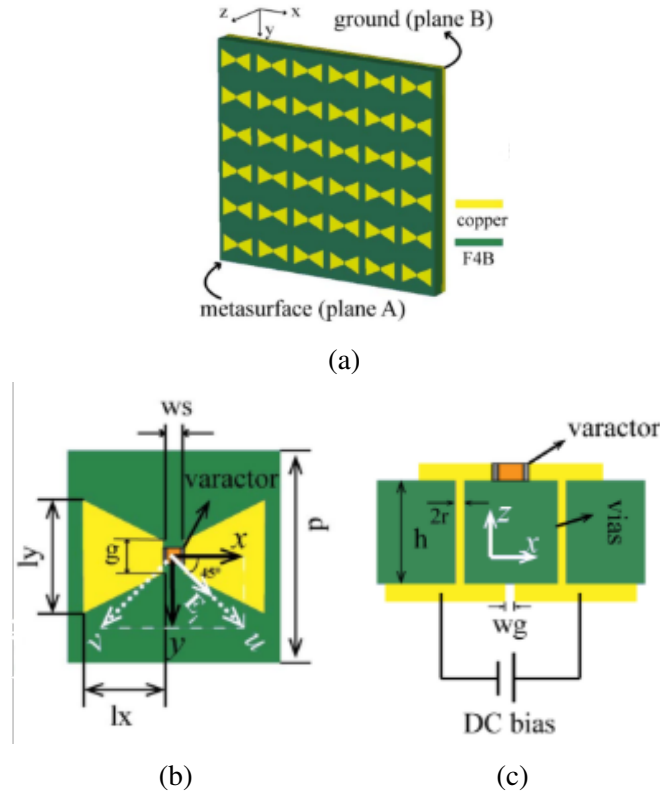


Figure 2.16: (a) The schematic view, (b) upper view, and (c) side view of the unit cell of the designed metasurface [8].

Recent studies have explored this polarization conversion capability extensively, recognizing its potential benefits for future communication systems that leverage multiple polarization methods for more efficient communication between various devices. Notably, research conducted in [72–74] has been pioneering in the development of passive metasurface-based polarization converters. In this context, "passive" indicates that the metasurface structures do not incorporate active components such as PIN diodes, varactor diodes, or integrated circuits (ICs).

The evolution of RIS design to include polarization control represents a critical advancement that addresses a fundamental limitation of earlier designs. Most early RIS structures were inherently polarization-sensitive, functioning optimally only for specific polarization states. By enabling polarization conversion and control, these newer designs unlock the polarization domain as an additional degree of freedom for communication

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system design. This capability is particularly valuable for modern MIMO systems that utilize polarization diversity to increase channel capacity without additional spatial dimensions. The transition from passive to active polarization control further enhances this functionality by enabling dynamic adaptation to changing channel conditions or communication requirements.

However, due to the increasing demand for configurability and self-adaptivity, research has shifted towards active metasurface structures that operate in multi-mode. An example of such a metasurface with active elements is presented in [8], where a metasurface-based polarization converter can achieve linear-to-linear or linear-to-circular polarization conversion by adjusting the bias voltage of an embedded varactor diode (0 V and -19 V) (Figure 2.15). Figure 2.16 provides (a) a schematic view and (b) an upper view, and (c) a side view of the unit cell of the designed metasurface, which consists of a single layer of F4B with a thickness of 6mm.

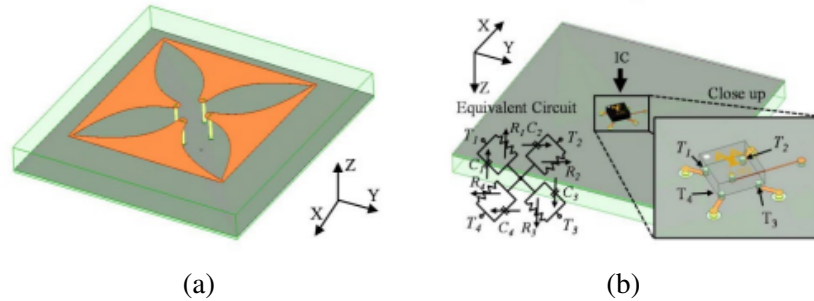


Figure 2.17: Perspective view of a meta-atom proposed in [9]; (a) top view, (b) bottom view showing the IC and its equivalent circuit.

Although the active metasurface design in [8] demonstrates significant functionality, it is limited to polarization transformation with two distinct modes. In contrast, the authors of [75] have developed a multifunctional active metasurface capable of both beam deflection and polarization conversion. The most advanced metasurface structures, incorporating programmable ICs to achieve reconfigurability in absorption, anomalous reflection, and polarization conversion, are discussed in [9, 75, 76]. Figure 2.17 presents

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a meta-atom from [9], showing (a) a top view and (b) a bottom view with the IC and its equivalent circuit, which features eight tunable parameters ($R1, C1$ to $R2, C2$).

The integration of custom ICs into RIS designs represents the cutting edge of current research, enabling unprecedented levels of functionality and control precision. These designs mark the transition from simple, discrete-state elements to fully programmable unit cells with near-continuous tuning capabilities for both amplitude and phase. This advancement enables more sophisticated electromagnetic wave manipulation, including simultaneous control of multiple parameters (phase, amplitude, polarization) that was impossible with earlier designs. The use of specialized ICs also offers a path to address practical implementation challenges like power consumption, control complexity, and fabrication reproducibility. However, these benefits come with increased manufacturing complexity and cost, presenting a commercialization challenge that must be addressed for widespread adoption.

While these innovative metasurface structures offer multiple functionalities, they also come with challenges such as fabrication difficulties, narrow bandwidth, and complex DC biasing requirements. Table 2.1 provides a comparative summary of various designed metasurfaces, highlighting their functionalities and design complexities. This comparison underscores the progress and ongoing challenges in developing versatile and efficient metasurfaces for advanced applications.

The literature review reveals a clear evolutionary trajectory in RIS design, from simple single-function surfaces to complex multi-functional intelligent systems. This progression has been driven by increasingly sophisticated hardware architectures and control methods, culminating in designs that integrate sensing, feedback, and machine learning capabilities. Throughout this evolution, researchers have navigated fundamental trade-offs between performance parameters (resolution, tunability, functionality) and practical considerations (complexity, power consumption, size). The insights gained from analyzing these trade-offs inform this thesis's approach to RIS design and optimization,

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emphasizing solutions that balance theoretical performance gains with implementation feasibility.

Table 2.1: Summary of the Metasurface Structures and their Applications

Reference	RIS Application	Design Complexity	Bit Control of Reflection	Functionalities
[2]	Space-time coding reflection	Low	1	Phase control
[3]	-	Moderate (bulky)	Continuous	Phase control
[4]	Backscatter communication	Low	1	Phase control
[5]	Wireless communication	High	2	Phase control
[6]	Satellite communications	Moderate	2	Phase control
[7]	Cloaking	Low	2	Phase control
[63]	Polarization converter	Low	2	Phase and polarization control
[76]	-	High	Semi-continuous	Phase and amplitude control

2.2 Optimization Techniques for RIS-Assisted Wireless Networks

In the previous section, we explored the hardware aspects of RIS structures and discussed some potential applications for these intelligent surfaces. This section, however, will focus exclusively on the system developments that have been made in the context of emerging RIS technology integrated with conventional wireless networks. We will begin by covering the fundamental concepts of RIS-assisted wireless networks in detail. Following this, we will delve into the latest research efforts aimed at optimizing the reflection properties of intelligent surfaces and developing robust channel models for wireless networks that utilize RIS technology. Finally, we will examine the various models of RIS-assisted wireless networks developed through ray-tracing techniques.

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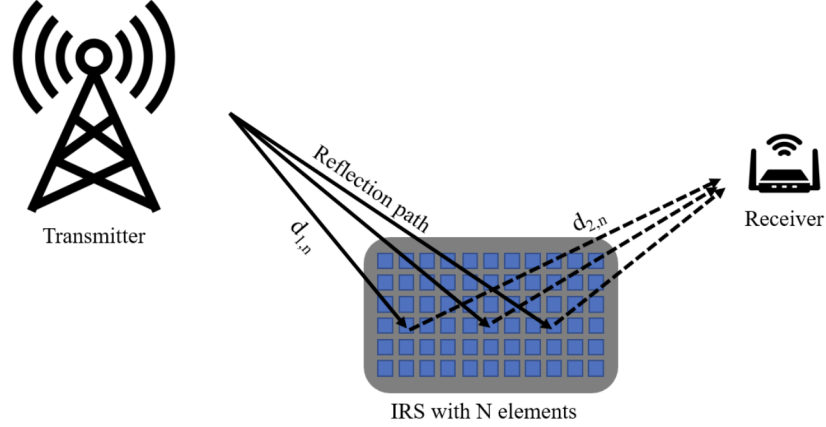


Figure 2.18: Illustration of the channel model for an RIS-assisted wireless communication.

One of the fundamental aspects of RIS-assisted wireless communication is the channel model. In a basic single-user scenario, the RIS introduces additional signal paths between the transmitter (e.g., base station or access point) and the receiver (user). As illustrated in Figure 2.18, the received signal at the user is a combination of the direct path from the transmitter and the reflected paths from the RIS elements.

For simplicity, we consider a scenario with a single transmitter, such as a Base Station (BS), and a receiver in a wireless communication system (Figure 2.18). As illustrated in the figure, with N elements in the RIS, there are N distinct paths from the BS to the receiver. We assume the communication operates in a narrowband system at a given carrier frequency f_c . Let $x(t)$ denote the complex-valued baseband signal transmitted from the BS. Initially, we focus on the propagation of the signal reflected from a single element (n -th element, where $n \in \{1, 2, \dots, N\}$) of the RIS. As shown in Figure 2.18, considering only one reflecting element, the signal travels via two paths from the BS to the receiver: the BS-to-RIS path and the RIS-to-receiver path. Given these assumptions, the passband signal $y_n(t)$ received is described as follows:

$$y_n(t) = \Re \left\{ \left[\alpha_{1,n} e^{-j\xi_{1,n}} \beta_n e^{j\theta_n} \alpha_{2,n} e^{-j\xi_{2,n}} x(t) \right] e^{j2\pi f_c t} \right\} \quad (2.1)$$

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where $\alpha_{1,n}, \xi_{1,n}, \alpha_{2,n}, \xi_{2,n}$ represent the attenuation coefficients and phase shifts that the signal undergoes while passing through the BS-RIS and RIS-receiver channels, respectively. Additionally, β_n and θ_n denote the amplitude coefficient and phase shift induced by the n -th unit cell on the RIS's surface, where $\theta_n \in [0, 2\pi]$ and $\beta_n \in [0, 1]$. We can redefine Eq. 2.1 by introducing two parameters for the BS-RIS and RIS-receiver channels: $h_{r,n}^* = \alpha_{1,n}e^{-j\xi_{1,n}}$ and $g_n = \alpha_{2,n}e^{-j\xi_{2,n}}$. Now, the baseband signal model of (1) is described by:

$$y_n(t) = \beta_n e^{j\theta_n} h_{r,n}^* g_n x(t) \quad (2.2)$$

If we consider only the first reflection from the surface and ignore subsequent reflections due to high path loss, as well as neglect the coupling effects between neighboring elements, the total received signal at the receiver can be obtained by superimposing the reflected signals from each unit cell of the metasurface. Thus, the total received signal $y(t)$ at the receiver is given by:

$$y(t) = \left(\sum_{n=1}^N \beta_n e^{j\theta_n} h_{r,n}^* g_n \right) x(t) = \mathbf{h}_r^H \mathbf{\Theta} \mathbf{g} x(t) \quad (2.3)$$

In Eq. 2.3, $\mathbf{h}_r^H = [h_{r,1}^*, h_{r,2}^*, \dots, h_{r,N}^*]$, $\mathbf{\Theta} = \text{diag}(\beta_1 e^{j\theta_1}, \beta_2 e^{j\theta_2}, \dots, \beta_N e^{j\theta_N})$, and $\mathbf{g} = [g_1, g_2, \dots, g_N]^T$, with $\text{diag}(x)$ denoting a diagonal matrix with the elements in x on its main diagonal. Note that from now on, vectors and matrices are denoted by bold-face lower-case and upper-case letters. Based on the far-field propagation condition, it can be assumed that the average received power from the signal reflected by the n -th element of the RIS ($P_{r,n}$) is inversely proportional to $d_{1,n}^{a_1} d_{2,n}^{a_2}$, where a_1 and a_2 denote the corresponding path loss exponents that typically range between 2 and 6, given by the following formula [77]:

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$$P_{r,n} \propto \frac{1}{d_{1,n}^{a_1} d_{2,n}^{a_2}} \quad (2.4)$$

It is worth noting that if the RIS is replaced by an infinitely large Perfect Electric Conductor (PEC), the total received signal power, P_r , is inversely proportional to the square of the summation over the distances between the two-hop links based on free-space propagation assumption and image theory [78], which is given by:

$$P_r \propto \frac{1}{(d_1 + d_2)^2} \quad (2.5)$$

So far, we have become familiar with the basic principles of the channel model of a simple RIS-assisted point-to-point wireless communication. Now, it is time to study the reflection optimization of the RIS in wireless communication under various system configurations, such as single-user single-antenna, multi-user multi-antenna, narrowband, and broadband system setups.

We first consider an RIS-assisted wireless communication system with one antenna and one user (SISO configuration), where the Access Point (AP) serves the user through a narrowband system over a flat-fading channel. In this context, $\mathbf{g}$, $\mathbf{h}_r^H$, and $\mathbf{h}_d^*$ represent the channels between the AP and the RIS, the RIS and the user, and the AP and the user, respectively. Referring to the reflection model given in Eq. 2.3 and considering a direct path between the transmitter and receiver, the received signal can be formulated as:

$$y = (\mathbf{h}_r^H \mathbf{\Theta} \mathbf{g} + \mathbf{h}_d^*) \sqrt{P_t} x + z, \quad (2.6)$$

where z is the additive white Gaussian noise (AWGN) with zero mean and variance σ^2 . It should be noted that from now on, the parameter t (e.g., $x(t) \rightarrow x$) has been omitted for simplicity. P_t is the total signal power emitted by the antenna, and x represents the transmitted information signal modeled as an independent and identically distributed

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(i.i.d.) random variable with zero mean and unit variance. As such, the Signal-to-Noise Ratio (SNR) at the receiver is represented as [79]:

$$\gamma = \frac{P_t |\mathbf{h}_r^H \mathbf{\Theta} \mathbf{g} + \mathbf{h}_d^*|^2}{\sigma^2} = \frac{P_t \left| \sum_{n=1}^N h_{r,n}^* \beta_n e^{j\theta_n} g_n + h_d^* \right|^2}{\sigma^2} \quad (2.7)$$

Formulating the SNR, one can calculate the maximum achievable rate in bits per second per Hertz (bps/Hz), which is represented by $r = \log_2(1 + \gamma)$. Our objective is to maximize the achievable rate or SNR, and we have two sets of parameters, θ and β , which we can optimize. Considering full knowledge of the channels $\mathbf{g}$, $\mathbf{h}_r^H$, and $\mathbf{h}_d^*$, the optimization problem we need to solve is written as:

$$\begin{aligned} \text{(P1):} \quad & \max_{\theta, \beta} \left| \sum_{n=1}^N h_{r,n}^* \beta_n e^{j\theta_n} g_n + h_d^* \right|^2 \\ \text{s.t.} \quad & 0 < \theta_n < 2\pi, \quad n = 1, \dots, N; \\ & 0 < \beta_n < 1, \quad n = 1, \dots, N. \end{aligned} \quad (2.8)$$

In (P1), $\theta = [\theta_1, \dots, \theta_N]^T$ and $\beta = [\beta_1, \dots, \beta_N]^T$, which denote the reflection phase shift and amplitude induced by the RIS, respectively. According to [79, 80], the optimal phase distribution for the RIS (solutions to (P1)) is given by:

$$\theta_n = \text{mod} [\zeta - (\phi_n + \psi_n), 2\pi], \quad n = 1, \dots, N \quad \text{for } \beta > 0 \quad (2.9)$$

where ζ , ϕ_n , and ψ_n are the phases of g_n , h_d^* , and $h_{r,n}^*$, respectively. It is worth noting that Eq. 2.9 is independent of the matrix β . It is evident that only with a set of phase distributions calculated using Eq. 2.9 and an RIS comprising lossless unit cells ($\beta = 1$) can we achieve an SNR to its maximum value with (P1).

Now, let us increase the complexity of the wireless communication system by adding more antennas at the AP side, i.e., a MISO wireless channel. Having more than one

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antenna at the transmitter means that beamforming can be performed by the AP (active beamforming) and the RIS (passive beamforming) separately. Before proceeding further, it is important to note that if there is a direct path between the transmitter and receiver, it is best for the AP to direct its beam towards the user due to the superiority of active beamforming over passive beamforming, considering the double path loss for the latter. For the new system, the optimization problem is given as:

$$\begin{aligned}
 (\text{P2}): \quad & \max_{\omega, \theta} |(\mathbf{h}_r^H \Theta \mathbf{G} + \mathbf{h}_d^H) \omega|^2 \\
 \text{s.t.} \quad & \|\omega\|^2 \leq P_t, \\
 & 0 < \theta_n < 2\pi, \quad n = 1, \dots, N.
 \end{aligned} \tag{2.10}$$

where P_t , ω , and $\mathbf{G}$ denote the total transmit power, transmit beamforming vector at the AP (active beamforming), and channel matrix from the AP to the RIS, respectively. Analyzing (P2), we observe that (P2) is a non-convex optimization problem because its objective function is not concave with respect to ω and θ and the coupling between them. However, (P2) can be considered a convex optimization problem if ω is fixed in the first step, transforming (P2) into a SISO wireless system optimization problem (P1). Conversely, the parameters of the RIS (θ) can be set to fixed values while ω is optimized for the best SNR. Sub-optimality can be achieved by utilizing the two mentioned optimization problems in an iterative loop [80].

In general, several methods have been proposed in recent works to obtain suboptimal solutions to (P2). In [81], the phase shift value for each unit cell is optimized in a closed form, while other phase shifts are fixed in each iteration. A branch-and-bound algorithm is introduced in [82] that guarantees globally optimized solutions for the antennas at the AP and phase shifters at the RIS. Additionally, authors in [83] have deployed deep reinforcement learning to obtain phase shifts for the RIS, maximizing the downlink SNR with relatively low computational complexity and running time.

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Previously, we investigated SISO and MISO RIS-assisted wireless communication systems. Now, it is time to explore RIS-aided MIMO systems and review the pertinent literature. It is worth noting that transitioning from SISO to MIMO systems significantly increases the complexity of the contributing optimization problems. Notably, in MIMO systems, spatial multiplexing techniques are widely used to transmit multiple data streams simultaneously to different antennas, thereby enhancing system performance. Consequently, for further enhancement, the reflection coefficients of the RIS must be optimized in conjunction with the transmit covariance matrix at the transmitter [10]. The optimization problem for an RIS-assisted MIMO system is examined in the following section.

According to [10], the channel of an RIS-assisted MIMO system setup can be described as:

$$\hat{\mathbf{H}} = \mathbf{H}_d + \mathbf{H}_r \mathbf{\Theta} \mathbf{G} \quad (2.11)$$

where $\mathbf{H}_d \in \mathbb{C}^{N_r \times N_t}$, $\mathbf{G} \in \mathbb{C}^{N \times N_t}$, and $\mathbf{H}_r \in \mathbb{C}^{N_r \times N}$ describe the channels from the AP to the user, from the AP to the RIS, and from the RIS to the user, respectively. Now, if we let $\mathbf{Q} \in \mathbb{C}^{N_t \times N_t}$ denote the transmit covariance matrix, with N_r and N_t specifying the number of antennas at the AP and the user, the optimization problem for the channel capacity is given as:

$$\begin{aligned} \text{(P3): } & \max_{\mathbf{Q}, \mathbf{\Theta}} \log_2 \det \left(\mathbf{I}_{N_r} + \frac{1}{\sigma^2} \hat{\mathbf{H}} \mathbf{Q} \hat{\mathbf{H}}^H \right) \\ \text{s.t. } & 0 < \theta_n < 2\pi, \quad n = 1, \dots, N; \\ & \beta_n = 1, \quad n = 1, \dots, N; \\ & \text{tr}(\mathbf{Q}) \leq P_t; \\ & \mathbf{Q} \succeq 0. \end{aligned} \quad (2.12)$$

The optimization problem shown in Eq. 2.12 is a non-convex problem, and it should

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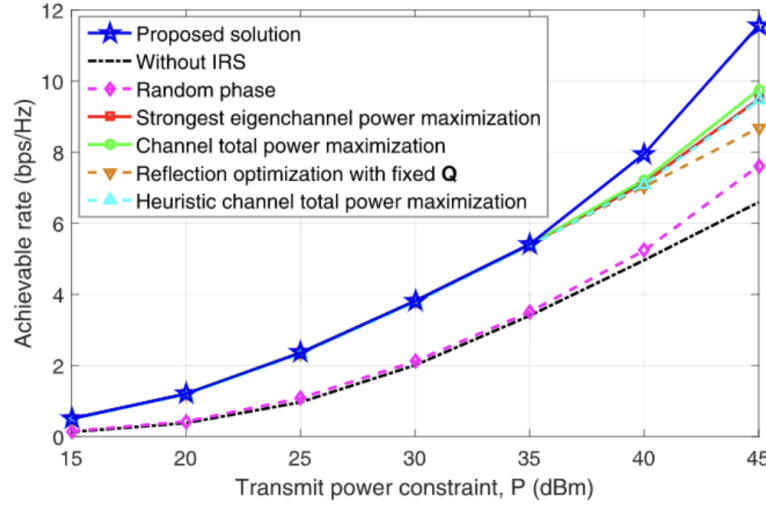


Figure 2.19: Achievable rate versus Transmit power for an RIS-aided MIMO system [10].

be noted that (P3) is more difficult to solve compared to (P1) and (P2). Reference [10] has proposed an Alternating Optimization (AO) algorithm that can calculate at least one local solution to (P3). This AO-based algorithm iteratively optimizes the phase shift of one element of the RIS (θ_n) and the transmit covariance matrix ($\mathbf{Q}$) at each step, with other parameters fixed. Figure 2.19 shows the performance of the AO-based algorithm in enhancing the achievable rate of an RIS-assisted MIMO system. In [84], a novel study has been conducted on a MIMO system with two RISs assisting the network. Furthermore, a low-complexity algorithm has been introduced to maximize the channel throughput by optimizing the phase shifts of the two RISs as well as the transmit covariance matrix. It should be noted that in this work, the number of antennas at the AP/user is fixed.

So far, the RIS-assisted wireless systems that have been mentioned earlier have all served a single user. In this part of the review, we will explore research works that have studied SISO and MISO wireless systems with multiple users (Figure 2.20). In this regard, [85] can be mentioned as one of the first works that investigated which multiple access schemes can benefit most from RISs present in the network. In this work, with

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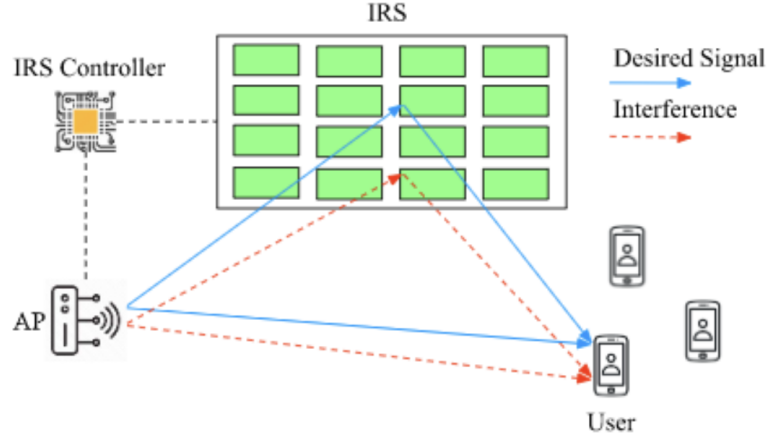


Figure 2.20: An RIS-assisted multi-user MISO system [11].

the assistance of an RIS, two users are served by a multi-antenna AP using either time division multiple access (TDMA), frequency division multiple access (FDMA), or non-orthogonal multiple access (NOMA) network schemes. Under such a setup, it was shown that TDMA may perform better than FDMA in RIS-assisted multiple access wireless networks, while NOMA can perform even better when compared with the two orthogonal multiple access techniques (i.e., TDMA and FDMA).

It should be noted that the system setup in this work has been catered for only two users. In the case of a multi-user RIS-assisted wireless network with $K > 2$, calculating an optimized phase distribution for the RIS under FDMA and NOMA configurations becomes challenging. To overcome such difficulty, [86] has proposed a novel method for an RIS-assisted OFDMA multi-user system, in which the phase distribution of the RIS is dynamically changed in different time slots within each channel coherence block, serving only a subset of users in each time slot.

Earlier in this review, all the proposed techniques regarding the optimization of the RIS reflection (Table 2.2) have been, as previously mentioned, based on the full knowledge of the CSI from the AP to the user, from the AP to the RIS, and from the RIS to the user. This part of the literature review is thus devoted to exploring the methods

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Table 2.2: Summary of Works on Reflection Optimization in RIS-assisted Wireless Systems

Reference	System Type	Objective	Optimization Method
[80]	Single-user MISO	Transmit power minimization	AO
[81]	Multi- and single-user MIMO	Transmit power minimization	AO
[82]	Single-user MISO	Rate maximization	Manifold optimization
[83]	Single-user MISO	Transmit power minimization	Deep learning
[10]	Single-user MIMO	Rate maximization	AO
[84]	Double-RIS single-user MIMO	Rate maximization	AO

proposed so far to obtain the CSI of RIS-assisted wireless communication systems. To gain a brief insight, consider a K -user MIMO wireless network with a BS comprising N_B antennas and each user equipped with a N_u -element antenna. Now, considering a narrowband communication system with flat-fading channels, and reciprocal channels between the uplink and downlink, the number of channel coefficients that an RIS with N elements introduces to the system is equal to $K \times NN_u + N_B N$, adding to the coefficients of a conventional multi-user MIMO system ($K \times N_u N_B$ coefficients). The substantial channel coefficients induced by the RIS in the wireless network make the channel estimation process challenging. However, some techniques have been proposed in existing research works that can reduce the complexity of CSI acquisition to some extent. In the current literature, there are two main approaches for CSI acquisition in RIS-assisted wireless communication networks that will be investigated in the following. In the first approach, the RIS structure is equipped with sensors, making it capable of receiving RF signals. These RIS structures are called semi-passive RISs since they can only receive RF signals. The process of channel estimation for wireless networks with semi-passive RIS structures involves, in the first step, estimating the channels

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between the RIS-user and RIS-BS with all reflection elements in the OFF mode using the sensors (RF receivers). The direct channel between BS-user is also estimated by exchanging pilot signals between them. Now that CSI of all channels is obtained, RIS reflection is designed for higher quality communication using the optimization techniques discussed earlier. In [87–89], deep learning techniques have been deployed to estimate the channels between the RIS-user and RIS-BS in SISO systems by using the channel information gained from a group of active elements in the RIS (elements with sensors).

The second approach, however, does not involve active elements (RF receivers) in the RIS. The process of CSI acquisition in wireless systems with passive RIS structures is known as passive channel estimation. It is worth noting that passive channel estimation has been given more attention than semi-passive channel estimation, primarily because adding sensors and active RF chains to the RIS structure would increase costs and deteriorate energy efficiency. Regarding CSI acquisition, in passive channel estimation, the cascaded channels between the BS-RIS and RIS-user are estimated instead of calculating each channel separately. From a technical point of view, the number of channel coefficients in passive mode is considerably higher than that of semi-passive mode. This is because each cascaded channel between the BS and k -th user includes the common CSI of BS-RIS, indicating an inherent redundancy in such channels.

The procedure for passive channel estimation comprises three steps performed in each channel coherence block. In the first step, the BS and user exchange orthogonal training signals while the reflection coefficients are set to a different pre-designed pattern with respect to each pilot signal. In the second phase, the CSI is estimated, and the reflection coefficients are calculated based on the CSI and sent to the RIS controller. In the final step, the phase distribution is set for maximum data delivery from the BS to the users. In [90], to estimate the CSI, for each pilot signal, one element of the RIS is set to the ON state while others are switched to their OFF state. The CSI is finally estimated

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when at least $N + 1$ orthogonal pilots are exchanged between the BS and the user (N is the number of elements in the RIS). It is worth mentioning that the channel estimation in this approach is not accurate since one element in the RIS cannot make much of a difference; hence the pilot signal received at the BS is rather weak. To overcome this issue, all elements are set to their ON state but with orthogonal reflection coefficient patterns with respect to each pilot signal [91, 92].

To reduce the calculations in CSI estimation and speed up the training process, [93] has proposed an element grouping method, where adjacent unit cells in the RIS are grouped and considered as a super-element for channel estimation. Finally, in MIMO and MISO systems with large antenna elements at the BS and/or the user, it is necessary to exploit methods such as deep learning to accelerate the training overhead, thereby speeding up the process [94–96].

2.3 Ray-Tracing-Based Channel Modeling for RIS-Assisted Wireless Networks

Accurate channel modeling and simulation are crucial for the development and optimization of RIS-assisted wireless networks, particularly in the context of 6G communication systems. RIS technology holds the promise of significantly enhancing signal quality, coverage, and energy efficiency by dynamically controlling the electromagnetic environment. To harness these benefits, it is essential to understand how RIS interacts with various channel conditions, especially in complex indoor scenarios where line-of-sight (LoS) paths may be obstructed. Comprehensive channel modeling enables the prediction and analysis of key performance metrics such as received power, channel capacity, and angular power spectral density (PSD). These insights are vital for designing efficient RIS deployment strategies, optimizing network performance, and ensuring the reliable

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transmission of high-speed data required for advanced applications like holographic communications and real-time ultra-high definition video streaming.

Ray tracing stands out as a powerful tool for simulating wireless communication channels, particularly in environments enhanced by RIS. By accurately modeling the propagation of electromagnetic waves, ray tracing can simulate complex interactions such as reflection, diffraction, and scattering, which are crucial for understanding the behavior of RIS-assisted networks. The method involves tracing the paths of rays from the transmitter (Tx) to the receiver (Rx) through a virtual environment that mimics real-world conditions. This approach allows for detailed analysis of how RIS can manipulate these rays to improve signal strength and coverage in non-line-of-sight (NLoS) scenarios. Utilizing a 3D ray tracing simulator, such as Wireless Insite [97], researchers can evaluate different RIS deployment configurations, study the impact of various materials, and optimize the placement of RIS elements. The ability to simulate multiple frequencies, including millimeter wave (mmWave) bands, further enhances the tool's applicability, providing comprehensive insights that guide the practical deployment of RIS in indoor and other challenging environments. This section will explore various research studies that have developed novel ray tracing methods for channel modeling of RIS-assisted wireless systems.

The ray concept in electromagnetics emerges from the high-frequency approximation of Maxwell's equations. This approximation is valid when the wavelength is much smaller than the characteristic dimensions of the problem geometry. In this regime, the electric and magnetic fields can be expressed as:

$$\mathbf{E}(\mathbf{r}) = \mathbf{e}(\mathbf{r})e^{-j\beta_0 S(\mathbf{r})} \quad (2.13)$$

$$\mathbf{H}(\mathbf{r}) = \mathbf{h}(\mathbf{r})e^{-j\beta_0 S(\mathbf{r})} \quad (2.14)$$

2.3 RAY-TRACING-BASED CHANNEL MODELING FOR RIS-ASSISTED WIRELESS NETWORKS

where $\mathbf{E}(\mathbf{r})$ and $\mathbf{H}(\mathbf{r})$ are the vector electric and magnetic fields, respectively. The terms $\mathbf{e}(\mathbf{r})$ and $\mathbf{h}(\mathbf{r})$ represent slowly varying vector amplitude functions, $\beta_0 = \frac{2\pi}{\lambda}$ is the free-space wavenumber, $S(\mathbf{r})$ is the eikonal function representing the optical path length, and $\mathbf{r}$ is the position vector in 3D space.

The exponential term $e^{-j\beta_0 S(\mathbf{r})}$ describes the rapid phase variations of the wave, while $\mathbf{e}(\mathbf{r})$ and $\mathbf{h}(\mathbf{r})$ account for slower amplitude and polarization changes. This separation of rapidly oscillating phase and slowly varying amplitude is key to the ray approximation, allowing us to treat the wave propagation as a ray phenomenon.

By substituting these expressions into Maxwell's equations and considering the limit as $\beta_0 \rightarrow \infty$, we arrive at the eikonal equation:

$$|\nabla S|^2 = n^2 \quad (2.15)$$

where n is the refractive index of the medium and can be calculated as $n = \sqrt{\mu_r \epsilon_r}$, with μ_r and ϵ_r being the relative permeability and permittivity of the medium, respectively. This equation is fundamental to the ray theory as it governs the behavior of the wavefronts (surfaces of constant phase) and, consequently, the ray trajectories, which are orthogonal to these wavefronts.

The eikonal equation essentially describes how the phase of the wave varies in space, with the gradient of $S(\mathbf{r})$ giving the direction of wave propagation at each point. This allows us to trace the path of electromagnetic energy through the medium, forming the basis of ray tracing techniques widely used in computational electromagnetics.

The ray paths can be determined by solving the differential equation:

$$\frac{d}{ds} \left(n \frac{d\mathbf{r}}{ds} \right) = \nabla n \quad (2.16)$$

where s is the arc length along the ray path. This equation, known as the ray equation,

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describes how the ray bends in a medium with varying refractive index. It is a direct consequence of applying Fermat's principle to the eikonal equation.

In a homogeneous medium, where the permittivity ϵ , permeability μ , and refractive index n are constant throughout the space, the gradient of the refractive index vanishes ($\nabla n = 0$). Consequently, the general ray trajectory equation simplifies to:

$$\frac{d^2 \mathbf{r}}{ds^2} = 0 \quad (2.17)$$

This second-order differential equation has a general solution of the form:

$$\mathbf{r} = \mathbf{a}s + \mathbf{b} \quad (2.18)$$

where $\mathbf{r}$ is the position vector along the ray path, and $\mathbf{a}$ and $\mathbf{b}$ are constant vectors. This solution describes a straight line in the homogeneous medium, with $\mathbf{a}$ representing the direction of propagation and $\mathbf{b}$ providing an initial position. This result aligns with our intuition that light travels in straight lines in uniform media.

The ray concept, as formulated above, provides a mathematical foundation for Fermat's principle of least time. This principle states that light travels between two points along the path that requires the least time. From this fundamental principle, one can derive the laws of reflection, refraction, and diffraction. For instance, Snell's law of refraction can be derived by applying Fermat's principle at the interface between two media with different refractive indices.

The high-frequency approximation of Maxwell's equations, as formulated above, allows us to model EM wave propagation using the concept of rays. This approach is particularly useful in complex environments where the wavelength is smaller than the characteristic dimensions of objects in the scene. It enables efficient analysis of EM wave behavior in scenarios involving multiple reflections, refractions, and diffractions,

2.3 RAY-TRACING-BASED CHANNEL MODELING FOR RIS-ASSISTED WIRELESS NETWORKS

making it invaluable for applications in areas such as wireless communication, radar systems, and optical design.

However, it is important to note the limitations of the ray approximation. As it is based on the high-frequency limit, it becomes less accurate when dealing with wavelengths comparable to the size of obstacles or apertures in the system. In such cases, diffraction effects become significant, and full-wave solutions to Maxwell's equations may be necessary. Additionally, the ray approach does not directly account for polarization effects, which can be crucial in some applications.

The EM field distribution can be effectively described by considering three primary types of rays: direct rays, representing LoS propagation between the source and receiver; reflected rays, accounting for interactions with surfaces; and diffracted rays, which describe the phenomenon of waves bending around obstacles or passing through apertures, extending the field into shadow regions.

2.3.1 Direct Rays

Direct or LoS rays represent the simplest form of propagation, where electromagnetic waves travel directly from the transmitter to the receiver without encountering any obstacles. In an ideal free-space environment, the path loss for LoS propagation can be calculated using the Friis transmission equation:

$$L_{\text{LoS}} = 20 \log_{10} \left(\frac{4\pi d}{\lambda} \right) \quad (2.19)$$

where L_{LoS} is the path loss in dB, d is the distance between the transmitter and receiver, and λ is the wavelength of the signal. This equation assumes isotropic antennas and no atmospheric effects.

2.3.2 Reflected Rays

Reflection occurs when electromagnetic waves encounter a surface that is large compared to the wavelength. The behavior of reflected rays follows the law of reflection, where the angle of incidence equals the angle of reflection. The amplitude of the reflected wave depends on the reflection coefficient, which varies with the material properties and the polarization of the incident wave.

For a single reflection, the electric field of the reflected wave can be expressed as:

$$E_r = E_i \cdot R \cdot \exp(-jkr) \quad (2.20)$$

Where E_r is the reflected field, E_i is the incident field, R is the reflection coefficient, k is the wavenumber $\left(\frac{2\pi}{\lambda}\right)$, and r is the total path length. The reflection coefficient R differs for perpendicular and parallel polarizations:

$$R_{\perp} = \frac{\eta_2 \cos(\theta_1) - \eta_1 \cos(\theta_2)}{\eta_2 \cos(\theta_1) + \eta_1 \cos(\theta_2)} \quad (2.21)$$

$$R_{\parallel} = \frac{\eta_2 \cos(\theta_2) - \eta_1 \cos(\theta_1)}{\eta_2 \cos(\theta_2) + \eta_1 \cos(\theta_1)} \quad (2.22)$$

Where η_1 and η_2 are the intrinsic impedances of the two media, and θ_1 and θ_2 are the angles of incidence and refraction, respectively.

2.3.3 Diffracted Rays

Diffraction occurs when electromagnetic waves encounter edges, corners, or small openings relative to the wavelength. This phenomenon allows waves to propagate into shadowed regions behind obstacles. To incorporate diffraction effects into ray-based models, two primary theories have been developed: the Geometrical Theory of Diffraction (GTD) and the Uniform Theory of Diffraction (UTD).

The Geometrical Theory of Diffraction, introduced by J.B. Keller, extends geometrical optics to include diffracted rays. GTD posits that when an incident wave strikes an edge or vertex, it produces diffracted rays emanating from these points. While GTD improved field predictions in shadow regions, it has a limitation of predicting infinite field strengths at shadow and reflection boundaries.

The Uniform Theory of Diffraction, developed by Kouyoumjian and Pathak, addresses GTD's limitations. UTD introduces transition functions that ensure the total field remains finite and continuous everywhere, including at shadow and reflection boundaries. This makes UTD particularly suitable for accurate field predictions across all regions of space.

The general form of the edge-diffracted electric field is given by the equation:

$$E^d = E^i(Q_E) \cdot D \cdot A(s) \exp(-jks) \quad (2.23)$$

This formula encapsulates the key components of the diffracted field. $E^i(Q_E)$ represents the incident field at the diffraction point Q_E , which serves as the source of the diffracted ray. D is the dyadic diffraction coefficient, which describes how the edge diffracts the incident field. As elaborated in the reference, D can vary depending on the specific type of edge encountered. $A(s)$ is a spreading factor that accounts for the amplitude variation along the diffracted ray path. The exponential term $\exp(-jks)$ represents the phase, where k is the wavenumber and s is the distance from the diffraction point.

2.4 RT

At the core of RT engines, there are two fundamental methods for tracing rays from the transmitter to the receiver: the direct method and the inverse method. These approaches

form the basis for how ray paths are calculated in radio propagation modeling. Regardless of the method used, it is of great importance to take into account a key feature for all rays: from point A to point B, rays take the least amount of time possible to travel, following Fermat's principle.

2.4.1 Direct RT

The direct method, also known as the Shooting and Bouncing Ray (SBR) method, is a fundamental approach in ray tracing for radio propagation modeling. In this method, a multitude of rays are emitted from the transmitter in various directions, sampling the 3D environment. The number and distribution of these rays as well as their separation angle are determined by the engine's configuration to ensure adequate coverage of the propagation space. As rays propagate through the environment, they interact with geometrical objects present in the 3D model, including reflection, diffraction, and scattering. For each ray's interaction and traveling distance, a loss coefficient is calculated. This process continues until the contribution of the signal along its path can be determined using appropriate propagation formulas, such as those discussed earlier in this section.

The final step in the SBR method involves identifying and analyzing the rays that reach the vicinity of the receiver. These rays represent valid propagation paths and form the basis for characterizing the radio channel. Each received ray carries important information: its delay, which represents the time taken to travel from the transmitter to the receiver; its total travel distance; its power level at the receiver, calculated by considering the initial transmission power and the cumulative losses incurred along its path; and its angle of arrival, which is crucial for spatial channel characterization. This angle of arrival information is particularly important for technologies such as smart antennas and MIMO systems. This collection of ray data provides a comprehensive

multipath profile of the propagation environment, enabling detailed analysis of the channel characteristics such as delay spread, angular spread, and received signal strength at the receiver location. It is worth noting that this method scales in computational overhead linearly with the number of transmitters considered in the engine, which can be a significant consideration in complex environments with multiple sources.

2.4.2 Inverse RT

The inverse method, also known as the image method or ray backtracing, approaches the problem of ray tracing from a different perspective compared to the direct method. Instead of launching rays from the transmitter, this method starts at the receiver and works backwards to determine possible paths to the transmitter.

The process begins by considering the receiver location and identifying potential reflection points in the environment. For each reflective surface, an image of the transmitter is created by mirroring its position across the surface. These image points represent potential sources from which rays could have originated to reach the receiver after a single reflection.

The method then proceeds to check if there is a clear, unobstructed path between the receiver and each image point. If such a path exists, it represents a valid ray path from the transmitter to the receiver via that reflection point. This process is repeated for higher-order reflections, creating images of images to account for multiple reflections. Figure 2.21 illustrates the Inverse RT method, which is an approach to modeling electromagnetic wave propagation in complex environments. In the illustration, we see a 2D environment with two main obstacles, labeled A and B, represented by gray rectangles. These obstacles serve as potential reflective surfaces for electromagnetic waves. The transmitter, denoted as Tx, is represented by a green dot, while the receiver, Rx, is shown as a red dot. The key to understanding the Inverse RT method lies in the

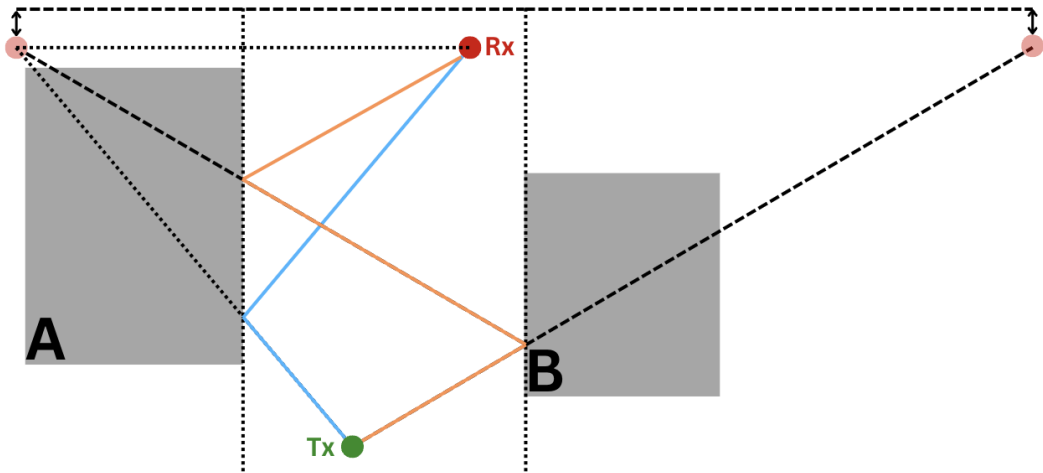


Figure 2.21: 2D illustration of ray tracing using inverse method.

light pink dots positioned at the corners of the image, which represent image points.

The Inverse RT method begins its analysis at the receiver location and works backwards to determine possible paths from the transmitter. This is accomplished by creating virtual transmitter locations, or image points, by reflecting the actual transmitter position across the surfaces of obstacles A and B. These image points are crucial in identifying potential reflection points and constructing valid ray paths.

The figure shows two ray paths between the transmitter and receiver. The blue ray is a ray that has been reflected once by obstacle A, demonstrating how electromagnetic waves can change direction upon encountering a reflective surface. In contrast, the orange ray exhibits a more complex path, having been redirected first by obstacle A and then by obstacle B. This double reflection illustrates how waves can interact with multiple surfaces in the environment before reaching the receiver. These reflected paths are determined by tracing lines from the image points to the receiver, represented by the dashed black lines in the figure. Where these dashed lines intersect with the obstacles, typically at their edges, we find valid reflection points. This method of analysis allows for the identification of intricate propagation paths that might not be immediately apparent in direct ray tracing approaches.

This visual representation effectively demonstrates how the Inverse RT method can efficiently identify reflected paths without the need to trace numerous rays from the transmitter, as would be required in the direct ray tracing method. It showcases the method's ability to handle multiple reflections and provide a comprehensive view of multipath propagation in a given environment. This approach is particularly valuable in scenarios with a limited number of reflective surfaces and when the analysis focuses on specific receiver locations, making it an important tool in the field of radio wave propagation modeling and wireless communication system design.

One of the key advantages of the inverse method is its efficiency in scenarios with a limited number of reflections and a complex receiver environment. It can be particularly effective when the number of receivers is small compared to the number of transmitters or when analyzing specific receiver locations in detail.

However, it is important to note that the computational complexity of the inverse method increases exponentially with the number of reflections considered, as the number of image points grows rapidly. This can make it less suitable for environments with many reflective surfaces or for large-scale simulations with numerous receivers.

Both the direct and inverse RT methods have their strengths and are often used in combination or selected based on the specific requirements of the propagation modeling task at hand.

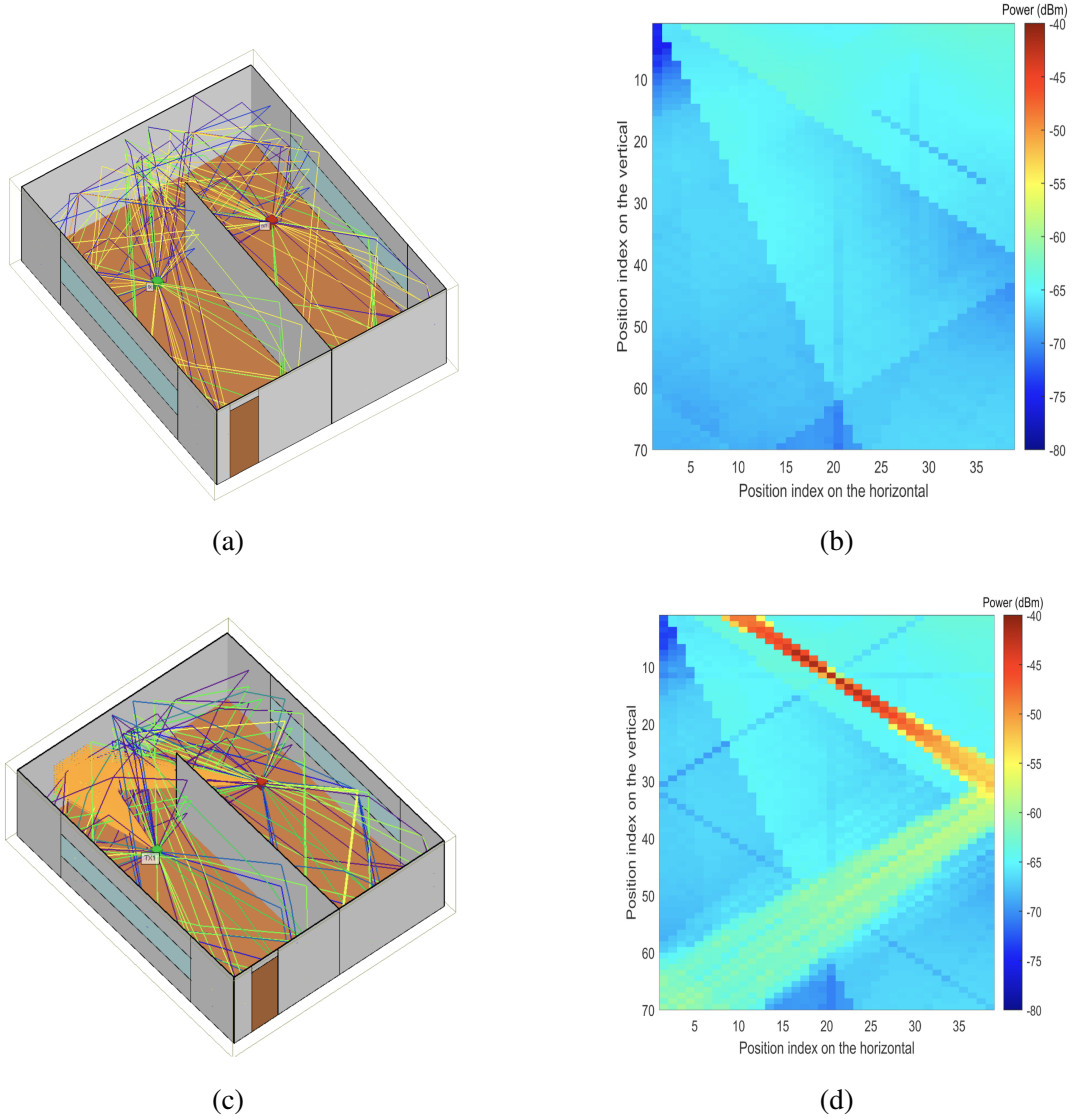


Figure 2.22: Visualization of ray distribution and signal power in an indoor scenario. (a) Ray tracing from the Tx to the Rx without the presence of the RIS in the room. (b) Corresponding signal power distribution in the room without RIS. (c) Ray tracing from the Tx to the Rx with the RIS structure present in the room, demonstrating the altered ray paths due to the RIS. (d) Corresponding signal power distribution in the room with the RIS, showing enhanced signal coverage and power levels [12].

In [12], Huang et al. propose a method to realize the steering function of RIS in a ray tracing simulator for indoor scenarios where the transmitter (Tx) and receiver (Rx) are obstructed by a wall. The authors demonstrate the flexibility of their method by applying it to different deployment locations and carrier frequencies. They investigate the

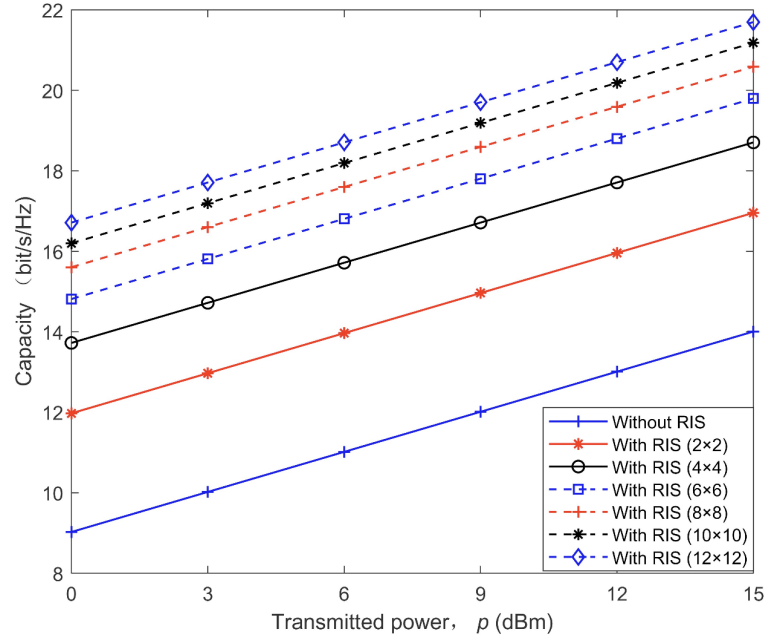


Figure 2.23: Comparison of the simulation results for capacity with varying numbers of RIS elements and different transmitted power levels [12].

coverage enhancement of RIS-assisted wireless communication systems and compare the performance for different deployment locations and carrier frequencies (Figure 2.22). The simulation results show that deploying RIS on the middle of the wall in the boresight of both Tx and Rx is the optimal choice when Tx, Rx, and RIS center are maintained at the same height, achieving a capacity of around 7 bit/s/Hz at 5.4 GHz with 144 RIS elements. When Tx is elevated, the location near Tx is a better choice for RIS deployment.

The authors also study the impact of the number of RIS elements and signal-to-noise ratio (SNR) on the channel capacity. They observe that the coverage is proportional to the transmitted power and the number of RIS elements. Notably, the capacity enhancement is most significant when the number of RIS elements is increased from 0 (without RIS) to 4, showing an improvement of around 3 bit/s/Hz under the same transmitted power (Figure 2.23). This is attributed to the fact that the four central elements near the core area of the beam have significant power density according to the

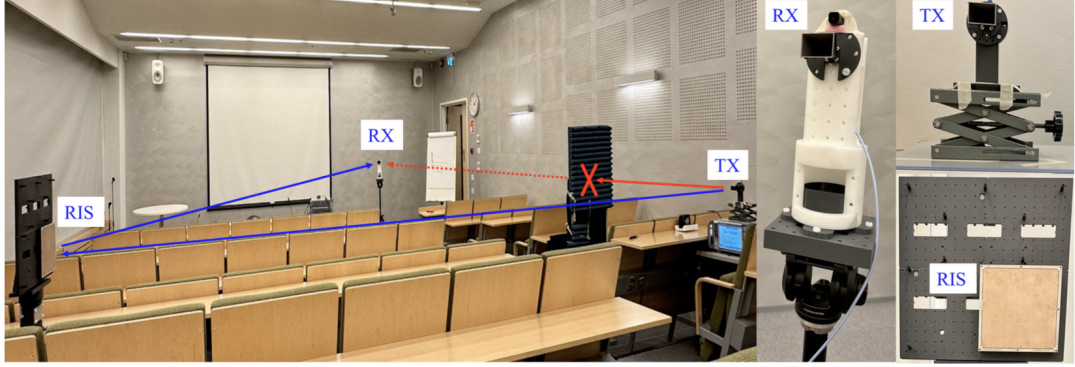


Figure 2.24: Measurement setup in the auditorium featuring an 48×48 -sized RIS, along with the TX and RX antennas [13].

Poynting vector. The results presented in this paper provide valuable insights for the deployment of RIS in practical applications, especially in indoor scenarios. It is worth noting that in the research work however, there is a notable lack of detailed information concerning the efficiency and computational speed of the employed ray tracing method. Research work in [13] systematically explores the EM and communication aspects of RIS structures by employing a combination of EM simulations, system-level simulations, ray-tracing methods, and practical measurements. Initially, the authors simulated both ideal, lossless RISs and realistic lossy anomalous reflectors using various ray tracers, comparing their large-scale fading characteristics. The analysis was extended to include continuous and quantized reflection phases, considering one to four-bit resolutions for unit cells. Furthermore, they conducted over-the-air communication measurements using a manufactured AR prototype in an indoor environment to validate the simulation results. The comprehensive study confirmed that the macroscopic EM model aligns well with the communication models for both ideal and realistic RIS designs.

The research introduces a two-method approach for analyzing large-scale fading in RIS-assisted links, validated against both theoretical models and numerical simulations. Method 1 utilizes a theoretical path loss model tailored for far-field propagation scenarios, integrating parameters like RIS efficiency and geometrical considerations.

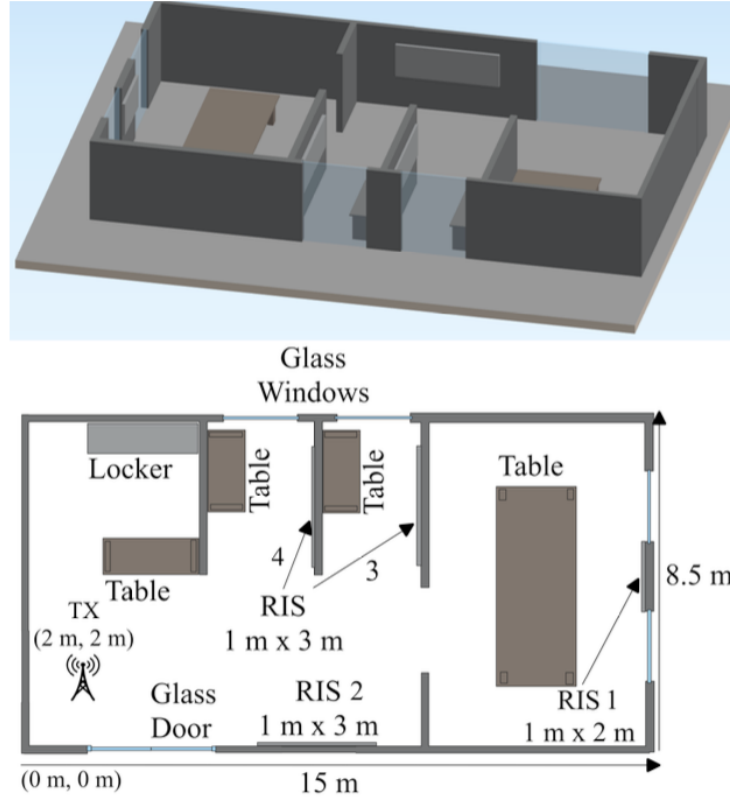


Figure 2.25: Three-dimensional view (top) and detailed description (bottom) of the propagation environment simulated in [14].

Method 2, on the other hand, employs the concept of RIS directivity and gain, calculated via CST software for various RIS sizes and configurations. These methods demonstrated close agreement in the path loss estimations for LOS links, emphasizing the efficacy of the proposed models. The authors further expanded their analysis through ray tracing simulations in multipath scenarios, highlighting the impact of environmental reflections on received signal power. As depicted in Figure 2.24 Practical measurements conducted in an auditorium setting corroborated the theoretical and simulation results, underscoring the robustness of the proposed models and the significant potential of RIS technology in enhancing wireless communication systems.

In [14], authors explore the integration of RISs in Terahertz (THz) communication systems to enhance coverage probability in indoor environments. The study focuses

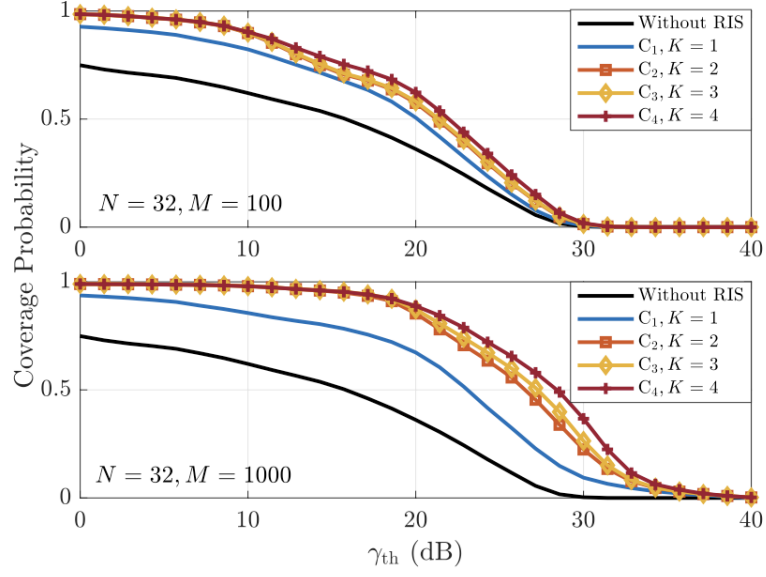


Figure 2.26: Coverage probability simulation results for different simulation cases [14].

on a multiple-input single-output system operating at 0.2 THz, employing multiple RISs to mitigate the severe path losses associated with THz frequencies. Using a ray tracing methodology, the authors simulate the impact of RIS deployment on system performance, specifically examining received power, signal-to-noise ratio, and coverage probability. The results demonstrate that RIS can significantly improve indoor coverage, with up to a 52% enhancement in system coverage and a 42.5 dB improvement in signal-to-noise ratio when multiple RISs are employed.

The study employs a detailed ray tracing simulation framework to characterize the propagation environment and assess the impact of RIS on THz communication channels. The simulation environment includes an office setup with multiple RIS strategically placed to optimize signal reflection and transmission (Figure 2.25). The ray tracing model accounts for various propagation phenomena, including specular reflection, diffraction, diffuse scattering, and atmospheric molecular absorption. The simulation results indicate that increasing the number of RIS elements and strategically positioning

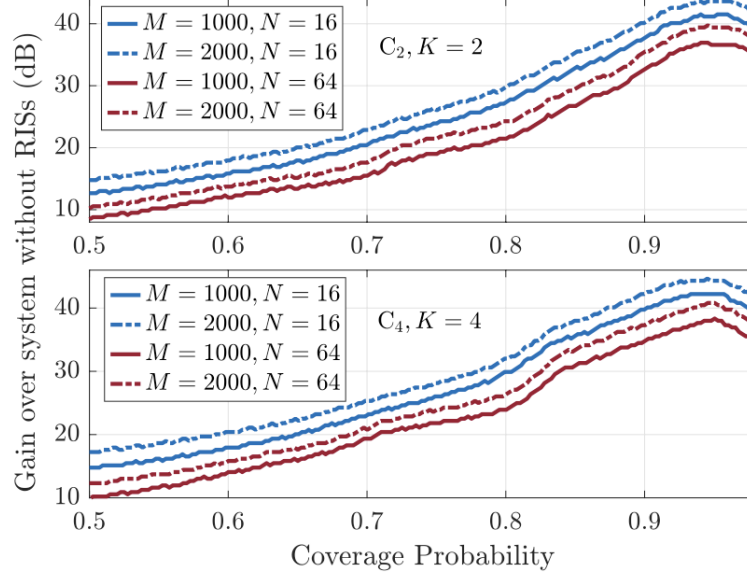


Figure 2.27: SNR gain as a function of coverage probability for various RIS and antenna configurations [14].

them within the environment can lead to substantial improvements in coverage probability and signal-to-noise ratio. For instance, in scenarios with four RISs, each equipped with 1000 elements, the system coverage at a signal-to-noise ratio threshold of 20 dB reaches 88%, compared to only 36% in a non-RIS-assisted setup (Figure 2.26).

The work also highlights the cost-benefit relationship between the number of passive RIS elements and the active antennas in the access point. It is noted that increasing the number of RIS elements can compensate for a lower number of active antennas, thereby enhancing system performance without significantly increasing complexity. The study concludes that deploying RIS in THz indoor systems is a promising approach to overcoming the high path losses and coverage limitations of THz communications. By leveraging the unique properties of RIS to control and direct electromagnetic waves, significant improvements in coverage and signal-to-noise ratio can be achieved, making it a viable solution for future 6G networks. The results of this study are further illustrated in the SNR gain plots for different numbers of RIS elements and antennas (Figure 2.27). In [15], a hybrid numerical method combining full-wave analysis with ray-tracing was

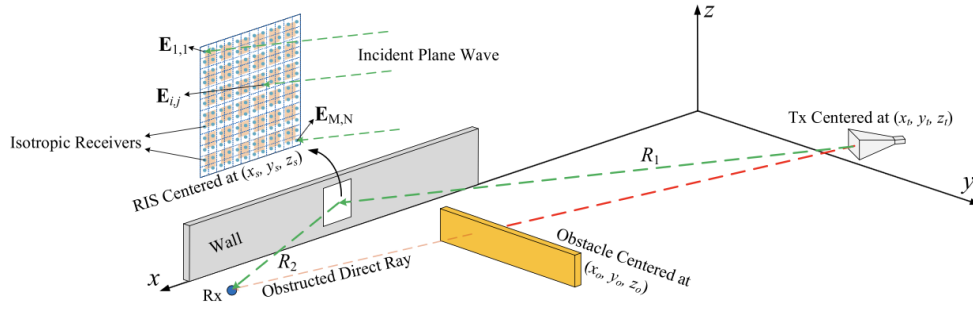


Figure 2.28: Typical Reconfigurable Intelligent Surface-enabled communication channel [15].

introduced to efficiently model propagation in RIS-enabled communication channels. The study addresses the challenge of accurately modeling the interaction between Reconfigurable Intelligent Surfaces and complex environments without excessive computational resources. Full-wave simulation is used to obtain the radiation pattern of the transmitter and the complex radar cross section of the RIS, which is then imported into a ray-tracer as a secondary transmitter. This approach allows for the detailed modeling of interactions, such as reflections, transmissions, and diffractions, within complex indoor environments, thereby determining the total received signal strength. Figure 2.28 shows a typical RIS-enabled communication channel, highlighting how the surface acts as a secondary transmitter to bypass obstructions and enhance non-line-of-sight communication.

The proposed method is validated against finite element results in representative indoor propagation scenarios. For instance, a typical RIS-enabled communication channel is simulated to compare the electric field distributions obtained by the hybrid method and full-wave analysis. The results show excellent agreement, demonstrating the accuracy and efficiency of the hybrid approach. The study highlights that while full-wave analysis provides precise modeling capabilities, its computational demands are significantly higher compared to the hybrid method, which remains efficient even in complex geometries. Figure 2.29 compares the simulation accuracy between the

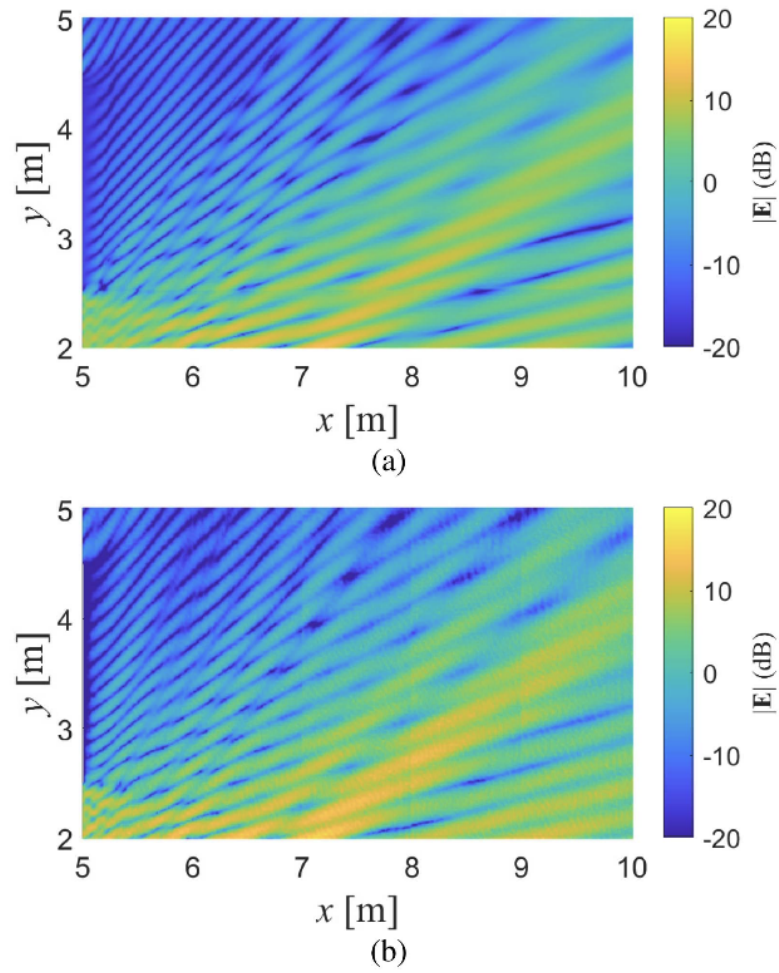


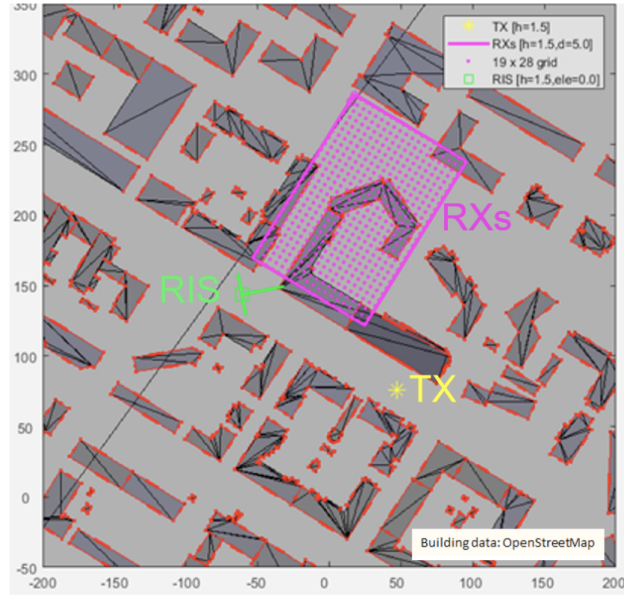
Figure 2.29: 2D simulation of E-field distribution in the environment by (a) the ray-tracing method proposed in [15] and (b) HFSS.

proposed ray-tracing method and a full-wave simulation of the environment using a commercialised high frequency software (HFSS).

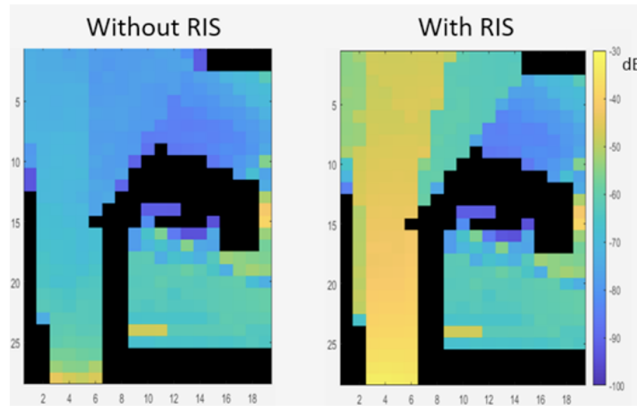
The study concludes that the hybrid method combining full-wave analysis with ray-tracing is an effective solution for modeling RIS-enabled communication channels. By treating the surface as a secondary transmitter, the method captures the essential interactions between the RIS and its environment, ensuring accurate propagation modeling while maintaining computational feasibility. This approach is particularly beneficial for analyzing large-scale indoor environments where traditional full-wave analysis would be impractical. Overall, the hybrid method offers a robust framework for future research and development in RIS technology, providing a balance between accuracy and computational efficiency.

Authors in [16] present a ray tracing approach for deterministic radio channel modeling, with a focus on simulating the channel characteristics of RISs in urban environments. The ray tracer utilizes the NVIDIA OptiX Ray Tracing Engine and the CUDA parallel computing platform. The RIS is modeled as a uniform planar array of reconfigurable reflecting elements. The authors provide a detailed description of the electromagnetic formulation and assumptions used in the RIS model, which treats the RIS as a phased array of metallic plates with controllable phase shifts.

The ray tracing simulations involve computing point-to-point path models for transmitter-receiver, transmitter-RIS, and RIS-receiver pairs. These models predict the strengths of propagation paths and can be used in subsequent simulations involving antennas and beamforming. The authors demonstrate the RIS propagation in an urban environment using a 3D model of the Etu-Lyötty suburb in Oulu, Finland. The simulations compare the received signal power levels with and without the RIS, illustrating the potential for significant improvements in signal power and coverage when the visibility conditions between the RIS, transmitter, and receiver are favorable.



(a)



(b)

Figure 2.30: (a) Configuration of the TX, RXs, and RIS in the urban simulation environment, and (b) distributed signal power in the specified in the purple grid with/without RIS structure in the environment [16].

The paper also examines the impact of beam steering errors on the received signal levels, showing that misalignment can cause significant link losses. Figure 2.30 compares the signal coverage in the modeled area with and without the RIS. The results clearly demonstrate that the coverage in the line-of-sight region of the RIS is significantly increased, with mild improvements in non-line-of-sight regions as well. The authors conclude that RISs can provide notable advantages in signal levels and coverage,

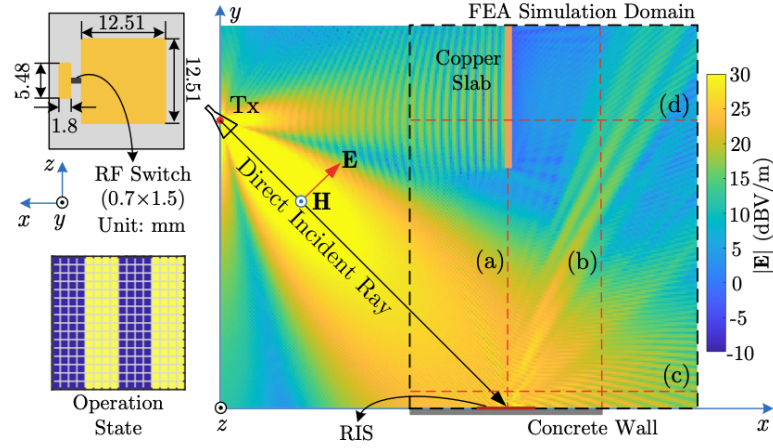


Figure 2.31: Signal power distribution in an indoor area by using the propagation model proposed in [17].

particularly in scenarios with good visibility between the RIS and network nodes. However, they also note that RISs may not always improve signal levels, especially when the signal propagation is already good without the RIS. The paper highlights the importance of ray tracing tools in studying and analyzing wireless links and systems, particularly at high frequencies where comprehensive channel models are scarce.

In the work [17], a method was proposed to accurately model wave propagation in realistic RIS-enabled communication channels. The method combines the accuracy of full-wave analysis with the efficiency of ray-tracing, providing a rigorous way to analyze realistic RIS-enabled channels. The authors apply Huygens' principle to find an equivalent surface current source that can generate the same scattered field as the original RIS. The equivalent electric and magnetic current densities on the surface are computed using full-wave analysis and electromagnetic boundary conditions. The resulting equivalent source is then integrated into ray-tracing to derive the RIS propagation model.

Figure 2.31 illustrates the RIS-enabled channel used to validate the proposed method. The channel consists of a rectangular horn antenna directly illuminating an RIS mounted on a dielectric wall. An obstacle in the form of a copper slab is placed near the RIS. The

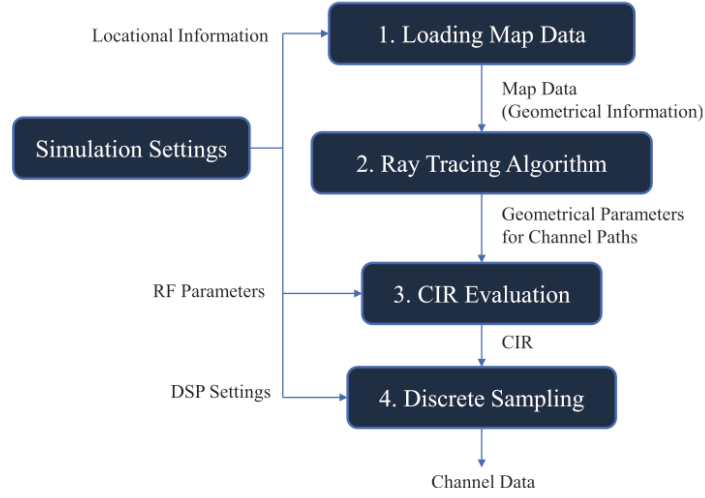


FIGURE 1. Flowchart of general RT-based simulator.

Figure 2.32: Flowchart of WiThRay RT-based simulator [18].

RIS unit cell structure, operation state (yellow for switch-ON and blue for switch-OFF), and the electric field distribution obtained by the proposed method are displayed. The finite-element simulation domain and sampling points for comparison are also shown. The near-field computation is applied in the region $r < 2$ m.

The proposed method in [17] was validated by comparing the results with those obtained from Ansys HFSS finite-element analysis and a previously developed method by the authors. The comparison demonstrates that the proposed method provides results very close to the finite-element analysis in the near-field region of the RIS, outperforming the previous method. In the far-field region, both the proposed method and the previous method yield similar results. By incorporating a full-wave simulation round, the proposed method accounts for all factors contributing to the scattering characteristics of an RIS. The subsequent ray-tracing of the equivalent source allows for rapid computation of wave propagation across the environment. Overall, the authors conclude that their method offers a highly accurate and efficient approach to analyze realistic RIS-enabled channels.

Authors in [18] presented WiThRay, an open-source RT-based channel simulator designed for emerging smart wireless environments. WiThRay incorporates several key features, such as a modified RT algorithm following Fermat's principle, scattering ray calibration for precise EM propagation analysis, and support for RIS structures. The simulator is designed to generate realistic channel data for performance assessment of various wireless communication techniques, including channel estimation, beamforming, and localization, under realistic EM wave propagation conditions. Figure 2.32 illustrates the general procedure of most RT-based simulators, which involves loading map data, applying the RT algorithm, evaluating the CIR, and performing discrete sampling.

WiThRay's RT algorithm, called the bypassing on edge (BE) algorithm, enhances the efficiency of the inverse algorithm by reducing computational complexity. The simulator also dynamically adjusts the scattering area to include dominant channel paths and calibrates the scattering grid for MIMO scenarios, ensuring that EM waves propagate in their original waveform. WiThRay models the wideband effect and Doppler shift caused by mobile objects, generating realistic channel data for high-mobility scenarios. Furthermore, the simulator supports RIS systems by employing the dyadic EM response model.

It is demonstrated that the versatility of WiThRay through several example applications. They evaluate the accuracy of Orthogonal Frequency-Division Multiplexing (OFDM) uplink channel estimation, compare the performance of various downlink multi-user MIMO beamforming techniques, and study RIS-enabled coverage extension. The authors conclude that WiThRay is a valuable tool for the wireless research community, facilitating the development and testing of communications and signal processing techniques in 6G smart wireless environments.

2.5 Summary

This literature review has provided a detailed exploration of the current state of research on RIS and their applications in wireless communication systems. The review has covered three main areas: RIS unit cell designs and configurations, optimization techniques, and ray-tracing-based channel modeling for RIS-assisted wireless networks. In the area of RIS unit cell designs, we have seen a progression from simple designs with limited functionality to more complex structures capable of manipulating both the phase and amplitude of incident electromagnetic waves. Notable advancements include the development of space-time-coding digital metasurfaces, supercell designs for improved tunability, and structures capable of polarization conversion. These innovations demonstrate the increasing sophistication and versatility of RIS technology, paving the way for more efficient and adaptable wireless communication systems.

The review of optimization techniques has highlighted the challenges and proposed solutions for implementing RIS in practical wireless networks. Key areas of focus include the development of efficient algorithms for optimizing RIS reflection coefficients, methods for acquiring CSI in RIS-assisted systems, and techniques for enhancing system performance in various network configurations. The literature shows a trend towards more sophisticated optimization methods, including the use of machine learning techniques, to address the complexities of RIS-enhanced networks.

The examination of ray-tracing-based channel modeling has underscored the importance of accurate propagation models for RIS-assisted systems. The review has covered various approaches to ray tracing, including direct and inverse methods, and their application to RIS-enhanced environments. These models provide valuable insights into the behavior of RIS in complex propagation scenarios, aiding in the design and optimization of RIS deployments.

Chapter 3

Design and Development of the RIS

In this chapter, we delve into the hardware development of the RIS, a key technology for enhancing wireless communication systems. The design and implementation of a functioning RIS surface involves several critical steps, each of which will be examined in detail.

First, we will explore the design of the unit cell, the fundamental building block of the RIS structure. This section will focus on the electromagnetic properties and physical configuration of individual elements that collectively form the RIS.

Following this, we will investigate the control board circuit design. This crucial component enables the dynamic reconfiguration of the RIS, allowing it to adapt to changing wireless environments and optimize signal propagation.

The third section will address the surface integration procedure, covering computer-aided design (CAD) modeling and the development of a double-opening 3D-printed object designed to hold both the RIS surface and the control board. This integrated approach ensures proper alignment and protection of the RIS components.

Finally, we will examine the surface optimization procedure. This section will cover techniques and algorithms used to fine-tune the RIS performance, maximizing its effectiveness in enhancing wireless communication.

2.5 SUMMARY

Through these four sections, we aim to provide a comprehensive overview of the hardware development process for RISs, from the microscopic level of individual unit cells to the macroscopic optimization of the entire surface. This approach will offer insights into both the theoretical principles and practical considerations involved in creating an effective RIS system.

In this section, we focus on the design of the RIS unit cell, the fundamental component that enables the reconfigurability of the intelligent surface. The unit cell's design is crucial as it directly impacts the overall performance and functionality of the RIS.

We will begin by investigating the critical parameters and materials essential for creating reconfigurable unit cells. This includes an analysis of substrate properties, and the selection of tunable elements that facilitate phase and amplitude control.

Next, we will explore the procedure for making a unit cell reconfigurable. This involves integrating active elements, such as varactor and PIN diodes, and designing appropriate biasing networks to enable dynamic control of the unit cell's electromagnetic properties. To streamline the design process and optimize performance, we will discuss design process automation techniques. These methods leverage computational tools and algorithms to efficiently explore the vast design space and identify optimal unit cell configurations. Notably, we will introduce how programming languages like Python can be integrated with electromagnetic simulation software utilized to automate design tasks and fine-tune the physical parameters of the unit cell, enhancing the efficiency and effectiveness of the design process.

Finally, we will present comprehensive simulation results for our developed unit cell. These simulations, conducted using advanced electromagnetic modeling software, HFSS from Ansys Electronics, will demonstrate the unit cell's performance across various operating conditions and validate its reconfigurability.

Through this systematic approach, we aim to provide a thorough understanding of the RIS unit cell design process, from theoretical considerations to practical implementation

and performance evaluation. This knowledge forms the foundation for developing effective and efficient RIS-based systems for next-generation wireless communications.

3.1 Design Parameters and Considerations

In the design of RISs, several key parameters and considerations must be carefully evaluated to optimize performance. This section examines three imperative aspects that significantly impact RIS unit cell functionality: the reflection coefficient and phase range, substrate material properties and thickness, and polarization sensitivity. The reflection coefficient, characterized by the S_{11} parameter, provides insights into the unit cell's insertion loss and phase alteration capabilities. Substrate selection involves balancing low dielectric losses with desired bandwidth and physical size constraints. Additionally, achieving polarization insensitivity through symmetrical design is essential for consistent performance in diverse electromagnetic environments. By thoroughly analyzing these factors, we can develop RIS unit cells that efficiently manipulate incident waves while maintaining broad operational bandwidth and reliable functionality across various deployment scenarios.

3.1.1 Reflection Coefficient and Phase Range

In the design of a reflective unit cell for RISs, the most critical parameter to study is the reflection coefficient. This parameter is fundamental in evaluating the performance of the unit cell in two key aspects:

Insertion Loss: The reflection coefficient allows us to quantify how much energy loss the unit cell imparts to the incident EM waves. A high-performance unit cell should minimize this loss to ensure efficient reflection of the incident signal.

Phase Alteration: The reflection coefficient also indicates the unit cell's effectiveness in altering the phase of the reflected waves. This capability is crucial for the beamforming

3.1 DESIGN PARAMETERS AND CONSIDERATIONS

and wavefront shaping functionalities of the RIS.

These essential parameters can be extracted from the S_{11} parameter (also known as the reflection coefficient or return loss) in high-frequency simulation software. The S_{11} parameter, typically expressed in decibels (dB), represents the ratio of the reflected signal to the incident signal.

In the context of RIS unit cell design:

- The magnitude of S_{11} indicates the reflection efficiency. Values closer to 0 dB suggest lower insertion loss and higher reflection efficiency.
- The phase of S_{11} represents the phase shift introduced by the unit cell. The range of achievable phase shifts is a key performance metric for RIS unit cells.

By analyzing the S_{11} parameter across the frequency range of interest and under various tuning conditions, we can begin to characterize the unit cell's performance. This initial analysis serves as a foundation for further, more comprehensive evaluation of the unit cell. While S_{11} provides crucial insights into reflection efficiency and phase shift capabilities, it is important to note that this is just the starting point for a thorough performance assessment.

3.1.2 Substrate Material and Thickness

Another crucial consideration in the design of RIS unit cells is the selection of substrate material and its thickness. The choice of substrate significantly impacts the performance of the unit cell, particularly at high frequencies. To minimize additional losses to incident electromagnetic waves, materials with low dielectric loss tangent ($\tan \delta$) are preferred. A lower $\tan \delta$ value indicates less energy dissipation within the substrate, thereby preserving more of the incident wave energy for reflection. This becomes increasingly important at higher frequencies where material losses tend to be more pronounced.

3.1 DESIGN PARAMETERS AND CONSIDERATIONS

In addition to low loss, the thickness and permittivity of the substrate play vital roles in determining the bandwidth of the unit cell. Thicker substrates with lower relative permittivity values are generally of interest for RIS structures. These characteristics contribute to a wider operational bandwidth, which is desirable for supporting a broader range of frequencies or for enhancing the tunability of the unit cell.

However, it's important to note that increasing substrate thickness may also lead to increased overall unit cell size, which could impact the spatial resolution of the RIS. Therefore, a careful balance must be struck between bandwidth requirements and physical size constraints when selecting the substrate parameters for RIS unit cell design. This balance is crucial for optimizing the overall performance and practicality of the RIS system.

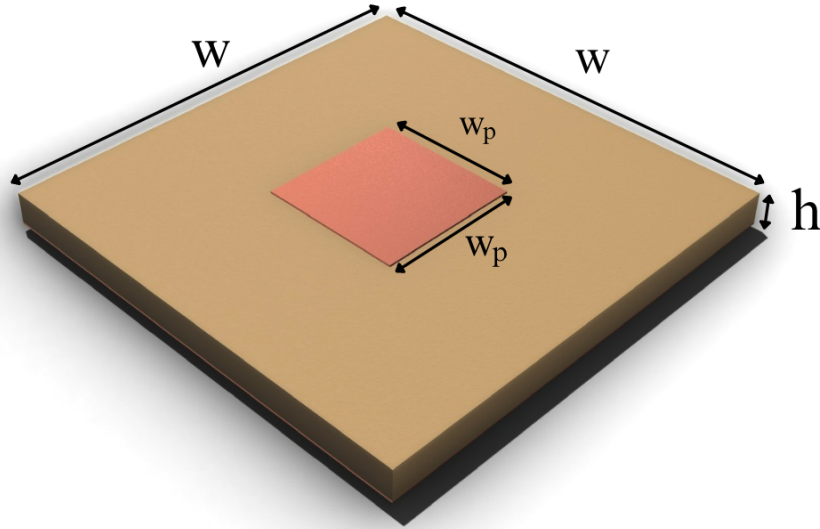


Figure 3.1: 3D view of the one-layer unit cell model for electromagnetic simulation.

For the investigation of fundamental electromagnetic parameters, a simple one-layer unit cell is designed using HFSS, as depicted in Figure 3.1. This model comprises a

3.1 DESIGN PARAMETERS AND CONSIDERATIONS

square substrate of Rogers RT/duroid 5880, chosen for its specific dielectric properties suitable for high-frequency applications. Atop the substrate, we placed a square metallic patch.

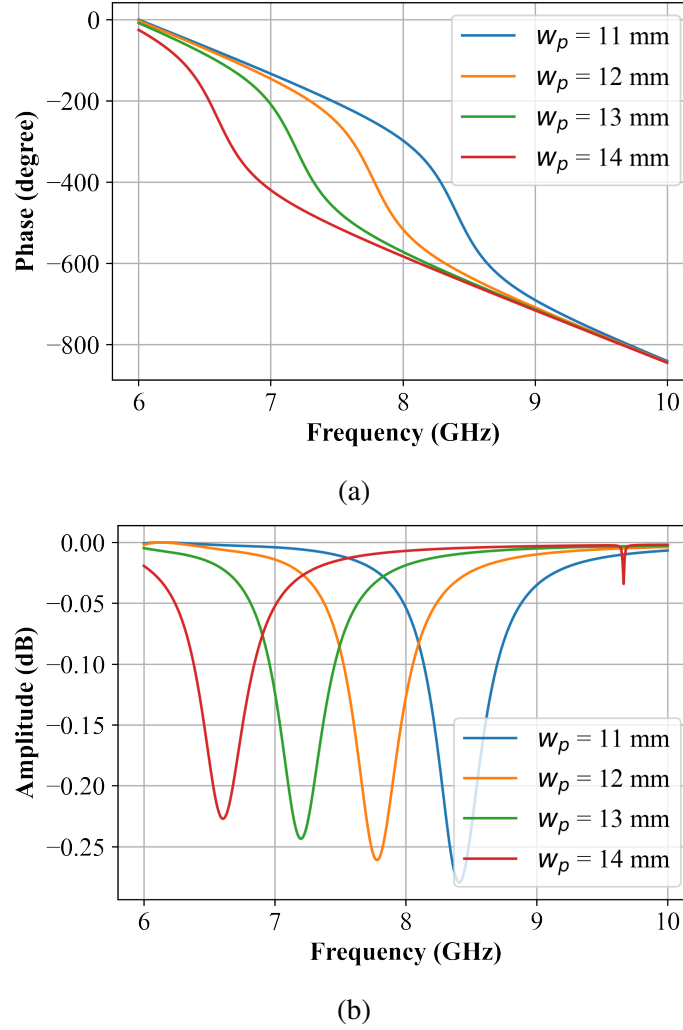


Figure 3.2: (a) Reflection phase, and (b) reflection amplitude of the proposed unit cell for different patch sizes (w_p) ranging from 11 to 14 mm over a frequency range of 6 to 10 GHz.

The S11 parameter plots shown in Figure 3.2 reveal the impact of patch size on the unit cell's resonant behavior. As the patch size increases from 11 mm to 14 mm, the resonant frequency shifts to lower values, evident from both the phase and amplitude responses.

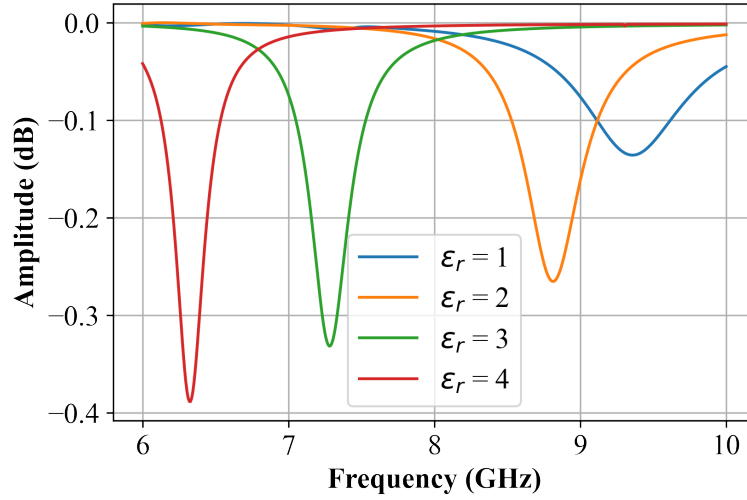


Figure 3.3: The reflection amplitude of the unit cell over a frequency range of 6 to 10 GHz, for different relative permittivities (ϵ_r) ranging from 1 to 4.

Figure 3.3 depicts the reflection amplitude of the unit cell (Figure 3.1) for various substrate relative permittivities ranging from 1 to 4, over a frequency span of 6 to 10 GHz. The plot reveals that as ϵ_r increases, the resonance frequency shifts towards lower values, with the resonance dips becoming sharper and deeper. This trend indicates stronger electromagnetic interactions at specific frequencies for higher permittivity materials. However, the lower frequency shift and narrower bandwidth associated with higher ϵ_r values suggest that substrates with permittivities closer to free space ($\epsilon_r \approx 1$) are more advantageous for RIS applications. Such materials would likely provide broader operational bandwidth and higher frequency resonances, potentially enabling more versatile and efficient RIS designs across a wider frequency spectrum.

The impact of substrate losses on the reflection characteristics of the unit cell is investigated by varying the $\tan \delta$ of the substrate material. Figure 3.4 presents the amplitude of the reflection coefficient in decibels over a frequency range of 6-10 GHz for $\tan \delta$ values of 0.0009, 0.005, 0.01, and 0.02. The results clearly demonstrate that the loss tangent of the substrate significantly influences the reflection properties of the unit cell. As $\tan \delta$ increases, indicating higher dielectric losses in the substrate, the overall

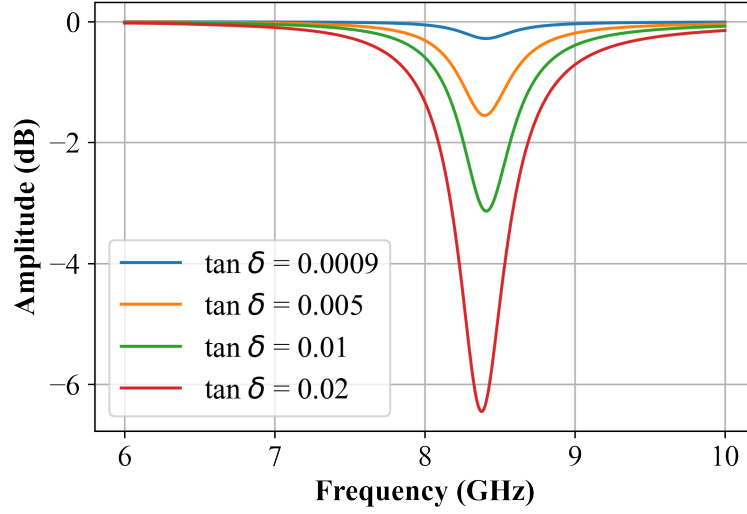


Figure 3.4: Reflection coefficient amplitude versus frequency for the unit cell with varying substrate loss tangent ($\tan \delta$) values, ranging from 0.0009 to 0.02.

reflection amplitude decreases across the frequency range. This effect is particularly pronounced around 8.5 GHz, where the differences in reflection amplitude between the various $\tan \delta$ values are most evident. The illustration underscore the critical role of substrate material selection in RIS design, as the loss tangent can substantially impact the surface's ability to efficiently manipulate incident electromagnetic waves.

3.1.3 Polarization considerations

Polarization insensitivity is another factor that should be carefully considered in RIS unit cell design. RIS structures are typically deployed in environments with random polarization illuminations, making it essential to minimize the unit cell's sensitivity to polarization variations. This insensitivity ensures consistent performance regardless of the incident wave's polarization state, which is crucial for reliable operation in real-world scenarios. Generally, polarization insensitivity can be achieved by designing symmetrical structures. Symmetry in the unit cell geometry helps to ensure that the reflection characteristics remain consistent across different polarization angles. However,

achieving this symmetry becomes challenging when incorporating active components such as varactor diodes, which are often necessary for tunability. These components can introduce asymmetries that lead to polarization-dependent behavior. To address this issue, multi-layer structures can be developed as a potential solution. By carefully designing multiple layers with complementary characteristics, it is possible to compensate for asymmetries introduced by active components and maintain a high degree of polarization insensitivity. This approach, while more complex, allows for the integration of tunable elements without sacrificing the broadband polarization performance necessary for effective RIS operation in diverse electromagnetic environments.

3.2 Achieving Reconfigurability

Reconfigurability is a fundamental characteristic of RISs that distinguishes them from static reflective surfaces. In the context of RIS unit cells, reconfigurability refers to the ability to dynamically alter the electromagnetic properties of each unit cell, particularly its reflection phase and potentially its amplitude. This dynamic control allows the RIS to adaptively manipulate incident electromagnetic waves, enabling functionalities such as beamforming, wavefront shaping, and intelligent environmental modification for wireless communication enhancement. The essence of reconfigurability lies in the capacity to adjust these properties in real-time or near-real-time, responding to changing communication needs or environmental conditions. This adaptive capability is what makes RISs "intelligent" and allows them to optimize wireless signal propagation in complex and varying scenarios.

3.2.1 Reconfigurability Methods

Various methods have been developed to achieve reconfigurability in RIS unit cells, with the choice of method largely dependent on the operational frequency range. For terahertz

and visible light regimes, advanced materials such as graphene and liquid crystals have shown promising results. Graphene, with its tunable conductivity controlled by electrostatic bias, offers exceptional reconfigurability at extremely high frequencies. Liquid crystals, whose molecular orientation can be altered by applied electric fields, provide another avenue for achieving reconfigurability in these higher frequency bands. In contrast, for microwave and millimeter-wave frequency bands, which are currently more relevant for wireless communications, semiconductor devices such as PIN diodes and varactor diodes are commonly employed. PIN diodes, which can be switched between 'ON' and 'OFF' states, allow for discrete phase control, typically used in 1-bit or multi-bit designs. Varactor diodes, whose capacitance can be continuously varied with applied bias voltage, enable more granular control over the reflection phase, allowing for finer tuning of the unit cell's electromagnetic response. These semiconductor-based approaches offer robust and reliable reconfigurability in the frequency ranges most pertinent to current and near-future wireless communication systems.

3.2.2 PIN Diode Implementation

PIN diodes are widely used in RIS designs due to their favorable characteristics for RF switching applications. In a typical RIS unit cell, PIN diodes are employed to control the reflection phase by altering the effective electrical length of resonant elements. When forward-biased, PIN diodes act as low-resistance switches, allowing current flow and effectively connecting different parts of the unit cell. In the reverse-biased state, they present high impedance, essentially disconnecting portions of the structure.

The implementation of PIN diodes in RIS often involves integrating them into metasurface designs, where they can be used to switch between different resonant modes. This allows for discrete phase control, typically achieving two or four distinct phase states per unit cell. The switching speed of PIN diodes is relatively fast, enabling

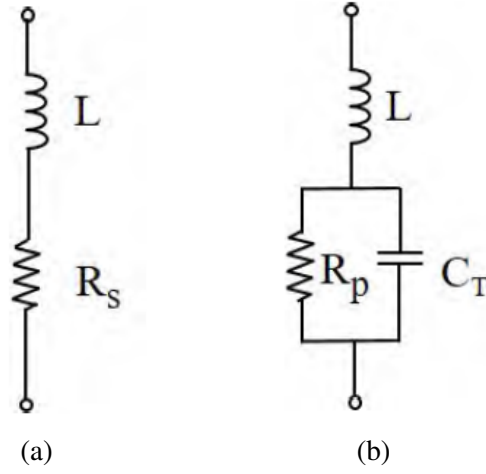


Figure 3.5: The equivalent circuit of a PIN diode is shown for both (a) ON and (b) OFF states. In the circuit, L represents the package inductance, R_s denotes the series resistance during forward bias, C_T corresponds to the total capacitance under reverse bias, and R_p is the reverse parallel resistance.

rapid reconfiguration of the RIS in response to changing channel conditions or user requirements.

The equivalent circuit of a PIN diode can be modeled differently depending on whether it is in the forward-bias (ON) or reverse-bias (OFF) condition (Figure 3.5). In the ON state, the equivalent circuit is dominated by a series resistance R_s , which represents the low resistance encountered when the diode is forward-biased. In contrast, in the OFF state, the circuit is primarily characterized by a small capacitance C_T that corresponds to the diode's reverse-biased condition, where the resistance R_p becomes negligible. The inductance L , associated with the package, is typically insignificant at microwave frequencies and can often be ignored in these equivalent circuit models. For example, the MA4GP907 PIN diode, with a series resistance $R_s = 4.2 \Omega$ and a total capacitance $C_T = 0.025 \text{ pF}$, is often used to implement reconfigurability in RIS designs.

One of the key advantages of PIN diodes in RIS design is their robustness and reliability under high-power RF conditions. They can handle significant power levels without compromising performance, making them suitable for various applications, including

those requiring high transmit powers. Additionally, PIN diodes offer good linearity, which is crucial for maintaining signal integrity in complex communication systems. However, PIN diode implementations also face challenges. The discrete nature of their phase control limits the granularity of beam steering and wavefront shaping capabilities. Furthermore, the need for biasing networks to control multiple PIN diodes can increase the complexity of the overall RIS design, potentially leading to increased power consumption and fabrication costs.

3.2.3 Varactor Diode Implementation

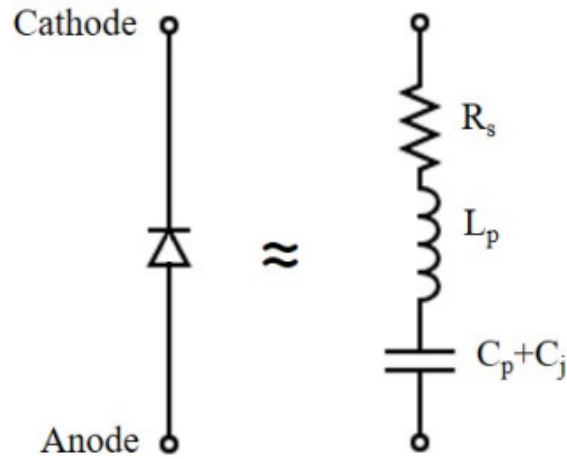


Figure 3.6: Equivalent circuit model of a varactor diode. The diode is represented by a resistor R_s in series with an inductance L_p and a parallel combination of capacitance $C_p + C_j$.

Varactor diodes, also known as varicap diodes, are semiconductor devices widely used in RIS designs for their voltage-dependent capacitance characteristics. In a typical RIS unit cell, varactor diodes are employed to achieve continuous phase control by varying the capacitance of resonant elements. This variable capacitance is controlled by applying a reverse bias voltage across the diode, allowing for smooth and continuous adjustment of the reflection phase.

3.2 ACHIEVING RECONFIGURABILITY

The implementation of varactor diodes in RIS often involves incorporating them into tunable resonant structures within each unit cell. This allows for a wide range of phase shifts, typically achieving a continuous phase control over nearly 360 degrees. The tuning speed of varactor diodes is generally fast, enabling dynamic reconfiguration of the RIS to adapt to changing propagation environments or user requirements.

The equivalent circuit of a varactor diode can be modeled as shown in Figure 3.6. In this model, C_j represents the voltage-dependent junction capacitance, which is the primary element exploited for phase control. R_s is the series resistance, which contributes to insertion loss. L_p represents the package inductance, and C_p is the parallel parasitic capacitance.

In the reverse-bias condition, which is the typical operating mode for RIS applications, the capacitance C_j varies inversely with the applied voltage. This relationship is often expressed as:

$$C_j = \frac{C_0}{(1 + V/V_0)^m} \quad (3.1)$$

where C_0 is the capacitance at zero bias, V is the applied reverse voltage, V_0 is the built-in potential of the junction, and m is the grading coefficient (typically between 0.3 and 0.5 for abrupt junctions).

For example, the SMV1405 varactor diode, with a tuning range of 0.63 pF to 2.67 pF over a reverse voltage of 0 to 30 V, is commonly used in RIS designs for its wide capacitance range and low series resistance.

One of the key advantages of varactor diodes in RIS design is their ability to provide continuous and fine-grained phase control. This allows for more precise beam steering and wavefront shaping compared to discrete-state devices. Additionally, varactor diodes typically have lower power consumption than PIN diodes, as they operate under reverse bias and draw minimal current.

However, varactor diode implementations also face challenges. They are generally

more sensitive to RF power levels than PIN diodes, which can limit their use in high-power applications. The nonlinear capacitance-voltage relationship can also introduce distortion in some configurations, requiring careful design to maintain signal integrity. Furthermore, the need for analog control voltages to adjust multiple varactor diodes can increase the complexity of the bias network and control circuitry in large-scale RIS implementations.

3.2.4 Comparison of PIN and Varactor Diode Performance

In overall, the choice between PIN diodes and varactor diodes for RIS implementation depends on the specific requirements of the application. PIN diodes offer robust performance under high-power conditions, fast switching speeds, and good linearity, making them suitable for applications where discrete phase states are sufficient and power handling is crucial. They are often preferred in scenarios requiring rapid reconfiguration and resilience to high RF power levels. On the other hand, varactor diodes provide continuous phase control, allowing for more precise beam steering and wavefront shaping. This makes them advantageous in applications demanding fine-grained control over the reflected signal phase.

The power consumption characteristics of these diodes differ significantly. PIN diodes typically require higher bias currents to maintain their ON state, potentially leading to increased power consumption in large-scale RIS deployments. Varactor diodes, operating under reverse bias, generally consume less power, which can be a critical factor in energy-efficient designs or battery-operated systems.

In terms of linearity and distortion, PIN diodes generally exhibit better performance, especially at higher power levels. This makes them preferable in scenarios where signal integrity is paramount. Varactor diodes, while capable of continuous tuning, may introduce nonlinear effects that require careful management in the circuit design.

The complexity of control circuitry also differs between the two. PIN diodes often require simpler digital control schemes, as they operate in discrete states. Varactor diodes, needing precise analog voltage control, may require more sophisticated bias networks and control systems, potentially increasing the overall system complexity and cost.

Ultimately, the selection between PIN and varactor diodes in RIS design involves balancing factors such as phase resolution, power handling, linearity, power consumption, and system complexity. Modern RIS designs may even incorporate both types of diodes to leverage their respective strengths in different parts of the system or for different operational modes.

3.3 Design Automation

The design of RIS unit cells often involves iterative processes and multiple parameter adjustments to achieve desired performance characteristics. Automation of this design process can significantly enhance efficiency and allow for exploration of a wider design space. Although commercial 3D high frequency simulation software applications, such as Ansys High Frequency Structure Simulator (HFSS) and CST Studio Suite, have many modules and tools to make the design process easier, they sometimes lack the flexibility needed for developing complex structures. Python, a versatile and powerful programming language, has emerged as an ideal solution to bridge this gap. Known for its simplicity, readability, and extensive ecosystem of scientific libraries, Python offers the flexibility and computational capabilities required for advanced electromagnetic design workflows. By leveraging Python's integration with electromagnetic simulation software, it becomes possible to streamline the design workflow, perform parametric sweeps, and implement sophisticated optimization algorithms. This sub-section discusses the methodologies and tools used to automate the RIS unit cell design process,

focusing on Python-HFSS integration and the implementation of parametric sweeps and optimization algorithms. In the following, an Example will be presented to showcase the efficiency and effectiveness of these automated design processes in the context of RIS unit cell development.

3.3.1 Python-HFSS Integration

Ansys HFSS is an industry-standard software for simulating 3D full-wave electromagnetic fields. It utilizes the finite element method and adaptive meshing to provide accurate solutions for high-frequency electromagnetic problems. HFSS is widely used in the design and analysis of antennas, RF/microwave components, and complex electromagnetic structures, making it an ideal tool for RIS unit cell design.

HFSS uses Visual Basic (VB) scripts as the primary language to interface with its graphical user interface (GUI) for modeling and simulating 3D HF structures. Each action performed in the GUI of the software is recordable as a Visual Basic Script (VBS) script, and by executing the script, the same set of actions will be performed in the HFSS GUI environment. This feature allows for a certain level of automation and reproducibility in the design process. However, while VB scripts offer a degree of automation, they can be limited in terms of flexibility and integration with external tools. This is where Python integration becomes particularly valuable, offering a more versatile and powerful programming environment for controlling HFSS simulations and post-processing results.

```
1 Set oEditor = oDesign.SetActiveEditor("3D Modeler")
2 oEditor.CreateRectangle Array("NAME:RectangleParameters",
    "IsCovered:=", true, "XStart:=", _
3   "-0.5mm", "YStart:=", "-0.5mm", "ZStart:=", "0mm", "
    Width:=", "0.5mm", "Height:=", _
```

3.3 DESIGN AUTOMATION

```
4  "0.5mm", "WhichAxis:=", "Z"), Array("NAME:Attributes",
    "Name:=", "Rectangle1", "Flags:=", _
5  "", "Color:=", "(143 175 143)", "Transparency:=", 0, "
    PartCoordinateSystem:=", _
6  "Global", "UDMId:=", "", "MaterialValue:=", "" & Chr
    (34) & "PEC" & Chr(34) & "", "SurfaceMaterialValue:="
    "", _
7  "" & Chr(34) & "" & Chr(34) & "", "SolveInside:=", true
    , "ShellElement:=", _
8  false, "ShellElementThickness:=", "0mm", "
    ReferenceTemperature:=", "20cel", "
    IsMaterialEditable:=", _
9  true, "UseMaterialAppearance:=", false, "IsLightweight
    :=", false)
```

Listing 3.1: A VBS function to create a PEC sheet in HFSS.

Python's integration with HFSS allows for a more flexible and powerful approach to automation. For example, to create a 1×1 mm² square sheet on the XY plane, the VBS code given in Listing 3.1 is executed. In a Pythonic environment, this set of commands can be encapsulated into functions, allowing for more streamlined and customizable creation of structures in the HFSS environment. This functional approach opens up new possibilities for complex design automation. For instance, we can generate a random array of zeros and ones to represent a 2D surface, where ones indicate the presence of sheets and zeros represent their absence. This approach allows for the rapid creation and modification of intricate RIS unit cell designs. By using Python's powerful array manipulation libraries, such as NumPy, we can efficiently generate these arrays and translate them into HFSS commands, effectively creating a programmable interface for

3.3 DESIGN AUTOMATION

RIS design.

```
1 import numpy as np
2 import HFSSClass
3
4 hfss = HFSSClass.HFSS()
5
6 hfss.openProject()
7 patch_size = 1
8 array_2D = np.array([[1, 0, 1],
9                      [1, 1, 1],
10                     [0, 0, 1]])
11
12 total_x = array_2D.shape[1]*patch_size
13 total_y = array_2D.shape[0]*patch_size
14
15 for j in range(array_2D.shape[0]):
16     for i in range(array_2D.shape[1]):
17         if array_2D[i, j] == 1:
18             hfss.createSheet(
19                 Xlength=patch_size,
20                 Ylength=patch_size,
21                 Centerpoint=[i*patch_size - total_y/2 +
22                             patch_size/2, j*patch_size-total_x/2 +
23                             patch_size/2, 0],
24                 name='Patch_'+str(i)+'_'+str(j)
25             )
```



```
24 hfss.runVBS()
```

Listing 3.2: A Python code for creating a customized 3x3 grid of PEC patches.

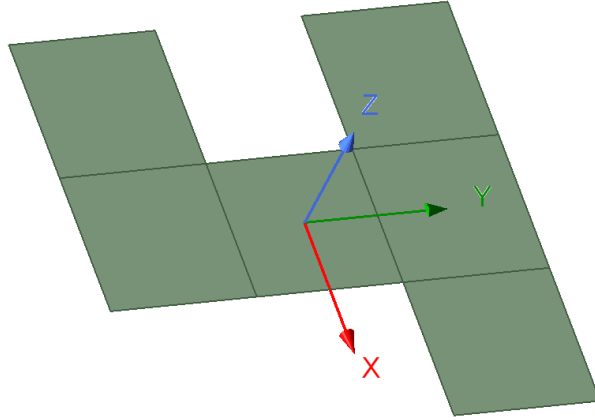


Figure 3.7: Customized patch created in HFSS using HFSSClass API in Python.

To demonstrate this concept, a simple Python code can be developed to create a 3x3 grid of patches in HFSS (Listing 3.2). The code utilizes the NumPy library to define a 2D array representing the patch layout. The HFSS Python API is then used to create sheets for each patch, with their positions calculated based on the array indices. This approach results in a structure as shown in Figure 3.7, where five $1 \times 1 \text{ mm}^2$ patches are arranged in a specific pattern within a 3x3 grid on the XY plane.

This method of integrating Python with HFSS not only automates the design process but also introduces a level of flexibility and complexity that would be challenging to achieve through the GUI or VBS alone. It enables the exploration of a vast design space, allowing for the creation of RIS structures with varying degrees of complexity and randomness, which can be crucial in optimizing performance characteristics. Through the study on the topic, nearly all design modules in HFSS have been collected as functions in the HFSSClass class. These functions can be used for a variety of design and simulation purposes, providing a comprehensive toolkit for RIS unit cell development.

3.3.2 Parametric Sweeps and Optimization Algorithms

While HFSS provides a powerful environment for electromagnetic simulations, its capabilities for parameter sweeps and optimization are relatively limited, offering only a handful of optimization methods and parameter sweep functionalities. This limitation can constrain the design process, particularly for complex structures like RIS unit cells where multiple parameters may need to be optimized simultaneously. In contrast, the Python ecosystem offers a vast array of open-source libraries developed by a global community of developers. These libraries provide access to hundreds of thousands of tools and algorithms that can be leveraged for optimization and machine learning purposes. By integrating these advanced algorithms with HFSS through Python, we can significantly enhance the optimization capabilities in RIS unit cell design. Using the latest optimization algorithms can guarantee a better design outcome in several ways. Firstly, these algorithms often employ more sophisticated search strategies that can efficiently explore large, multi-dimensional parameter spaces. This is particularly crucial in RIS design, where multiple geometric and material parameters may need to be tuned simultaneously to achieve desired performance characteristics. Moreover, many of these algorithms are designed to handle complex, non-linear problems, which are common in electromagnetic design. They can navigate through local optima and find global or near-global optimal solutions, potentially leading to designs that might be overlooked by simpler optimization methods. Another advantage of using Python-based optimization is the ability to define custom objective functions. This flexibility allows designers to optimize for multiple performance metrics simultaneously, such as reflection phase range, bandwidth, and loss, creating more holistic and application-specific designs.

3.4 Proposed RIS Unit Cell

This section presents a detailed analysis of the proposed unit cell design for our RIS. We begin by describing the structural parameters of the unit cell, providing a comprehensive overview of its physical composition and dimensions. Subsequently, we conduct an in-depth examination of the unit cell's reflection coefficients.

Our investigation then proceeds to analyze the effects of parametric variations on the unit cell's behavior, offering insights into its tunability and operational characteristics. Following this, we delineate the measurement setup and methodology employed to validate our theoretical and simulated findings. This approach ensures a rigorous evaluation of the unit cell's real-world performance.

Finally, we present a comparative analysis of the simulated and measured results, discussing any discrepancies and validating the efficacy of our proposed design. This comprehensive examination aims to establish the viability and potential of our RIS unit cell for enhancing wireless communication systems.

Table 3.1: Parameter values for the proposed RIS unit cell.

Parameter	Symbol	Value (mm)
Width of substrate	w_s	20
Width of the first layer rectangular patch	w_1	5.42
Length of the first layer rectangular patch	l_1	11.22
Width of the second layer rectangular patch	w_2	9.14
Length of the second layer rectangular patch	l_2	8.4
Gap length between two patches (first layer)	g_1	1.6
Gap length between two patches (second layer)	g_2	1
Diameter of the circular vias	d_v	1.2
Distance of the via from center along x axes	l_v	2.45
Distance of the via from center along y axes	w_v	1.48

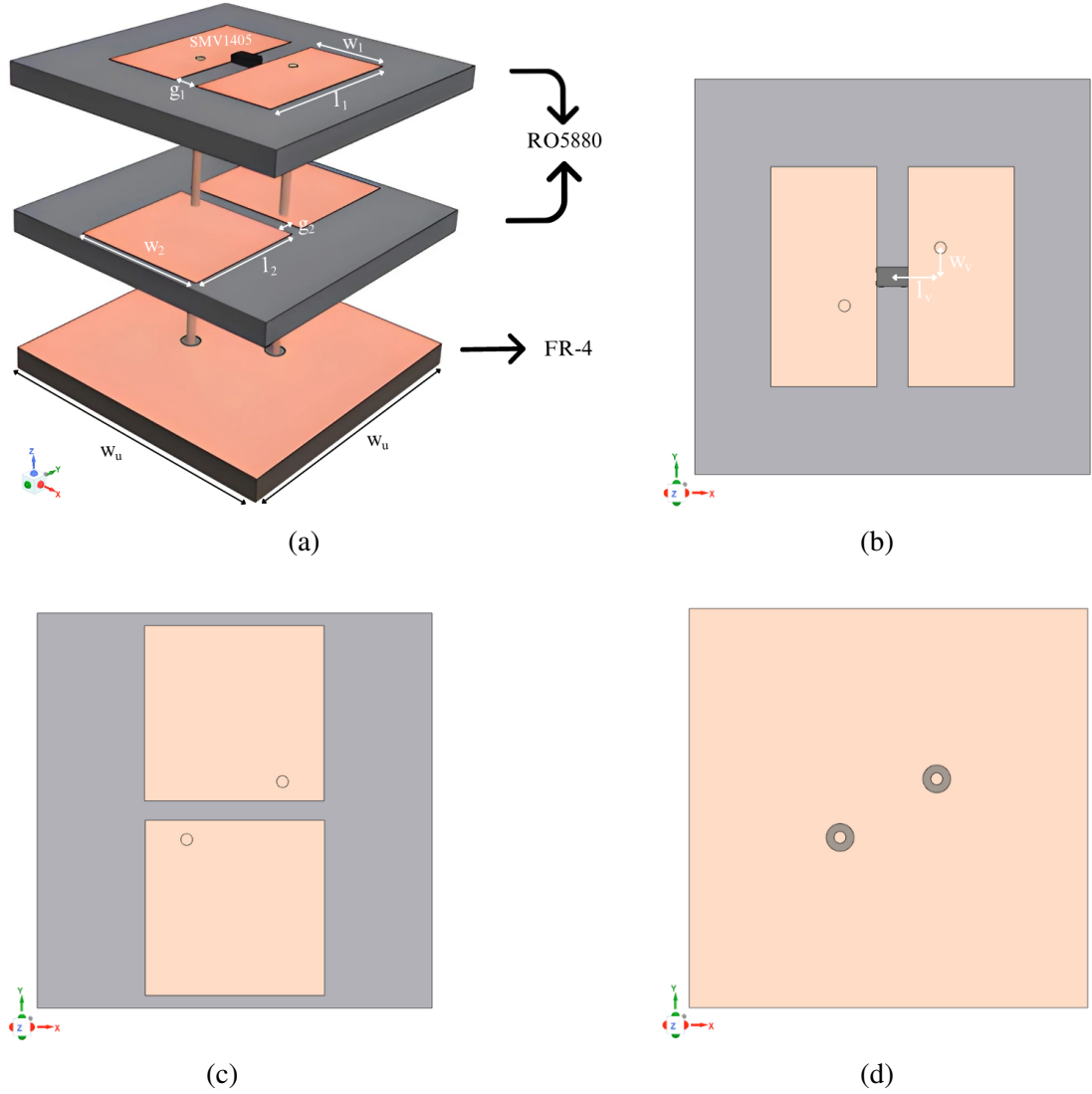


Figure 3.8: Structural representation of the proposed RIS unit cell. (a) Exploded perspective view showing the layered composition: two Rogers RT/duroid 5880 substrates sandwiching three conductive layers. (b) Top view of the first (upper) conductive layer featuring a split rectangular patch. (c) Top view of the second (middle) conductive layer with two rectangular patches. (d) Top view of the third (bottom) conductive layer serving as the ground plane with two circular vias.

3.4.1 Unit Cell Design Parameters

The structural configuration of the proposed RIS unit cell is illustrated in Figure 3.8. The unit cell's architecture consists of a multi-layer design, incorporating three distinct substrate layers, each measuring 1.57 mm in thickness. The substrate composition is carefully selected to optimize electromagnetic performance: two layers utilize Rogers RT/duroid 5880 substrate, chosen for its excellent low-loss characteristics at high frequencies, while the third layer employs FR-4 material.

The strategic use of Rogers RT/duroid 5880 for the upper two substrate layers is crucial in minimizing reflection losses, thereby enhancing the overall efficiency of the unit cell. The FR-4 layer, positioned at the bottom of the structure, serves a dual purpose. Firstly, it provides mechanical support, and secondly, it facilitates DC biasing for the positioned varactor diode (SMV1405), which is a key component in achieving the unit cell's reconfigurability.

The unit cell's electromagnetic behavior is tailored for both TE and TM polarization responses at its designated operating frequency. The topmost conducting layer is engineered to resonate with TE-polarized electromagnetic waves, while the second layer is optimized to alter reflection phase for TM-polarized illumination. This dual-layer approach enables the unit cell to effectively manipulate incident waves of different polarizations.

In terms of physical dimensions (Table 3.1), the unit cell adopts a square geometry with a uniform width (w_s) of 20 mm. The conductive elements on each layer are precisely dimensioned to achieve the desired electromagnetic properties. The first (top) layer features two metal patches separated by a gap. These patches measure 5.42 mm in width (w_1) and 11.22 mm in length (l_1), with an inter-patch gap of 1.6 mm (g_1). The second (middle) layer contains two rectangular patches with dimensions of 9.14 mm in width (w_2) and 8.4 mm in length (l_2). These patches are separated by a gap of 1 mm

(g_2).

The third (bottom) layer serves as the biasing board for the unit cell. Its top conducting layer acts as the ground plane (Figure 3.8 (d)), while the underside contains two metalized pads. These pads are to provide DC voltage supplies to the varactor diode. A key feature of this design is the incorporation of two through-vias. These vias establish electrical connections between the top layer patches and their corresponding pads on the bottom conducting layer, enabling effective control of the varactor diode and, consequently, the unit cell's reflective properties.

3.4.2 Reflection Parameters

The electromagnetic performance of the proposed unit cell is simulated using Ansys HFSS software, a commercial tool for high-frequency electromagnetic field simulation. Figure 3.9 illustrates the simulation setup, where periodic boundaries were applied to the XZ and YZ planes surrounding the unit cell. This configuration effectively models an infinite array of unit cells, providing insights into the structure's response when integrated into a large-scale RIS. Excitation was provided through a Floquet port, which is particularly suited for simulating periodic structures under plane wave illumination. The simulation results are primarily characterized by the S11 parameter, whose phase and magnitude directly correspond to the reflection phase and loss of the structure under illumination, respectively. These parameters translate the unit cell's ability to manipulate incoming electromagnetic waves.

Figure 3.10 presents the unit cell's reflection phase characteristics for both TE and TM polarized electromagnetic waves within the 5 to 5.5 GHz frequency band. The graph depicts the phase response for various capacitance values of the varactor diode, demonstrating the unit cell's tunability. A noticeable feature of these results is the similarity between the frequency responses for TE and TM polarizations. This

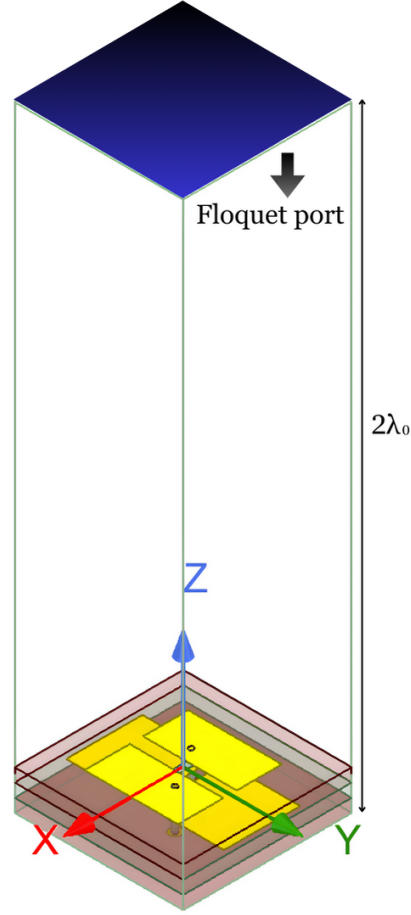


Figure 3.9: Simulation configuration in HFSS.

consistency across polarizations is a significant achievement, indicating that the unit cell design effectively maintains its phase manipulation capabilities regardless of the incident wave's polarization. Such behavior is particularly valuable for applications requiring dual-polarized operation, as it ensures uniform performance across different signal polarizations.

Figure 3.11 illustrates the reflection amplitude characteristics of the unit cell in response to both TE- and TM-polarized illumination across the 5-5.5 GHz frequency band. The graph presents these results for a range of varactor diode capacitance values, spanning from 1 pF to 2.7 pF, demonstrating the unit cell's tunable nature.

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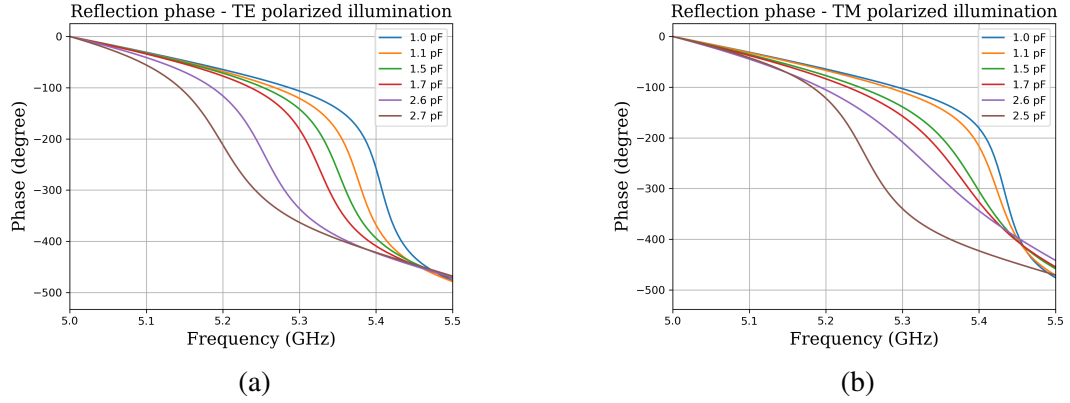


Figure 3.10: Reflection phase of the unit cell under illumination with (a) TE-polarized (b) TM-polarized EM waves with different values for varactor's capacitance (1-2.7 pF).

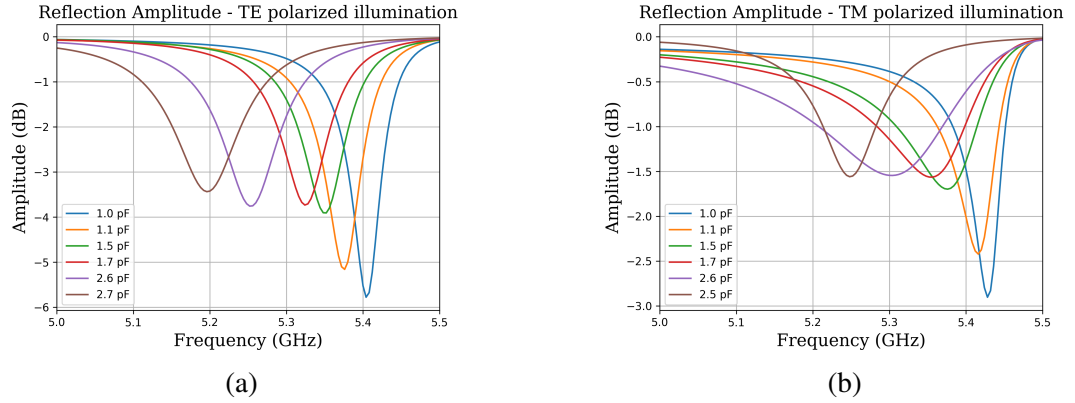


Figure 3.11: Reflection amplitude of the unit cell under (a) TE-polarized (b) TM-polarized illumination with different values for varactor's capacitance (1-2.7 pF).

A notable observation from the simulation results is the difference in reflection loss between the two polarizations. For TE-polarized illumination, the reflection loss varies between 3 to 6 dB across the frequency band and capacitance range. In contrast, TM-polarized illumination exhibits a significantly lower reflection loss, ranging from 1.5 to 3 dB. This lower reflection loss for TM polarization translates to higher efficiency in reflecting incident waves, which can be particularly advantageous in applications where TM polarization is predominant or in scenarios requiring energy-efficient wave manipulation.

The disparity in reflection loss between TE and TM polarizations can be attributed to

the specific layered design of the unit cell. As previously described, the first conducting layer is optimized for TE polarization, while the second layer is tailored for TM polarization. This design choice results in different electromagnetic interactions for each polarization, leading to the observed variations in reflection efficiency.

It is important to note that while lower reflection loss is generally desirable for energy efficiency, the choice between TE and TM optimization may depend on the specific requirements of the intended application. For instance, in scenarios where polarization diversity is crucial, the ability to manipulate both polarizations, albeit with different efficiencies, could be more valuable than optimizing for a single polarization. Understanding these amplitude characteristics in conjunction with the phase response discussed earlier is crucial for comprehensively evaluating the unit cell's performance. The combination of phase control and amplitude behavior determines the overall effectiveness of the RIS in manipulating electromagnetic waves for various applications such as beamforming, signal focusing, or interference mitigation.

3.4.3 Parameter Sweep and Electric Field Distribution Analysis

To gain deeper insights into the unit cell's behavior, a parameter sweep study is performed, beginning with an analysis of the electric field distribution on the top and middle layers of the structure.

Figure 3.12 illustrates the magnitude of the electric field distribution on the top and middle conducting layers of the structure when subjected to TE and TM incident waves. This visualization provides crucial information about how different parts of the unit cell interact with electromagnetic waves of varying polarizations.

For TE polarization (Figure 3.12 (a)), it is observed that only the patches on the top layer are excited. This is due to the x-axis polarization of the incident wave, which aligns with the geometry of the top layer patches. The concentration of the electric

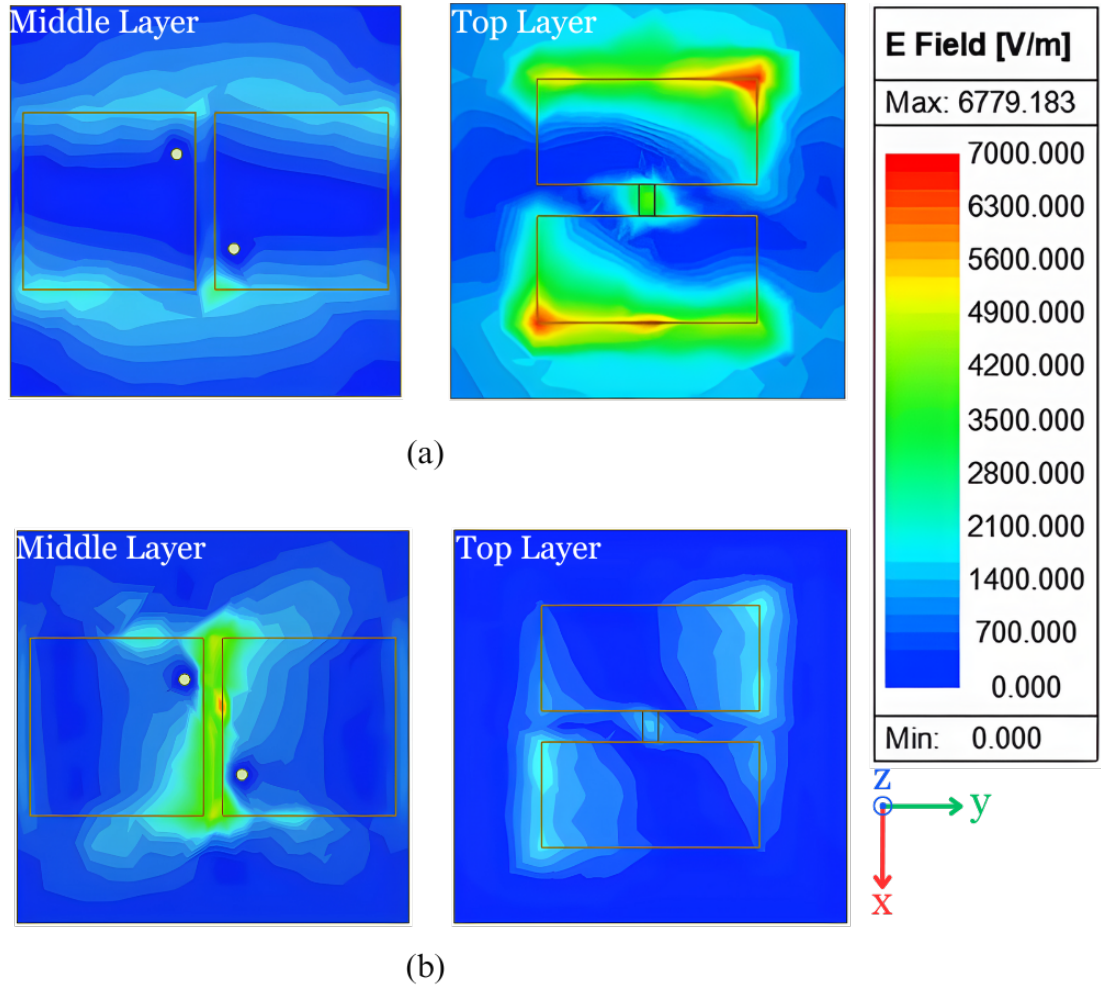


Figure 3.12: Magnitude of electric field distribution on top and middle conducting layers for (a) TE-polarized (along x-axis) and (b) TM-polarized (along y-axis) illumination scenarios.

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field in these areas indicates that the dimensions of these patches will have a significant impact on the unit cell's response to TE-polarized waves.

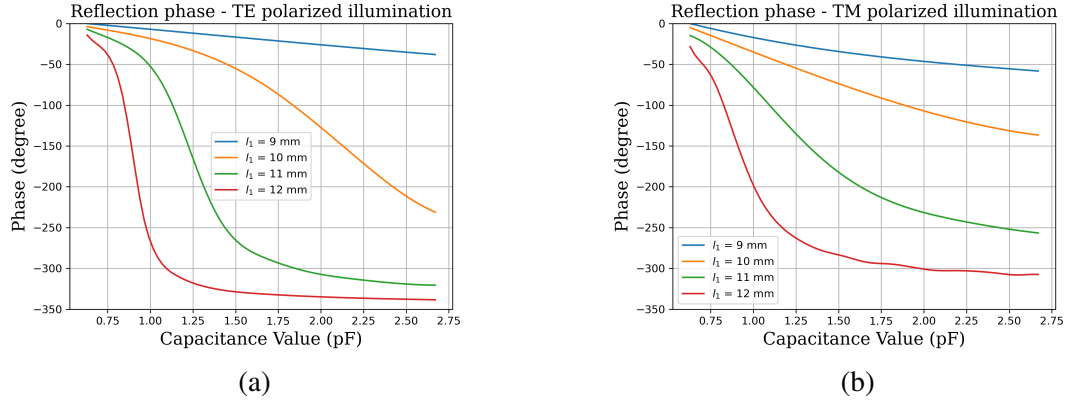


Figure 3.13: Reflection phase of the unit cell versus varactor's capacitance at 5.3 GHz under (a) TE-polarized (b) TM-polarized illumination for different values for l_1 (9-12 mm).

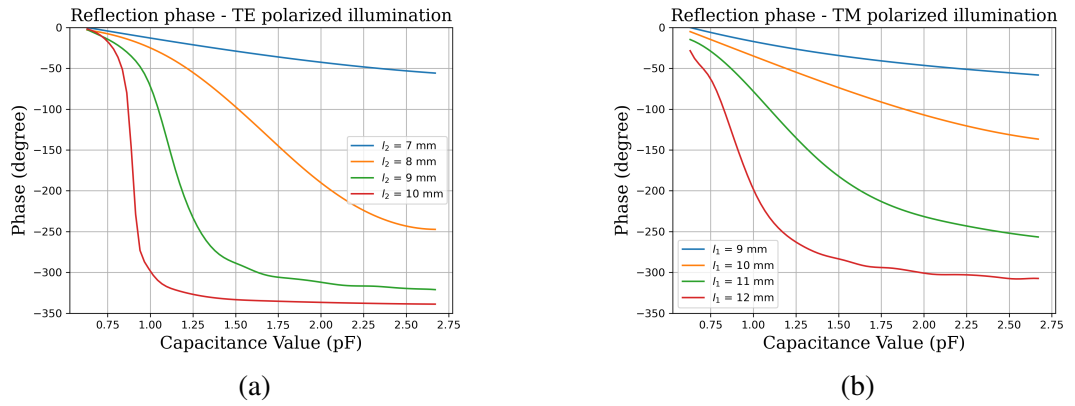


Figure 3.14: Reflection phase of the unit cell versus varactor's capacitance at 5.3 GHz under (a) TE-polarized (b) TM-polarized illumination for different values for l_2 (7-10 mm).

In contrast, for TM polarization (Figure 3.12 (b)), the middle conducting layer is predominantly excited. This layer contributes significantly to the phase change for TM polarization. The distinct excitation patterns between TE and TM polarizations explain the differences in reflection characteristics observed earlier and highlight the dual-polarization capabilities of the unit cell design.

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These distribution patterns offer valuable insights into how different layers respond to various polarizations, directly impacting the overall phase shift and reflection loss behavior of the structure. By identifying the areas of highest field concentration, we can pinpoint the structural parameters that will have the maximum effect on the unit cell's performance.

Based on these observations, we focused our parameter sweep on the dimensions of the patches that showed the highest electric field concentration. Specifically, we adjusted parameters l_1 and l_2 , which correspond to the lengths of the patches on the top and middle layers, respectively.

To evaluate the effects of these patch dimensions on the unit cell's performance, l_1 is varied across a range from 9 mm to 12 mm and l_2 is swept from 7 mm to 10 mm. Subsequent simulations were conducted for various varactor capacitance values at a frequency of 5.3 GHz, which lies within our band of interest.

Figure 3.13 and Figure 3.14 illustrate the results of the parameter sweep for l_1 and l_2 , respectively. These graphs show the reflection phase of the unit cell as a function of the varactor's capacitance at 5.3 GHz for both TE- and TM-polarized illumination.

For the l_1 sweep (Figure 3.13), we varied the parameter from 9 mm to 12 mm. The results demonstrate that adjusting l_1 significantly influences the phase response of the unit cell, particularly for TE-polarized waves. As l_1 increases, we observe a wider phase coverage, with the 12 mm configuration approaching a full 360-degree phase shift for TE polarization. Similarly, Figure 3.14 presents the results of the l_2 sweep, ranging from 7 mm to 10 mm. The impact of l_2 variations is particularly noticeable for TM-polarized waves, where larger l_2 values lead to a broader phase coverage.

The selection of the optimal values for l_1 (11.22 mm) and l_2 (8.4 mm) was based on three primary quantifiable metrics: (1) phase coverage range, (2) phase tuning linearity, and (3) reflection amplitude. Figure 3.13 demonstrates that $l_1 = 11.22\text{mm}$ achieves approximately 330° of phase coverage for TE polarization across the varactor's

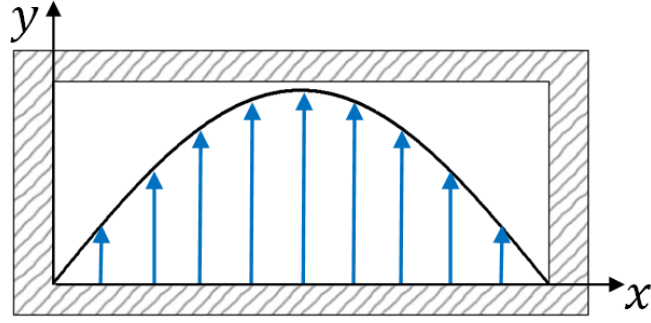


Figure 3.15: E-Field distribution at the aperture of a rectangular waveguide for TE_{10} operating mode.

capacitance range, while maintaining acceptable phase coverage for TM polarization. This value represents an optimal trade-off, as larger values (e.g., 12 mm) would approach 360° phase coverage but would result in non-linear phase variation with respect to capacitance, particularly in the 1.8-2.7 pF range. Similarly, Figure 3.14 shows that $l_2 = 8.4\text{mm}$ provides approximately 320° of phase coverage for TM polarization while ensuring relatively linear phase variation across the varactor's tuning range.

Additionally, these parameter values were selected to maintain reasonable reflection amplitude across the operating band. Our simulations revealed that $l_1 = 11.22\text{ mm}$ and $l_2 = 8.4\text{mm}$ yield reflection losses below 6 dB for TE polarization and below 3 dB for TM polarization throughout the frequency range of interest, as shown in Figure 3.11. Alternative parameter values either resulted in higher reflection losses or reduced phase coverage, making them less suitable for our dual-polarization RIS application.

These simulations highlight the sensitivity of the unit cell's phase response to dimensional changes. Optimizing l_1 and l_2 is essential for achieving the desired 360-degree phase coverage while maintaining smooth phase transitions across the varactor's tuning range.

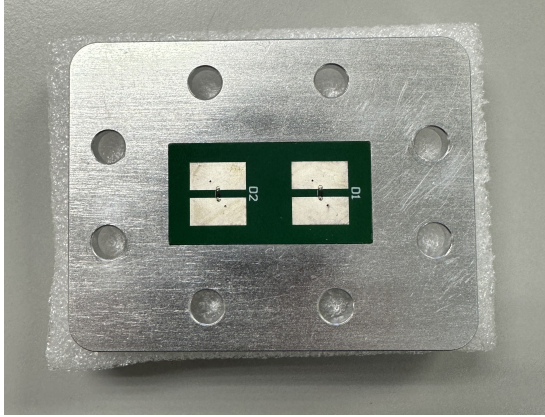
3.5 Unit Cell Measurement and Validation

The transition from theoretical design and simulation to practical implementation of the RIS unit cell necessitates experimental validation. This section presents an approach to measuring and validating the unit cell's performance. We begin by detailing the measurement setup and methodology, including the equipment used and procedures followed to ensure accurate characterization of the unit cell's electromagnetic properties. This is followed by a comparative analysis of the simulated and measured results, focusing on key parameters such as reflection phase, and amplitude response. Finally, we discuss any discrepancies between simulated and measured results, exploring potential limitations in both the simulation models and measurement techniques.

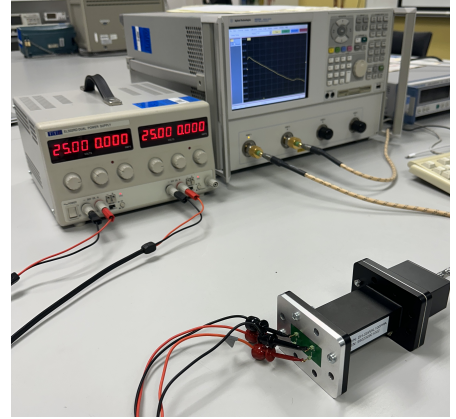
3.5.1 Measurement setup and methodology

To measure the reflection parameters of a unit cell, a general method that can be employed is a setup involving a waveguide. In this study, we focused on the waveguide method due to its ability to provide a controlled environment for precise measurements. This approach involves placing a unit cell, or a small array of unit cells, at the end of a rectangular waveguide and measuring the S_{11} parameter of that waveguide. Figure 3.15 illustrates the E-field distribution at the waveguide's aperture for the TE₁₀ mode, which is the dominant mode in rectangular waveguides. Illuminating the unit cell with this field distribution effectively replicates an illumination with semi-plane waves, closely approximating the conditions under which the unit cell would operate in a larger RIS array. This method allows for accurate characterization of the unit cell's reflection properties, including both magnitude and phase, under controlled and repeatable conditions. The waveguide setup also provides the advantage of isolating the unit cell from external electromagnetic interference, ensuring that the measured data accurately represents the unit cell's intrinsic behavior.

3.5 UNIT CELL MEASUREMENT AND VALIDATION



(a)



(b)

Figure 3.16: (a) A 1x2 array of unit cells designed to be placed at the aperture of a WR159 rectangular waveguide. (b) Measurement setup designed to measure reflection parameter of the proposed unit cell.

Figure 3.16 (a) shows the unit cells under test, where two unit cells are placed together in a custom-designed flange. This flange, with a thickness matching that of the unit cells, is designed to fit at the end of the WR159 waveguide. Figure 3.16 (b) illustrates our experimental setup, consisting of a Vector Network Analyzer (VNA) connected directly to a WR159 commercial rectangular waveguide via an SMA coaxial cable. A DC power supply is also visible, used for biasing the varactor diodes on the unit cells. This configuration allows for accurate S_{11} measurements while enabling dynamic control of the unit cell's properties through voltage adjustment. It is worth noting that the unit cells can be rotated by 90 degrees within the flange to facilitate S_{11} measurements for both TE and TM illuminations. This setup effectively replicates illumination with semi-plane waves, closely approximating the conditions under which the unit cells would operate in a larger RIS array.

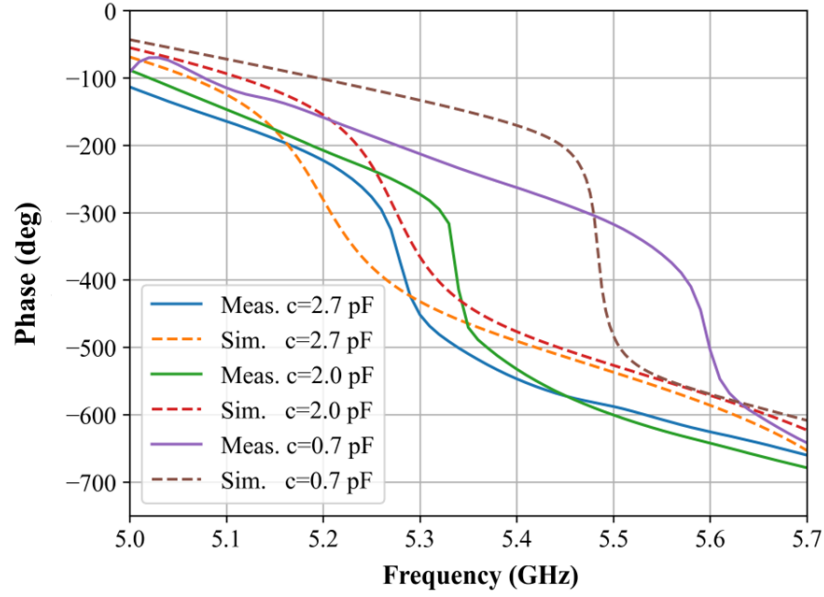


Figure 3.17: Comparison of simulated and measured reflection phase for TE (x-polarized) illumination of the unit cell at various varactor capacitance values (0.7 pF, 2.0 pF, and 2.7 pF) across the frequency range of 5.0 to 5.7 GHz.

3.5.2 Comparison of simulated and measured results

The performance of the proposed unit cell design is evaluated through both simulations and experimental measurements. Figures 3.17, 3.18, 3.19, and 3.20 illustrate a comparative analysis of the simulated and measured reflection characteristics for both TE (x-polarized) and TM (y-polarized) illuminations across the frequency range of 5.0 to 5.7 GHz.

Figure 3.17 illustrates the reflection phase for TE illumination. The measured results show good agreement with the simulations, particularly for capacitance values of 2.7 pF and 2.0 pF. For these cases, the phase variation trends are closely matched, with only slight frequency shifts observed. However, for the 0.7 pF case, there is a more noticeable discrepancy between the simulated and measured results, especially in the higher frequency range.

Figure 3.18 depicts the reflection phase for TM illumination. Similar to the TE case, there is generally good agreement between simulated and measured results. The phase

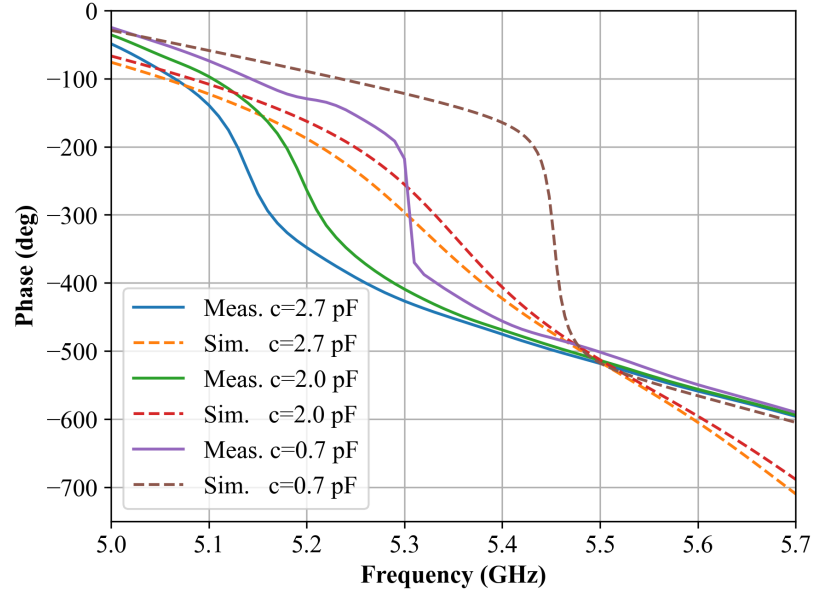


Figure 3.18: Reflection phase response of the unit cell under TM (y-polarized) illumination: Simulated vs. measured results for different varactor capacitances over 5.0-5.7 GHz.

variation patterns are consistent across all capacitance values, though some frequency shifts are evident, particularly for the 0.7 pF case.

Figures 3.19 and 3.20 present the reflection amplitude for TE and TM illuminations, respectively. For TM illumination (Figure 3.20), the measured results show deeper resonance dips compared to the simulations, especially for the 2.7 pF and 2.0 pF cases. The TE illumination results (Figure 3.19) demonstrate better alignment between simulated and measured data, with resonance frequencies and depths closely matched across all capacitance values.

3.5.3 Discussion of discrepancies and limitations

While the measured results generally align well with simulations, some discrepancies are observed. These differences can be attributed to several factors, each contributing to the variance between theoretical predictions and practical implementation.

A primary source of discrepancy lies in the simulation approach versus the physical

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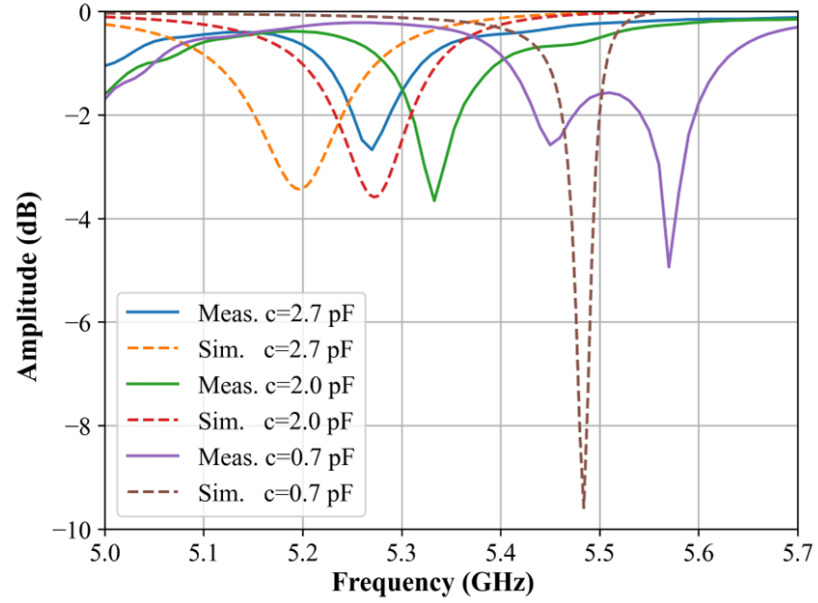


Figure 3.19: Unit cell reflection amplitude under TE (x-polarized) illumination: Measured and simulated results for multiple varactor capacitances from 5.0 to 5.7 GHz.

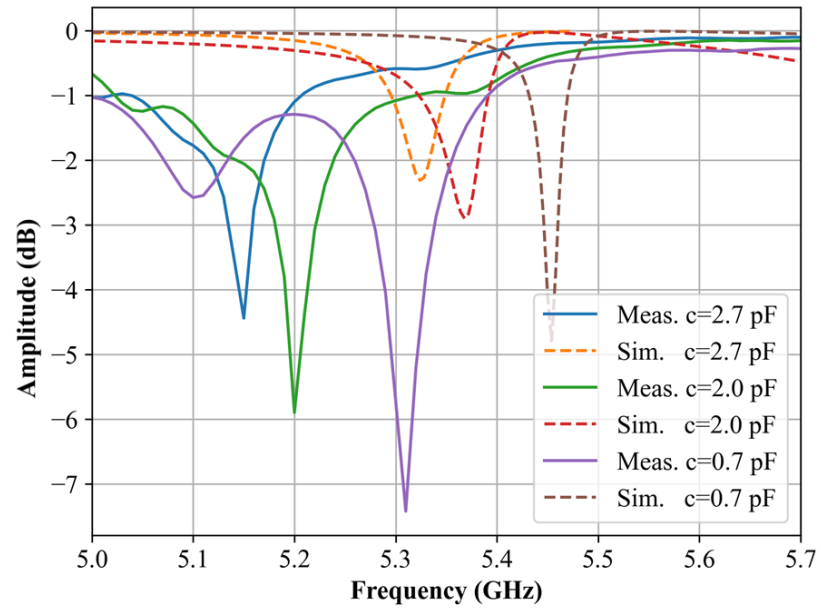


Figure 3.20: Comparison of simulated and measured reflection amplitude for TM (y-polarized) illumination of the unit cell at various varactor capacitance values (0.7 pF, 2.0 pF, and 2.7 pF) across the frequency range of 5.0 to 5.7 GHz.

3.5 UNIT CELL MEASUREMENT AND VALIDATION

setup. Simulations assumed an infinite array of unit cells in both x and y directions, leveraging periodic boundary conditions. However, the physical measurements were conducted on a setup containing only two unit cells. This disparity in array size can lead to edge effects and mutual coupling differences, potentially altering the electromagnetic response of the measured structure compared to the idealized infinite array.

Another significant factor is the non-uniform electromagnetic field distribution within the waveguide. Unlike the plane wave assumption often used in simulations, the field at the waveguide's aperture is not uniformly distributed for TE_{10} propagation mode (Figure 3.15). This non-uniformity in the excitation field can cause the unit cells to respond differently compared to their behavior under ideal plane wave illumination. The resulting discrepancies are particularly noticeable in the phase and amplitude responses, especially at certain frequencies.

Fabrication tolerances also play a role in the observed differences. Inherent limitations in the fabrication process can introduce small deviations from the designed dimensions and material properties. These variations, while minor, can accumulate to cause frequency shifts in the unit cell's response to electromagnetic illumination. Such shifts are evident in some of the measured results, particularly in the resonant frequencies of the structure. Despite these discrepancies, the observed similarities between simulated and measured behaviors provide a solid foundation for further refinement. With targeted modifications in design parameters and improvements in the fabrication process, it is feasible to develop a unit cell with the desired operating frequency band and performance characteristics.

It is important to note that these limitations do not undermine the validity of the overall design but rather highlight areas for future improvement. The insights gained from this comparison between simulation and measurement are valuable for refining the design process and enhancing the accuracy of future simulations. As RIS structures continue to evolve, addressing these discrepancies will be crucial in bridging the gap between

theoretical models and practical implementations, ultimately leading to more efficient and reliable RIS designs for advanced wireless communication systems.

3.6 Control Board Circuit

The effective implementation of RISs in wireless communication systems hinges on the ability to precisely and dynamically control the electromagnetic properties of each unit cell within the surface. This fine-grained control is typically achieved by adjusting the bias voltages applied to varactor diodes integrated into each unit cell, thereby modifying the phase shift imposed on incident electromagnetic waves. The design of a robust, efficient, and scalable control system to manage these bias voltages across potentially multitude of unit cells presents an engineering challenge.

This section delves into the intricacies of designing a control board circuit capable of individually addressing and biasing the varactor diodes in each RIS unit cell. We begin by examining the core functions and purpose of the control board within the larger RIS system architecture. Following this, we outline the key requirements and specifications that guide the design process, considering factors such as speed and power consumption. Given the complexity of the control task, we conduct a comparative analysis of various control hardware options, including microcontrollers, field-programmable gate arrays (FPGAs), and single-board computers like the Raspberry Pi. Each platform offers distinct advantages and trade-offs in terms of processing power, flexibility, and ease of implementation, which we evaluate in the context of RIS control applications.

The section then proceeds to detail the step-by-step design procedure for the proposed control board. This encompasses component selection, with a focus on choosing appropriate digital-to-analog converters (DACs), voltage regulators, and other critical elements that influence the overall system performance. We present the schematic design, elucidating the interconnections between components and the overall circuit

topology.

Finally, we present a comprehensive analysis of the proposed control board architecture. We evaluate its performance in terms of key metrics such as update speed and power consumption. This detailed performance evaluation provides insights into the practical limitations and capabilities of the control board, informing future optimizations and design iterations for RIS systems targeting various application scenarios in next-generation wireless networks.

3.6.1 Function and Purpose of the Control Board

RIS structures rely on active electronic components integrated into each unit cell to dynamically alter their electromagnetic properties. These components, which may include PIN diodes, varactor diodes, or specialized integrated circuits, enable real-time adjustment of the RIS configuration without physical intervention.

The primary function of the control board is to provide precisely regulated DC bias voltages to these active components. By modulating these bias voltages, the control board can effectively tune the phase shift or reflection characteristics of each individual unit cell within the RIS. This granular control is fundamental to achieving the desired wavefront manipulation and beamforming capabilities. As the scale of RIS structures grows, potentially incorporating hundreds or thousands of unit cells, the complexity of the biasing network increases significantly. The control board serves as a centralized management system for this extensive network, coordinating the voltages applied to each unit cell across the entire surface. It acts as an interface between high-level control algorithms - which may determine optimal RIS configurations based on channel conditions or user positions - and the physical hardware of the RIS.

The purpose of the control board extends beyond mere voltage regulation. It must also facilitate rapid reconfiguration of the entire RIS, translating desired phase patterns

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into appropriate bias voltages and updating the state of all unit cells with minimal latency. This speed is essential for adapting to dynamic channel conditions in mobile communication scenarios. The control board often incorporates feedback mechanisms to monitor the actual state of the RIS, ensuring that the intended configuration is accurately realized. It may also manage power distribution across the RIS, optimizing energy consumption while maintaining performance.

3.6.1.1 Key requirements and specifications

The design of the control board is heavily influenced by the specific active components employed in the RIS unit cells. Different types of active components necessitate distinct control strategies and hardware specifications. We will examine two common types of active components used in RIS designs: PIN diodes and varactor diodes.

PIN Diodes: When PIN diodes are utilized in the unit cell design, the control board typically needs to provide only two discrete voltage levels. However, the number of outputs required from the control system can be substantial. Consider the unit cell structure illustrated in Figure 2.8 designed with five PIN diodes, enabling four distinct modes for phase shifting. Consequently, this single unit cell requires five separate voltage outputs from the biasing network to achieve its various phase shifting configurations. As the number of unit cells in the RIS increases, the complexity of the control circuitry grows significantly, posing challenges in terms of routing, power distribution, and control signal management.

Varactor Diodes: In contrast, unit cells employing varactor diodes present a different set of requirements. Typically, fewer active components are needed per unit cell to achieve the desired functionality. However, the control board must be capable of generating a continuous range of voltage levels to bias the varactor diode effectively. Figure 3.21 illustrates the relationship between the biasing voltage (ranging from 0 to 30 V) and the resulting capacitance values for the SMV1405 varactor diode. This

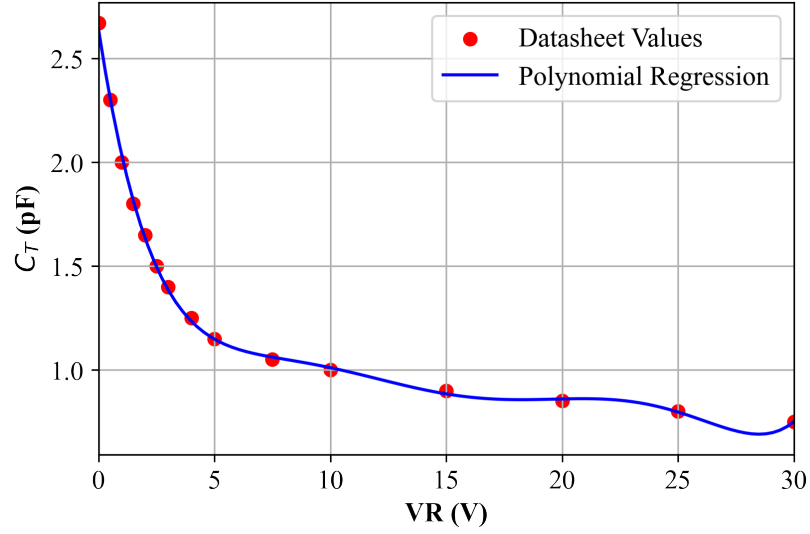


Figure 3.21: Capacitance values of SMV1405 varactor diode for different biasing voltages ranging from 0 to 30 V.

characteristic demonstrates that for varactor diodes, the control board must provide a wide range of precisely controlled voltages. While the number of outputs may be lower compared to PIN diode-based designs, the complexity lies in generating and maintaining accurate voltage levels across this broad range.

These differing requirements highlight the need for a flexible and adaptable control board design. For PIN diode-based RIS, the focus is on managing numerous digital outputs efficiently. In contrast, varactor diode-based systems require high-resolution digital-to-analog converters (DACs) and precise voltage regulation circuitry to achieve the desired continuous voltage control.

3.6.2 Comparison of Control Hardware Options

The heart of any RIS control board is its central processing unit, responsible for executing control algorithms, managing data flow, and coordinating the actuation of individual unit cells. Several hardware platforms are suitable for this role, each offering distinct advantages and trade-offs. In this section, we examine three primary options for

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implementing the control logic: microcontrollers, FPGAs, and single-board computers like the Raspberry Pi.

As we delve into each option, we will consider factors such as computational capabilities, power requirements, development complexity, and suitability for different scales of RIS deployment. This comparison will provide insights into selecting the most appropriate hardware platform for various RIS applications, from small experimental setups to large-scale commercial implementations.

3.6.2.1 Microcontrollers

Microcontrollers are highly energy-efficient, making them suitable for battery-powered or energy-constrained RIS deployments. They offer low-latency response times, which is beneficial for real-time phase adjustment in dynamic environments. Microcontrollers are also cost-effective, especially for smaller-scale RIS implementations. Their simplicity and wide availability make them accessible for rapid prototyping and development. Many microcontrollers feature built-in ADCs and DACs, which can be directly utilized for controlling varactor diodes. They also typically include numerous general-purpose input/output (GPIO) pins, useful for controlling PIN diode-based RIS designs.

However, the primary limitation of microcontrollers is their relatively low processing power compared to other options. This can become a bottleneck for large-scale RIS systems requiring complex real-time calculations. Microcontrollers also have limited memory, which may constrain the sophistication of control algorithms that can be implemented. Scaling to very large RIS arrays may require multiple microcontrollers, increasing system complexity.

An example of a microcontroller suitable for RIS control is the STM32F4 series from STMicroelectronics. The STM32F407VGT6 board, for instance, features an ARM Cortex-M4 core running at up to 168 MHz, 1 MB of flash memory, and 192 KB of RAM. It offers 10 GPIO pins, multiple ADC and DAC channels, and various communication

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interfaces (SPI, I2C, UART). This board provides a good balance of processing power, peripherals, and energy efficiency for small to medium-sized RIS implementations.

The STM32F4 series also supports direct memory access (DMA), allowing for efficient data transfer between memory and peripherals without CPU intervention. This feature can be particularly useful for updating large arrays of RIS elements rapidly. Additionally, its low power modes enable energy-saving strategies during periods of reduced activity, which is beneficial for energy-efficient RIS operation.

3.6.2.2 Raspberry Pi

The Raspberry Pi is a series of small single-board computers developed by the Raspberry Pi Foundation. Originally designed for promoting computer science education, these devices have found widespread use in various applications, including embedded systems and IoT projects.

Raspberry Pi offers a full-fledged Linux-based operating system, providing a familiar development environment for software engineers. This allows for the use of high-level programming languages like Python, C++, or Java, which can significantly speed up development time and reduce complexity compared to microcontroller or FPGA programming.

The processing power of Raspberry Pi boards is substantially higher than typical microcontrollers. For instance, the Raspberry Pi 4 Model B features a quad-core ARM Cortex-A72 processor running at 1.5 GHz, capable of handling complex control algorithms and signal processing tasks efficiently.

Raspberry Pi boards come with a wide range of built-in interfaces, including USB, Ethernet, Wi-Fi, and Bluetooth. This wealth of connectivity options facilitates easy integration with other systems and enables remote control and monitoring of the RIS. The availability of a large community and extensive documentation makes troubleshooting and development easier. Additionally, the Raspberry Pi's GPIO pins, while fewer in

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number compared to FPGAs, are sufficient for many RIS control applications and can be easily programmed.

Despite its advantages, the Raspberry Pi has some limitations for RIS control applications. It consumes more power than microcontrollers or many FPGAs, which may be a concern for energy-efficient designs or battery-powered systems.

The real-time performance of Raspberry Pi can be less deterministic compared to microcontrollers or FPGAs due to its use of a full operating system. This could potentially introduce latency in time-critical RIS control operations.

While the GPIO capabilities of Raspberry Pi are versatile, they may be insufficient for very large RIS arrays without additional expansion hardware. The analog I/O capabilities are also limited, often requiring external ADC/DAC modules for precise control of varactor diode-based RIS designs.

3.6.2.3 FPGAs

FPGAs are integrated circuits designed to be configured by the user after manufacturing. They consist of an array of programmable logic blocks and reconfigurable interconnects, allowing the implementation of complex digital computations in hardware.

FPGAs offer several significant advantages for RIS control applications. Their high number of GPIO pins makes them ideal for controlling large arrays of RIS elements simultaneously. This is particularly beneficial for PIN diode-based designs requiring numerous digital control signals.

One of the most compelling features of FPGAs is their ability to perform parallel processing. This allows for the simultaneous control and monitoring of multiple RIS elements, enabling rapid reconfiguration of large surfaces. The parallel nature of FPGA processing also results in very low latency, making them excellent for applications requiring real-time response to changing channel conditions.

FPGAs are exceptionally fast, with clock speeds that can reach hundreds of MHz. This

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speed, combined with their parallel processing capabilities, allows for the implementation of complex control algorithms and signal processing tasks directly in hardware, potentially offloading computational burden from other system components.

Additionally, FPGAs offer flexibility through reconfigurability. Their hardware description language (HDL) based programming allows for precise timing control and the implementation of custom digital interfaces, which can be advantageous for integrating with various RIS designs and external systems.

However, the primary drawback of FPGAs is the complexity of their programming. They typically require knowledge of hardware description languages like VHDL or Verilog, which have a steeper learning curve compared to other software programming languages. This can increase development time and costs.

Another consideration is that FPGAs often require the user to implement any necessary interfaces from scratch. While this offers flexibility, it also means that functionalities like UART, SPI, or I2C communications, which come built-in with many microcontrollers, need to be manually implemented on FPGAs.

The DE0-Nano board by terasIC is an example of an FPGA platform suitable for RIS control applications. This compact board features an Altera Cyclone IV FPGA, offering 22,320 logic elements, 594 Kbits of embedded memory, and 153 user I/O pins. The abundance of I/O pins makes it well-suited for controlling large RIS arrays. The hardware includes 32 MB of SDRAM and 2 Kb of EEPROM, providing ample memory for implementing complex control algorithms.

3.6.3 Control Circuitry Design

This section details the systematic approach taken in this work to design and implement the control circuitry for our RIS prototype. The design procedure follows a methodical path, ensuring that each decision is informed by the specific requirements of RIS

operation and the constraints of our chosen active elements.

3.6.3.1 Design Procedure

The design procedure for the RIS control board followed a structured and iterative approach, aimed at ensuring the final control board would meet the desired requirements of dynamically controlling a large-scale RIS. This methodology allowed for progressive refinement of the design, from initial concept to full implementation. The following steps outline the systematic process undertaken in the development of the control circuitry:

1. Specification of Purpose and Requirements:

For our RIS prototype, we established the following specific requirements:

- **Voltage Range:** The control system must provide precise voltage outputs in the range of 0-30V to adequately bias the varactor diodes across their full operating range.
- **Resolution:** A minimum of 12-bit resolution (4,095 discrete levels) is required to achieve fine-grained phase control with sufficient precision for beamforming applications.
- **Number of Channels:** The system must support at least 36 independently controllable outputs to drive each unit cell in our 6×6 RIS array.
- **Update Rate:** The control system should be capable of updating all voltage outputs at a minimum rate of 100 Hz to support dynamic beamforming scenarios.
- **Scalability:** The design should allow for potential expansion to larger arrays with minimal modifications.

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- **Power Efficiency:** The control circuitry should minimize power consumption to ensure practical deployment scenarios.
- **Cost-effectiveness:** The system should utilize readily available components to maintain a reasonable implementation cost.

These requirements have been met through our methodical component selection and system design. The voltage range of 0-30V is achieved through the amplification stage using the LM324AMX operational amplifiers. The MCP4728 DAC provides the required 12-bit resolution. Our final 36-output control board accommodates the complete RIS array. The combination of the DE0-Nano FPGA with the I2C interface to the DACs enables update rates exceeding 100 Hz. The modular design approach, using multiple quad-output DACs, ensures scalability to larger arrays if needed. Component selection was guided by power efficiency considerations, and all components were chosen to balance performance with cost-effectiveness.

2. Component Identification:

Following the requirements specification, potential components for the control system were identified. This step likely involved evaluating various integrated circuits, microcontrollers, digital-to-analog converters (DACs), and other essential elements based on their specifications, performance characteristics, and compatibility with the RIS architecture.

3. Prototype Development:

A preliminary version of the circuit board was developed to validate the design concept. In this case, a control board capable of generating 4 voltage outputs was constructed. This prototype served as a proof-of-concept and allowed for initial performance testing and design iteration.

4. Scalability Testing:

The prototype board's performance was tested to ensure it met the specified requirements. This phase involved assessing factors such as voltage accuracy, response time, power consumption, and phase change speed. The results from these tests informed necessary adjustments to the design before scaling up.

5. Full-Scale Board Development:

Based on the successful validation of the prototype, the full-scale control board was developed. This final version incorporated any optimizations or modifications identified during the testing phase and was designed to accommodate the complete array of RIS elements.

3.6.3.2 Component selection

Three key components were chosen for their specific features and compatibility with the system requirements: the DE0-Nano FPGA development board for its versatile processing capabilities and ample I/O pins, the MCP4728 12-Bit Quad Output DAC for its precise voltage control and low power consumption, and the LM324AMX operational amplifier for its ability to boost and accurately amplify the DAC output signals. In the following, the reasoning behind the component selection will be studied in details.

The DE0-Nano FPGA development board was selected as the core processing unit. This choice was based on several advantageous features. It is cost-effective, providing a balance between performance and affordability. With 153 I/O pins, it offers ample connectivity for interfacing with other components. The 50 MHz operating frequency ensures rapid execution of control algorithms. Additionally, the board accommodates 22,320 Logic Elements (LEs), providing sufficient resources for implementing complex control schemes and potential future expansions. The versatility of this FPGA allows for the implementation of various control algorithms and protocols, making it suitable

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for the dynamic nature of RIS control.

For precise voltage control, the MCP4728 12-Bit Quad Output DAC was chosen. This DAC aligns well with RIS control requirements due to its low power consumption, which is essential for maintaining the overall energy efficiency of the RIS system. It provides 4 buffered voltage outputs ranging from 0 to 5.5 volts. The 12-bit resolution allows for precise voltage control, necessary for accurate phase shifting in RIS elements. Moreover, its I2C compatibility enables straightforward integration with the FPGA controller, facilitating efficient command transmission for voltage adjustments. The ability to generate accurate voltage levels through a standardized interface makes this DAC ideal for controlling multiple RIS elements with high precision.

To boost the voltage output from the DAC, the LM324AMX operational amplifier IC was selected. This amplifier offers several beneficial features. It has a high DC voltage gain of 100 dB, ensuring accurate amplification of the DAC output. Its wide power supply range, allowing single supply operation from 3 V to 32 V, provides flexibility in system design. The low power consumption aligns with the energy efficiency goals of the RIS system. Additionally, the quad package design, featuring four internally compensated op-amps in a single package, reduces board space and complexity. The LM324AMX's ability to amplify the DAC's output while maintaining signal integrity is crucial for achieving the required voltage range for effective RIS element control.

The synergy between these components creates a robust and efficient control system capable of precisely manipulating the RIS elements. The FPGA provides the necessary processing power and flexibility, the DAC ensures accurate voltage generation, and the operational amplifier enables the system to achieve the required voltage range for RIS element actuation.

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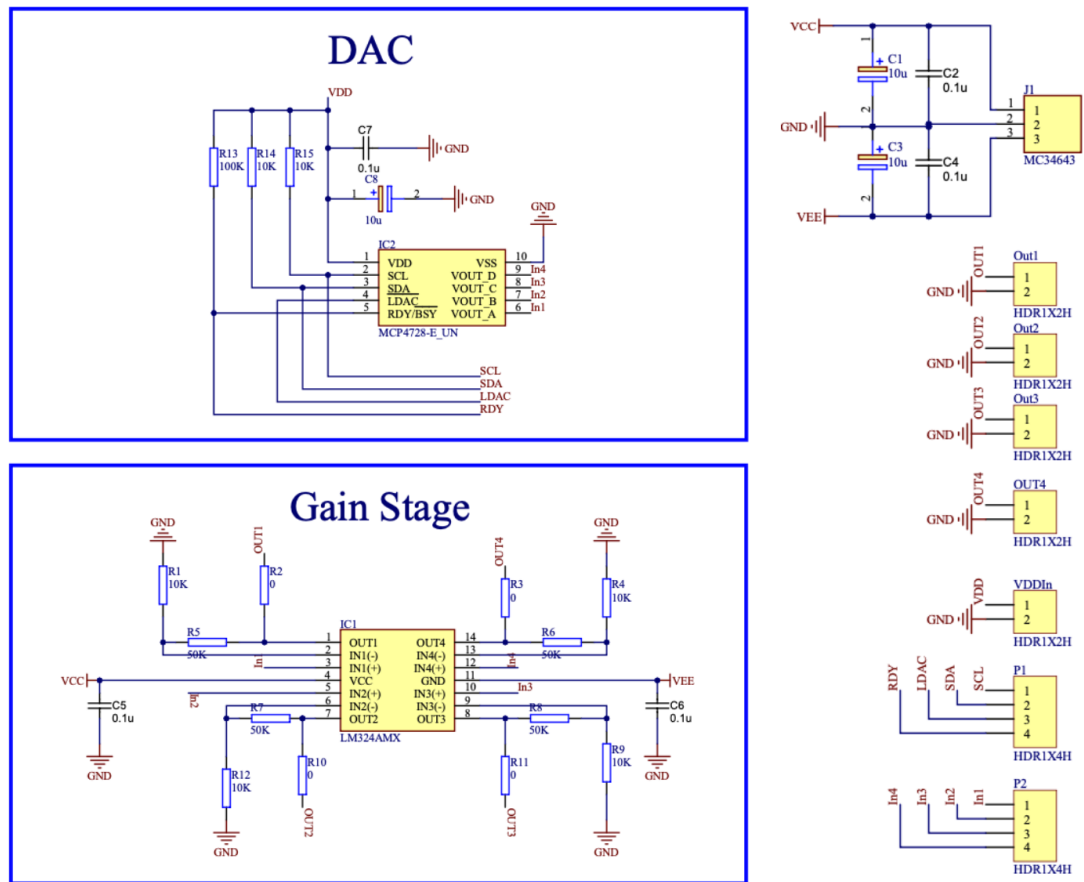


Figure 3.22: Schematic of a 4-output, 12-bit voltage generator with a range of 0-30 V.

3.6.3.3 Schematic overview and PCB layout

Figure 3.22 presents the schematic diagram of a prototype circuit with 4 outputs capable of producing voltage levels ranging from 0 to 30 V with resolution of 4095 voltage levels. This schematic illustrates the interconnections between the key components discussed earlier: the DAC (MCP4728), and the amplifier (LM324AMX). The design leverages the DAC's accurate voltage generation, and the operational amplifiers' ability to boost the voltage to the required range [98].

Figure 3.23 shows the physical implementation of the prototype control board. This board integrates the FPGA development kit (at the top) with our custom-designed PCB (at the bottom) containing the DAC and operational amplifier circuits. The key components are labeled to show their correspondence with the schematic in Figure 3.22. The four output terminals visible on the right side of the custom PCB deliver the precisely controlled bias voltages (0-30V) to the varactor diodes in the RIS unit cells. When integrated with the complete RIS system, this control board is expected to provide dynamic voltage control with 12-bit resolution (4095 discrete levels), enabling fine-grained phase adjustment of each RIS element. The practical performance metrics of this implementation, including voltage accuracy, update speed, and power consumption, are evaluated in Section 3.7.

The circuit consists of several distinct functional blocks that work together to provide precise voltage control to the RIS elements:

FPGA-DAC Interface: The DE0-Nano FPGA board communicates with the MCP4728 DAC via the I2C protocol, utilizing the SDA (Serial Data) and SCL (Serial Clock) lines. The FPGA is programmed to generate the appropriate I2C commands to set the desired voltage levels on each of the DAC's four output channels. Pull-up resistors (not shown in the schematic) are included on the I2C lines to ensure reliable communication.

Voltage Amplification Stage: Each output from the MCP4728 DAC (which ranges

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from 0-5V) connects to a non-inverting amplifier configuration built around one of the four amplifiers in the LM324AMX package. As shown in the schematic, each amplifier circuit uses a pair of resistors ($R1$ and $R2$) to establish the gain of the amplifier according to the formula:

$$Gain = 1 + \frac{R2}{R1}$$

With $R1 = 10k\Omega$ and $R2 = 47k\Omega$ as depicted in the schematic, the gain is calculated as:

$$Gain = 1 + \frac{47k\Omega}{10k\Omega} = 5.7$$

This gain factor transforms the 0-5V DAC output range into approximately 0-28.5V, which aligns with the required 0-30V range for effectively biasing the varactor diodes in the RIS elements.

Power Supply Circuit: The operational amplifiers require a power supply voltage exceeding the maximum desired output voltage. The circuit includes a 30V power supply connection to the LM324AMX, ensuring the amplifiers can produce the full range of required output voltages. Decoupling capacitors (not explicitly shown in this schematic) are incorporated to filter power supply noise and ensure stable operation.

Output Connections: The amplified voltage outputs (VOUT1 through VOUT4) are routed to connection points that interface with the RIS elements. These connections must be designed to minimize signal degradation and ensure accurate voltage delivery to the varactor diodes.

Complete Signal Path: The overall signal flow begins with the FPGA determining the desired phase shift for each RIS element and calculating the corresponding voltage level. These digital values are converted to analog voltages by the DAC via I2C commands. The operational amplifiers then scale these voltages to the appropriate range needed for varactor biasing. Finally, these precisely controlled voltages are delivered to the RIS elements, where they adjust the capacitance of the varactor diodes, thereby controlling the phase shift imposed on incident electromagnetic waves.

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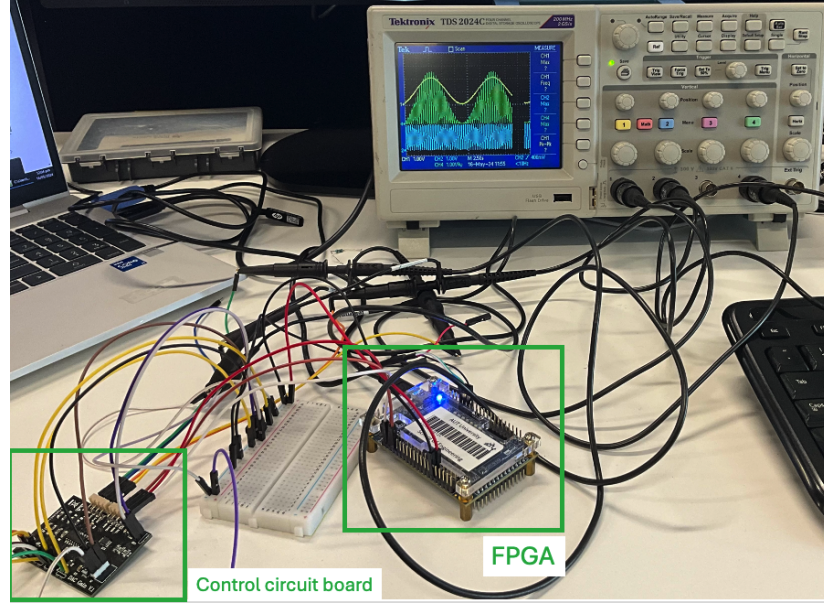


Figure 3.23: Testing setup for the RIS control circuit, showing the FPGA, 4-output voltage generator circuit, and an oscilloscope.

This circuit design provides several advantages for RIS control. The 12-bit resolution of the DAC translates to 4,096 distinct voltage levels, allowing for fine-grained control of the varactor capacitance and, consequently, precise phase adjustment. The modular nature of the circuit, with four independent channels per board, facilitates scalability - multiple boards can be networked together through additional I2C addressing to control larger RIS arrays. Furthermore, the non-inverting amplifier configuration maintains the linear relationship between the digital input values and the output voltages, simplifying the control software.

To validate the circuit's performance, we implemented a test setup using the FPGA to send voltage level commands to the DAC via the I2C communication protocol. The output voltages were then measured and visualized using an oscilloscope. Figure 3.23 shows the complete testing setup for the circuit design.

The FPGA was programmed using VHDL, while Python scripts were utilized to generate the voltage signals, all of which are available in a GitHub repository [98]. The DAC is configured to receive 96 bits of data sent from a computer through a serial port,

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operating at a baud rate of 115200 bps. With these configuration settings and an I2C data rate of 400 kbps, the system is capable of updating the output voltages at a rate of 100 times per second, providing responsive control for the RIS elements.

In Figure 3.23, it can be observed the oscilloscope display showing three distinct output signals. These signals were generated using computer commands, demonstrating the system's ability to produce multiple, independently controlled voltage outputs. The oscilloscope trace shows waveforms with different amplitudes and frequencies, indicating the flexibility and precision of the voltage control system.

After successfully testing the 4-output circuit prototype, we proceeded to design and implement the final control circuit with 36 outputs, as illustrated in Figure 3.24. The green components visible in the figure each represent the complete circuitry shown earlier in Figure 3.22. The schematic reveals a systematic arrangement of nine quad-output DAC units (U_DACamp blocks), each controlling four outputs. These units are commanded through 9 I2C bus lines (SCL and SDA lines), enabling centralized control from the FPGA.

An important consideration in our design was the loss associated with the switching elements used in the RIS. The varactor diodes employed as tunable components in our RIS introduce insertion loss that varies with the applied bias voltage. At lower bias voltages (0-5V), the varactor diodes exhibit higher resistance, resulting in insertion losses of approximately 2.5-3 dB per element. As the bias voltage increases (5-30V), the insertion loss decreases to approximately 1-1.5 dB per element due to the reduced series resistance of the varactor.

This variable insertion loss has two significant effects on the RIS performance:

1. **Amplitude Variation:** The reflected signal's amplitude varies with the phase setting, creating an amplitude-phase relationship that must be accounted for in the control algorithms. In our implementation, we prioritized phase control accuracy, accepting the amplitude variations as a trade-off. For applications requiring uniform amplitude,

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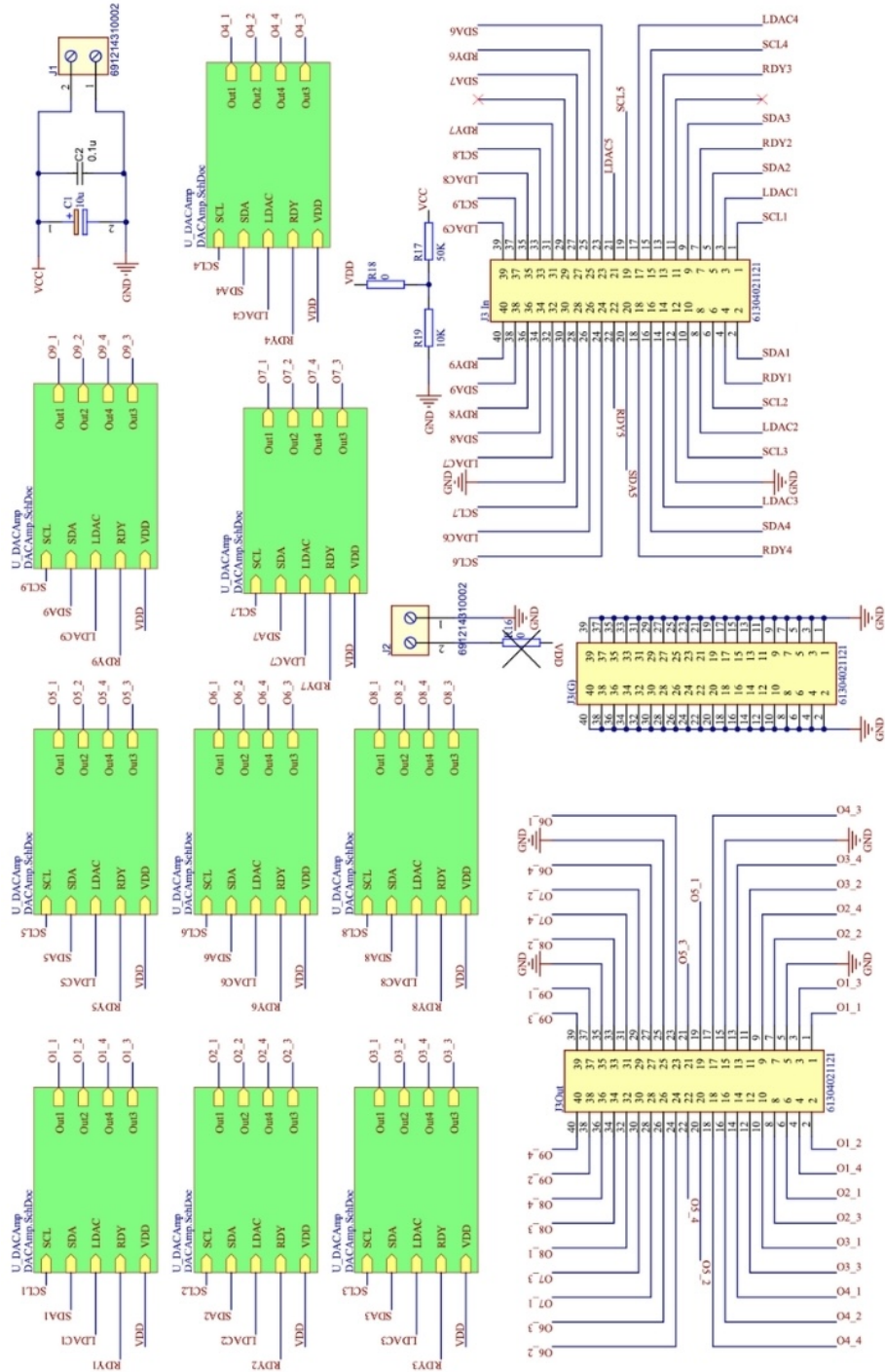


Figure 3.24: Schematic of the final 36-output RIS control circuit. Green components encapsulate the circuitry from Figure 3.22.

additional compensating circuits could be incorporated.

The control board has been designed to minimize additional losses in the biasing network. The high input impedance of the varactor diodes ($>1\text{ M}\Omega$ at DC) ensures that negligible current flows through the biasing lines, resulting in minimal resistive losses in the control circuitry itself. The operational amplifiers in our design maintain stable output voltages regardless of small variations in the varactor impedance, ensuring consistent performance across the entire RIS.

With the successful design and implementation of the 36-output control circuit, we have established a foundation for precise manipulation of a large-scale RIS. This scalable design provides the necessary infrastructure for advanced wavefront shaping and beam steering capabilities. Moving forward, our next objective is to integrate this control system with the physical RIS structure. This integration will allow us to conduct comprehensive performance evaluations of the complete RIS system. Specifically, we will investigate critical parameters such as the operational speed of the controller in a real-world setting and the total power consumption of the entire RIS structure.

3.7 Proposed RIS

In this section, we present the final structure of the proposed 6x6 RIS and analyze its performance characteristics. The discussion begins with an overview of the integrated RIS design, which combines the metasurface cells and control circuitry into a cohesive unit. We then examine the performance metrics of the assembled RIS, including its reflection efficiency and phase control capabilities across the operating frequency range. Additionally, we evaluate the power consumption of the RIS system under various operating conditions. The section concludes with an exploration of optimization approaches for determining optimal phase distributions across the RIS elements.

3.7.1 CAD Design

The design and fabrication of the RIS necessitated a modular approach due to manufacturing constraints. Instead of producing a single large surface, individual 1x2 unit cells were fabricated and integrated into a custom-designed holder structure. This approach required the development of a 3D-printed housing to securely position the unit cells and accommodate the control circuit board.

The holder structure was designed using CAD software to ensure precise fit and functionality. Figure 3.28 illustrates the 3D model of the complete assembly, with the component parts shown separately. The unit cell frame features a series of parallel bars onto which the 1x2 unit cells are adhered. This design allows the unit cells to be placed adjacent to one another, forming a cohesive array while maintaining individual accessibility. The CAD model also incorporates a dedicated space for the control circuit board, integrating the electronic components. This modular design approach not only addressed the manufacturing limitations but also provides flexibility for potential future modifications or replacements of individual components.

3.7.2 RIS Performance

The performance of the proposed RIS is characterized primarily by its update speed and power consumption, two factors that influence the system's overall efficacy and efficiency in real-world applications.

The speed of the RIS is a key advantage, leveraging the parallel processing capabilities of the FPGA to update all 36 outputs simultaneously. This synchronous update occurs as soon as data is transmitted from the computer to the control board. The system's speed is governed by two data rates: the BAUD rate between the computer and the FPGA, and the I2C data rate between the FPGA and the DACs. For reliable data transmission, we have configured the BAUD rate to 115200 bps between the computer and FPGA. The

3.7 PROPOSED RIS

DACs can operate in three I2C transmission modes: 100 kbps, 400 kbps, and 3.4 Mbps. We selected the 400 kbps mode as it provides an optimal balance between speed and reliability, avoiding potential data loss or board damage that could occur from excessive current draw at higher speeds. This configuration enables an output voltage update rate of 100 times per second across all channels. It is worth noting that this update rate is not fixed and can be further optimized. By adjusting the DAC's transmission mode, I2C rate, and BAUD rate, we estimate that the update speed could potentially be increased by a factor of approximately 5, offering even more responsive control for dynamic RIS applications.

Power consumption is another aspect of our RIS design, directly impacting the system's energy efficiency and operational costs. The majority of power in our RIS is consumed by two main components: the DACs and the amplifiers. We conducted power consumption measurements under maximum load conditions, where all unit cells are set to their maximum voltage (corresponding to minimum capacitance values for the varactor diodes). Under these conditions, we found that the DACs collectively consume 0.21 Watts, while the amplifiers use 0.57 Watts. This relatively low power consumption, totaling less than 1 Watt even at peak operation, demonstrates the energy efficiency of the design. Such efficiency is important for the practical deployment of RIS technology, especially in scenarios where energy conservation is a priority or in large-scale implementations where the cumulative power savings become significant. The final RIS design consists of an 8×8 array of unit cells operating at 5.2 GHz with the frequency bandwidth between 5.1 and 5.4 GHz., where the wavelength is approximately 5.77 cm. This corresponds to a surface size of approximately $8\lambda \times 8\lambda$, which provides sufficient spatial resolution for effective wavefront manipulation while maintaining a reasonable physical size for practical implementation. This dimension was selected based on both theoretical analysis and practical considerations. Link budget analysis indicates that this size offers a favorable trade-off between implementation complexity

and performance enhancement, with the ability to provide up to 2 dB improvement in received signal strength in specific deployment scenarios. The efficiency of the RIS, defined as the ratio of reflected power to incident power, was measured to be approximately 80% across the operating bandwidth, with variations of $\pm 5\%$ depending on the phase configuration of the elements. This efficiency accounts for various loss mechanisms including dielectric losses, conductor losses, and losses due to the discrete phase resolution of the unit cells.

3.7.3 Comparative Analysis with Existing RIS Designs

To properly contextualize our proposed RIS design, we provide a comparative analysis with existing RIS designs from literature. Table 3.2 summarizes various metasurface structures and their applications, which serves as a reference point for our comparative discussion.

Our proposed RIS offers several advantages in comparison to existing designs. Unlike the single-bit phase control approaches in [2] and [4], our design implements continuous phase control through analog varactor-based tuning, providing significantly higher phase resolution. This continuous phase tuning capability offers superior wavefront manipulation compared to discrete-state designs, enabling more precise beam focusing and steering capabilities. While [76] also offers semi-continuous phase control, our implementation achieves this with lower design complexity and power consumption. In terms of functionality, our design provides both phase and amplitude control capabilities, similar to [76], but with a more integrated and compact form factor. The 8×8 array size (approximately $8\lambda \times 8\lambda$) offers sufficient aperture for effective beam manipulation while maintaining reasonable complexity. In comparison, designs like [3] provide continuous phase control but with more bulky implementations that limit practical deployment scenarios.

Regarding energy efficiency, our RIS consumes less than 1 Watt at peak operation (0.78W total), which is considerably lower than more complex designs such as [5] and [76]. This efficiency is particularly important for practical deployments where power availability may be limited. Our measured 80% reflection efficiency across the operating bandwidth is competitive with other designs in the literature, though it should be noted that designs optimized for narrower bandwidths may achieve slightly higher reflection efficiencies in their specific operating ranges.

With respect to operating bandwidth, our design maintains stable performance across a 500 MHz bandwidth centered at 5.2 GHz (approximately 9.6% fractional bandwidth), which is comparable to [6] and [63]. While some specialized designs may offer wider bandwidths, they typically sacrifice other performance metrics or increase complexity substantially.

Our implementation strikes a balance between complexity and performance. The design complexity is classified as moderate, similar to [6], but offers enhanced functionality. Unlike the polarization converter in [63] which is optimized for a specific functionality, our design provides general-purpose wavefront manipulation capabilities with continuous phase control, making it suitable for a wide range of applications including wireless communications, sensing, and energy focusing.

A unique advantage of our design is the update speed of 100 updates per second across all elements simultaneously, with potential for up to 5× faster updates through optimization of the control system parameters. This rapid reconfigurability enables dynamic adaptation to changing channel conditions in real-time, which is particularly valuable for mobile communication scenarios. In contrast, many existing designs in the literature do not explicitly address or quantify update speeds.

Finally, our design's modular approach, with individually accessible 1×2 unit cells mounted on a custom-designed holder, offers practical advantages for maintenance and future upgrades that are not present in monolithic designs. This modularity, combined

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with the integrated control system featuring an FPGA-based controller with high-precision DACs, provides a complete solution that bridges the gap between theoretical RIS capabilities and practical implementation considerations.

In summary, when compared to existing designs in the literature, our proposed RIS offers a balanced combination of performance metrics including continuous phase control, moderate complexity, high energy efficiency, and rapid reconfigurability, making it well-suited for practical wireless communication applications.

Table 3.2: Comparison of the proposed with other RIS structures.

Reference	RIS Application	Design Complexity	Bit Control of Reflection	Functionalities
[2]	Space-time coding reflection	Low	1	Phase control
[3]	-	Moderate (bulky)	Continuous	Phase control
[4]	Backscatter communication	Low	1	Phase control
[5]	Wireless communication	High	2	Phase control
[6]	Satellite communications	Moderate	2	Phase control
[7]	Cloaking	Low	2	Phase control
[63]	Polarization converter	Low	2	Phase and polarization control
[76]	-	High	Semi-continuous	Phase and amplitude control
Proposed RIS	Wireless Communication	Low	Semi-continuous	Phase control

3.7.4 Beam Steering Capabilities

To demonstrate the beam steering capabilities of our RIS design, we performed full-wave electromagnetic simulations using Ansys HFSS. Figure 3.25 shows the 8×8 RIS structure as modeled in HFSS, optimized to reflect an incident beam toward a specific direction (30° from normal).

The phase configuration of each unit cell was optimized to achieve maximum reflection in the desired direction. By applying the appropriate phase gradient across the surface, we can effectively control the direction of the reflected wavefront. Figures 3.26 and 3.27 present the simulated far-field radiation patterns of the reflected beam at $\phi = 0$ and $\phi = 90$ planes, respectively.

As shown in these radiation patterns, the RIS successfully directs the majority of the incident energy toward $\theta = 30^\circ$, confirming the effectiveness of our design in manipulating electromagnetic waves. The main lobe in both planes is clearly visible at the designed angle of 30° , with side lobe levels maintained below -10 dB relative to the main beam. This beam steering capability is crucial for applications requiring dynamic control of the propagation environment, such as enhancing coverage in non-line-of-sight scenarios or mitigating interference in multi-user systems.

The directivity of the reflected beam was calculated to be approximately 19 dBi, which aligns well with theoretical expectations for an array of this size. The half-power beamwidth was measured to be approximately 14° in both principal planes, providing a sufficiently focused beam for directional communication while maintaining adequate coverage area.

3.8 Summary

This chapter has presented a comprehensive overview of the design and development process for a RIS. We have explored the critical components and considerations involved in creating an effective RIS, from the fundamental unit cell design to the integration of a sophisticated control system.

The unit cell design process highlighted the importance of careful material selection and geometric optimization to achieve the desired electromagnetic properties. Through rigorous simulation and experimental validation, we demonstrated a unit cell capable of

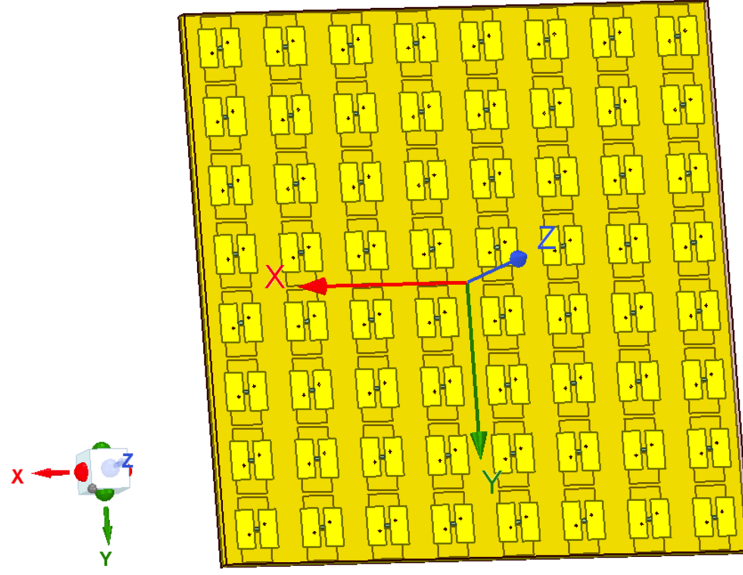


Figure 3.25: Perspective view of the 8×8 RIS structure simulated in HFSS, optimized for beam reflection toward 30° from normal incidence.

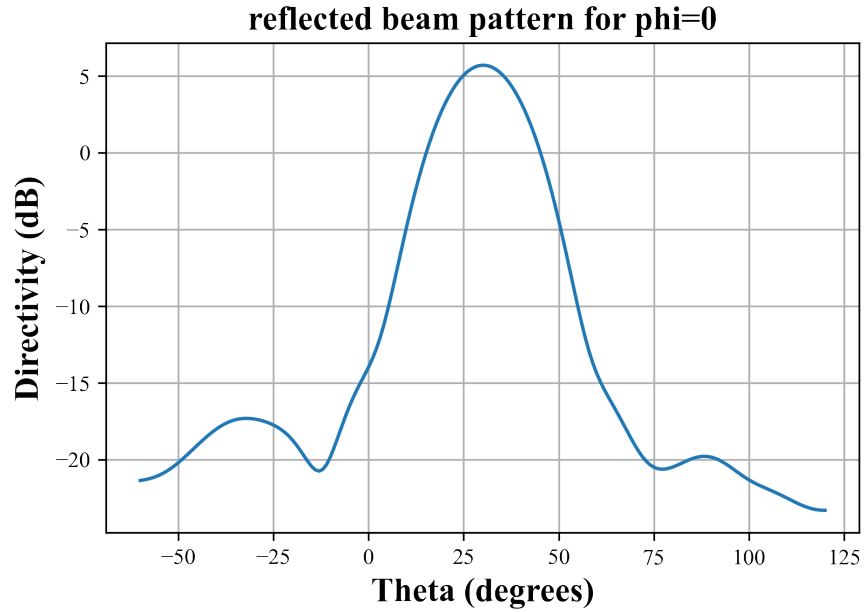


Figure 3.26: Reflected beam pattern in the $\phi = 0$ plane, showing maximum reflection at $\theta = 30$ as designed.

providing a wide phase range the frequency band for both TE and TM illuminations. The control board development showcased the balance between performance, power efficiency, and scalability. By leveraging an FPGA-based system with high-precision

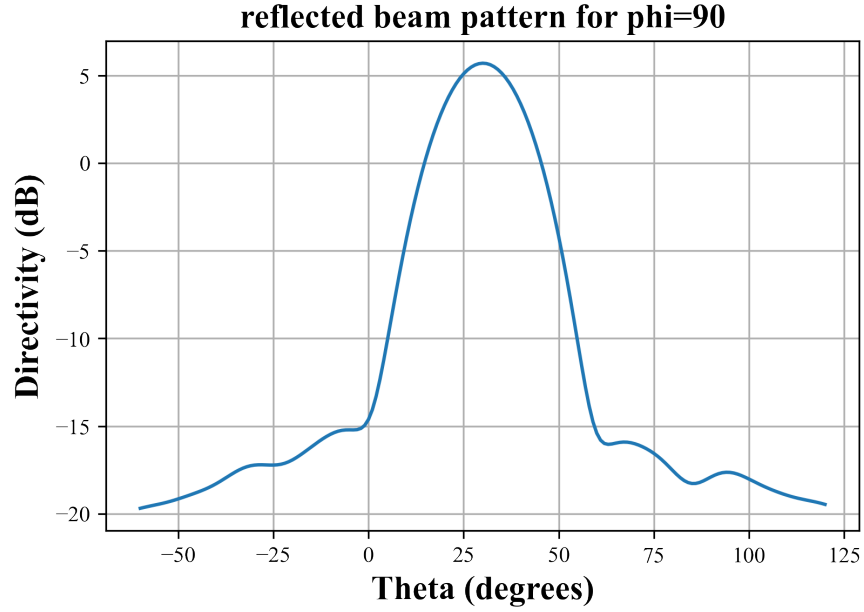


Figure 3.27: Reflected beam pattern in the $\phi = 90$ plane, demonstrating consistent beam focusing toward $\theta = 30$.

DACs and operational amplifiers, we achieved a control mechanism capable of dynamically adjusting 36 independent outputs at a rate of 100 updates per second, while maintaining low power consumption under 1 Watt.

Performance analysis of the complete RIS system revealed promising results in terms of reflection efficiency, phase control capabilities, and power consumption. The ability to rapidly update the RIS configuration while maintaining energy efficiency demonstrates the potential of this technology for dynamic wireless environments.

In conclusion, this chapter has laid a solid foundation for the practical implementation of RIS technology in next-generation wireless communication systems. The insights gained from this design process and the resulting prototype provide valuable contributions to the evolving field of smart radio environments.

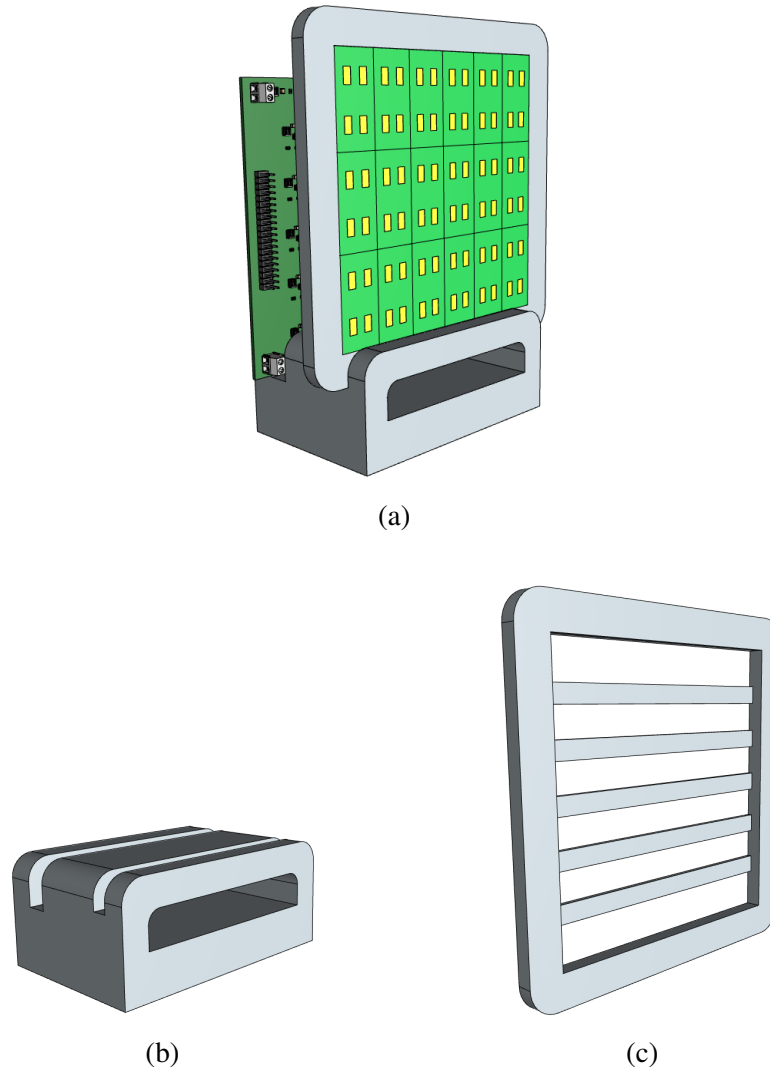


Figure 3.28: CAD design of the RIS assembly. (a) Complete assembled structure showing the unit cell array and control board. (b) Base holder for the control circuit board and the unit cell frame. (c) Unit cell holder frame with parallel bars for mounting 1x2 unit cells.

Chapter 4

RIS Optimization

The optimization of phase distribution in RISs is a critical aspect of enhancing wireless communication systems. This chapter delves into the various methodologies employed to achieve optimal phase configurations, each with its unique approach and set of requirements.

One prominent technique relies on comprehensive channel estimation to determine the optimal phase distribution. This method necessitates detailed channel information for each path between the user equipment (UE) and individual RIS elements, as well as between the base station (BS) and RIS elements. While this approach can yield highly accurate results, it comes at the cost of increased complexity, requiring additional pilot signals and potentially an RF chain for each RIS element.

An alternative strategy, particularly effective in sparse multi-path environments, focuses on estimating the angle of arrival (AoA) of signal paths at the RIS. By optimizing the phase distribution based on these AoA estimates, the system can maximize the signal-to-noise ratio (SNR) for the targeted UE. This method offers a more efficient solution in terms of hardware requirements, necessitating fewer RF chains for estimation compared to the full channel estimation approach.

A third technique, well-suited for indoor environments with relatively stable channel

conditions, employs a time-based optimization approach. This method relies solely on signal power information provided by the UE. The RIS communicates with the BS to receive UE signal power data, which it then uses to gradually refine the phase distribution over time. This approach is particularly advantageous in scenarios where UEs are predominantly stationary, allowing for iterative optimization without the need for continuous, complex channel estimations.

In the following sections, we will explore the second method in detail, examining its application in optimizing phase distribution for space-time-coding intelligent reflecting surfaces. Additionally, we will present experimental results from our proposed RIS implementation using the third method, providing practical insights into its effectiveness and potential applications in real-world scenarios.

4.1 Space-Time-Coding RIS

Space-Time-Coding Reconfigurable Intelligent Surfaces (STC-RIS) represent an advancement in the field of wireless communications. These innovative structures leverage the principles of space-time coding, traditionally used in multiple-antenna systems, and apply them to RISs. By doing so, STC-RIS offers enhanced capabilities in manipulating electromagnetic waves, potentially leading to improved system performance, increased spectral efficiency, and more robust communication links.

The concept of STC-RIS combines the flexibility of reconfigurable intelligent surfaces with the diversity gains offered by space-time coding techniques. This allows for more sophisticated control over the propagation environment, enabling dynamic adaptation to changing channel conditions and user requirements. Unlike conventional RIS, which typically focus on spatial manipulation alone, STC-RIS incorporates temporal variations in its reflection patterns, opening up new dimensions for signal optimization and interference management.

Unlike conventional RIS, which primarily focuses on manipulating the reflection angle of incident electromagnetic waves, STC-RIS can also alter the frequency of the reflected signals. This additional capability opens up significant opportunities to enhance wireless communication in different ways. By dynamically controlling both the spatial and frequency domains, STC-RIS can enable frequency diversity, which is particularly valuable in frequency-selective channels. The ability to shift signals to different frequency bands can help avoid interference, overcome spectrum congestion, and potentially increase system capacity. Furthermore, this frequency manipulation capability provides an additional degree of freedom that can be leveraged for secure communications, as the frequency-shifted signal components can be directed toward intended receivers while being unintelligible to potential eavesdroppers. Additionally, the frequency diversity introduced by STC-RIS can enhance the system's robustness against jamming attacks and improve overall reliability in challenging propagation environments. These capabilities represent a significant advancement over conventional RIS technology and open new avenues for optimizing wireless networks.

In the following subsections, we will delve deeper into the theoretical foundations of space-time-coding RIS. We will explore the underlying principles that govern their operation and examine how they differ from traditional RIS implementations. This theoretical background will provide the necessary context for understanding the unique challenges and opportunities presented by STC-RIS.

Subsequently, we will propose and discuss an efficient method for calculating the phase distribution in STC-RIS structures. This approach aims to address the complexities associated with optimizing both spatial and temporal aspects of the reflecting surface simultaneously.

4.1.1 Theory

In this subsection, we discuss the fundamental concept of STC-RIS. A schematic of a 10×10 RIS is depicted in Figure 4.1. Each unit cell within the RIS, denoted as U_{pq} , has a reflection coefficient Γ_{pq} that encompasses both phase and amplitude information. For simplicity, we assume the amplitude of all unit cells is unity, and we can only vary the phase of each unit cell, which ranges from 0° to 180° . Hence, we define the reflection coefficient as follows:

$$\Gamma_{pq} = e^{j\varphi_{pq}}, \quad p, q = 1, 2, \dots, 10 \quad (4.1)$$

4.1.1.1 Far-Field Pattern Calculation

When a plane wave impinges on the RIS, the far-field pattern of the reflected waves $E(\theta, \phi)$ can be computed using the array factor formula:

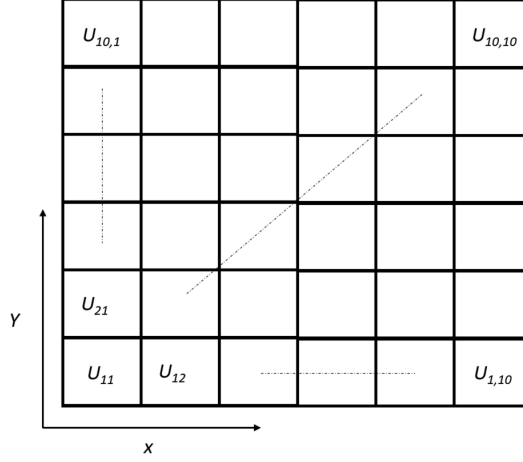
$$E(\theta, \phi) = \frac{E_0(\theta, \phi)}{PQ} \sum_{p=1}^P \sum_{q=1}^Q \Gamma_{pq} F_{pq}(\theta, \phi) \quad (4.2)$$

where the element factor $F_{pq}(\theta, \phi)$ is given by:

$$F_{pq}(\theta, \phi) = \exp \left(j \frac{2\pi}{c_0} f_c [(q-1)d_y \sin(\theta) \cos(\phi) + (p-1)d_x \sin(\theta) \sin(\phi)] \right) \quad (4.3)$$

It is important to note that Equations 4.2 and 4.3 assume a general angle of incidence θ and ϕ , which are not necessarily from boresight. In practice, these angles can take any value as depicted in Figure 4.2 where incident angles θ_1 and θ_2 represent different possible angles of arrival.

In these equations, Γ_{pq} is the reflection coefficient of the unit cell U_{pq} , $E_0(\theta, \phi)$ is the far-field pattern of the reflected electromagnetic waves from the unit cell, d_y and d_x are the vertical and horizontal spacings between unit cells, f_c is the frequency of the


 Figure 4.1: Schematic of a 10×10 RIS.

incident wave, and P and Q represent the total number of unit cells in the x and y directions, respectively. The far-field pattern of the RIS can be calculated by defining the phase shift of each unit cell using Equations 4.1 and 4.2.

4.1.1.2 Incorporating Time as a Parameter

To extend the static RIS model into a space-time-coding RIS, we explicitly incorporate time as an additional parameter. This is achieved by making the reflection coefficients Γ_{pq} time-dependent, denoted as $\Gamma_{pq}(t)$. The time dependency is implemented through a periodic sequence of L different phase configurations, with each configuration maintained for a duration of T_s , resulting in a total period of $T = L \cdot T_s$. The local frequency $f_{\text{local}} = 1/T$ defines how quickly the RIS cycles through these configurations.

Mathematically, the time-dependent reflection coefficient can be represented as:

$$\Gamma_{pq}(t) = \Gamma_{pq}^{(n)}, \quad \text{for } (n-1)T_s \leq t < nT_s, \quad n = 1, 2, \dots, L \quad (4.4)$$

where $\Gamma_{pq}^{(n)}$ is the reflection coefficient of unit cell (p, q) during the n -th time sequence. To extend the model, we incorporate time as an additional parameter. By considering specific phase distributions of the RIS over several time sequences, we can alter both

the frequency of the reflected electromagnetic waves impinging on the RIS and their reflection direction. In essence, periodically changing the phase distribution of the RIS enables modulation of the impinging electromagnetic waves at different harmonics of the frequency associated with the changes in the unit cells' phase shifts.

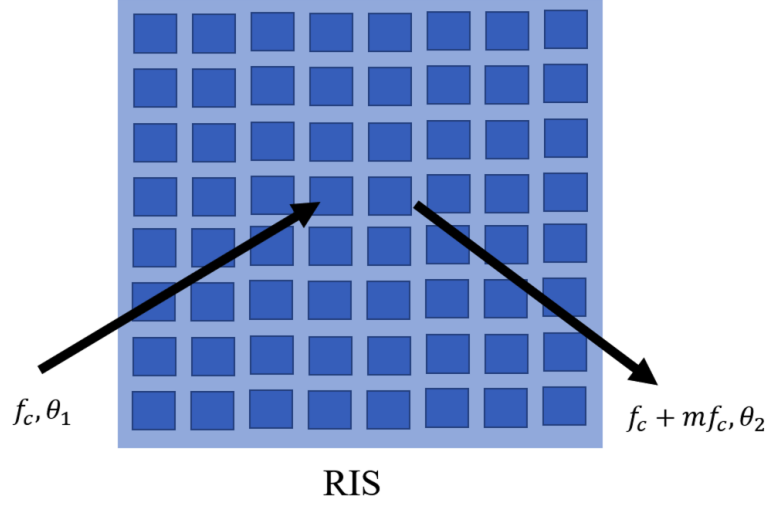


Figure 4.2: Conceptual depiction of the reflection effect created by STC-RIS.

Due to the periodic time variation of the reflection coefficients, the reflected signal contains not only the original frequency f_c but also harmonic components at frequencies $f_c + m \cdot f_{\text{local}}$, where m is an integer. This frequency shift phenomenon, which is a direct consequence of introducing time as a parameter in our model, is the foundation for Equations 4.5 and 4.6.

The formula for calculating the reflected far-field pattern for the RIS at the m -th harmonic frequency is given by:

$$F_m(\theta, \phi) = \sum_{p=1}^P \sum_{q=1}^Q F_{pq}(\theta, \phi) \exp \left(j \frac{2\pi}{\lambda_c} \left[(p-1)d_x \sin(\theta) \cos(\phi) + (q-1)d_y \sin(\theta) \sin(\phi) \right] \right) a_{pq}^m \quad (4.5)$$

where the coefficient a_{pq}^m is defined as:

$$a_{pq}^m = \sum_{n=1}^L \Gamma_{pq} \text{sinc}\left(\frac{\pi m}{L}\right) \exp\left[-j \frac{\pi(2n-1)}{L}\right] \quad (4.6)$$

Here, L denotes the number of time sequences during which the phase distribution of the RIS is altered, and F_m represents the far-field pattern of the reflected waves at the m -th harmonic frequency shifted from the frequency of the incident electromagnetic waves. It is important to note that the coefficients a_{pq}^m in Equation 4.3 can be synthesized to achieve the desired equivalent amplitudes and phases for each individual unit cell at a specific frequency.

4.1.2 Efficient phase distribution calculation for STC-RIS

In this subsection, we discuss a fast and efficient method for the fast calculation of phase distribution in STC-RIS. The method is developed to significantly reduce the computational complexity and processing time associated with traditional approaches while maintaining high accuracy in steering the EM waves. The proposed method is evaluated in the context of a RIS operating at 1.4 GHz with a 10×10 array of unit cells, each capable of phase modulation in four discrete modes.

4.1.2.1 Proposed Method

The proposed method for calculating the phase distribution in RIS involves two main phases:

Phase 1: Fast Calculation using 2-D IFFT:

The first phase of the proposed method employs a two-dimensional inverse fast Fourier transform (2-D IFFT) to expedite the calculation of the phase distribution. Typically, calculating the reflected far-field pattern requires four nested loops: two loops for the angular variables θ and ϕ , and two loops for the phase of each unit cell in the array. To reduce this computational burden, we replace the double summation in Equation 4.2

with a 2-D IFFT, defined as:

$$f(p, q) = \frac{1}{N_x N_y} \sum_{m=0}^{N_x-1} \sum_{n=0}^{N_y-1} F(m, n) e^{j \frac{2\pi m p}{N_x}} e^{j \frac{2\pi n q}{N_y}}, \quad (4.7)$$

where the spectral functions are calculated at discrete angular coordinates. The points in the (u, v) plane are defined by the Fourier transform as:

$$\begin{aligned} u &= \frac{2\pi}{N_x d_x k_0} p, \quad p = 0, 1, 2, \dots, N_x - 1, \\ v &= \frac{2\pi}{N_y d_y k_0} q, \quad q = 0, 1, 2, \dots, N_y - 1. \end{aligned} \quad (4.8)$$

The primary advantage of using spectral functions in this calculation is the substantial reduction in computational time, achieved by substituting the double summations with a Fourier transform.

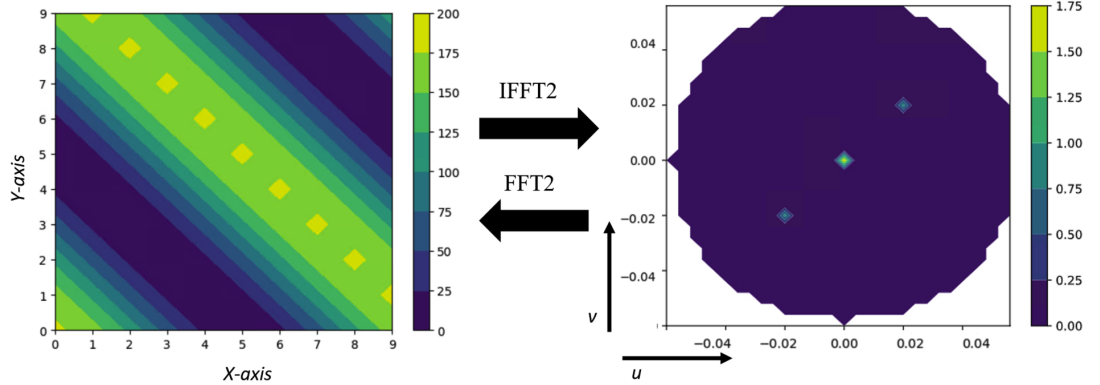


Figure 4.3: Phase distribution of a 10×10 RIS calculated using the proposed 2-D IFFT method for reflection towards $\theta = 20^\circ$ and $\phi = 30^\circ$.

As an illustrative example, consider a 10×10 RIS designed to redirect incident EM waves with a central frequency of 2.4 GHz towards $\theta = 20^\circ$ and $\phi = 30^\circ$. By knowing the target angles θ and ϕ , we can quickly calculate u_0 and v_0 in the (u, v) plane and derive the phase distribution for the unit cells using the discrete 2-D Fourier transform, as shown in Figure 4.3.

Phase 2: Optimization of Phase Pattern over Time

The second phase of the proposed method involves optimizing the phase pattern across different time steps to achieve maximum radiation in the desired direction and at a specific harmonic frequency. The local frequency f_{local} , which was introduced in the time-dependent model, determines the rate at which the RIS cycles through different phase configurations. This frequency directly relates to the time parameter in our model and defines the frequency shift of the harmonics in the reflected signal.

The optimization process starts by defining L and m , where L is the number of sequences and m is the harmonic order. The objective is to maximize radiation towards a specified direction at the m -th harmonic frequency ($f_c + m \times f_{\text{local}}$). The input parameters consist of an array of L pairs, where each pair (x_n, y_n) defines the phase distribution of the n -th sequence. This distribution is calculated in the first step and then shifted by x_n unit cells in the x direction and y_n unit cells in the y direction.

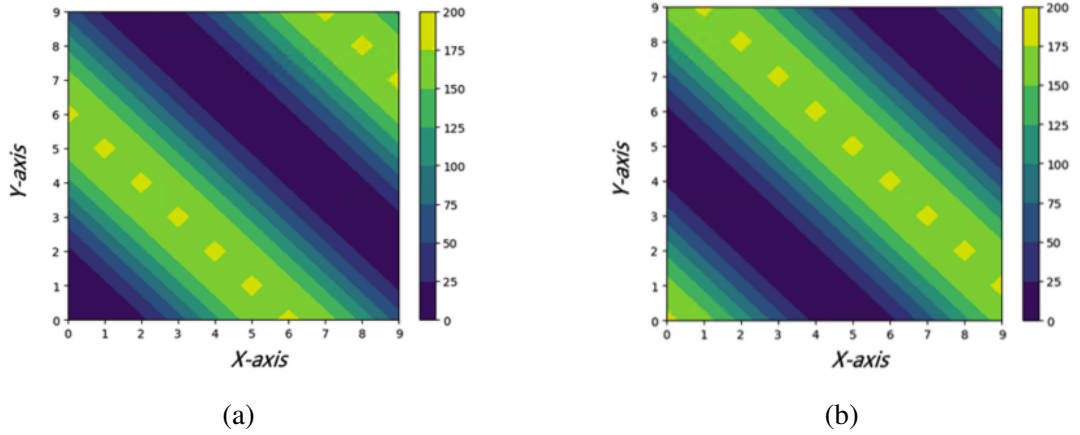


Figure 4.4: (a) Phase distribution calculated using 2-D FFT. (b) Phase distribution shifted by (1, 5) unit cells in the x and y directions, respectively.

For optimization, we employ the Non-dominated Sorting Genetic Algorithm II (NSGA-II) to achieve maximum radiation from the RIS at the specified direction and harmonic frequency. Figure 4.4 illustrates an example where the phase distribution is shifted by (1, 5) unit cells in the x and y directions, respectively.

4.1 SPACE-TIME-CODING RIS

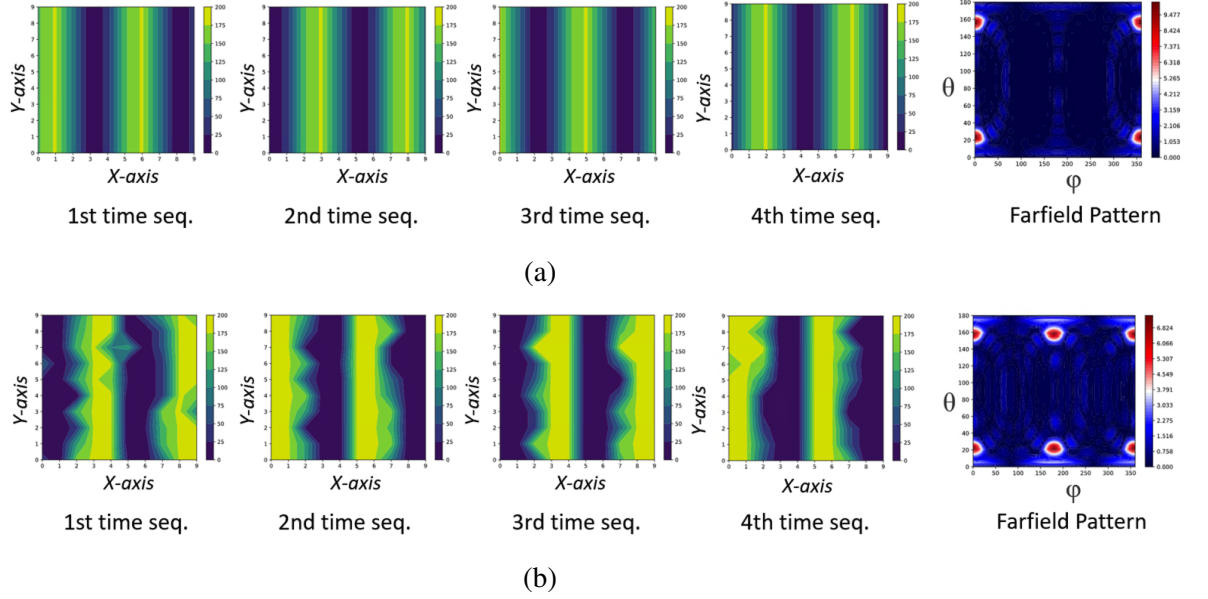


Figure 4.5: Comparison of phase distributions and far-field patterns achieved by (a) the proposed method and (b) a general optimization method.

4.1.2.2 Results

We evaluate the efficiency of the proposed method by comparing it with a conventional optimization approach. In this example, a 10×10 RIS with a central frequency $f_c = 2.4$ GHz and a local frequency $f_{\text{local}} = 200$ MHz is used. The objective is to reflect the incident EM waves towards $\theta = 20^\circ$ and $\phi = 0^\circ$ at the $m = 2$ harmonic frequency ($f_c + 2 \times f_{\text{local}}$). The optimization parameters include a population size of 50 and 30 iterations.

The results show that our proposed method significantly reduces the optimization time. The conventional method takes 6 minutes and 37 seconds to complete 1500 iterations with a population size of 50. In contrast, our method completes the optimization in just 7.54 seconds, representing a 98.02% reduction in processing time. Figure 4.5 compares the phase distributions and far-field patterns obtained using both methods, demonstrating that our method achieves similar accuracy with a fraction of the computation time.

4.2 RIS Optimization

The optimization of the proposed RIS was conducted through a signal power maximization approach. To demonstrate this optimization process, an experimental setup was devised to measure and enhance the transmission between two antennas via the RIS.

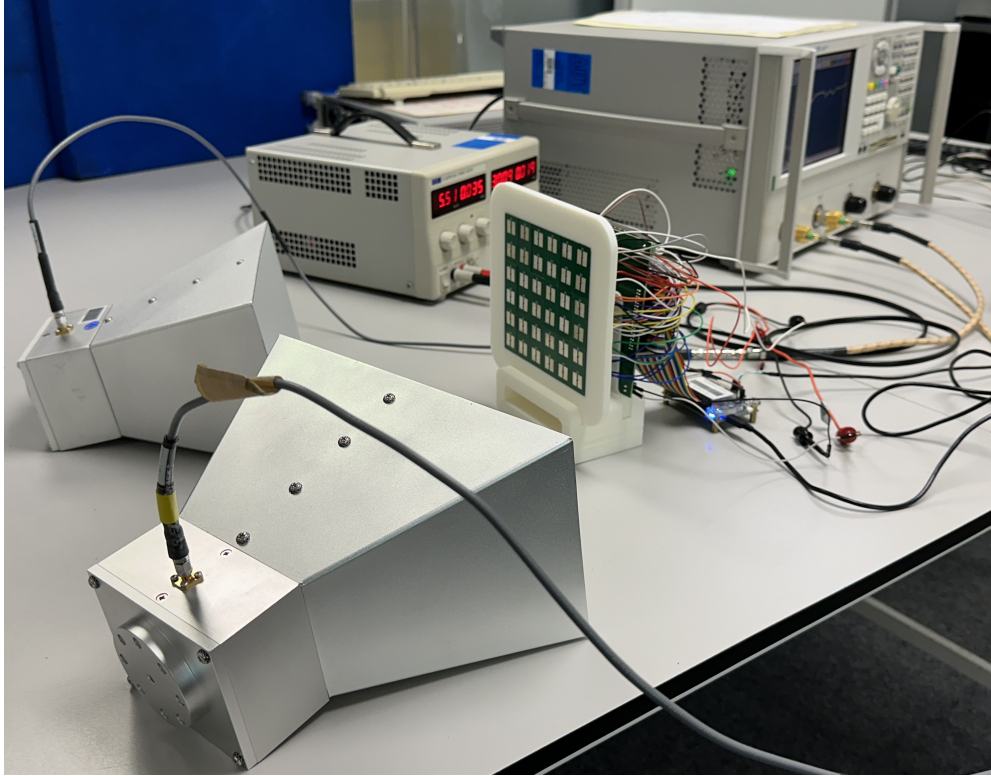


Figure 4.6: Experimental setup for RIS optimization. The configuration shows two horn antennas positioned at 30-degree angles from the RIS surface normal, connected to a VNA for S_{21} measurements. The RIS and its control circuitry are visible in the center, with additional measurement equipment in the background.

4.2.1 Experimental Setup

The setup, as shown in Figure 4.6, consists of two horn antennas positioned to face the RIS. These antennas are strategically placed at a 30-degree angle from the perpendicular norm of the RIS surface. This angular positioning allows for the evaluation of the RIS's ability to redirect signals effectively. The antennas are situated at a radial distance of 30

cm from their apertures to the RIS, ensuring a consistent measurement environment.

Both horn antennas are connected to a Vector Network Analyzer (VNA), which enables the precise measurement of the S_{21} parameter between the two antennas. The S_{21} parameter represents the transmission coefficient, quantifying how much of the signal transmitted from antenna 1 is received by antenna 2 after interaction with the RIS.

The primary objective of this setup is to maximize/minimize the magnitude of S_{21} , denoted as $|S_{21}|$. By optimizing this parameter, we aim to enhance the signal transmission from the first antenna to the second antenna through the intelligent manipulation of the RIS elements. This optimization process involves adjusting the phase configurations of the RIS units to create constructive interference at the receiving antenna, thereby maximizing the received signal power.

Through this experimental configuration, we can systematically evaluate and optimize the performance of the RIS, demonstrating its capability to enhance wireless signal transmission in controlled environments. The setup provides a practical means to validate the theoretical principles of RIS operation and to fine-tune its performance for optimal signal redirection and amplification.

4.2.2 Optimization Results

The optimization of the RIS was conducted using GA algorithm, with the objective of manipulating the S_{21} parameter. This parameter represents the transmission coefficient between the transmitting and receiving antennas, effectively quantifying the power transfer through the RIS-assisted path.

The GA was configured with a population size of 50 and allowed to evolve over 10 generations. This optimization process was aimed at finding the optimal phase distribution across the RIS elements to achieve two distinct goals: maximizing and minimizing the S_{21} parameter. Maximizing S_{21} corresponds to enhancing the RF

4.2 RIS OPTIMIZATION

power transmission from the transmitter to the receiver, while minimizing S_{21} aims to suppress this transmission.

The optimization procedure was carried out for both TE and TM polarizations of the incident wave, allowing for an evaluation of the RIS performance under different electromagnetic field configurations.

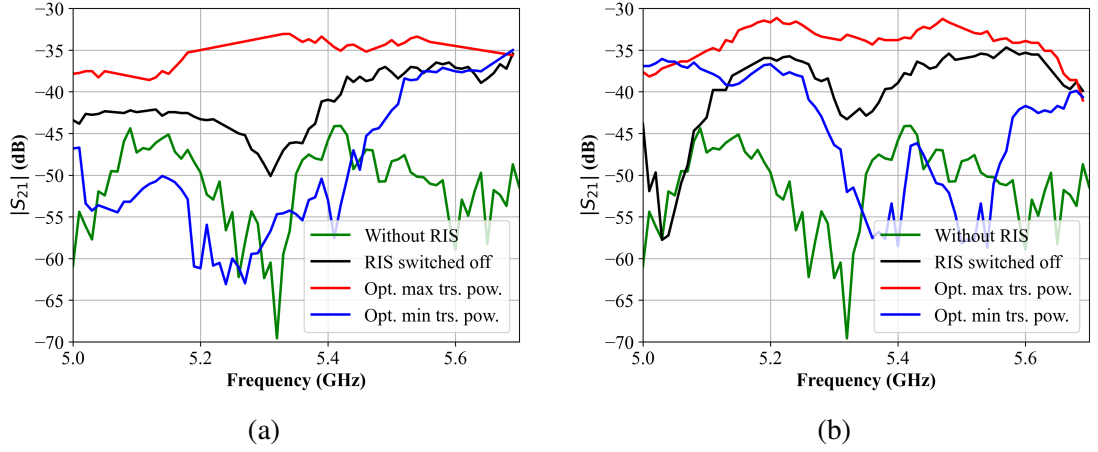


Figure 4.7: Optimization results for RIS-assisted transmission. (a) TE polarization results showing $|S_{21}|$ versus frequency for three scenarios: RIS switched off (black), optimized for maximum transmission power (red), and optimized for minimum transmission power (blue). (b) Corresponding results for TM polarization under the same optimization scenarios.

Figure 4.7 (a) presents the optimization results for TE polarization. The black curve represents the baseline scenario with the RIS switched off, providing a reference for the system's performance without RIS intervention. The red curve illustrates the S_{21} response when the RIS is optimized for maximum power transmission, demonstrating a significant enhancement in signal strength across the frequency range. Conversely, the blue curve shows the S_{21} response when the RIS is optimized for minimum power transmission, effectively creating a null in the signal path.

Similarly, Figure 4.7 (b) displays the optimization results for TM polarization. The curve colors maintain the same significance as in Figure 4.7, allowing for direct comparison between the TE and TM cases. This dual-polarization analysis provides

4.2 RIS OPTIMIZATION

insights into the RIS's capability to manipulate electromagnetic waves with different field orientations.

These results underscore the RIS's ability to dynamically control the electromagnetic environment, which offers the flexibility to either enhance or suppress signal propagation between two points in space. This capability has profound implications for improving wireless communication systems, particularly in scenarios requiring adaptive signal routing or interference mitigation.

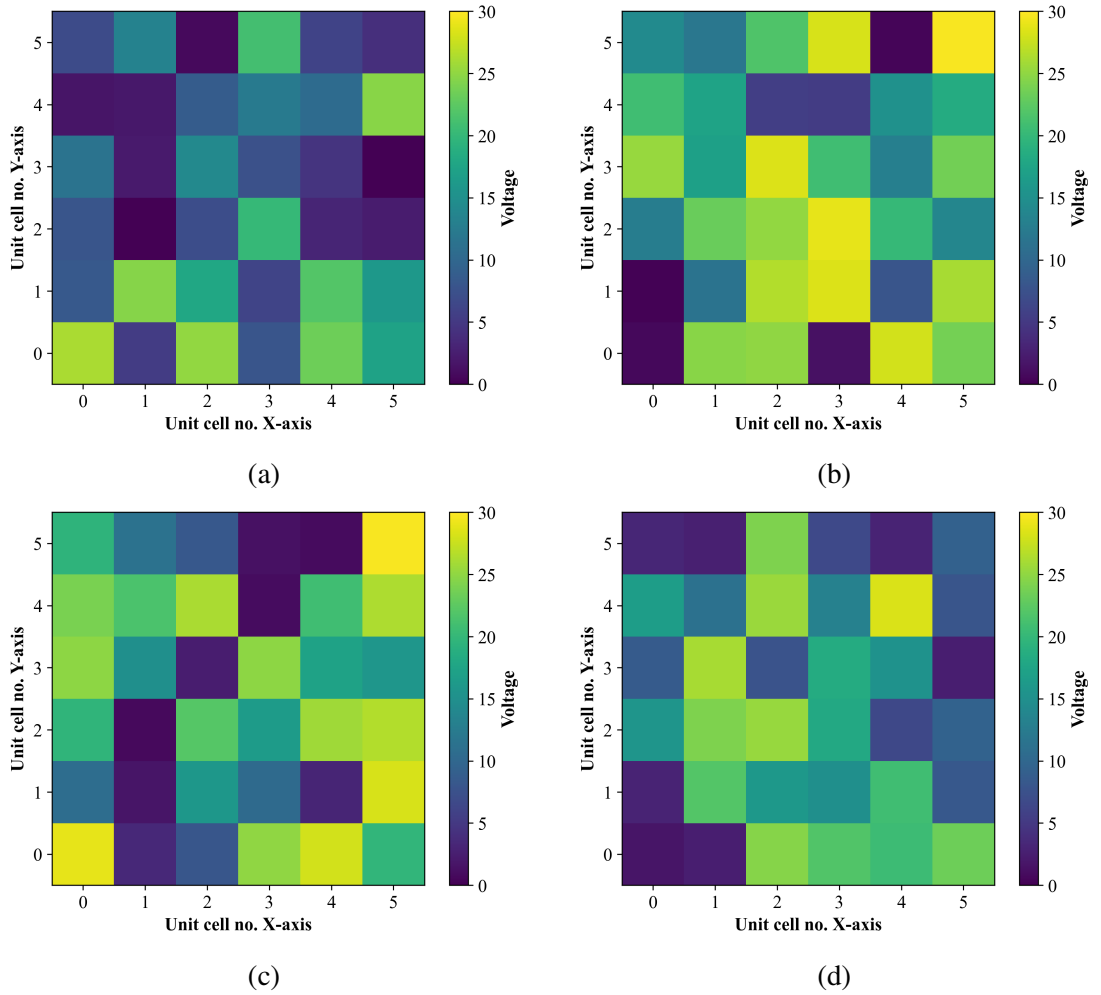


Figure 4.8: Optimized voltage distributions across the RIS surface for (a) maximum and (b) minimum power transmission in TE illumination, and (c) maximum and (d) minimum power transmission in TM illumination. Color scale represents applied voltage (0-30 V) to each unit cell.

The optimized phase distributions across the RIS surface for various scenarios are illustrated in Figure 4.8. These heatmaps represent the voltage applied to each unit cell of the RIS, which directly correlates to the phase shift introduced by that cell. Figure 4.8 (a) and (b) depict the voltage distributions for maximum and minimum power transmission, respectively, under TE illumination. Similarly, Figure 4.8 (c) and (d) show the corresponding distributions for TM illumination. The color scale, ranging from 0 to 30 V, indicates the magnitude of the applied voltage to each unit cell. These optimized configurations demonstrate the RIS's ability to manipulate the incident electromagnetic waves through phase control.

4.2.3 Transmission Power Maximization

The RIS optimization was conducted using a Genetic Algorithm (GA) algorithm, configured with a population size of 50 and evolved over 10 generations. This process aimed to find the optimal phase distribution across the RIS elements for both maximizing and minimizing the S_{21} parameter, under TE and TM polarizations. Fig. 4.9 (a) and 4.9(b) present the results under different RIS configurations for TE, and TM illumination, respectively. In both figures, the black curve represents the baseline scenario with the RIS switched off, the red curve illustrates maximum power transmission, and the blue curve shows minimum power transmission.

Fig. 4.10 illustrates the experimental setup for SNR optimization, situated within an anechoic chamber. This controlled environment minimizes electromagnetic reflections and external interference, which ensures measurement accuracy. The RIS is strategically positioned to interact with both the receiver and transmitter. The transmitter and receiver antennas are arranged at a 75-degree angle to each other, with the RIS placed at the angle's vertex.

Both antennas maintain a distance of 84 cm from the RIS. A Raspberry Pi, connected

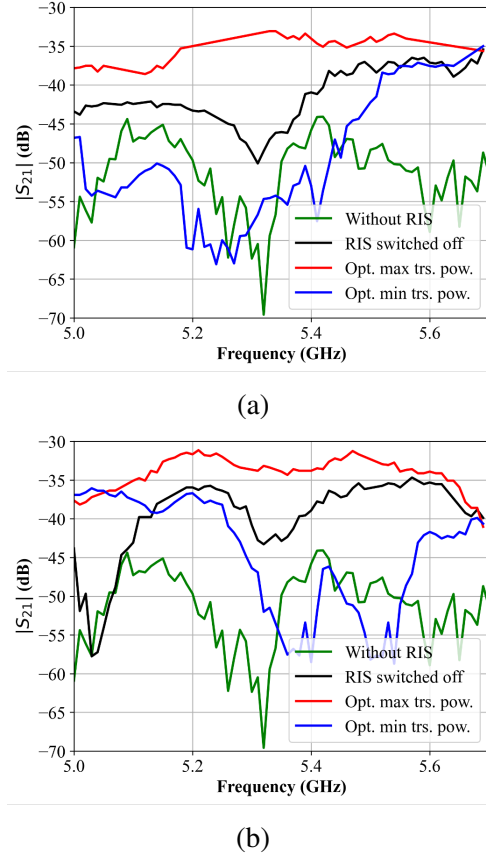


Figure 4.9: Comparison of $|S_{21}|$ under different RIS phase configurations for (a) TE, and (b) TM illuminations.

to the RIS, controls the phase shifts of the RIS unit cells. A USRP (B205mini) handles signal processing for data transmission between the antennas at 5.4 GHz. GNU Radio Software manages signal processing and USRP control. A laptop computer oversees both the USRP and Raspberry Pi operations.

As illustrated in Fig. 4.11, the optimization process involves a data stream transmitted from Tx to Rx, processed through the USRP. This data stream is sampled and modulated using quadratic phase shift keying (QPSK) modulation, then transmitted at a center frequency of 5.4 GHz. At the Rx side, the signal is down-converted to baseband frequency and undergoes signal processing for carrier recovery and phase synchronization. A M-ary phase-shift keying (MPSK) SNR estimator module measures the signal's SNR every 1000 samples. Given the receiver's sampling rate of 1 MHz,

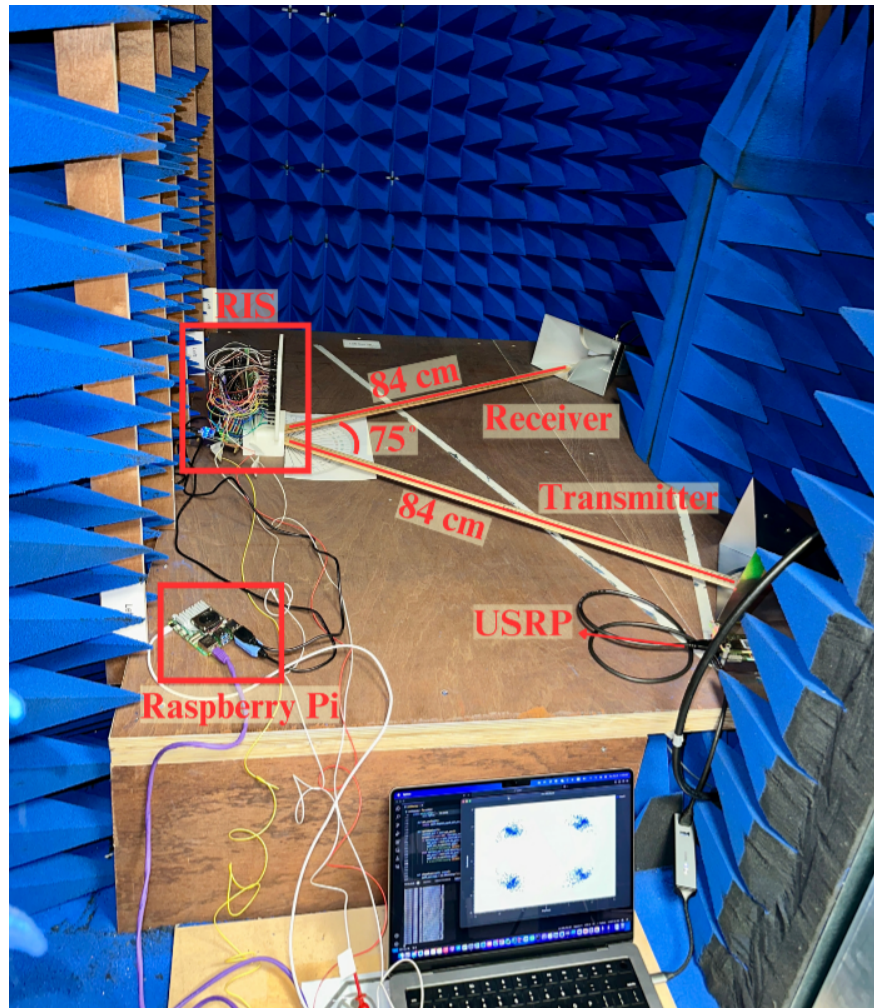


Figure 4.10: Overall measurement setup of the proposed RIS.

4.2 RIS OPTIMIZATION

the time required for 10 SNR measurements corresponds to the RIS reconfiguration time. Consequently, every 10000 samples, the mean value of 10 SNR measurements is calculated and utilized as the objective function for the GA optimization algorithm whose output is an array of 36 with each element corresponds to each RIS unit cell. The GA algorithm is configured with a population size of 60 and runs for 10 generations.

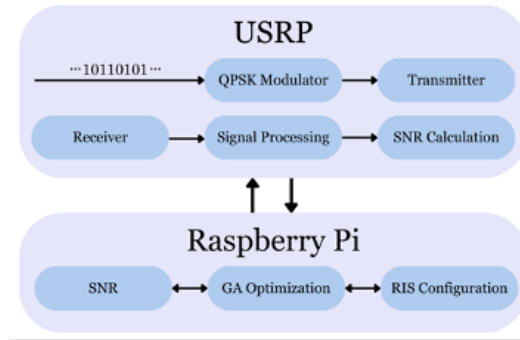


Figure 4.11: SNR optimization process using USRP for signal processing and Raspberry Pi for RIS configuration optimization.

The USRP handles the signal processing tasks, including QPSK modulation, transmission, reception, and SNR calculation. The Raspberry Pi manages the optimization process, running the GA algorithm to determine optimal RIS configurations based on the SNR feedback from the USRP. This setup enables real-time optimization of the RIS configuration to maximize SNR at the receiver.

Fig. 4.12 illustrates the evolution of the SNR over time during the optimization process for TE and TM illumination. Initially, SNR starts at approximately 20 dB and increases within the first 6 seconds. By the 6-second mark, the SNR approaches 22 dB and 21.7 dB for TE and TM reflection, respectively. The results suggesting the optimization algorithm has converged to a near-optimal solution for the RIS phase configuration for both TE and TM illumination polarizations. The overall improvement from start to finish is about 2 dB and 1.7 dB for TE and TM illuminations, which represents enhancement in signal quality.

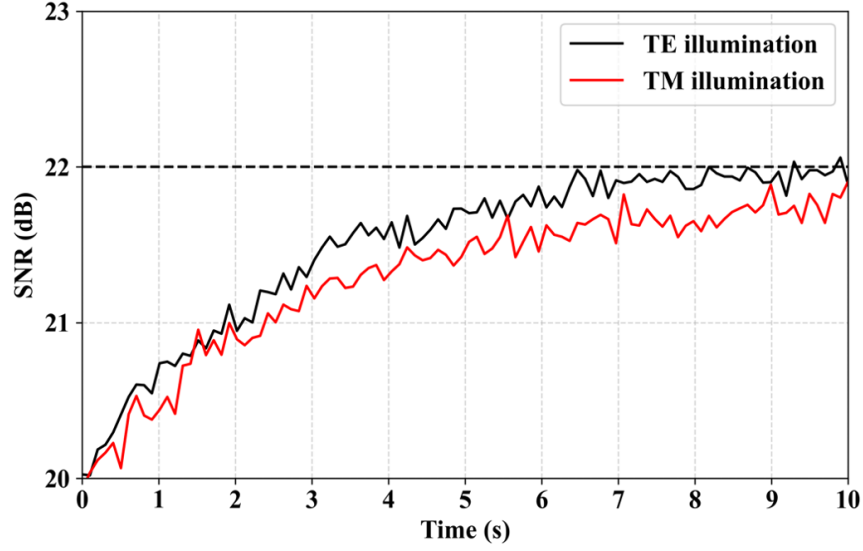


Figure 4.12: Evolution of SNR over time during optimization for TE and TM illumination.

4.3 Summary

This chapter has explored the critical aspect of phase distribution optimization in RIS, presenting various methodologies and their applications in enhancing wireless communication systems.

We introduced an efficient method for calculating phase distribution in STC-RIS, utilizing a 2D IFFT coupled with a genetic algorithm optimization. This method demonstrated a 98.02% reduction in processing time compared to conventional optimization approaches, while maintaining comparable accuracy in steering electromagnetic waves. The chapter also presented experimental results from a practical RIS implementation, optimizing transmission power between two antennas. Using a genetic algorithm, the RIS was able to both maximize and minimize power transmission for both TE and TM polarizations, showcasing its ability to dynamically control the electromagnetic environment.

Further experimental work demonstrated the real-world performance of RIS in SNR optimization. Using a controlled setup in an anechoic chamber, we employed a USRP

4.3 SUMMARY

for signal processing and a Raspberry Pi to control the RIS configuration. The genetic algorithm optimization process showed significant improvements in SNR, with increases of approximately 2 dB for TE illumination and 1.7 dB for TM illumination. The optimization converged efficiently within about 6 seconds, highlighting the practical feasibility of real-time RIS adaptation.

These findings highlight the potential of RIS technology in revolutionizing wireless communications. The ability to rapidly and efficiently optimize phase distributions enables RIS to adapt to changing channel conditions in real-time, offering significant improvements in signal strength, spectral efficiency, and interference management.

In conclusion, this chapter has demonstrated that optimized RIS systems have the potential to play an effective role in next-generation wireless networks, offering unprecedented control over the propagation environment and paving the way for more efficient and reliable communication systems.

Chapter 5

RT-Based Propagation Modeling

In this chapter, we discuss propagation modeling for RIS-assisted wireless systems, building upon the foundations laid in previous chapters. The development of a novel dual-polarized RIS and the optimization of phase distribution in RIS structures have set the stage for a more comprehensive understanding of how these systems interact with their environments. Propagation modeling serves as a tool in estimating field strengths and signal characteristics in wireless communications, taking into account various system parameters such as frequency, propagation environment features, and antenna configurations.

The focus of this chapter is to explore a framework for propagation modeling specifically tailored for RIS-assisted communication systems. This framework, initially developed in MATLAB, provides a robust platform for simulating and analyzing the behavior of electromagnetic waves in complex environments where RIS elements are present. By leveraging ray-tracing techniques, we can accurately model the interactions between transmitted signals, RIS structures, and the surrounding environment, offering valuable insights into system performance and optimization strategies.

Following the introduction of the MATLAB-based framework, we extend our discussion to a more comprehensive simulator known as WiPy-RT, implemented in the Python

environment. This advanced tool builds upon the principles established in the MATLAB framework, offering enhanced capabilities and flexibility for modeling RIS-assisted wireless systems. The WiPy-RT simulator incorporates state-of-the-art Python libraries as well as novel algorithms and models to provide a more efficient and faster representation of signal propagation in diverse scenarios.

Throughout this chapter, we will explore the key features and functionalities of both the MATLAB framework and the WiPy-RT simulator. We will discuss the underlying principles of ray-tracing techniques as applied to RIS-assisted systems, the incorporation of environmental factors, and the methods used to calculate and predict signal strengths and propagation characteristics. Additionally, we will examine how these tools can be utilized to optimize RIS configurations, evaluate system performance, and inform the design of efficient and effective RIS-assisted wireless networks.

5.1 Propagation Modeling of RIS-Assisted Communication

This section presents a framework for propagation modeling of RIS-assisted communication in indoor environments using ray tracing techniques. We begin by introducing the fundamental concepts and motivations behind our proposed framework, highlighting its significance in the context of RIS-enhanced wireless systems. The section then delves into the intricacies of ray tracing as applied to RIS-assisted propagation, detailing the environment setup and key assumptions underpinning our model. We will describe the process of calculating Power Delay Profiles (PDPs) and present both an accurate and an approximate implementation of our framework. A thorough comparison of these models is provided, followed by an in-depth analysis of system performance through channel gain, phase shift, and Bit Error Rate (BER) evaluations. We explore the impact

of various factors such as RIS size on model accuracy and discuss the computational efficiency gains achieved by our approximate model. Throughout this section, we aim to provide a clear understanding of the approach in our research to RIS-assisted propagation modeling, and its practical implications..

5.1.1 Site-Specific Channel Modelling

Channel models are imminent part of the design and optimization of wireless communication systems. They provide essential insights into how signals propagate through complex environments, allowing engineers to predict system performance and develop effective communication strategies. Traditionally, geometry-based stochastic channel models (GSCM) have been widely used to characterize various scenarios such as urban microcellular, urban macrocellular, and indoor environments. These models offer a statistical representation of channel behavior based on general geometric properties of the environment.

As wireless technologies advance into higher frequency bands like mmWave and THz, the channel features become increasingly complex. One notable characteristic of these high-frequency channels is their geometrical sparsity, which often leads to rank deficiency in high-dimensional channel matrices. This sparsity presents both challenges and opportunities for system design, necessitating novel approaches to beamforming and signal processing [99].

In GSCM, the Power Delay Profile (PDP) is a key channel parameter that is typically defined stochastically. While this approach provides a generalized view of channel behavior, it may not capture the specific nuances of individual environments. This is where site-specific channel parameters come into play. By moving beyond stochastic models to site-specific characterizations, we can further improve wireless communication techniques through targeted optimization.

5.1 PROPAGATION MODELING OF RIS-ASSISTED COMMUNICATION

Site-specific channel modeling allows for a more accurate representation of the actual propagation environment. Instead of relying on statistical averages, these models take into account the precise geometrical relationships between communication terminals and environmental features. This level of detail enables more effective planning and optimization of wireless networks, particularly in complex indoor or urban scenarios where small-scale environmental factors can significantly impact signal propagation. One powerful tool for generating site-specific channel parameters is the RT algorithm. Without the need for extensive on-site measurements, RT can provide detailed geometry-based information about the propagation environment in a deterministic manner. This approach offers an effective and flexible means of obtaining accurate, site-specific channel models, which can be used for the design and deployment of advanced wireless systems, especially those utilizing technologies like RIS technology.

5.1.2 Indoor RIS-Assisted SISO Propagation Model

This section presents a framework for RT-based propagation modeling of a Single-Input Single-Output (SISO) Orthogonal Frequency-Division Multiplexing (OFDM) system in an RIS-assisted indoor environment. Our proposed model is designed to capture the complex interactions between transmitted signals, the RIS, and the indoor environment. We focus on scenarios where direct LOS paths between the TX and UE are obstructed, but both have clear LOS to the RIS. The framework incorporates detailed considerations of multi-path propagation, reflection characteristics, and the unique properties of the RIS. By leveraging RT techniques, we aim to provide an accurate and computationally efficient method for predicting signal propagation in these sophisticated environments.

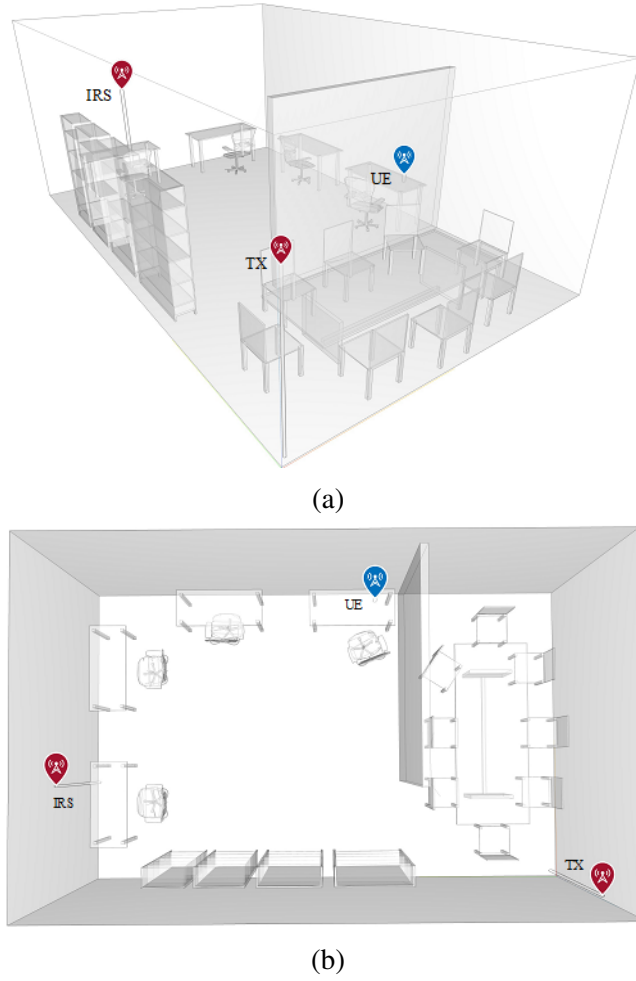


Figure 5.1: (a) Perspective view; and (b) Top view of the indoor environment that includes a TX, UE (RX), and RIS.

5.1.3 Environment Setup and Assumptions

The foundation of our propagation modeling framework is an indoor environment that simulates an office space. We adopt an existing office model from MATLAB, which consists of two rooms separated by a concrete partition. This setup is designed to create a propagation scenario where the LOS path between the TX and UE is deliberately obstructed. The TX is positioned in one room with a clear view of the RIS, while the UE is located in the adjacent room. The adopted 3D environment as well as antennas

5.1 PROPAGATION MODELING OF RIS-ASSISTED COMMUNICATION

and RIS locations inside the environment is shown in Figure 5.1. The RIS itself is modeled as a 20x20 element array, with each element spaced at $\lambda/2$ intervals, operating at a frequency of 5.8 GHz. To enhance the accuracy of our model, we define specific material properties for walls, furniture, and other objects within the environment, as these significantly affect ray propagation and reflection characteristics. Our framework assumes a maximum of two reflections for each ray path, balancing computational efficiency with model accuracy.

In implementing our propagation model, we leverage two MATLAB modules: RayTracing and siteviewer. The RayTracing module computes the propagation paths using 3D environment geometry. This module is particularly suited for our frequency range of 5.8 GHz, as it is designed to be effective from 100 MHz to 100 GHz. We utilize RayTracing to determine multiple propagation paths between the TX, RIS, and UE, capturing the complex multi-path nature of our indoor environment. The module's capability to calculate path loss and phase shift for each ray, considering both horizontal and vertical polarizations, is essential for our detailed analysis.

Complementing the RayTracing module, we employ the siteviewer module for 3D visualization of our propagation model. Siteviewer allows us to display the TX site, UE location, and RF propagation visualizations within the modeled office environment. We specifically use the 3D model visualization mode, which enables us to import and view our office space as a 3D model represented by glTF files. This visual representation is invaluable for understanding and validating the spatial relationships between the TX, RIS, UE, and various environmental elements.

5.1.4 PDP Calculation

The calculation of PDP is an imperative step in our framework for accurately modeling the propagation characteristics of the RIS-assisted indoor environment. Our

5.1 PROPAGATION MODELING OF RIS-ASSISTED COMMUNICATION

approach to PDP calculation is methodical and considers multiple scenarios to ensure a comprehensive representation of the channel.

First, RIS is removed from the environment, and the PDP for the TX-UE channel is determined. At this point, any rays that would intersect the location of the RIS should be excluded from the PDP calculation, as they will be considered in the subsequent stage. Following this, the PDP for the TX-RIS-UE channel is calculated. This involves separately computing the PDP for the channels between TX and each RIS unit cell. Each unit cell is modeled as an isotropic antenna placed at its center, and ray tracing is used to calculate the PDP for the channels between the RIS cell and TX, and between the RIS cell and UE. In this context, an isotropic antenna implies that the RIS unit cells are not sensitive to the incident angle of the impinging rays. The sensitivity pattern of a unit cell depends on its physical structure, with different structures exhibiting various patterns. Numerous patterns for RIS unit cells have been explored in the literature [100].

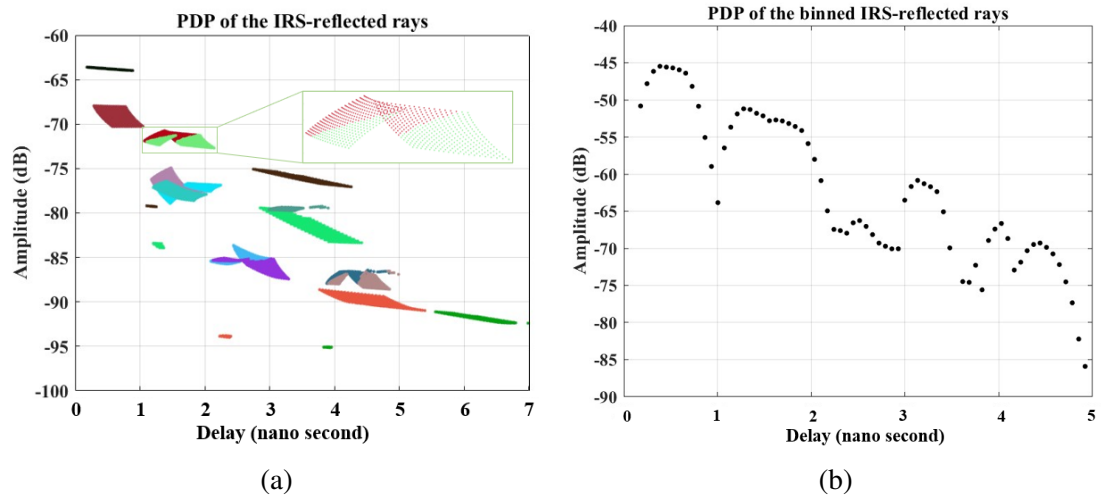


Figure 5.2: PDP of RIS-reflected rays calculated with accurate model **(a)** Without data binning; and **(b)** With data binning using 70 bins in time axis.

Let $d_{t,n}$ and $d_{r,n}$ represent the distances between the n^{th} RIS cell and TX, and between the n^{th} RIS cell and RX, respectively. The total power of the transmitted rays, which

are reflected by the RIS and eventually received at the UE, can be calculated as follows [101]:

$$P_r^{TX-RIS-UE} = P_t G_t G_r \left(\frac{A}{4\pi} \right)^2 \left| \sum_{n=1}^N \frac{R_n e^{-j\Phi_n}}{d_{t,n} d_{r,n}} \right|^2, \quad (5.1)$$

$$\Phi_n = \frac{2\pi}{\lambda} (d_{t,n} + d_{r,n}) + \phi_n, \quad (5.2)$$

where P_t is the transmit power of TX, N is the number of cells, A is the surface area of the unit cell that captures and reflects each ray's transmit power [100], R_n and Φ_n are the reflection loss and phase change for the n^{th} path, ϕ_n is the phase shift of the unit cells in the n^{th} cell, and G_t and G_r are the antenna gains of TX and UE, respectively. To improve the accuracy of the model, we extend Equation (5.1) to account for multiple rays between TX and each RIS unit cell, and similarly between each RIS unit cell and the UE. If we denote the set of rays from TX to the n^{th} RIS cell as $\{t_{n,i}\}_{i=1}^{M_{t,n}}$ and the set of rays from the n^{th} RIS cell to the UE as $\{r_{n,j}\}_{j=1}^{M_{r,n}}$, where $M_{t,n}$ and $M_{r,n}$ are the number of rays for each path, respectively, then the received power can be expressed as:

$$P_r^{TX-RIS-UE} = P_t G_t G_r \left(\frac{A}{4\pi} \right)^2 \left| \sum_{n=1}^N \sum_{i=1}^{M_{t,n}} \sum_{j=1}^{M_{r,n}} \frac{R_{n,i,j} e^{-j\Phi_{n,i,j}}}{d_{t,n,i} d_{r,n,j}} \right|^2, \quad (5.3)$$

$$\Phi_{n,i,j} = \frac{2\pi}{\lambda} (d_{t,n,i} + d_{r,n,j}) + \phi_n + \theta_{t,n,i} + \theta_{r,n,j}, \quad (5.4)$$

where $d_{t,n,i}$ and $d_{r,n,j}$ are the distances of the i^{th} ray from TX to the n^{th} RIS cell and the j^{th} ray from the n^{th} RIS cell to UE, respectively. $R_{n,i,j}$ represents the combined reflection loss, $\theta_{t,n,i}$ and $\theta_{r,n,j}$ are additional phase shifts due to interactions with environmental objects along the paths, and ϕ_n is the controllable phase shift of the n^{th} RIS unit cell.

To improve the accuracy of the model, each ray from TX to the n^{th} RIS cell is divided

into multiple rays that travel from the n^{th} cell to the UE. For instance, if the PDP for the TX-RIS and RIS-UE channels for the n^{th} cell are modeled with $M_{t,n}$ and $M_{r,n}$ rays, respectively, then there will be $M_{t,n} \times M_{r,n}$ rays for the n^{th} cell, resulting in a total of $M_{t,n} \times M_{r,n} \times N$ RIS-reflected rays, as illustrated in Figure 5.2.

Figure 5.2 (a) shows clusters of rays grouped by different colors. Each cluster contains 400 rays reflected from the RIS surface, each from a different unit cell. Different clusters of rays, represented by various color codes, correspond to groups of rays following similar trajectories while interacting with different unit cells. To make the data in Figure 5.2 (a) clearer, data binning has been employed. The time span between 45 and 52 ns is divided into 70 bins, and rays within the same bin are aggregated (see Figure 5.2 (b)). Since each ray has both magnitude and phase, the sum of the rays within the same bin is equivalent to vector summation. In the final step, rays reflected by the RIS are added to the non-RIS reflected rays.

In the subsequent subsection, a faster framework is introduced to approximate the channel calculation for an RIS-assisted indoor environment.

5.1.5 Proposed Approximate Model

While our initial framework provides accurate results for modeling RIS-assisted indoor communication, as validated by numerous studies that have established ray tracing as a highly reliable deterministic channel modeling technique [102, 103]. Specifically, for RIS-assisted communications, ray tracing has been shown to achieve accuracy within 2-3 dB of measured field results when proper material parameters and environment geometry are considered [104]. This accuracy stems from ray tracing's ability to account for the precise geometric relationships between transmitters, receivers, and environmental elements, along with the electromagnetic properties of materials. However, this accuracy comes at the cost of significant computational time. For instance, to accurately

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model the PDP of a SISO system with 400 RIS elements using the RT method, 400 RT realizations are required between the TX and RIS, and another 400 realizations between the RIS and UE. On a standard computer with a Core-i7 CPU and 32 GB of memory, the total simulation time is approximately 86.58 seconds. To address this limitation and enhance the scalability of our approach, we propose an approximate model that drastically reduces simulation time while maintaining a high level of accuracy.

In the proposed approximate model, only three RT realizations are needed: between TX and UE (excluding rays that interact with the RIS), between TX and the center of the RIS, and between UE and the center of the RIS. Initially, all rays between TX and the RIS center, as well as between UE and the RIS center, are identified, and the reflection point and loss of each ray are recorded. Next, Euclidean distances between TX and each RIS unit cell, UE and each RIS unit cell, TX and reflection points, UE and reflection points, and between reflection points and RIS unit cells are computed. Using these distances, all possible TX-RIS-UE paths can be determined.

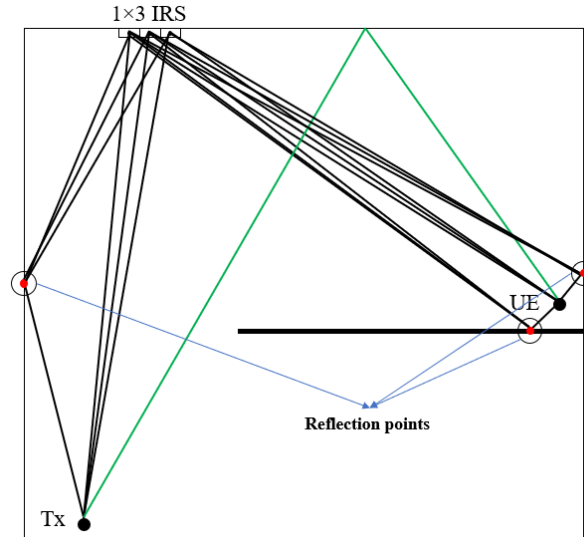


Figure 5.3: 2D simplified environment of the office room in Figure 5.1.

To further illustrate, Figure 5.3 shows a simplified 2D environment with a 3-cell RIS, where the black and green lines represent the TX-RIS-UE and TX-UE ray paths,

respectively. In the final step, the path loss and phase shift of each ray are calculated based on its propagation distance, the phase shift of each unit cell, and reflection loss. For rays that do not interact with the RIS, their propagation loss and phase are calculated as follows:

$$|P_r|_{dB} = G_{t,dB} + G_{r,dB} - FSPL(d_t) - L_{reff} \quad (5.5)$$

$$\angle P_r = e^{j\frac{2\pi}{\lambda}d_t} \quad (5.6)$$

Here, $FSPL(\cdot)$ denotes the free-space propagation loss, d_t is the total propagation distance of each ray, and L_{reff} represents the reflection coefficient of the material reflecting the ray (e.g., concrete, wood, etc.). For rays that do interact with the RIS, the amplitude and phase are calculated using equations (5.5) and (5.6), with the reflection losses of the environment and RIS considered as well.

The reflection coefficient of each unit cell depends significantly on its structural parameters, such as the number and material of dielectric layers, the pattern of conductor layers, and any lumped elements used. The variation in reflection loss is typically between 0.1 and 3 dB, based on the measured values provided in [4–6]. While this parameter can be adjusted in the model for specific unit cell structures, the worst-case scenario of a 3 dB reflection loss for the RIS is considered in all calculations presented in this chapter.

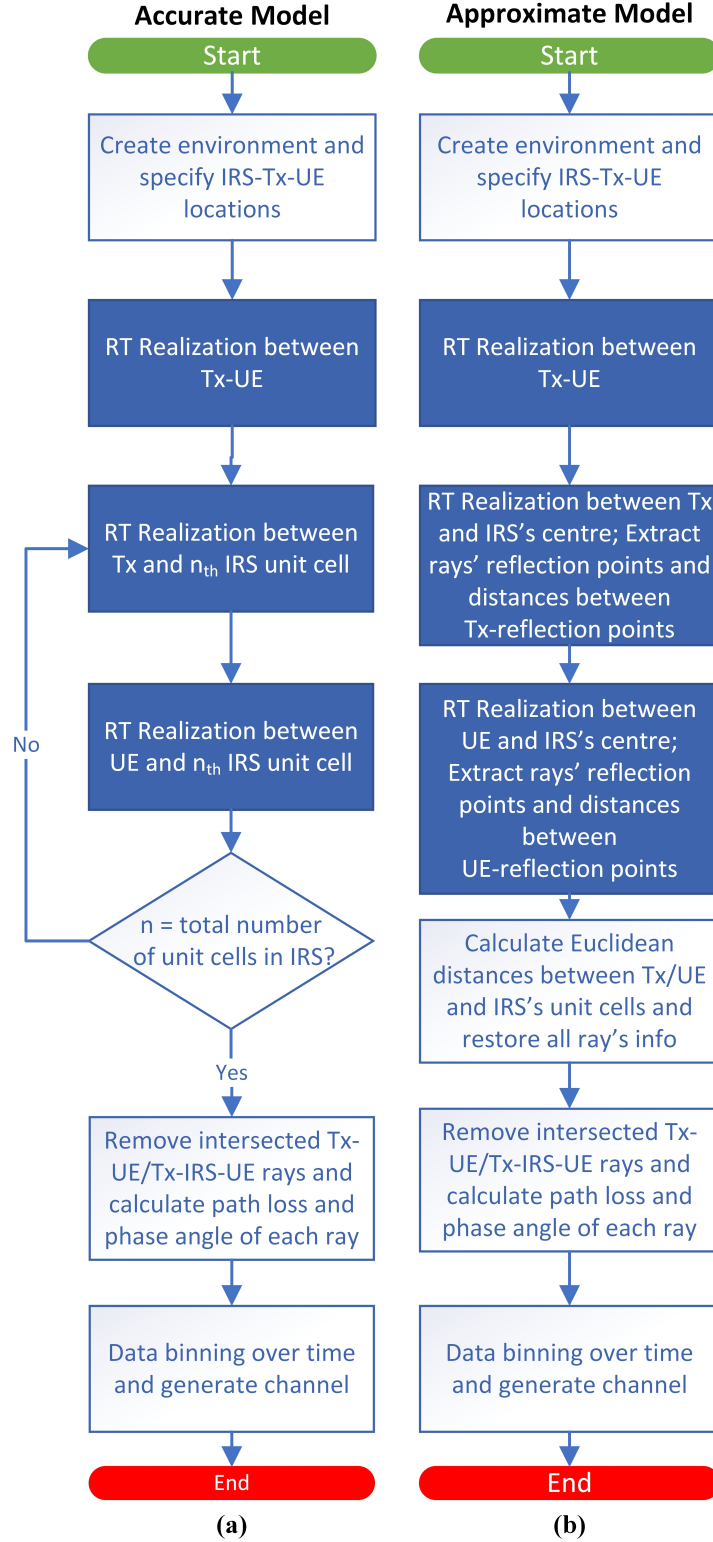


Figure 5.4: Frameworks for **(a)** accurate; and **(b)** approximate modeling of deterministic channels in RIS-assisted indoor environments.

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Figure 5.4 illustrates the procedural steps for both the accurate and approximate models when calculating the channels between TX and UE with RIS assistance. Each blue block represents an RT realization, which computes rays between different points in the environment. The primary computational demand comes from these blocks, and reducing their number significantly decreases the overall processing time. For the given environment, the accurate model requires a total of 801 RT realizations, whereas the approximate model only requires three, reducing the total runtime by 99.6% from 86.58 seconds to just 0.35 seconds.

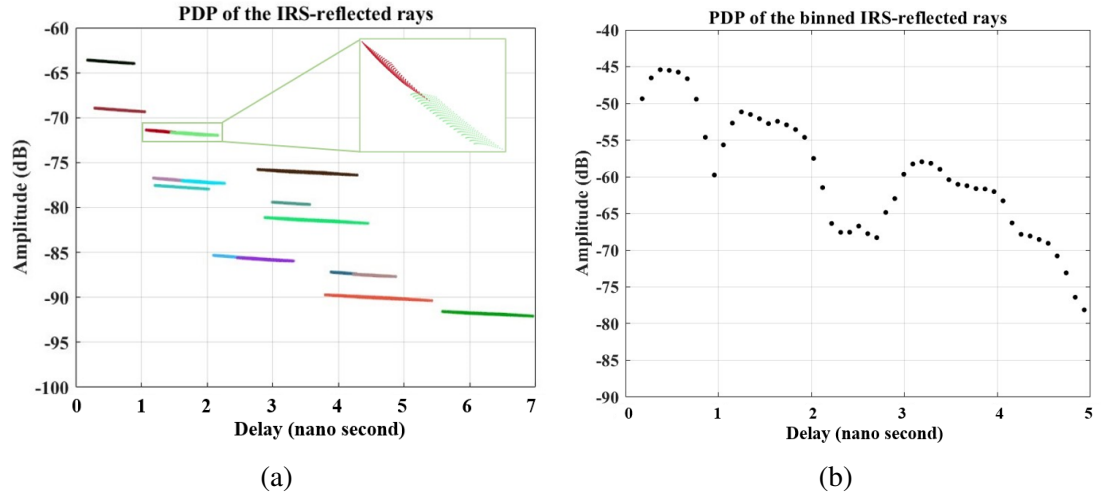


Figure 5.5: Power Delay Profile of RIS-reflected rays calculated with approximate model (a) Without data binning; and (b) With data binning using 70 bins in time axis.

Figure 5.5 shows the amplitude of the PDP of TX-RIS-UE rays calculated using the proposed approximate model. The results indicate that the approximate model achieves similar accuracy to the more detailed model. Figure 5.6 provides a direct comparison of the total PDPs generated by the two different models, demonstrating that the approximate model effectively captures the detailed timing patterns of wireless channel behavior.

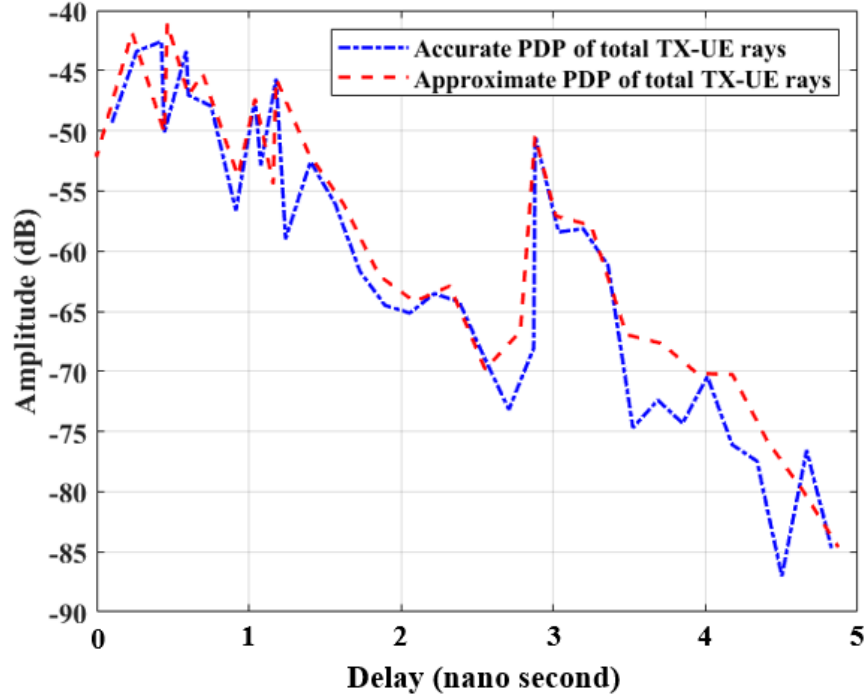


Figure 5.6: Comparison between the total PDPs calculated by accurate and approximate RT models.

5.1.6 Channel Model

In this subsection, two deterministic channel models are developed based on the computed PDPs, through which data is transmitted from the TX to the UE. The system setup is shown in Figure 5.7.

At the transmitter, the data is encoded using a 1/2 Low-Density Parity-Check (LDPC) encoder. The encoded data is then mapped onto Quadrature Amplitude Modulation (QAM) symbols using a 16-QAM modulator. These modulated symbols are further processed through an Orthogonal Frequency Division Multiplexing (OFDM) block, which segments the data into 214 sub-carriers, including 25 pilots and 17 guard bands. The resultant signal is then combined with Gaussian white noise and transmitted through a channel generated by both the accurate and approximate ray-tracing models.

Upon reception, the received data is processed through an inverse OFDM block. This block estimates the channel characteristics using OFDM pilots. The QAM symbols are

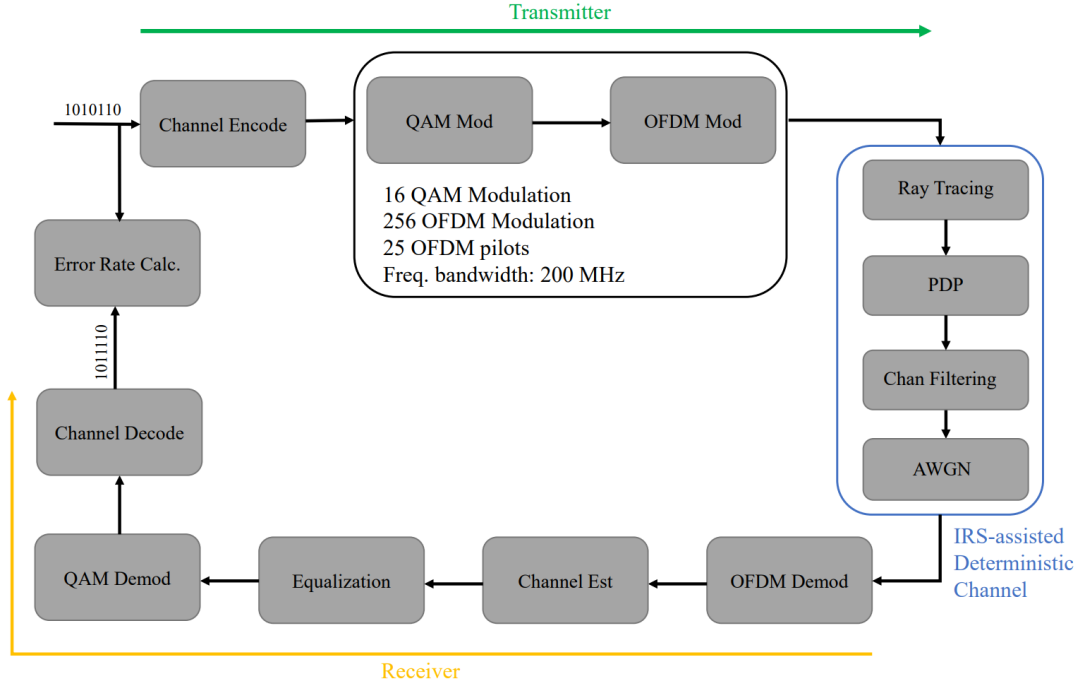


Figure 5.7: System setup for data transmission.

then extracted based on the equalized channel and passed through subsequent stages, including QAM demodulation and channel decoding. Throughout this process, several key parameters are evaluated, including the estimated amplitude and gain of the channel, as well as the Bit Error Rate (BER).

Figure 5.8 illustrates the channel gains between TX and UE calculated using both accurate and approximate PDPs. The transmission is carried out in the presence of a RIS, with the phase shift of its elements set to zero. The locations of the TX, UE, and RIS are assigned as shown in Figure 5.1. Figure 5.9 (a) and (b) show the RIS phase shifts optimized for minimal BER, calculated by the approximate and accurate models, respectively. The optimization process employs a single-objective Genetic Algorithm (GA), where the solution space consists of a 400-element array, with each element ranging between 0 and 360 degrees. The GA operates with a population size of 200 and terminates when the derivative between two successive solutions (BERs) reaches a threshold of $1e-5$. Figure 5.9 (c) depicts the difference between the phase distributions

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of both models. It can be observed that the phase error for each unit cell ranges between -8° and 6° . To statistically validate the models, they are further evaluated under 100 random TX and UE locations. For each of the 100 locations, the direct path between TX and UE is blocked, while both have a direct line of sight to the RIS. Figure 5.10 shows the probability density function (PDF) of the phase error between the accurate and approximate models for each RIS unit cell. The results indicate that the mean phase error value is close to zero, with the phase error range mostly falling between $\pm 5^\circ$.

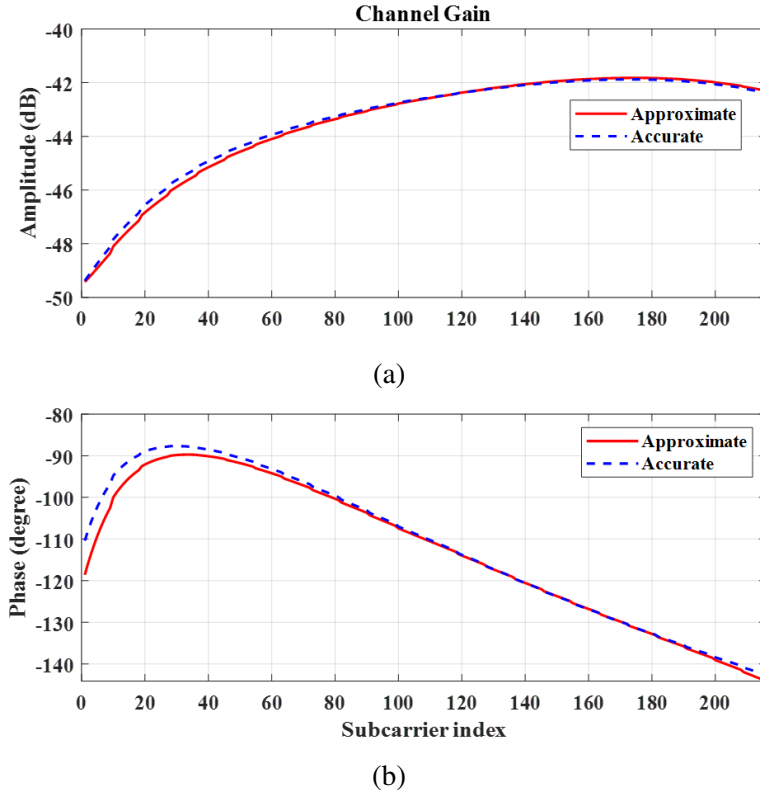


Figure 5.8: **(a)** Amplitude; and **(b)** Phase of the channel gains derived from accurate and approximate PDPs.

Figure 5.11 illustrates the phase error PDF for three RIS sizes: 5×5 , 20×20 , and 40×40 . Since the distance between unit cells is maintained at $\lambda/2$, an increase in the number of RIS unit cells translates to a physically larger RIS structure. As expected, the phase error range increases with the RIS size, which may be reduced by grouping

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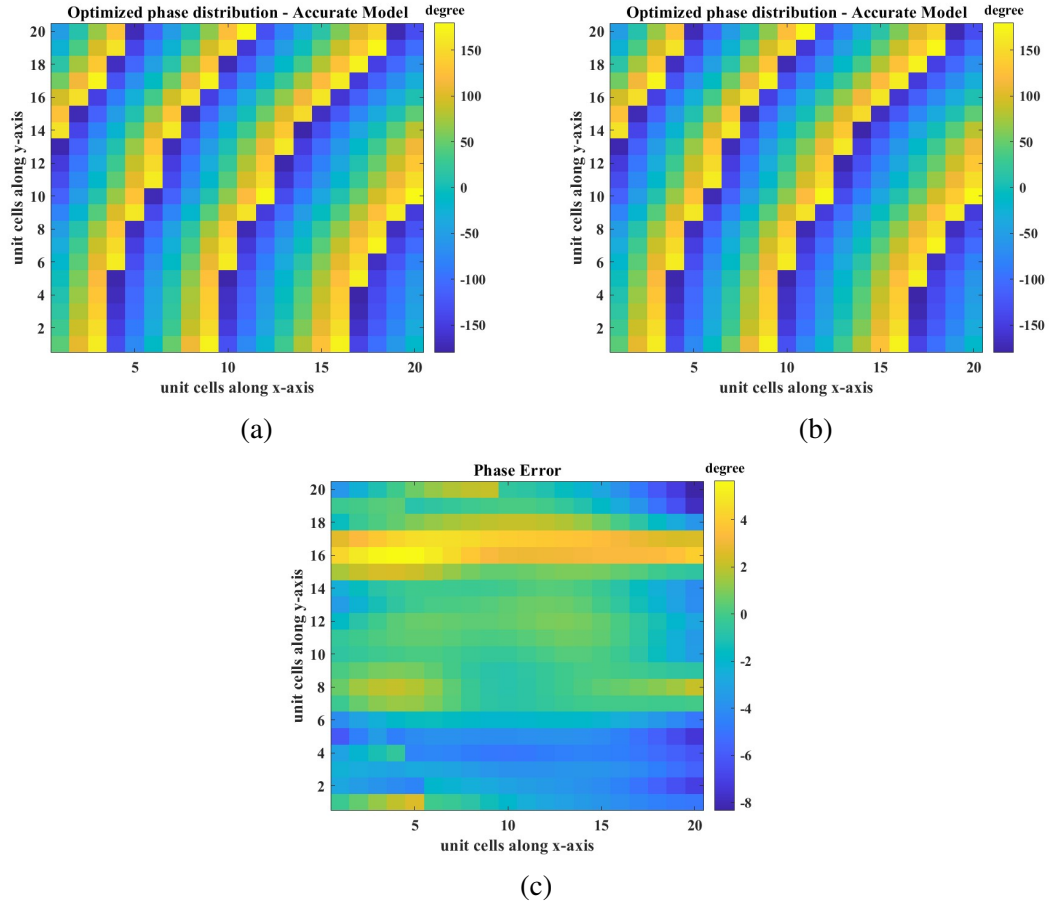


Figure 5.9: Optimized RIS phase distribution generated by: **(a)** Approximate model; and **(b)** Accurate model. The sub-figure **(c)** shows the difference between **(a)** and **(b)**.

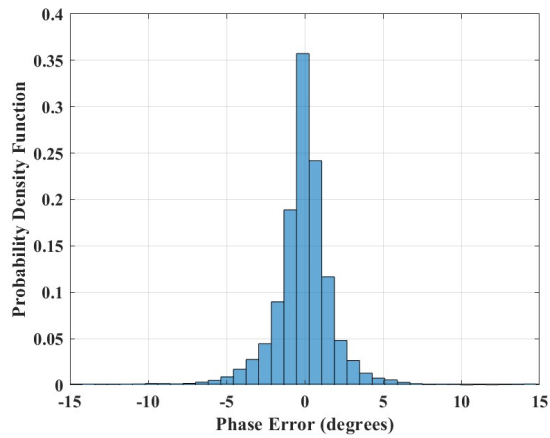


Figure 5.10: PDF of unit cell phase error between accurate and approximate models.

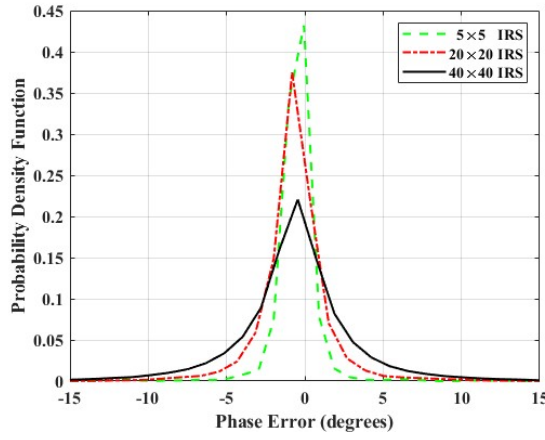


Figure 5.11: PDF of unitcell's phase error for 5×5 , 20×20 , and 40×40 RIS structures.

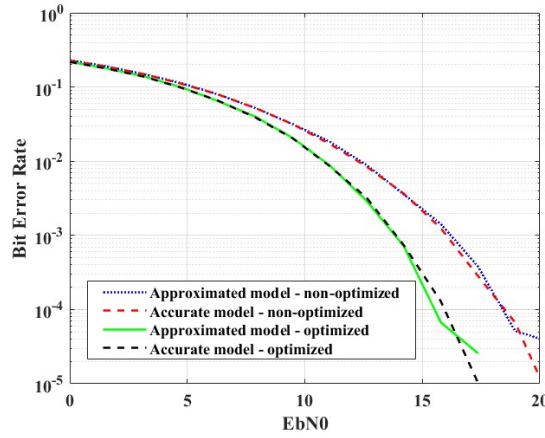


Figure 5.12: BER of RIS-assisted communication calculated with approximate and accurate PDPs for different values of E_b/N_0 .

the unit cells. Figure 5.12 evaluates the BER obtained by both models as a function of E_b/N_0 for a 20×20 RIS. The results show that the BER values are acceptable under moderate to high E_b/N_0 , and the performances of both models are strikingly similar, underlining the accuracy of the approximate approach even for a considerably large RIS structure.

5.2 WiPy-RT: A Fast Ray Tracing Modeling Platform for RIS-assisted Wireless Channels

In the previous section, a propagation modeling framework implemented in MATLAB was presented. This framework utilized MATLAB modules for performing ray tracing and identifying ray paths. Additionally, an approximation approach was introduced to enhance the framework's speed and efficiency. However, MATLAB-based solutions come with certain limitations. These include the requirement for a costly license, the need for substantial RAM memory for software startup, and potential scalability issues when dealing with large-scale simulations. Furthermore, MATLAB's proprietary nature can sometimes hinder collaborative research and limit the integration of cutting-edge algorithms developed by the open-source community.

In contrast, the Python environment offers a more flexible and accessible approach to scientific computing and simulation. Python boasts a rich ecosystem of open-source libraries that have been developed and refined by a global community of researchers and developers. Libraries such as NumPy, Numba, and SciPy provide robust numerical computing capabilities, while Matplotlib and Plotly offer advanced visualization tools. For 3D modeling and manipulation, PyVista, Trimesh, and PyTorch3D have emerged as powerful, versatile solutions. These libraries, among many others, enable researchers to build sophisticated simulation environments without the constraints associated with proprietary software.

While significant advancements have been made in RT-based propagation modeling for wireless communications, the incorporation of RIS technology into these models is still in its infancy. There exists a substantial research gap in accurately and efficiently modeling the behavior of RIS within complex wireless systems using RT techniques. The unique properties of RIS, including their ability to dynamically alter the electromagnetic environment, present novel challenges for traditional RT approaches. Furthermore, as

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wireless environments become increasingly complex, particularly with the integration of RIS, there is a pressing need for RT tools that can maintain high accuracy while also offering computational efficiency. This balance is important for handling the intricate scenarios expected in future wireless networks, especially in urban and dense IoT environments.

The key technical challenges in RIS-assisted RT modeling include: (1) efficiently handling the complex electromagnetic interactions between incident waves and numerous RIS unit cells, (2) accurately representing the phase-shifting behavior of RIS structures without prohibitive computational overhead, and (3) developing algorithms that maintain precision while dramatically reducing simulation time. These challenges are particularly acute in applications requiring rapid assessment of multiple RIS configurations or large-scale simulation environments.

Addressing these challenges would have significant practical impact across multiple domains. For network design, faster RIS-assisted RT simulation would enable rapid prototyping and optimization of network topologies. For device manufacturers, it would accelerate the development cycle of RIS hardware by providing quick feedback on different unit cell configurations. In real-world applications, such efficient modeling tools would facilitate the deployment planning of RIS-enhanced networks in smart cities, industrial IoT environments, and high-density urban areas where coverage optimization is critical.

In this context, WiPy-RT has been developed as a high-performance ray tracing simulator designed specifically for modeling RIS-enabled wireless environments. WiPy-RT addresses the aforementioned challenges by offering a novel approach to RT simulation that combines high accuracy with computational efficiency, particularly in modeling RIS-enabled environments. Our simulator leverages state-of-the-art machine learning techniques and efficient algorithms to overcome the limitations of traditional RT methods, especially when dealing with complex, RIS-enhanced wireless scenarios.

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WiPy-RT leverages the strengths of the Python ecosystem, offering an interactive interface that utilizes highly configurable and open-source Python libraries. This GPU-accelerated simulator excels in simulating first-order diffraction and multi-reflection scenarios, supporting up to 6 orders of reflection. It is capable of modeling RIS behavior with large-scale unit cell arrays, making it particularly suitable for advanced wireless communication research, including the simulation of massive MIMO systems and intelligent reflecting surfaces.

WiPy-RT is developed entirely in Python, leveraging efficient and versatile open-source libraries such as PyVista, Trimesh, PyTorch3D, and Scikit-learn. This choice of implementation not only ensures wide accessibility and ease of use for researchers but also allows for seamless integration with other Python-based tools commonly used in wireless communications research. At its core, WiPy-RT employs an advanced ray launching method, ensuring swift and efficient channel model realization for complex indoor and outdoor smart wireless environments. The simulator is capable of identifying direct, multi-order reflected, and one-order diffracted EM waves, providing a comprehensive representation of the wireless channel. For point-to-point channel modeling, WiPy-RT also incorporates the inverse method, offering flexibility in simulation approaches.

WiPy-RT's key features include its ability to handle complex 3D environments efficiently, its GPU acceleration for rapid simulations, and its flexibility in modeling various wireless propagation phenomena. The simulator's Python-based architecture allows for easy integration with other data processing and machine learning libraries, facilitating more comprehensive analyses and predictive modeling.

The key contributions of this work are:

- Addressing the computational inefficiency gap in existing simulators through an intelligent ray launching method strategy with KDE ray emission model. This novel approach significantly improves the efficiency of ray tracing by adaptively

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focusing computational resources on the most relevant propagation paths. Compared to traditional uniform ray launching methods, our KDE-based approach achieves up to 40% reduction in simulation time while maintaining comparable accuracy.

- Solving the RIS unit cell interaction modeling challenge through an efficient method for RIS modeling using Random Forest Regression and Inverse RT for estimating travel distance between TX and RIS' unit cells. This hybrid approach allows for accurate modeling of RIS behavior without the computational overhead typically associated with full-wave analysis of large RIS structures. Our method demonstrates a 60% improvement in computation time for RIS modeling compared to conventional ray tracing techniques, while achieving less than 5% error in path loss estimation.
- Overcoming the platform accessibility limitations of existing solutions by implementing a comprehensive RT modeling platform in Python that outperforms existing solutions in terms of speed and scalability. WiPy-RT achieves simulation times that are up to 100 times faster than comparable MATLAB-based simulators for complex urban environments, making it particularly suitable for large-scale studies of 5G and 6G wireless networks.
- Demonstrating the effectiveness of WiPy-RT through extensive benchmarking against existing simulators and validation with real-world measurements. Our results show that WiPy-RT achieves an average accuracy improvement of 15% in predicting received signal strength in RIS-enabled environments, compared to traditional ray tracing methods.

These contributions collectively address the growing need for efficient and accurate modeling tools in the evolving landscape of wireless communications, particularly in

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the context of RIS-enabled 5G and 6G networks. By offering a unique combination of machine learning techniques, efficient algorithms, and a user-friendly Python implementation, WiPy-RT represents a significant advancement in the field of wireless channel modeling.

In this section, WiPy-RT will be presented in detail, highlighting its architecture, methodologies, and unique capabilities. This presentation will demonstrate how WiPy-RT addresses the challenges faced by existing simulators and offers new possibilities for researchers in the field of advanced wireless communications.

5.2.1 WiPy-RT Engine

This section provides an in-depth exploration of WiPy-RT's architecture and operational mechanisms, offering a detailed analysis of its approach to modeling intricate electromagnetic propagation scenarios. The following subsections present a thorough examination of the simulator's essential components, algorithms, and methodologies. We begin by scrutinizing the preprocessing stage, a critical phase where the environment is imported and structured, pivotal features are extracted, and the wireless system is defined. This initial step lays the foundation for accurate simulation by ensuring that all relevant environmental and system parameters are properly accounted for.

The discussion then progresses to the core of the simulator: the ray launching process. This subsection elucidates the sophisticated techniques employed to track, label, and organize rays as they traverse the complex environment.

The final subsection focuses on the post-processing phase, a vital stage where the wealth of information gathered from the simulated rays is interpreted and translated into meaningful channel characteristics. This analysis is essential for deriving practical insights that can inform the design and optimization of wireless communication systems.

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Through this examination, we aim to provide a clear understanding of WiPy-RT’s capabilities and its potential to advance the field of electromagnetic propagation modeling.

5.2.2 Preprocessing

The preprocessing stage in WiPy-RT forms the cornerstone for precise and efficient ray tracing simulations. This phase commences with the importation of environmental data, typically in STL format, which encapsulates the three-dimensional geometric information of the simulation environment. The processing of these files is accomplished through a synergistic combination of robust Python libraries: PyVista, Trimesh, and PyTorch3D, each contributing unique capabilities to the preparation of environmental data for subsequent ray tracing operations.

PyVista excels in structuring and visualizing the 3D environment, offering powerful tools for organizing and rendering complex geometries, thus enabling an intuitive representation of the simulation space. Complementing this, Trimesh provides advanced modules for environmental data manipulation, conceptualizing the entire environment as an assemblage of triangular mesh cells. Each cell encapsulates vital information: point coordinates, surface normal vectors, and data on adjacent cells. This granular representation facilitates efficient access to geometric features and aids in identifying and labeling objects with sharp edges, which is essential for accurate diffraction modeling. PyTorch3D further enhances the simulator’s performance by harnessing multi-dimensional tensors, enabling highly efficient vector computations. This approach significantly accelerates the process of identifying intersection points between rays and surfaces, a computationally demanding task at the heart of ray tracing algorithms. The integration of these libraries—PyVista’s visualization prowess, Trimesh’s detailed geometric representation, and PyTorch3D’s GPU-accelerated computations—establishes a comprehensive and efficient foundation for WiPy-RT’s ray tracing operations.

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Following the environmental import and structuring, WiPy-RT proceeds to identify and catalog key features of the simulation space, including the detection and marking of sharp edges. The preprocessing stage then involves the assignment of material properties and free space loss coefficients to environmental objects, which is vital for accurately modeling electromagnetic wave interactions with various surfaces and materials.

Subsequently, the simulator configures the RIS and antennas, specifying their positions, the number of unit cells in the RIS, and the antennas' farfield patterns. This setup ensures that the unique characteristics of wireless systems, particularly those incorporating RIS technology, are faithfully represented in the simulation.

The preprocessing phase concludes with the configuration of ray tracing parameters, including the number of reflections to be considered and the activation of diffraction effects. This preparation sets the stage for accurate and efficient ray tracing simulations. The subsequent subsection focuses on the core of the WiPy-RT engine, offering a detailed examination of the ray tracing process. It explores how rays are emitted from the transmitter, propagate through the environment, and interact with various surfaces, including the RIS. This exploration covers the mechanisms for tracking ray paths, handling reflections and diffractions, and modeling the unique electromagnetic behavior of RIS elements. The discussion also encompasses the simulator's approach to managing computational complexity, ensuring efficient performance even in intricate scenarios with multiple reflections and large numbers of RIS unit cells.

5.2.3 Ray Launch

The Ray Launch stage in WiPy-RT represents the core of the ray tracing process, where intelligent ray distribution is implemented to efficiently simulate electromagnetic wave propagation. To comprehensively model all possible paths from the transmitter to the receiver, an infinite number of rays with zero angle separation would theoretically

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be required. However, given that computational resources are finite, it is impractical to launch an infinite number of rays. Instead, WiPy-RT employs an intelligent ray launching strategy to balance accuracy and computational efficiency.

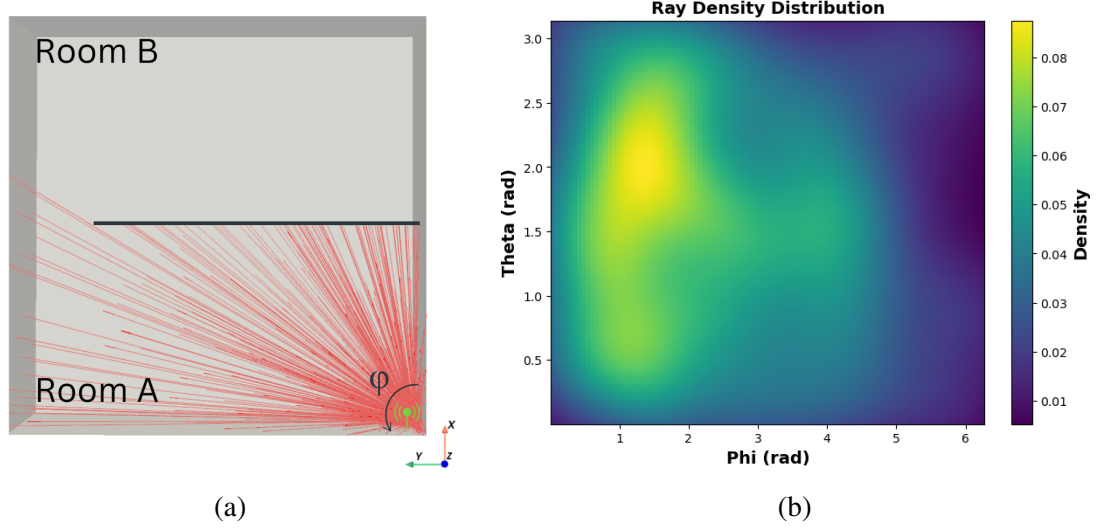


Figure 5.13: (a) Indoor environment divided into two rooms, with a source point located in the bottom right of room A. (b) Ray density distribution of the KDE model for the current source location with respect to θ and ϕ .

The simulator initiates the process by generating a limited number of rays with random azimuth (θ) and elevation (ϕ) angles. These angles, along with the distance each ray has traveled, are then fed into a Gaussian Kernel Density Estimation (KDE) model. Based on the ray density with respect to θ and ϕ , the model generates a considerable number of rays and performs ray tracing. WiPy-RT then identifies the unique rays emitting from the source and reaching the receiver. The choice of Gaussian KDE is deliberate, as it provides a robust statistical model for estimating the probability density function of the ray distribution. This approach allows for a more nuanced and adaptive ray launching strategy compared to uniform distribution methods.

The WiPy-RT's intelligent ray launching strategy is visually demonstrated in Figure 5.13 (a) depicts an indoor environment divided into two rooms, Room A and Room B, connected by a gate, with the antenna serving as the source point strategically positioned

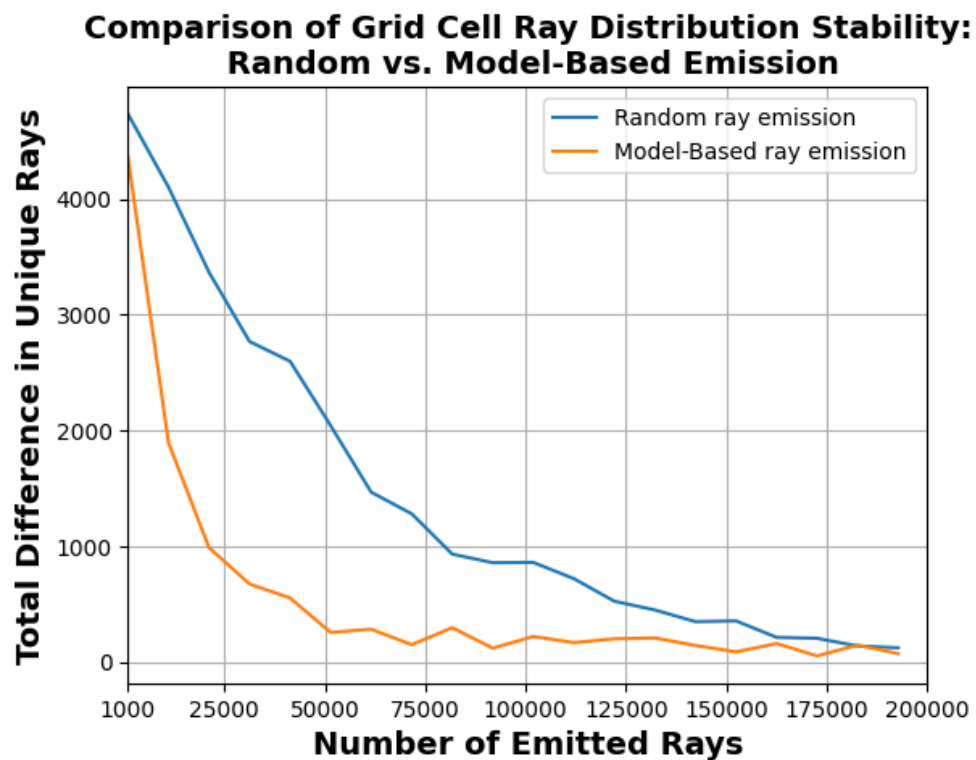


Figure 5.14: Convergence of unique ray distribution across grid cells for random vs. model-based ray emission methods, showing the total difference in unique rays as the number of emitted rays increases from 1,000 to 200,000.

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at the bottom right corner of Room A. The red lines emanating from this source represent the initial set of randomly generated rays, illustrating their diverse propagation paths throughout the environment. Figure 5.13 (b) showcases the ray density distribution derived from the KDE model, representing the probability density of rays with respect to azimuth (θ) and elevation (ϕ) angles. The color gradient, ranging from dark blue (lowest density) to bright yellow (highest density), illustrates the non-uniform distribution of rays, with a higher concentration in the direction of the gate connecting Room A and Room B. This increased density corresponds to rays with larger travel distances, critical for accurately modeling propagation between the two rooms. This adaptive distribution ensures that WiPy-RT allocates more computational resources to ray directions of greater importance in the simulation, thereby enhancing both efficiency and accuracy of the ray tracer engine. It should be noted that the number of rays used to create the ray density distribution is dependent on the size and complexity of the environment, allowing the simulator to adapt its computational resources according to the specific characteristics of each simulation scenario.

Following the establishment of the ray density distribution, the ray tracer engine in WiPy-RT proceeds to emit rays in accordance with this derived distribution. The number of rays selected for this stage is highly dependent on the complexity of the environment, particularly the number of mesh elements present in the 3D model. To determine the optimal number of rays for the ray tracer, WiPy-RT employs an adaptive approach. This involves emitting different numbers of rays from multiple randomized points within the environment and calculating a matrix of unique ray distances to a predefined grid surface. As the number of emitted rays increases, the error between successive snapshots of this distance matrix is evaluated. The process continues until the error falls below a specified tolerance threshold. This adaptive method ensures that the simulation strikes an optimal balance between computational efficiency and accuracy, tailoring the ray count to the specific complexities of each unique environment.

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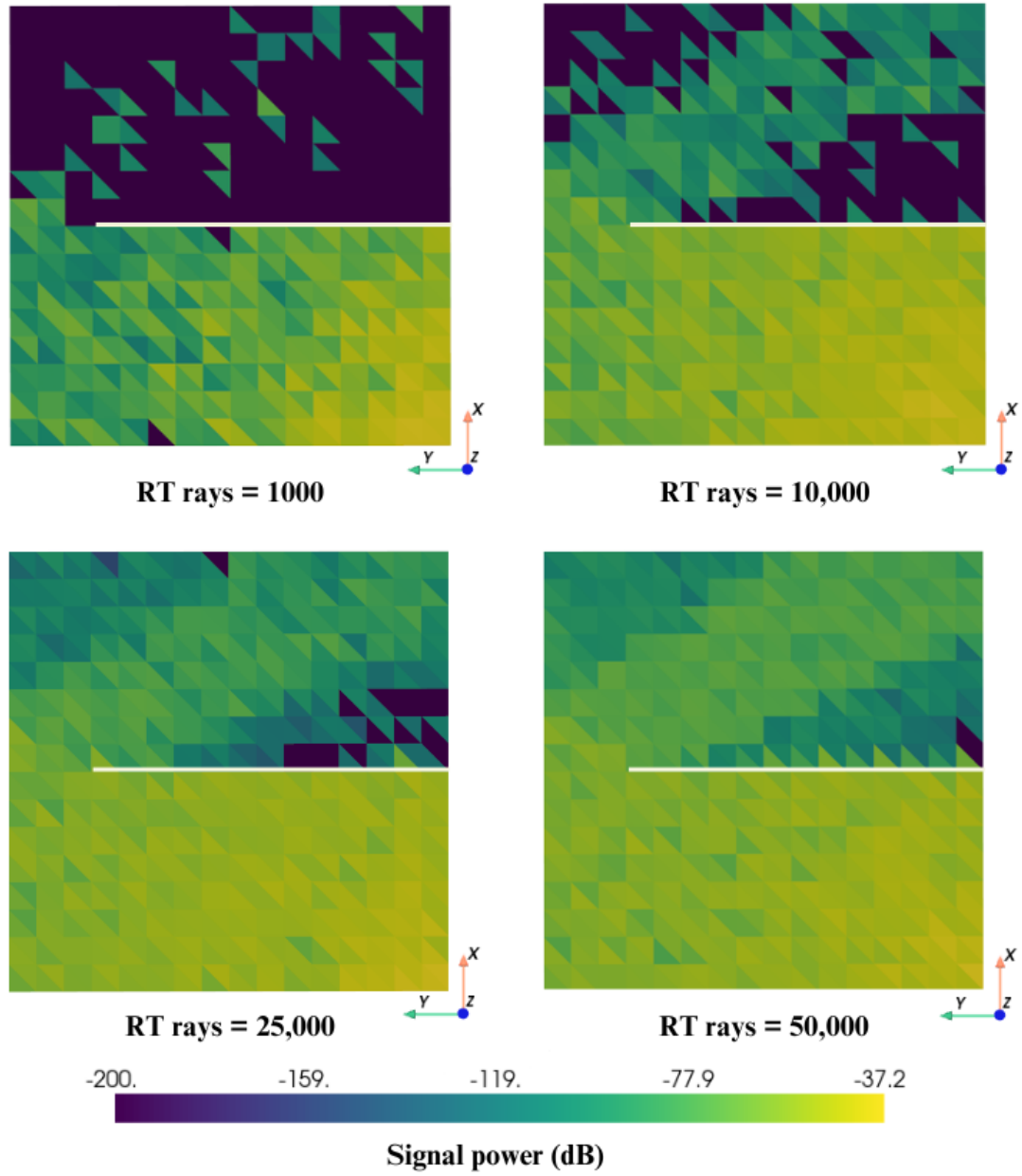


Figure 5.15: Signal power distribution on a triangular grid 0.5 meter above the floor of the two-room environment for varying numbers of emitted rays using the KDE ray distribution model, ranging from 1,000 to 50,000 rays.

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To illustrate this adaptive ray selection process, consider the environment depicted in Figure 5.13 (a). This room has overall dimensions of $10 \times 10 \times 2 \text{ m}^3$, with a separating wall positioned along the line from $[5, 0]$ to $[5, 8]$ in the XY plane, effectively dividing the space into two connected rooms. For this example, a grid is established 50 centimeters above the floor, covering the entire floor area of both rooms. This grid serves as the reference surface for calculating ray distances.

Figure 5.14 illustrates the convergence behavior of the ray tracing process for both random and model-based ray emission methods. The x-axis represents the number of emitted rays, ranging from 1,000 to 200,000, while the y-axis shows the total difference in unique rays received by each grid cell between consecutive simulations. The blue curve represents the random emission method, while the orange curve depicts the model-based emission approach. Both curves demonstrate a general downward trend as the number of emitted rays increases, indicating that the ray distribution across the grid cells becomes more stable with higher ray counts. Notably, the model-based emission (orange curve) converges more rapidly and maintains lower difference values throughout the range, suggesting superior efficiency and stability compared to the random emission method. This graph underscores the effectiveness of the model-based approach in achieving a consistent ray distribution with fewer emitted rays, thereby optimizing computational resources while maintaining simulation accuracy.

Figure 5.15 illustrates the evolution of signal power distribution in the two-room environment as the number of emitted rays increases using the KDE ray distribution model. The figure presents four panels, each depicting the signal power distribution on a triangular grid positioned 0.5 meters above the floor for different number of emission rays: 1,000, 10,000, 25,000, and 50,000 rays, respectively. For these simulations, the ray tracing engine is configured to account for up to 5 reflections and 1 diffraction in the environment. As the number of rays increases, a clear progression in the detail and accuracy of the power distribution is observable. With 1,000 rays, the distribution

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appears coarse and incomplete, particularly in Room B as there is almost no trace of diffracted and diffracted rays. As the ray count increases to 10,000 and then to 25,000, the power distribution becomes more refined, revealing intricate patterns and variations across both rooms. The simulation with 50,000 rays provides the most detailed and comprehensive representation of the signal power distribution, capturing subtle nuances in signal strength throughout the entire environment.

Having established an optimal number of emission rays through the adaptive process, WiPy-RT proceeds to simulate the behavior of RIS structures within the environment. The first step in this process involves a comprehensive analysis of all direct and first-order reflected rays that reach the RIS's surface. These rays are then systematically grouped based on their reflection history, creating distinct categories that represent different propagation paths.

For each group of rays incident on the RIS surface, it is crucial to determine the travel distance of the rays to each unit cell of the RIS. However, directly calculating this for every possible ray-cell combination would be computationally intensive. To address this challenge, WiPy-RT employs a Random Forest Regressor. This model estimates the distance between the transmitter and each unit cell of the RIS based on the populated rays within the same group. By leveraging the data from the rays that have been traced, the Random Forest Regressor can accurately predict the travel distances for all unit cells, including those not directly hit by traced rays. This approach significantly reduces computational overhead while maintaining a high degree of accuracy in modeling the RIS behavior.

Following this estimation process, WiPy-RT then traces the rays from each RIS unit cell to the receiver. This crucial step takes into account the individual phase shift of each unit cell, allowing for a precise representation of how the RIS manipulates the incident electromagnetic waves. By considering these phase shifts, the simulator can accurately model the RIS's ability to control and optimize the propagation environment, reflecting

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its true impact on the overall channel characteristics. Finally, the signal power of the rays interacting with the RIS is calculated with the formula:

$$P_r^{TX-RIS-UE} = P_t G_t G_r \left(\frac{A}{4\pi} \right)^2 \left| \sum_{n=1}^N \frac{R_n e^{-j\Phi_n}}{d_{t,n} d_{r,n}} \right|^2. \quad (5.7)$$

where, P_t represents the transmit power of the transmitter, while G_t and G_r are the antenna gains of the transmitter and receiver, respectively. The term A denotes the surface area of the unit cell that captures and reflects each ray's transmit power. The variable N is the number of cells involved in the process. Each ray experiences a reflection loss R_n and a total phase change Φ_n , where

$$\Phi_n = \frac{2\pi}{\lambda} (d_{t,n} + d_{r,n}) + \phi_n. \quad (5.8)$$

The distances $d_{t,n}$ and $d_{r,n}$ are the distances between the n -th RIS cell and the transmitter, and the n -th RIS cell and the receiver, respectively. The wavelength is denoted by λ , and ϕ_n represents the phase shift of the unit cells in the n -th cell.

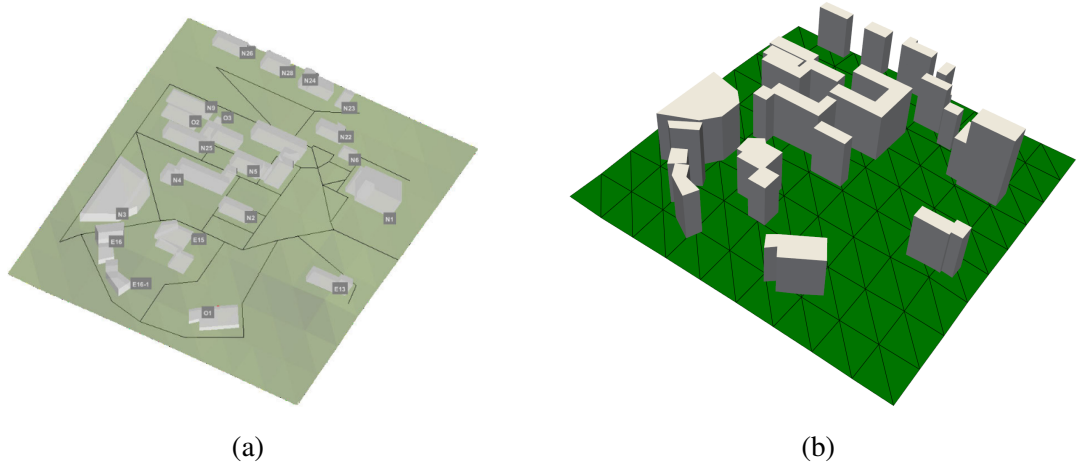


Figure 5.16: 3D map around Korea Advanced Institute of Science and Technology, South Korea [18] (a) visualized in MATLAB, (b) imported and visualized in Python.

5.2.4 Benchmark

In this section, we evaluate the performance of WiPy-RT by benchmarking it against a reference map proposed in the research work by Choi et al. [18], which introduced the WiThRay RT engine. The chosen map, depicted in Figure 5.16 (a), represents a three-dimensional environment surrounding the Korea Advanced Institute of Science and Technology (KAIST) in South Korea. This particular environment was selected for its complexity and diversity of structures, providing a test scenario for assessing the capabilities of WiPy-RT. WiThRay was fully implemented in MATLAB, and consequently, the 3D map data was originally detailed in a Microsoft Excel Worksheet file (xlsx format). To adapt this data for use in our Python-based WiPy-RT engine, we employed the Pandas library, a data processing tool in Python, to import the Excel data. Following the import, we utilized the VTK library to convert the imported data into an STL format, which is compatible with our simulation environment.

By utilizing this benchmark, we aim to provide a fair and meaningful comparison of WiPy-RT's performance against a state-of-the-art ray tracing engine. The KAIST map offers a rich urban landscape with various building heights, and shapes, allowing us to evaluate WiPy-RT's accuracy and efficiency in modeling complex electromagnetic propagation scenarios. This comparison will help demonstrate the strengths and potential areas for improvement in WiPy-RT, particularly in the context of modeling advanced wireless communication systems, including those incorporating RIS.

To evaluate WiPy-RT's performance, we set up a ray tracing scenario using the KAIST map. A TX was positioned at a fixed location in close proximity to a building. Regarding the material properties of the environment, the buildings' material was set to concrete, a common construction material in urban environments. To account for terrestrial reflections, we implemented a loss of 6 dB. As for the RT configuration, We allowed for up to 6 ray reflections, enabling the modeling of complex multi-path propagation

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through the urban landscape. Additionally, we included 1 ray diffraction to account for the bending of waves around obstacles, modeling propagation around building edges. Furthermore, we incorporated 1 ray reflection-diffraction, which accounts for rays that are reflected first and then diffracted from an edge. Finally, RT was performed using 200,000 rays at the TX's location. The antennas used for propagation is considered as omnidirectional antennas. The signal power distribution is calculated on a surface 1 meter above the ground covering the whole map.

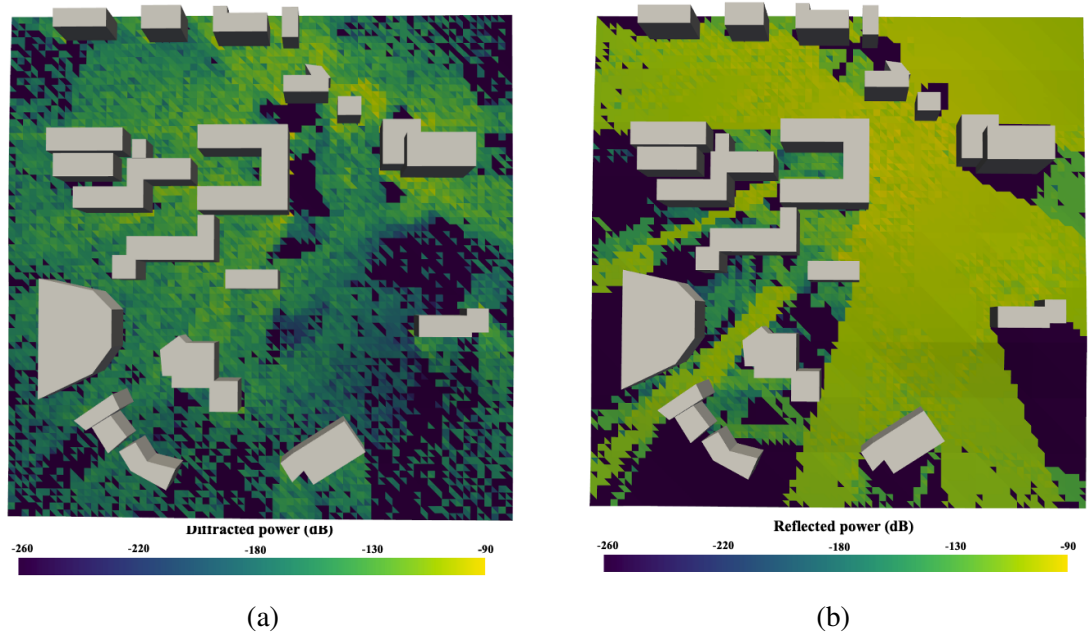


Figure 5.17: Distribution of signal power of (a) diffracted rays, (b) reflected rays simulated by WiPy-RT.

Figure 5.17 illustrates the distribution of signal power for both diffracted and reflected rays simulated by WiPy-RT. The simulation results are visualized on a surface positioned 1 meter above the ground, providing a view of signal propagation across the urban environment.

Figure 5.17 (a) depicts the power distribution of diffracted rays, while Figure 5.17 (b) shows the power distribution of reflected rays. The color scale, ranging from dark blue to yellow, represents signal strength in dB, with yellow indicating stronger signals and

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dark blue representing weaker signals.

These simulations were conducted using a high-performance computer equipped with an Intel(R) Xeon(R) W-2265 CPU featuring 24 processing cores, 128 GB of memory, and an NVIDIA GeForce RTX 3080 graphics card. The computational efficiency of WiPy-RT is evident in the simulation times: diffraction calculations were completed in 0.5 seconds, while reflection calculations took only 0.2 seconds. This rapid processing time, combined with the detailed visualization of signal propagation, demonstrates WiPy-RT's capability to efficiently model complex electromagnetic interactions in urban environments. The clear distinction between diffracted and reflected ray patterns provides valuable insights into the propagation characteristics of wireless signals in this scenario.

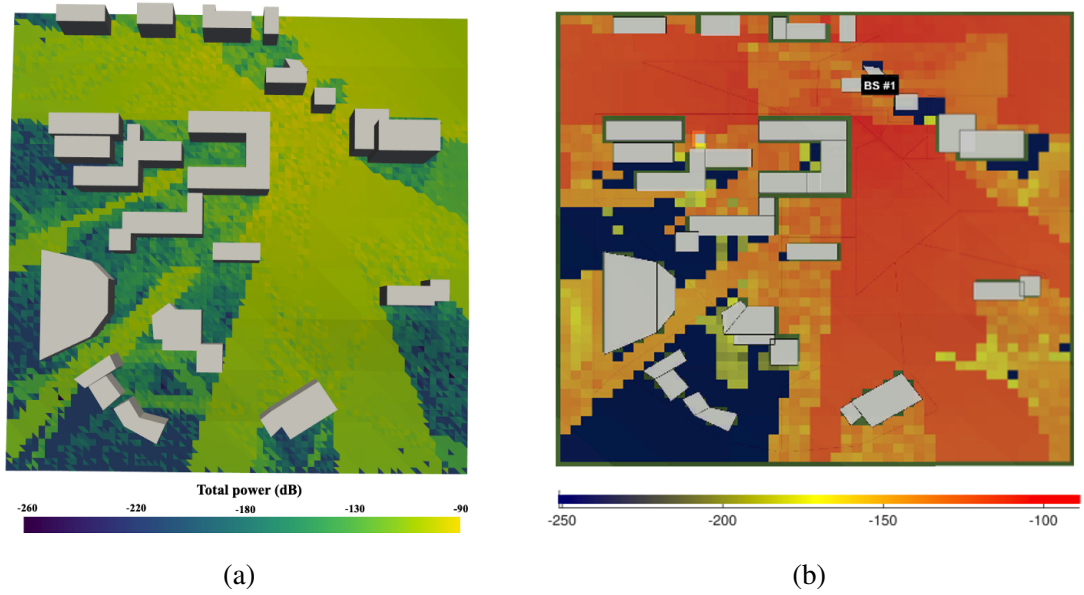


Figure 5.18: Distribution of total signal power simulated by (a) WiPy-RT and (b) WiThRay.

Figure 5.18 presents a comparative visualization of the total signal power distribution simulated by WiPy-RT and WiThRay. The total signal power encompasses both reflected and diffracted rays, providing a view of the electromagnetic propagation in the urban environment.

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Figure 5.18 (a) displays the results from WiPy-RT, while Figure 5.18 (b) shows the simulation output from WiThRay. A striking difference between the two simulations is the computational efficiency. WiPy-RT completed the entire simulation in just 0.7 seconds, which is the sum of the diffraction and reflection calculation times mentioned earlier. In contrast, WiThRay required 15 minutes and 14 seconds to complete the same simulation, highlighting the significant performance advantage of WiPy-RT.

Moreover, the power distribution simulated by WiPy-RT exhibits a higher level of detail compared to WiThRay. This is evident in the more nuanced variations in signal strength across the map in Figure 5.18 (a). The WiPy-RT simulation captures finer gradations in signal power, particularly in areas around buildings and in open spaces, potentially offering a more accurate representation of real-world signal propagation.

This comparison not only demonstrates the computational efficiency of WiPy-RT but also suggests its capability to produce more detailed and potentially more accurate simulations of complex urban electromagnetic environments. The higher resolution in power distribution could be particularly valuable for precise planning and optimization of wireless networks, especially in scenarios involving RIS

Here, we present WiPy-RT's simulation results for an RIS-assisted SISO communication scenario. Figure 5.19 depicts the map layout, with TX, RIS, and RX locations marked by green, blue, and red circles, respectively. The configuration lacks a LOS path between TX and RX, while the RIS maintains visibility to both transceivers. Three RIS configurations were considered: 10×10 , 30×30 , and 70×70 unit cells that are installed on the building's wall shown in Figure 5.19. The communication system operates at 5.8 GHz, with RIS unit cell spacing set to $\lambda/2$. The primary objective was to maximize signal power at the RX by optimizing the RIS phase distribution.

For the WiPy-RT engine simulation, 1,000,000 rays were emitted from the TX, and an equal number from the RIS's center. Figure 5.20 illustrates the optimized RIS phase distribution and its corresponding signal power distribution. For clarity, only the

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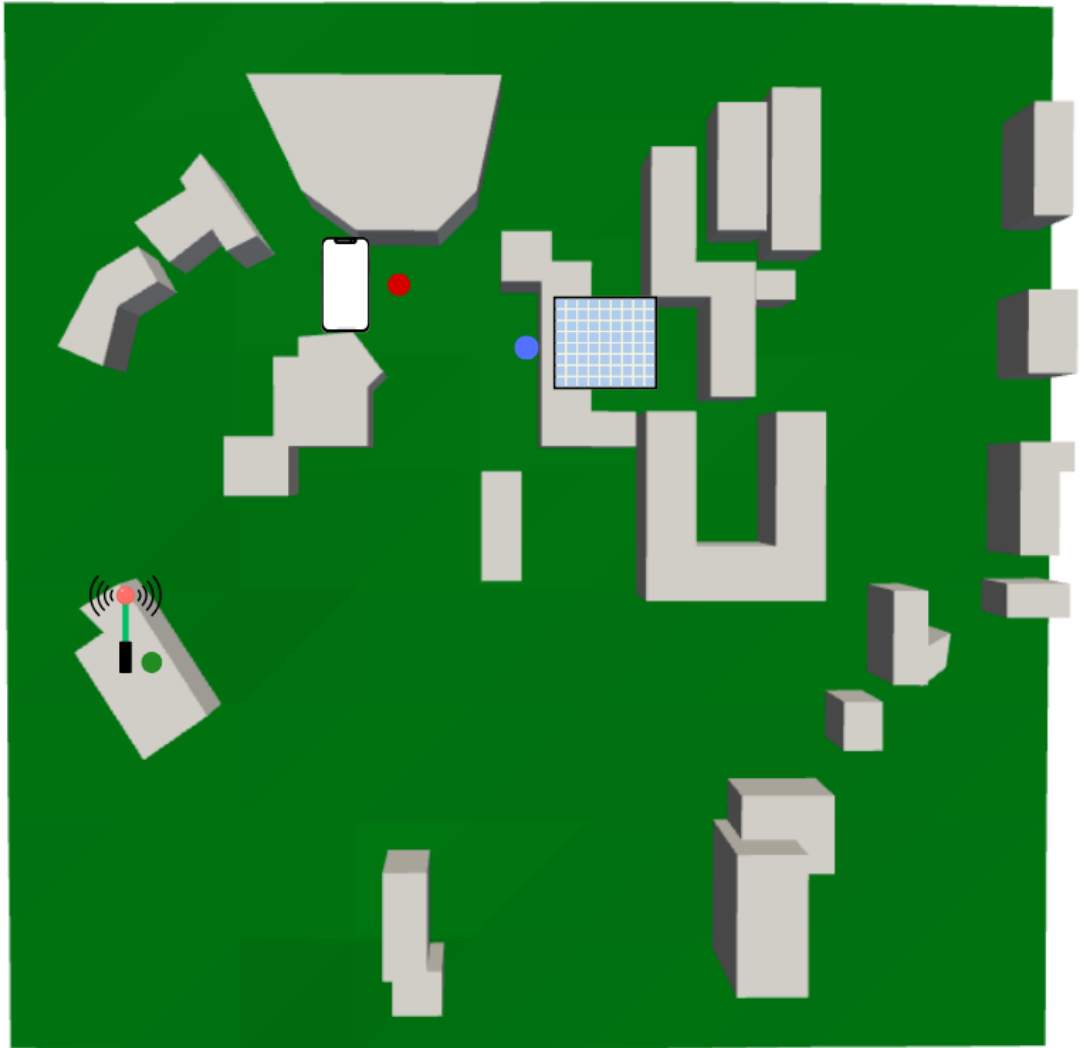


Figure 5.19: Map layout of the RIS-assisted SISO communication scenario. The TX (green circle), RIS (blue circle), and RX (red circle) positions are shown.

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signal power associated with the RIS has been plotted. This visualization allows for a focused examination of the RIS's impact on signal propagation and strength in the given environment.

Figure 5.20 displays the RIS reflection signal power distribution in the map for optimized RIS phase configurations. The figure presents results for three different RIS sizes with varying numbers of unit cells. On the right side of the figure, the optimized RIS phase distributions for maximum signal power at the RX are shown, while the left side illustrates the corresponding signal power distribution on the map. The results demonstrate a significant increase in signal power at the RX, ranging from -83 dBm for the 10×10 RIS to -47 dBm for the 70×70 RIS. This substantial improvement clearly indicates the effectiveness of the RIS in enhancing signal strength within the system. The simulation results suggest that for an RIS structure to be highly effective, a large number of unit cells is required. This observation underscores the importance of RIS size in achieving significant performance gains in wireless communication systems.

To further validate our RIS channel modeling approach, we analyzed both the temporal and frequency domain characteristics of the simulated channel. Figure 5.21 presents the power delay profile of the RIS-assisted SISO system, clearly distinguishing between direct TX-RX paths (blue) and RIS-reflected paths (red). The direct paths exhibit lower power levels (around -100 to -135 dB) compared to the RIS-reflected paths (approximately -80 dB), demonstrating the significant power enhancement achieved through the RIS. The temporal distribution of multipath components reveals that RIS-reflected signals arrive with delays between 0.95 and 1.35 microseconds, creating a distinct cluster of strong multipath components. Figure 5.22 illustrates the dramatic improvement in channel frequency response when using an optimized 70×70 RIS compared to the system without RIS. The RIS-assisted channel (solid red line) shows a gain improvement of approximately 30 dB across the entire 2.5 GHz frequency band compared to the non-RIS channel (dashed black line). The frequency-selective nature

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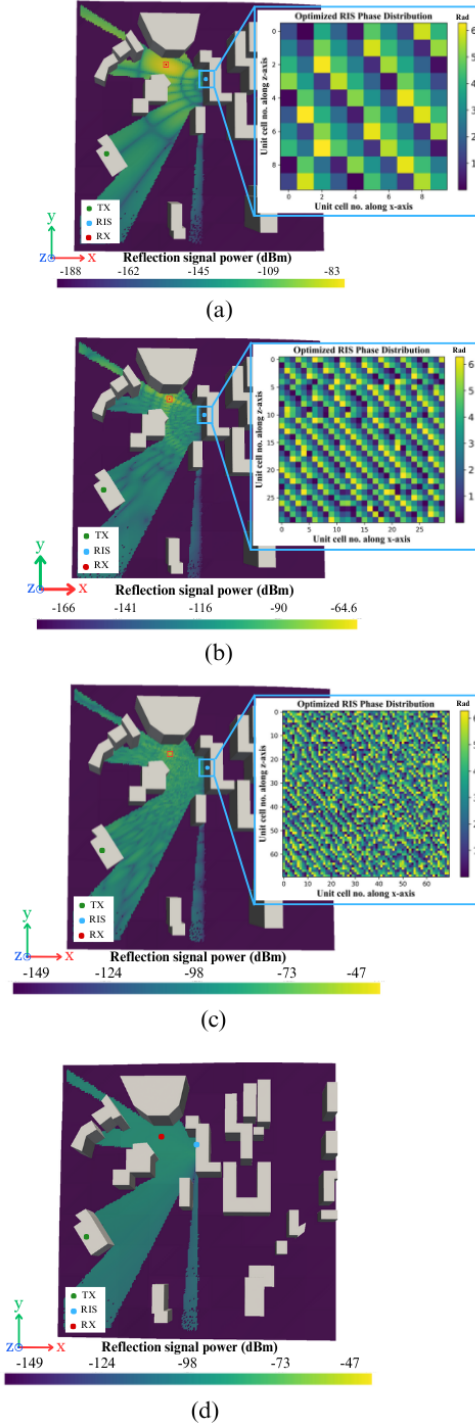


Figure 5.20: RIS reflection signal power distributions and corresponding optimized phase configurations (subsets) for (a) 10×10 , (b) 30×30 , and (c) 70×70 RIS structures. (d) Depicts RIS reflection signal power distribution for a 70×70 RIS with all unit cells being switched off.

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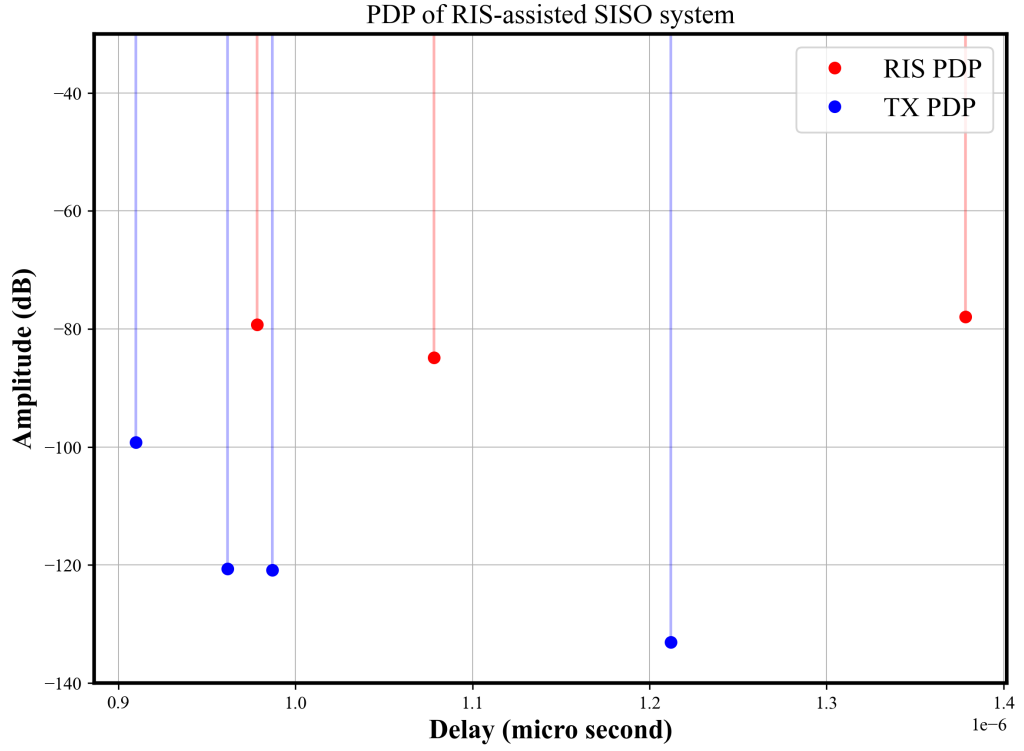


Figure 5.21: Power delay profile of direct (Tx-Rx) rays and RIS-reflected rays for the RIS-assisted SISO system.

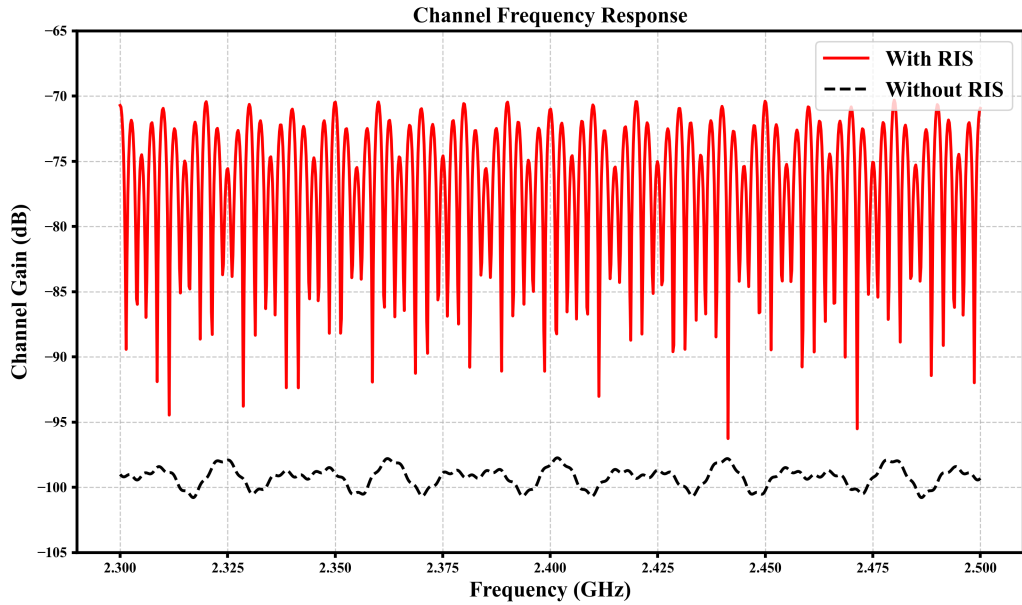


Figure 5.22: Channel frequency response comparison between scenarios with and without the optimized 70×70 RIS across the 2.3-2.5 GHz frequency band.

of the channel is evident in both cases, but the RIS significantly enhances the overall channel gain while maintaining a similar frequency-selective pattern.

5.3 Summary

This chapter has explored ray tracing-based propagation modeling for RIS-assisted wireless systems, highlighting the development and application of two significant simulation frameworks: a MATLAB-based model and the more advanced WiPy-RT simulator.

The MATLAB-based framework introduced an innovative approach to modeling RIS-assisted indoor communication, combining accurate ray tracing techniques with an efficient approximation method. This model demonstrated the ability to significantly reduce computational time while maintaining high accuracy in predicting channel characteristics. The framework's capability to handle complex indoor environments and its flexibility in modeling various RIS configurations make it a valuable tool for researchers and engineers in the field of RIS-enhanced wireless communications.

Building upon this foundation, the chapter introduced WiPy-RT, a high-performance, Python-based ray tracing simulator specifically designed for RIS-enabled wireless environments. WiPy-RT addresses the limitations of MATLAB-based solutions by leveraging the power of open-source libraries and GPU acceleration. WiPy-RT has the ability to handle complex 3D environments, model large-scale RIS arrays, and simulate various wireless propagation phenomena with high accuracy and speed.

Key innovations of WiPy-RT, such as its intelligent ray launching strategy using Gaussian Kernel Density Estimation (KDE), demonstrate the simulator's performance in balancing computational efficiency with accuracy. The benchmark comparison with the WiThRay engine further validated WiPy-RT's superior performance, showcasing its ability to produce more detailed simulations in a fraction of the time required by

5.3 SUMMARY

existing solutions.

Chapter 6

Conclusion and Recommendations for Future Work

6.1 Conclusion

This thesis provided a thorough investigation into RISs and their role in enhancing next-generation wireless communication systems. As we move towards 6G and beyond, RIS technology offers a promising approach to address the growing demands for improved capacity, coverage, and connectivity in wireless networks.

Our research made several contributions to the field of RIS-assisted wireless communications. We began with a comprehensive literature review, establishing a solid foundation in RIS structures, optimization techniques, and RT-based propagation modeling. Building on this, we developed a new dual-polarized RIS unit cell operating at 5.2 GHz, advancing the hardware aspect of RIS technology. We then explored RIS optimization, proposing an efficient method for space-time-coding RIS structures and utilizing genetic algorithms to optimize phase distribution for improved transmission power.

A significant focus of this work was on accurately modeling RIS-assisted wireless propagation. We introduced a new approximation method for RT-based simulations,

improving simulation efficiency. Additionally, we developed WiPy-RT, a Python-based simulation platform, providing researchers with a useful tool for studying RIS-enhanced wireless environments.

By examining RIS technology from hardware design, system optimization, and propagation modeling perspectives, this thesis offers a comprehensive view of the field's challenges and opportunities. Our findings and contributions provide a foundation for future research in RIS-assisted systems, exploring the technology's potential in enhancing wireless connectivity, capacity, and coverage.

As the field progresses towards practical implementations and standardization, the methods, tools, and insights presented in this thesis will serve as resources for researchers and engineers working on future wireless communication systems. Future work may build upon these contributions to refine RIS designs, develop more advanced optimization algorithms, and create more accurate and efficient propagation models.

This thesis has advanced our understanding and capabilities in RIS-assisted wireless communications, contributing to the ongoing efforts to develop effective RIS-enhanced wireless networks for next-generation communication systems.

6.2 Recommendations for Future Work

6.2.1 Limitations

Even though this thesis has made several contributions to the field of RIS-assisted wireless communications, the work involves certain limitations as well, which are:

1. The operating frequency mismatch of the RIS between TE and TM illumination polarizations, which stems from fabrication errors in the RIS unit cell design.
2. Speed restrictions in the voltage change rate for the control circuit board, which arise from code efficiency issues in signal transactions between the computer and

FPGA, FPGA and control board, and DAC configuration settings.

3. The WiPy-RT simulation platform developed in this work does not currently have the capability to simulate MIMO-RIS-assisted communications, limiting its applicability to more complex RIS-assisted scenarios.

6.2.2 Future works

Future work in the field of RIS and RIS-assisted communication can be pursued in various areas. Some potential directions for future research include:

1. Improving the bandwidth of RIS structures by designing wide-band dual-polarized RIS unit cells, which would enhance the versatility of RIS technology across a broader range of frequencies.
2. Focusing on the miniaturization of RIS unit cells to design more compact structures, potentially leading to more efficient and cost-effective RIS implementations.
3. Exploring RIS structures with different geometries beyond planar configurations, such as curved or conformal designs, to adapt to various deployment scenarios and improve performance in complex environments.
4. Developing faster control boards to enhance the real-time reconfigurability of RIS structures, allowing for more dynamic and responsive RIS-assisted communication systems.
5. Investigating the potential of RIS technology in backscatter communications for data transmission, which could lead to novel low-power communication paradigms with enhanced capacity in data transmission.
6. Applying RIS technology to radar systems to enhance detection capabilities, potentially improving the accuracy and range of radar applications.

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7. Extending the propagation modeling of RIS-assisted communications to include MIMO scenarios, providing a more comprehensive understanding of RIS performance in advanced wireless systems.

These future research directions aim to address current limitations and expand the capabilities of RIS technology, potentially leading to more efficient, versatile, and powerful RIS-assisted communication systems.

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