

DESIGN AND DEVELOPMENT OF RIS-AIDED UAV NETWORKS

M.Tech. Thesis

By

Sourosmita Das



**DEPARTMENT OF ELECTRICAL ENGINEERING
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DESIGN AND DEVELOPMENT OF RIS-AIDED UAV NETWORKS

A THESIS

*Submitted in partial fulfillment of the
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Sourosmita Das



**DEPARTMENT OF ELECTRICAL ENGINEERING
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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **DESIGN AND DEVELOPMENT OF RIS-AIDED UAV NETWORKS** in partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DEPARTMENT OF ELECTRICAL ENGINEERING, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the period from July 2025 to June 2026 under the supervision of Dr. Swaminathan Ramabadran, Associate Professor, Dr. Saptarshi Ghosh, Associate Professor, and Dr. Sumit Gautam, Assistant Professor, Department of Electrical Engineering, Indian Institute of Technology Indore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Signature of the student with date

(SOUROSMITA DAS)

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

Signature of Supervisor
of M.Tech Thesis with date
(DR. SWAMINATHAN R.)

22-05-2026
Signature of Supervisor
of M.Tech Thesis with date
(DR. SAPTARSHI GHOSH)

22 May 2026
Signature of Supervisor
of M.Tech Thesis with date
(DR. SUMIT GAUTAM)

SOUROSMITA DAS has successfully given her M.Tech Oral Examination held on **April 27, 2026**

Date: 22/05/26

Date: 22-05-2026

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Abstract

Reconfigurable intelligent surface (RIS)-assisted uncrewed aerial vehicle (UAV) communication systems have recently emerged as a promising solution for improving wireless coverage, beamforming flexibility, and communication reliability in beyond-5G and upcoming 6G wireless networks. By combining programmable electromagnetic wave manipulation with UAV mobility, UAV-mounted RIS platforms can establish adaptive virtual line-of-sight communication links in challenging propagation environments such as obstructed urban regions, disaster-affected areas, and infrastructure-limited scenarios. The integration of RIS with UAV platforms combines adaptive beamforming capability with aerial mobility, enabling improved wireless coverage and virtual line-of-sight communication links in challenging propagation scenarios.

Despite the advantages offered by UAV-assisted RIS systems, practical deployment conditions significantly affect communication reliability and overall system performance. Most existing studies primarily focus on idealized RIS-assisted communication models assuming perfect operating conditions, while the limited works considering practical impairments often analyze them independently. Furthermore, analytical modeling, practical implementation, and experimental characterization of RIS structures are generally investigated separately in existing literature, with relatively little emphasis on developing a unified framework combining both theoretical analysis and practical validation.

Motivated by these challenges, this thesis investigates the performance of UAV-aided RIS communication systems under practical operating conditions over Nakagami- m fading channels. Firstly, an analytical framework is developed for UAV-assisted RIS communication systems considering practical impairments such as UAV orientation fluctuations, RIS phase estimation errors, and imperfect channel state information (CSI). Tractable analytical expressions for key communication performance metrics are derived using moment-based approximation techniques. The analytical results are further validated through extensive

Monte Carlo simulations under both ideal and impaired operating conditions.

Secondly, this thesis focuses on the electromagnetic simulation-based design of RIS structures for practical beam-steering and programmable reflection applications. A square patch-based RIS unit cell is designed and optimized at 5 GHz to obtain the desired reflection phase characteristics. Reflection coefficient magnitude and phase responses are analyzed for different patch dimensions, and a phase-length mapping framework is developed for quantized phase implementation. The extracted phase profiles are further utilized to implement RIS array configurations in MATLAB using generalized Snell's law.

Finally, fabricated RIS prototypes are experimentally characterized using horn antennas and Vector Network Analyzer (VNA)-based measurement setups under controlled operating conditions. The transmission coefficient magnitude is measured for different reflection angles and compared against a reference copper reflector to evaluate the practical beam-steering capability and reflection performance of the proposed RIS structure.

Overall, the work presented in this thesis bridges the gap between idealized UAV-RIS communication models and practical deployment-oriented systems through analytical modeling, electromagnetic simulation, hardware prototyping, and experimental validation. Together, these contributions provide a realistic, end-to-end treatment of UAV-mounted RIS systems for next-generation wireless communication and disaster-management applications.

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Chapter 1

Introduction

1.1 Background

With the rapid evolution of beyond-5G and upcoming 6G wireless networks, coupled with the increasing demand for intelligent and reliable wireless connectivity, the future landscape of wireless communication systems presents significant challenges and opportunities. Modern wireless communication systems are expected to support high data rates, massive device connectivity, ultra-reliable low-latency communication, and seamless coverage in highly dynamic and obstructed environments. However, conventional wireless communication systems suffer from severe propagation losses, blockage effects, and poor coverage in dense urban regions, remote areas, and disaster-affected environments where direct line-of-sight (LoS) communication links are often unavailable. These limitations pose a major challenge in achieving reliable and energy-efficient communication for future wireless networks.

Reconfigurable intelligent surfaces (RIS) have recently emerged as a promising enabling technology for next-generation wireless communication systems due to their capability to dynamically control electromagnetic wave propagation through programmable signal reflections [1, 2]. RIS consists of a large array of passive reflecting elements whose individual phase responses can be adjusted to intelligently reconfigure the wireless environment. Through appropriate phase control, RIS can improve signal strength, enhance communication coverage, mitigate blockage effects, and increase spectral and energy efficiency with relatively low hardware complexity and power consumption compared to conventional active relaying techniques.

In parallel, uncrewed aerial vehicles (UAVs) are increasingly being explored as flexible

aerial communication platforms capable of rapidly establishing wireless connectivity in environments where conventional communication infrastructure is unavailable, damaged, or obstructed [3, 4]. UAV-assisted communication systems are particularly useful in disaster-hit regions, emergency response scenarios, remote areas, and dense urban environments where communication links are severely affected by collapsed infrastructure, blocked propagation paths, or terrain obstacles. UAV-mounted RIS systems leverage the positional flexibility of aerial platforms alongside programmable electromagnetic reflections to extend coverage and create viable communication paths in otherwise obstructed propagation environments [5, 6].

Although UAV-assisted RIS systems provide considerable improvements in wireless coverage and communication reliability, their practical deployment introduces several challenges. In realistic operating environments, UAV hovering instability, environmental disturbances, hardware imperfections, and inaccurate channel estimation can lead to beam misalignment and degradation in overall system performance. In addition, most existing works primarily focus on idealized analytical models or simulation-based studies under simplified assumptions. Practical RIS implementation, beam-steering realization, and experimental validation are still relatively less explored in current literature, particularly under realistic wireless operating conditions.

Bridging the gap between theoretical analysis and practical implementation while addressing these challenges forms the core motivation of this thesis. Through analytical performance modeling, HFSS-based electromagnetic simulation, and experimental prototype characterization, this work develops a practical understanding of the performance of UAV-assisted RIS communication systems under realistic system and hardware impairments.

1.2 Literature Review

Recent advancements in RIS communication systems have demonstrated their potential for enhancing wireless communication reliability, coverage, and spectral efficiency through intelligent manipulation of electromagnetic wave propagation. In [7], the concept of transmission through large intelligent surfaces (LIS) was introduced, where intelligently controlled reflecting surfaces were utilized to improve the received signal quality by appropriately adjusting the phases of incident electromagnetic waves. The work also investigated the pos-

sibility of employing the intelligent surface itself as an access point (AP) for improving communication performance. In [8], the authors presented a comprehensive overview of RIS-assisted wireless communication systems and discussed their ability to manipulate the phase, amplitude, frequency, and polarization characteristics of impinging signals without requiring complex radio-frequency processing operations. The work further highlighted the potential applications and open research challenges of RIS-assisted wireless communication systems.

Several research works have further investigated the analytical performance of RIS-assisted wireless communication systems under different fading environments and network configurations. In [9], the performance of multiple RIS-assisted wireless networks with opportunistic RIS scheduling was investigated over independent non-identically distributed Nakagami- m fading channels. Closed-form expressions for outage probability (OP) and average symbol error probability (ASEP) were derived along with asymptotic analysis for diversity order and coding gain. Similarly, the work presented in [10] analyzed a cooperative communication system consisting of multiple RIS-assisted links and direct transmission links over Nakagami- m fading channels. The impacts of the number of RISs, reflecting elements, and fading parameters on system performance were thoroughly investigated.

UAV-assisted RIS communication systems have also attracted significant research attention due to their capability to provide flexible wireless coverage in obstructed and infrastructure-limited environments. In [11], the integration of UAVs with relay-assisted RIS systems was investigated under Nakagami- m fading channels using a selection combining approach. The obtained results demonstrated improved communication reliability in dynamic wireless environments. In [12], the performance of an integrated UAV-RIS relaying system was investigated considering different transmission modes including UAV-only, RIS-only, and integrated UAV-RIS communication. Closed-form expressions for key performance metrics were derived, and several optimization techniques were proposed for determining the optimal UAV altitude and number of RIS elements.

Recently, practical impairments in UAV-assisted RIS communication systems have garnered considerable research attention due to their impact on communication reliability and overall system performance. RIS phase uncertainties have also been investigated extensively in the literature. In [13], the OP performance of RIS-assisted wireless networks was analyzed by modeling RIS phase errors using the von Mises distribution under line-of-sight

channels to characterize the impact of phase uncertainty on system reliability. Furthermore, practical implementation constraints associated with discrete RIS phase shifts were investigated in [14], where beamforming optimization for RIS-assisted wireless communication systems with finite-resolution phase shifters was studied. The work demonstrated that practical discrete-phase RIS configurations can still achieve significant beamforming gains with acceptable performance degradation compared to ideal continuous phase-shift systems.

The impact of UAV hovering instability and angular fluctuations on UAV-mounted RIS systems has also been investigated in the existing literature. In [15], a comprehensive framework for UAV-mounted RIS systems under random hovering fluctuations was developed by considering the three-dimensional radiation pattern of the RIS. The obtained results demonstrated that UAV instability can significantly affect the performance of aerial RIS systems. Similarly, the work presented in [16] investigated an aerial RIS-assisted secure simultaneous wireless information and power transfer (SWIPT) system under UAV jitter conditions. The effects of UAV angular instability were modeled through channel estimation errors, and robust optimization techniques were proposed for improving the average secrecy rate under practical operating conditions. In [17], analytical channel models were derived for UAV-assisted millimeter-wave communication systems considering random UAV hovering fluctuations and antenna directivity mismatch. The results showed the significant impact of UAV instability and antenna beam directivity on communication reliability.

Imperfect channel state information (CSI) has further been identified as another important practical impairment affecting RIS-assisted communication systems. In [18], the impact of imperfect CSI on RIS-assisted wireless communication systems was investigated through the derivation of closed-form expressions for OP, average bit error rate (BER), and average capacity. The obtained results demonstrated that inaccurate CSI can significantly degrade communication performance and lead to diversity loss at high signal-to-noise ratio (SNR) regimes. Furthermore, the work presented in [19] analyzed RIS-assisted spatial shift keying systems under imperfect CSI and discrete RIS phase-shift conditions. Analytical expressions for average bit error probability were derived considering channel estimation errors and practical RIS implementation constraints, highlighting the effect of imperfect CSI on overall system reliability.

Significant research attention has also been directed toward the practical realization and experimental validation of RIS structures for beam steering and wavefront manipulation ap-

plications. Frequency selective surfaces (FSS) and metasurfaces have emerged as important technologies for realistic RIS implementation due to their capability to manipulate electromagnetic wave propagation using engineered periodic structures. In [20], various FSS structures, fabrication methods, and experimental studies were reviewed for electromagnetic wave filtering and reflection-control applications.

Phase-gradient metasurfaces have also been investigated for anomalous reflection and beam-steering applications. In [21], a square patch-based phase-gradient metasurface was designed using different quantized phase configurations. The results showed improved beamforming performance for higher-bit phase quantization structures. Practical RIS operation under varying incidence conditions was investigated in [22], where an angle-insensitive 3-bit RIS structure was proposed to maintain stable phase responses under oblique electromagnetic wave incidence. Simulation and experimental results verified the effectiveness of the proposed structure under realistic operating conditions.

Furthermore, digitally coded metasurfaces for anomalous reflection and beam steering were investigated in [23]. The proposed 1-bit and 2-bit coded metasurfaces were validated using electromagnetic simulations and fabricated prototype measurements, demonstrating improved directional beam control for higher-bit coding structures.

1.3 Motivations and Contributions

The primary objective of this thesis is to bridge theoretical UAV-assisted RIS communication models with practical implementation-oriented systems by combining analytical modeling, electromagnetic simulation, and experimental validation within a unified framework.

1.3.1 Chapter 2

The motivations behind the work in Chapter 2 are summarized as follows:

- Conventional wireless systems suffer from severe blockage effects and unreliable communication links in dense urban environments, disaster-hit regions, and infrastructure-limited scenarios where direct LoS communication is often unavailable.
- UAV-assisted RIS systems provide a promising solution for establishing virtual LoS communication links. However, realistic deployment conditions significantly affect

the communication reliability and overall system performance.

- Most existing RIS-assisted communication works primarily focus on idealized system models assuming perfect operating conditions. Although several existing studies investigate practical impairments, these impairments are typically analyzed individually rather than under a unified practical framework.
- The combined impact of system and channel non-idealities on UAV-mounted RIS communication systems under realistic operating conditions still remains insufficiently explored.

The contributions of the work in Chapter 2 are summarized as follows:

- An analytical framework for UAV-aided RIS communication systems operating over Nakagami- m fading channels is developed under practical impairments.
- Impairments including UAV orientation fluctuations, RIS phase uncertainty, and imperfect CSI are incorporated into the proposed system model.
- UAV angular instability is modeled through stochastic angular fluctuations affecting the RIS radiation pattern, while RIS phase uncertainty is modeled using the von Mises distribution. Imperfect CSI is also incorporated to evaluate the degradation in system performance caused by practical channel estimation errors.
- Tractable analytical expressions for OP, average symbol error rate (ASER), and ergodic capacity (EC) are derived using moment-based approximation techniques.
- The joint impact of UAV instability, RIS phase errors, imperfect CSI, and various system parameters on communication performance is thoroughly investigated.
- Monte Carlo simulations are utilized to validate the correctness of the derived analytical expressions.

1.3.2 Chapter 3

The motivations behind the work in Chapter 3 are summarized as follows:

- Most existing RIS-assisted works investigate analytical modeling, RIS design, and experimental validation independently, with relatively little emphasis on a unified framework combining theoretical analysis and realistic implementation.
- Practical RIS-assisted communication systems require accurate electromagnetic characterization of unit cells and reflection phase responses for effective beam-steering implementation.
- Quantized phase control and programmable beam steering are important for realizing practical and deployable RIS-assisted communication systems.
- Therefore, electromagnetic simulation-based RIS design and phase characterization become essential for validating the feasibility of realistic UAV-assisted RIS deployments.

The contributions of the work in Chapter 3 are summarized as follows:

- A square patch-based RIS unit-cell structure is designed and optimized using Ansys HFSS for operation at 5 GHz.
- Reflection coefficient analysis and phase characterization of the proposed RIS unit-cell are carried out using full-wave electromagnetic simulations.
- A phase-length mapping framework is developed for quantized RIS phase implementations.
- The extracted phase profiles are implemented in MATLAB using generalized Snell's law for RIS beam-steering realization.

1.3.3 Chapter 4

The motivations behind the work in Chapter 4 are summarized as follows:

- Existing RIS studies generally focus on analytical modeling and numerical simulations, while practical experimental characterization, hardware testbeds, and measurement-based validation remain comparatively limited.
- Experimental verification of UAV-RIS reflection characteristics and beam-steering capability is essential for evaluating realistic deployment feasibility.

- Practical measurement setups help bridge the gap between idealized analytical models and real-world UAV-mounted RIS systems.

The contributions of the work in Chapter 4 are summarized as follows:

- Fabricated RIS prototypes are experimentally characterized using two horn antennas and Vector Network Analyzer (VNA)-based measurement setups.
- Reflection performance and beam-steering characteristics of the fabricated RIS structures are experimentally evaluated under different operating conditions.
- Measured transmission coefficient ($|S_{21}|$) responses of the fabricated RIS are compared with a reference copper reflector to evaluate reflection performance and directional beam-steering behavior.
- The obtained measurement results demonstrate the practical feasibility of RIS-assisted directional reflection and beam-steering operation.

1.4 Organization of the Thesis

The rest of this thesis is organized as follows: In Chapter 2, the analytical modeling and performance analysis of UAV-assisted RIS communication systems under practical impairments is presented. In Chapter 3, electromagnetic simulation-based RIS design, phase characterization, and beam-steering analysis are discussed. Further, Chapter 4 presents the experimental characterization and practical validation of fabricated RIS prototypes using VNA-based measurement setups. Finally, Chapter 5 concludes the thesis and outlines possible future research directions related to realistic UAV-assisted RIS communication systems.

Chapter 2

Analytical Modeling under Practical Impairments

2.1 Introduction

While UAV-RIS integration offers a flexible path to reliable connectivity in obstructed environments, the analytical treatment of such systems rarely reflects how they behave under realistic operating conditions. UAV orientation fluctuations, phase uncertainty at the RIS, and imperfect channel knowledge each introduce performance degradation that idealized models fail to capture.

In this chapter, we investigate the performance of a UAV-assisted RIS communication system under practical impairment conditions including stochastic UAV orientation deviations, RIS phase estimation errors, and imperfect CSI over Nakagami- m fading channels. The UAV orientation fluctuations are modeled through random angular deviations affecting the 3D RIS radiation pattern, and phase uncertainties are characterized using the von Mises distribution. Practical channel estimation errors are also incorporated to evaluate the degradation in performance metrics. Furthermore, the combined impact of these impairments on communication reliability is analytically investigated. Specifically, tractable analytical expressions for OP, ASER, and EC are derived using Gamma approximation and quadrature-based techniques. Moreover, numerical results along with insightful performance discussions are presented to analyze the effects of various practical system parameters on the considered UAV-assisted RIS communication framework. Finally, the derived analytical results are verified through Monte Carlo simulations.

2.2 Organisation of Chapter

The remaining sections of this chapter are organized as follows: Section 2.3 presents the system model for the proposed UAV-assisted RIS communication framework under practical impairment conditions. The UAV orientation fluctuation model, RIS phase error model, imperfect CSI model, and the combined channel model are also discussed in this section. In Section 2.4, analytical expressions for OP, ASER and EC are derived. Further, Section 2.5 presents the numerical results and performance discussions obtained from the analytical and simulation-based analysis. Finally, concluding remarks are presented in Section 2.6.

2.3 System model

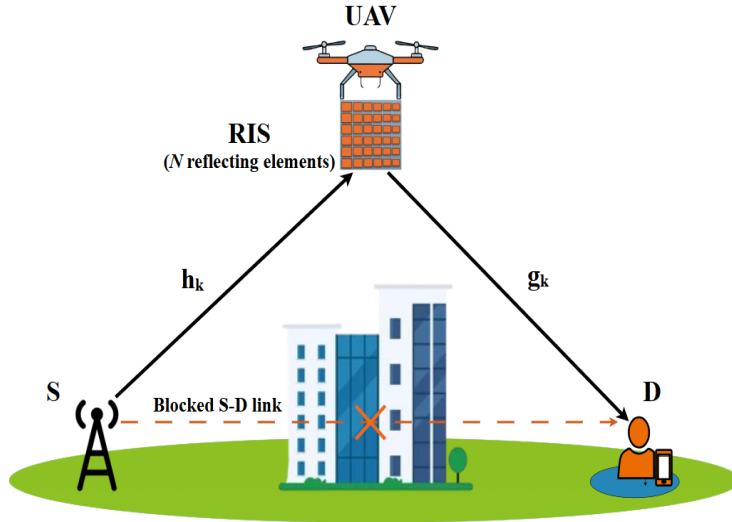


Figure 2.1: System model of RIS-Aided UAV communication system.

We consider a UAV-assisted RIS communication system as shown in Fig. 2.1, where a UAV-mounted RIS assists communication between a ground-based source node (S) and destination node (D). Due to blockage caused by obstacles such as buildings, terrain, or damaged infrastructure, the direct LoS communication link between the S and D is assumed to be unavailable. Therefore, communication is established through the UAV-mounted RIS, which reflects the incident signal from the source toward the destination by appropriately configuring the phase shifts of its reflecting elements.

The UAV-mounted RIS is deployed at an altitude h and consists of N passive reflecting elements. The S and D are assumed to be located on the ground plane, while the UAV-RIS

provides flexible aerial positioning for establishing virtual LoS communication links. The small-scale fading of both the source-to-RIS and RIS-to-destination links is modeled using Nakagami- m fading distribution.

In practical UAV-assisted RIS communication systems, the UAV platform may experience random hovering fluctuations due to environmental disturbances and mechanical vibrations, resulting in stochastic orientation deviations that affect the RIS radiation pattern and beam alignment. Furthermore, RIS phase adjustments may suffer from practical phase estimation errors and imperfect CSI, leading to degradation in coherent signal combining performance. Therefore, the considered system model incorporates UAV orientation fluctuations, RIS phase uncertainties, and imperfect CSI to provide a realistic performance characterization of UAV-assisted RIS communication systems under practical operating conditions.

2.3.1 UAV-Assisted RIS Communication Model

The positions of the S and D nodes are represented by $\mathbf{v}_s = (x_s, y_s, 0)$ and $\mathbf{v}_d = (x_d, y_d, 0)$, respectively, in Cartesian coordinates. Since both nodes are located on the ground plane, their altitudes are assumed to be zero. The UAV-mounted RIS is deployed at an altitude h with coordinates $\mathbf{v}_u = (x_u, y_u, h)$. The corresponding horizontal projections are denoted as $\mathbf{w}_s = (x_s, y_s)$, $\mathbf{w}_d = (x_d, y_d)$, and $\mathbf{w}_u = (x_u, y_u)$.

The elevation angles corresponding to the source-to-UAV and UAV-to-destination links are expressed as

$$\theta_u = \tan^{-1} \left(\frac{h}{|\mathbf{w}_u - \mathbf{w}_s|} \right), \quad (2.1)$$

$$\theta_d = \tan^{-1} \left(\frac{h}{|\mathbf{w}_u - \mathbf{w}_d|} \right). \quad (2.2)$$

The probability of LoS communication for link i , where $i \in \{u, d\}$, is modeled as

$$p_L(\theta_i) = (1 + l_i \exp(-n_i(\theta_i - l_i)))^{-1}, \quad (2.3)$$

where l_i and n_i are environment-dependent parameters [24]. The path-loss exponent is further modeled as

$$\alpha(\theta_i) = p_L(\theta_i)k_i + w_i, \quad (2.4)$$

where k_i and w_i are constants associated with the considered propagation environment [25].

The small-scale fading between the source and the RIS, as well as between the RIS and the destination, is modeled using Nakagami- m fading distribution. Let $\bar{h}_k$ denote the channel

coefficient between the source and the k^{th} RIS element, and $\bar{g}_k$ denote the channel coefficient between the k^{th} RIS element and the destination. These channel coefficients are expressed as

$$\bar{h}_k = h_k e^{j\phi_u}, \quad \bar{g}_k = g_k e^{j\phi_d}, \quad (2.5)$$

where h_k and g_k represent the Nakagami- m distributed channel amplitudes, while ϕ_u and ϕ_d denote the corresponding channel phases.

Accordingly, the received signal at the destination through the UAV-mounted RIS can be expressed as

$$y = \sum_{k=1}^N \sqrt{A p_u d_u^{-\alpha(\theta_u)}} \bar{h}_k e^{j\phi_k} \sqrt{A d_d^{-\alpha(\theta_d)}} \bar{g}_k x + w, \quad (2.6)$$

where x denotes the transmitted signal, p_u represents the transmit power of the source node, A denotes system-dependent constants, d_u and d_d represent the source-to-RIS and RIS-to-destination link distances, respectively, and w is additive white Gaussian noise (AWGN) with variance N_0 .

The instantaneous SNR of the considered UAV-assisted RIS communication system is therefore given as

$$\gamma = \frac{A^2 p_u}{N_0} \left| \sum_{k=1}^N d_u^{-\frac{\alpha(\theta_u)}{2}} d_d^{-\frac{\alpha(\theta_d)}{2}} h_k g_k e^{j(\phi_u + \phi_d + \phi_k)} \right|^2. \quad (2.7)$$

Under ideal RIS phase adjustment, the RIS controller compensates the cascaded channel phases by selecting

$$\phi_k = -(\phi_u + \phi_d), \quad (2.8)$$

which enables coherent signal combining at the destination node. Therefore, the effective cascaded channel corresponding to the k -th RIS reflecting element can be represented as

$$z_k = h_k g_k. \quad (2.9)$$

As a result, considering $\gamma_0 = \frac{A^2 p_u}{N_0} d_u^{-\alpha(\theta_u)} d_d^{-\alpha(\theta_d)}$, the instantaneous SNR simplifies to

$$\gamma = \gamma_0 \left| \sum_{k=1}^N z_k \right|^2. \quad (2.10)$$

By utilizing the distribution of the product of two independent Nakagami- m random variables, the PDF of z_k is expressed as [9]

$$f_{z_k}(x) = \frac{4(\Theta_{k,1} \Theta_{k,2})^{m_{k,1} + m_{k,2}}}{\Gamma(m_{k,1}) \Gamma(m_{k,2})} x^{m_{k,1} + m_{k,2} - 1} K_{m_{k,1} - m_{k,2}}(2\Theta_{k,1} \Theta_{k,2} x), \quad (2.11)$$

where

$$\Theta_{k,j} = \sqrt{\frac{m_{k,j}}{\Omega_{k,j}}}, \quad j \in \{1, 2\}, \quad (2.12)$$

$\Gamma(\cdot)$ denotes the Gamma function, and $K_\nu(\cdot)$ represents the modified Bessel function of the second kind with order ν .

Further, the r -th moment of z_k is obtained as

$$\mathbb{E}[z_k^r] = \frac{\Gamma(m_{k,1} + \frac{r}{2}) \Gamma(m_{k,2} + \frac{r}{2})}{(\Theta_{k,1} \Theta_{k,2})^r \Gamma(m_{k,1}) \Gamma(m_{k,2})}. \quad (2.13)$$

2.3.2 UAV Orientation Fluctuation Model

In practical UAV-mounted RIS communication systems, maintaining perfectly stable UAV hovering conditions is challenging due to environmental disturbances such as wind turbulence, mechanical vibrations, and random aerial platform motion. These effects introduce random angular fluctuations in the orientation of the UAV-mounted RIS, resulting in beam misalignment and degradation in the reflected signal power. Therefore, incorporating UAV orientation instability becomes essential for realistic performance analysis of UAV-assisted RIS communication systems.

The UAV-mounted RIS is assumed to experience random angular fluctuations along the horizontal and vertical directions. Let ϵ_x and ϵ_y denote the angular deviations corresponding to the x - and y -axes, respectively. The UAV orientation fluctuations are modeled as zero-mean Gaussian random variables given by

$$\epsilon_x \sim \mathcal{N}(0, \sigma_\theta^2), \quad (2.14)$$

$$\epsilon_y \sim \mathcal{N}(0, \sigma_\theta^2), \quad (2.15)$$

where σ_θ^2 represents the variance associated with UAV hovering instability.

The random angular deviations affect both the RIS array factor and the individual RIS element radiation pattern. Accordingly, the normalized RIS array gain is expressed as [15]

$$G_a(Z_x, Z_y) = \left| \frac{\sin\left(\frac{N_q \pi}{2} Z_x\right)}{N_q \sin\left(\frac{\pi}{2} Z_x\right)} \right|^2 \left| \frac{\sin\left(\frac{N_q \pi}{2} Z_y\right)}{N_q \sin\left(\frac{\pi}{2} Z_y\right)} \right|^2, \quad (2.16)$$

where $N_q = \sqrt{N}$ denotes the dimension of the square RIS array containing N reflecting elements, while Z_x and Z_y represent the normalized angular deviations caused by UAV orientation fluctuations.

Furthermore, the radiation response of the RIS element is modeled using a cosine-based radiation pattern as [15]

$$G_e = \cos^3(\theta_t + \varepsilon_{\theta_t}) \cos^3(\theta_r + \varepsilon_{\theta_r}), \quad (2.17)$$

where θ_t and θ_r denote the elevation angles corresponding to the source-to-UAV and UAV-to-destination links, respectively, while ε_{θ_t} and ε_{θ_r} represent the corresponding angular perturbations introduced by UAV hovering instability.

Therefore, the overall RIS radiation gain under UAV orientation fluctuations can be expressed as

$$G = G_a G_e. \quad (2.18)$$

Since obtaining an exact closed-form PDF of the RIS radiation gain is mathematically intractable, a discrete sectorized approximation is employed for analytical tractability. Accordingly, the PDF of the RIS gain is approximated as

$$f_G(G) = \sum_{i=1}^J p^{(i)} \delta(G - q^{(i)}), \quad (2.19)$$

where $q^{(i)}$ denotes the i -th discrete RIS gain level, $p^{(i)}$ represents its corresponding probability, J is the total number of sectors, and $\delta(\cdot)$ denotes the Dirac delta function [15].

Incorporating the effect of UAV orientation fluctuations, the instantaneous received SNR of the UAV-assisted RIS communication system can be expressed as

$$\gamma = \gamma_0 G \left| \sum_{k=1}^N z_k \right|^2, \quad (2.20)$$

It can therefore be observed that increasing UAV orientation fluctuations reduce the effective RIS radiation gain.

2.3.3 RIS Phase Error Model

In the previous subsection, ideal RIS phase compensation was assumed, where the RIS controller perfectly aligns the reflected signals to achieve coherent combining at the destination node. However, practical RIS implementations suffer from hardware impairments or limited phase-shifter resolution, which introduce phase adjustment errors. These imperfections result in deviations between the optimal RIS phase configuration and the actual applied phase shifts, thereby degrading the achievable system performance.

Accordingly, the practical RIS phase corresponding to the k -th reflecting element is modeled as

$$\phi_k = \phi_k^{\text{opt}} + \theta_{\text{err}}, \quad (2.21)$$

where ϕ_k^{opt} denotes the optimal RIS phase required for coherent signal combining, while θ_{err} represents the RIS phase estimation error.

Under ideal RIS operation, the optimal phase is selected as

$$\phi_k^{\text{opt}} = -(\phi_u + \phi_d), \quad (2.22)$$

which compensates the cascaded channel phases associated with the source-to-RIS and RIS-to-destination links.

The RIS phase estimation error is modeled using the von Mises distribution due to its suitability for circular random variables and phase uncertainty modeling. Therefore, the PDF of θ_{err} is expressed as

$$f_{\theta_{\text{err}}}(x) = \frac{e^{\kappa \cos(x)}}{2\pi I_0(\kappa)}, \quad (2.23)$$

where κ denotes the concentration parameter controlling the severity of phase errors, and $I_0(\cdot)$ represents the modified Bessel function of the first kind and zeroth order [13].

The corresponding trigonometric moments of the von Mises distributed phase error are given by

$$\varphi_p = \mathbb{E} \left[e^{jp\theta_{\text{err}}} \right] = \frac{I_p(\kappa)}{I_0(\kappa)}, \quad (2.24)$$

where $I_p(\cdot)$ denotes the modified Bessel function of the first kind with order p .

By incorporating RIS phase estimation errors into the UAV-assisted RIS communication model, the instantaneous received SNR can be expressed as

$$\gamma = \gamma_0 G \left| \sum_{k=1}^N z_k e^{j\theta_{\text{err}}} \right|^2, \quad (2.25)$$

where G denotes the effective RIS radiation gain under UAV orientation fluctuations.

Defining

$$v = \sum_{k=1}^N z_k e^{j\theta_{\text{err}}}, \quad (2.26)$$

the instantaneous SNR can be rewritten as

$$\gamma = \gamma_0 G |v|^2. \quad (2.27)$$

Further, by defining

$$U = |v|^2, \quad (2.28)$$

the instantaneous SNR simplifies to

$$\gamma = \gamma_0 GU. \quad (2.29)$$

It can be observed that RIS phase estimation errors reduce the coherent signal combining capability of the RIS.

2.3.4 Imperfect CSI Model

In the previous subsections, the effects of UAV orientation fluctuations and RIS phase estimation errors were incorporated into the UAV-assisted RIS communication framework. However, practical RIS-assisted communication systems also suffer from imperfect CSI due to channel estimation errors. Consequently, inaccurate channel estimation degrades the coherent beamforming capability of the RIS-assisted communication system and reduces the achievable communication reliability.

Accordingly, the estimated channel coefficients corresponding to the source-to-RIS and RIS-to-destination links are modeled as

$$\hat{h}_k = \rho_h h_k + \sqrt{1 - \rho_h^2} e_{h_k}, \quad (2.30)$$

$$\hat{g}_k = \rho_g g_k + \sqrt{1 - \rho_g^2} e_{g_k}, \quad (2.31)$$

where h_k and g_k denote the actual channel coefficients, $\hat{h}_k$ and $\hat{g}_k$ represent the estimated channel coefficients, ρ_h and ρ_g denote the channel estimation correlation coefficients satisfying $0 \leq \rho_h, \rho_g \leq 1$, while e_{h_k} and e_{g_k} represent the corresponding channel estimation error components [18].

It can therefore be observed that larger values of ρ_h and ρ_g correspond to more accurate CSI estimation. The channel estimation error components e_{h_k} and e_{g_k} are modeled as independent Gaussian random variables with zero mean and variances determined by the corresponding channel estimation accuracy.

By incorporating imperfect CSI together with RIS phase estimation errors, the effective cascaded channel corresponding to the k -th RIS reflecting element can be expressed as

$$\hat{z}_k = \hat{h}_k \hat{g}_k e^{j\theta_{\text{err}}}, \quad (2.32)$$

where θ_{err} denotes the RIS phase estimation error modeled using the von Mises distribution.

Accordingly, the equivalent received signal component is represented as

$$v = \sum_{k=1}^N \hat{z}_k. \quad (2.33)$$

Therefore, by incorporating UAV orientation fluctuations, RIS phase errors, and imperfect CSI, the instantaneous received SNR can be expressed as

$$\gamma = \gamma_0 G |v|^2, \quad (2.34)$$

where G denotes the effective RIS radiation gain under UAV orientation fluctuations.

The first- and second-order trigonometric moments of the RIS phase error are utilized in deriving the statistical moments of the equivalent cascaded channel coefficient and are expressed as

$$\rho_1 = \frac{I_1(\kappa)}{I_0(\kappa)}, \quad (2.35)$$

$$\rho_2 = \frac{I_2(\kappa)}{I_0(\kappa)}, \quad (2.36)$$

where $I_1(\cdot)$ and $I_2(\cdot)$ denote the modified Bessel functions of the first kind with orders one and two, respectively.

2.3.5 Combined Channel Model

In the previous subsections, the effects of UAV orientation fluctuations, RIS phase estimation errors, and imperfect CSI were incorporated into the UAV-assisted RIS communication framework. By jointly considering these practical impairments, the equivalent cascaded channel corresponding to the k -th RIS reflecting element is represented as

$$\hat{z}_k = \hat{h}_k \hat{g}_k e^{j\theta_{\text{err}}}, \quad (2.37)$$

where $\hat{h}_k$ and $\hat{g}_k$ denote the imperfectly estimated channel coefficients corresponding to the source-to-RIS and RIS-to-destination links, respectively, while θ_{err} represents the RIS phase estimation error modeled using the von Mises distribution.

Accordingly, the equivalent cascaded channel coefficient is expressed as

$$v = \sum_{k=1}^N \hat{z}_k. \quad (2.38)$$

Further, defining $U = |v|^2$, the instantaneous received SNR of the considered UAV-assisted RIS communication system can be expressed as

$$\gamma = \gamma_0 G U, \quad (2.39)$$

where

$$\gamma_0 = \frac{A^2 p_u}{N_0} d_u^{-\alpha(\theta_u)} d_d^{-\alpha(\theta_d)}, \quad (2.40)$$

and G denotes the effective RIS radiation gain under UAV orientation fluctuations.

Since the equivalent cascaded channel coefficient v represents the sum of independent random variables, its statistical distribution can be accurately approximated using the first term of a Laguerre series expansion, resulting in a Gamma distribution. Accordingly, the PDF of v is approximated as

$$f_v(x) \approx \frac{1}{\Gamma(a_k) b_k^{a_k}} x^{a_k-1} \exp\left(-\frac{x}{b_k}\right), \quad (2.41)$$

where the corresponding Gamma approximation parameters are expressed as

$$a_k = \frac{(\mathbb{E}[v])^2}{\text{Var}(v)}, \quad (2.42)$$

$$b_k = \frac{\text{Var}(v)}{\mathbb{E}[v]}. \quad (2.43)$$

Using the statistical properties of Nakagami- m fading and the trigonometric moments of the von Mises distributed phase error, the mean of the equivalent cascaded channel coefficient is obtained as

$$\mathbb{E}[v] = N \mu_1 \rho_1, \quad (2.44)$$

where μ_1 denotes the first-order moment of the equivalent cascaded channel coefficient and ρ_1 denotes the first-order trigonometric moment of the RIS phase estimation error.

Similarly, the variance of v is expressed as

$$\text{Var}(v) = N \mu_2 \left(\frac{1 + \rho_2}{2} \right) + N(N-1) \mu_1^2 \rho_1^2 - (N \mu_1 \rho_1)^2. \quad (2.45)$$

where μ_2 denotes the second-order moment of the equivalent cascaded channel coefficient.

The CDF of v is therefore obtained as

$$F_v(v) = \frac{\gamma\left(a_k, \frac{v}{b_k}\right)}{\Gamma(a_k)}, \quad (2.46)$$

where $\gamma(\cdot, \cdot)$ denotes the lower incomplete Gamma function and $\Gamma(\cdot)$ represents the complete Gamma function.

Using transformation of random variables, the conditional PDF of the instantaneous SNR conditioned on the RIS radiation gain G can therefore be expressed as

$$f_{\gamma|G}(\gamma|G) = \frac{1}{2\Gamma(a_k)b_k^{a_k}}(\gamma_0 G)^{-\frac{a_k}{2}}\gamma^{\frac{a_k}{2}-1}\exp\left(-\frac{\sqrt{\gamma/(\gamma_0 G)}}{b_k}\right). \quad (2.47)$$

Accordingly, the conditional CDF of the instantaneous SNR can be expressed as

$$F_{\gamma|G}(\gamma|G) = F_v\left(\sqrt{\frac{\gamma}{\gamma_0 G}}\right) = \frac{\gamma\left(a_k, \frac{\sqrt{\gamma/(\gamma_0 G)}}{b_k}\right)}{\Gamma(a_k)}. \quad (2.48)$$

Since the RIS radiation gain G is also a random variable due to UAV orientation fluctuations, the unconditional CDF of the instantaneous SNR is obtained by averaging over the distribution of G as

$$F_{\gamma}(\gamma) = \mathbb{E}_G [F_{\gamma|G}(\gamma|G)]. \quad (2.49)$$

Using the discrete sectorized approximation of the RIS radiation gain, the unconditional CDF of the instantaneous SNR is finally expressed as

$$F_{\gamma}(\gamma) = \sum_{i=1}^J p^{(i)} F_v\left(\sqrt{\frac{\gamma}{\gamma_0 q^{(i)}}}\right), \quad (2.50)$$

where $q^{(i)}$ and $p^{(i)}$ denote the discrete RIS gain levels and their corresponding probabilities, respectively.

2.4 Performance Analysis

In this section, the performance of the considered UAV-assisted RIS communication system is analyzed in terms of OP, ASER and EC under the combined impact of UAV orientation fluctuations, RIS phase estimation errors, and imperfect CSI.

2.4.1 Outage Probability Analysis

OP is defined as the probability that the instantaneous received SNR falls below a predefined threshold value γ_{th} . Mathematically, the OP is expressed as

$$P_{\text{out}} = \Pr(\gamma < \gamma_{\text{th}}). \quad (2.51)$$

Using the CDF of the instantaneous SNR derived in the previous subsection, the OP can be written as

$$P_{\text{out}} = F_{\gamma}(\gamma_{\text{th}}). \quad (2.52)$$

Substituting the unconditional CDF expression of the instantaneous SNR yields

$$P_{\text{out}} = \sum_{i=1}^J p^{(i)} F_{\gamma} \left(\sqrt{\frac{\gamma_{\text{th}}}{\gamma_0 q^{(i)}}} \right), \quad (2.53)$$

where $q^{(i)}$ and $p^{(i)}$ denote the discrete RIS radiation gain levels and their corresponding probabilities, respectively.

Further, substituting the Gamma-distributed CDF of the equivalent cascaded channel coefficient ν , the OP is finally obtained as

$$P_{\text{out}} = \sum_{i=1}^J p^{(i)} \frac{\gamma \left(a_k, \frac{\sqrt{\gamma_{\text{th}}/(\gamma_0 q^{(i)})}}{b_k} \right)}{\Gamma(a_k)}, \quad (2.54)$$

It can therefore be observed that UAV orientation fluctuations, RIS phase estimation errors, and imperfect CSI collectively increase the OP by reducing the effective coherent combining gain of the RIS-assisted communication system.

2.4.2 Average Symbol Error Rate Analysis

The ASER of the considered UAV-assisted RIS communication system is derived using the CDF of the instantaneous received SNR. For M -ary phase shift keying (M-PSK) modulation, the ASER is expressed as

$$P_{\text{SER}} = \frac{p\sqrt{q}}{2\sqrt{2\pi}} \int_0^{\infty} F_{\gamma}(\gamma) \gamma^{-1/2} \exp\left(-\frac{q\gamma}{2}\right) d\gamma, \quad (2.55)$$

where p and q are modulation-dependent constants [11].

Substituting the unconditional CDF of the instantaneous SNR into the above expression yields

$$P_{\text{SER}} = \frac{p\sqrt{q}}{2\sqrt{2\pi}} \sum_{i=1}^J p^{(i)} \int_0^{\infty} F_{\gamma} \left(\sqrt{\frac{\gamma}{\gamma_0 q^{(i)}}} \right) \gamma^{-1/2} \exp\left(-\frac{q\gamma}{2}\right) d\gamma. \quad (2.56)$$

Since the above integral does not admit a tractable closed-form solution, the n -point Gauss–Laguerre quadrature method is employed for efficient numerical approximation. Accordingly, the ASER expression can be approximated as

$$P_{\text{SER}} \approx \frac{p\sqrt{q}}{2\sqrt{2\pi}} \sum_{i=1}^J p^{(i)} \sum_{l=1}^n W_l F_{\gamma} \left(\sqrt{\frac{\phi_l}{\gamma_0 q^{(i)}}} \right), \quad (2.57)$$

where W_l and ϕ_l denote the Gauss–Laguerre weights and nodes, respectively.

The obtained ASER expression demonstrates that increasing UAV orientation fluctuations, RIS phase uncertainty, and CSI estimation errors degrade the symbol detection reliability of the UAV-assisted RIS communication system.

2.4.3 Ergodic Capacity Analysis

EC represents the average achievable transmission rate over fading channels and is defined as

$$C = \mathbb{E} [\log_2(1 + \gamma)]. \quad (2.58)$$

Using the CDF-based representation, the EC can be expressed as

$$C = \frac{1}{\ln(2)} \int_0^\infty \frac{1 - F_\gamma(\gamma)}{1 + \gamma} d\gamma. \quad (2.59)$$

Substituting the unconditional CDF of the instantaneous SNR yields

$$C = \frac{1}{\ln(2)} \sum_{i=1}^J p^{(i)} \int_0^\infty \frac{1 - F_v\left(\sqrt{\frac{\gamma}{\gamma_0 q^{(i)}}}\right)}{1 + \gamma} d\gamma. \quad (2.60)$$

Since the above integral is mathematically intractable, the Gauss–Laguerre quadrature method is utilized for numerical evaluation. Accordingly, the EC can be approximated as

$$C \approx \frac{1}{\ln(2)} \sum_{i=1}^J p^{(i)} \sum_{l=1}^n W_l e^{\phi_l} \frac{1 - F_v\left(\sqrt{\frac{\phi_l}{\gamma_0 q^{(i)}}}\right)}{1 + \phi_l}, \quad (2.61)$$

where W_l and ϕ_l represent the Gauss–Laguerre quadrature weights and nodes, respectively.

The derived EC expression indicates that practical impairments such as UAV orientation instability, RIS phase estimation errors, and imperfect CSI reduce the achievable transmission rate by degrading the effective received SNR and coherent RIS beamforming gain.

2.5 Numerical Results and Discussions

In this section, numerical results are presented to evaluate the performance of the proposed UAV-assisted RIS communication system under practical impairments. The derived analytical expressions are validated using Monte Carlo simulations with 10^6 realizations, demonstrating close agreement between analytical and simulation results. Unless otherwise stated,

identical Nakagami- m fading parameters are considered for both the source-to-RIS and RIS-to-destination links, i.e., $m = 1$ and $\Omega = 1$. The outage threshold is set to $\gamma_{\text{th}} = 5$ dB, while the number of RIS reflecting elements is fixed at $N = 16$. For ASER analysis, binary phase shift keying (BPSK) modulation is assumed. Practical impairments are incorporated by modeling RIS phase estimation errors using the von Mises distribution with concentration parameter $\kappa = 7$, UAV orientation fluctuations using Gaussian angular deviations with standard deviation $\sigma = 3.5^\circ$, and imperfect CSI using correlation coefficients $\rho_h = \rho_g = 0.9$. Unless otherwise specified, the simulation parameters utilized throughout this chapter are listed in Table 2.1.

Fig. 2.2 presents the OP versus average SNR under ideal and impaired operating conditions, including RIS phase estimation errors, UAV orientation fluctuations, imperfect CSI, and their combined impact. The ideal RIS-assisted communication system achieves the best performance due to perfect phase alignment and coherent beamforming. However, the introduction of practical impairments progressively degrades the OP performance, with the combined impairment scenario exhibiting the worst performance. Specifically, at an average SNR of 20 dB, the ideal RIS-assisted communication scenario achieves an OP of approximately 10^{-3} . When RIS phase estimation errors are incorporated, the OP increases to nearly 3×10^{-3} . Further, the combined impact of UAV orientation fluctuations and RIS phase errors results in an OP of approximately 0.02. Finally, under the simultaneous presence of imperfect CSI, UAV orientation fluctuations, and RIS phase errors, the OP further degrades to nearly 0.14. This degradation is primarily caused by beam misalignment, inaccurate phase compensation, and channel estimation errors, which reduce the effective beamforming gain and received signal power. Therefore, practical impairments significantly influence the reliability of UAV-assisted RIS communication systems.

Fig. 2.3 presents the OP performance under different values of CSI correlation coefficients $\rho_h = \rho_g = \rho$. It is observed that increasing the CSI correlation coefficient significantly improves system performance. Specifically, at an average SNR of 20 dB, the OP values corresponding to $\rho = 0.8, 0.9, 0.95$, and 1 are approximately 0.45, 0.14, 0.06, and 0.02, respectively. This improvement occurs because larger values of ρ correspond to more accurate channel estimation, thereby enabling improved RIS phase adjustment and coherent beamforming. In contrast, imperfect CSI introduces channel estimation mismatch, resulting in inaccurate RIS phase compensation and reduced received signal power. Consequently,

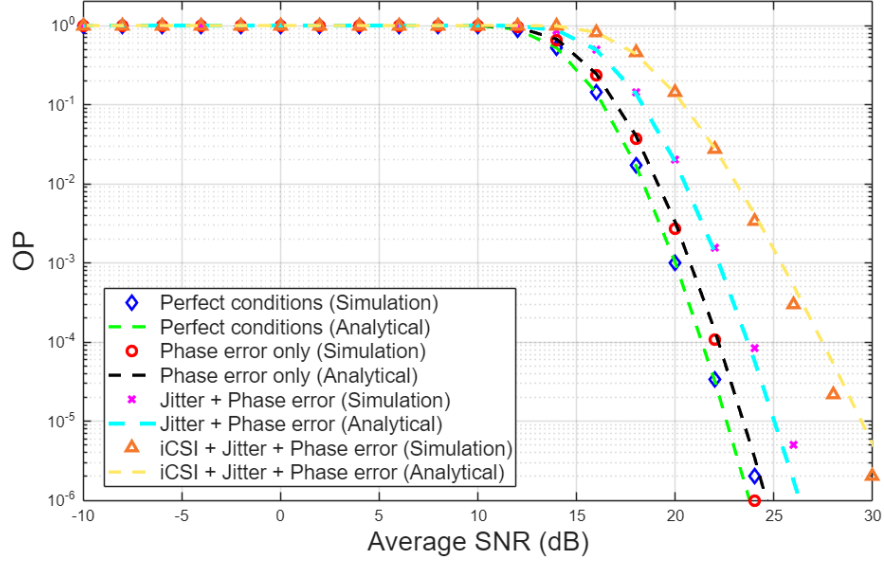


Figure 2.2: OP versus average SNR for ideal and impaired system conditions.

accurate CSI acquisition becomes essential for realizing reliable UAV-assisted RIS communication performance.

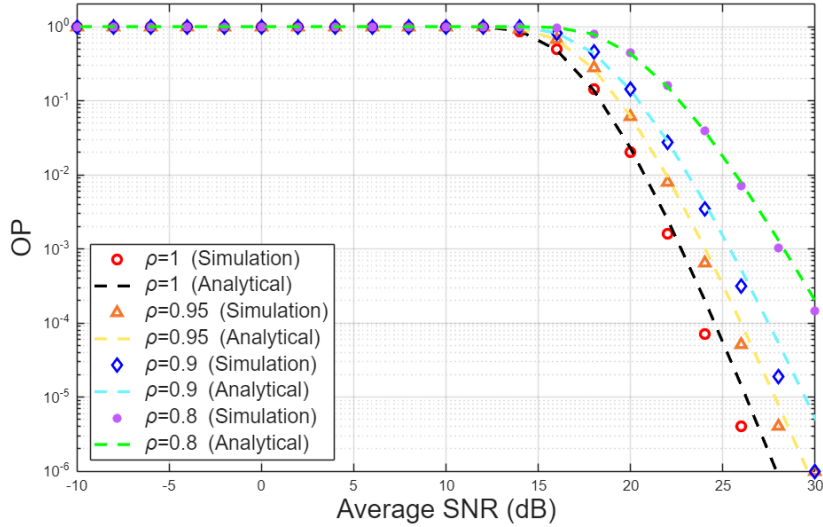


Figure 2.3: OP versus average SNR for varying CSI correlation coefficients.

Fig. 2.4 shows the ASER performance under different values of Nakagami- m fading parameters m and Ω . It is observed that increasing the fading parameter m improves the ASER performance because larger values of m correspond to less severe channel fading conditions. Similarly, increasing the spread parameter Ω enhances the average received signal power and improves communication reliability. For a target ASER of 10^{-4} , the configuration $(m, \Omega) = (1, 3)$ achieves approximate SNR gains of 3.5 dB, 6 dB, 7 dB and 9.5 dB

compared to (1,2), (3,1), (2,1), and (1,1), respectively. Furthermore, it is observed that increasing Ω produces a more significant performance improvement compared to increasing m . This behavior can be explained by the distinct roles of the two parameters. Specifically, increasing m reduces the severity of fading by mitigating channel fluctuations; however, it does not directly enhance the average received signal power. In contrast, increasing Ω directly scales the average channel gain, resulting in a higher effective SNR. Consequently, improvements in Ω lead to a more significant enhancement in ASER performance compared to increasing m , particularly in moderate-to-high SNR regimes where signal power dominates over fading effects.

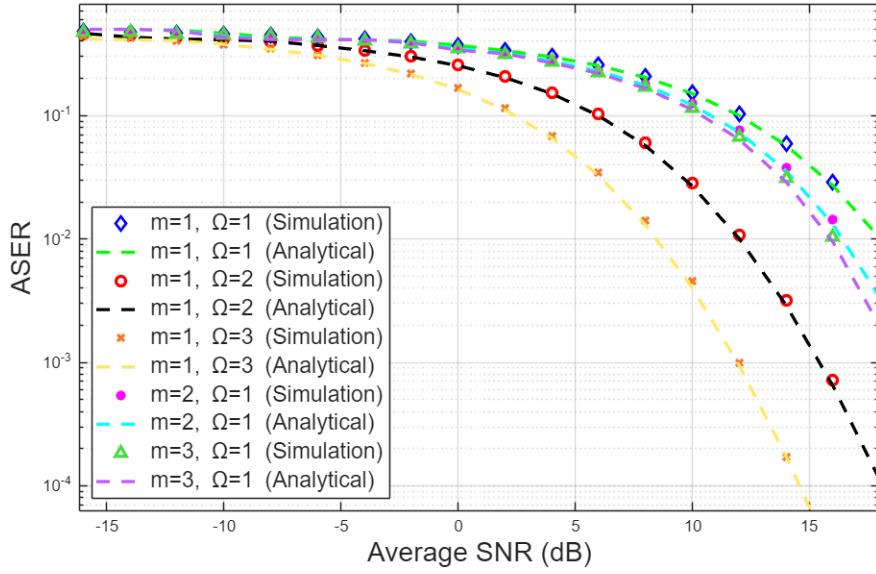


Figure 2.4: ASER versus average SNR for varying m and Ω values.

Fig. 2.5 illustrates the ASER performance of the proposed UAV-assisted RIS communication system for different values of the von Mises phase error concentration parameter κ . It is observed that increasing κ significantly improves the ASER performance of the system. This behavior occurs because larger values of κ correspond to lower RIS phase uncertainty and improved phase alignment among the reflected signals, thereby enhancing coherent signal combining at the destination node. Specifically, at an average SNR of approximately 25 dB, the ASER corresponding to $\kappa = 2$, $\kappa = 3$, $\kappa = 5$, and $\kappa = 50$ is observed to be approximately 1.3×10^{-3} , 2.3×10^{-4} , 6.4×10^{-5} , and 2×10^{-5} , respectively. It can therefore be observed that the ASER decreases considerably as κ increases from 2 to 50. However, for sufficiently large values of κ , the performance improvement gradually becomes less significant and approaches the ideal RIS phase compensation condition.

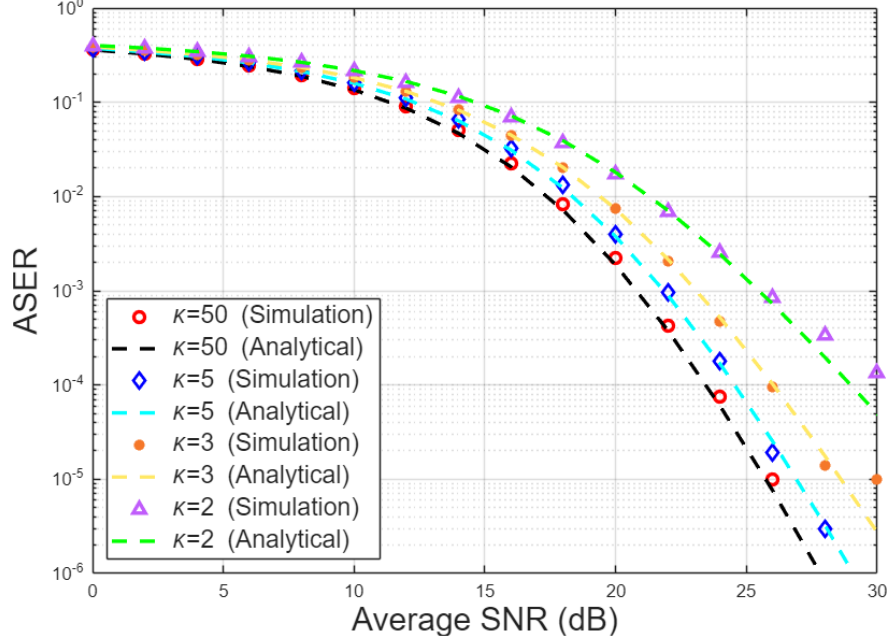


Figure 2.5: ASER versus average SNR for varying phase error severity.

Fig. 2.6 presents the EC performance under different numbers of RIS reflecting elements. It is observed that increasing N significantly enhances the achievable system capacity due to larger passive beamforming gain and improved effective channel strength. Specifically, at an average SNR of 25 dB, increasing the RIS size from $N = 8$ to $N = 32$ improves the EC by approximately 140%. This improvement occurs because increasing the number of RIS reflecting elements enhances coherent signal combining and increases the received SNR. Consequently, larger RIS arrays enable reliable high-capacity communication even under practical impairment conditions. Moreover, the obtained results highlight an important trade-off between RIS size and transmit power, where larger RIS arrays reduce the required transmit SNR needed to achieve a desired communication performance target.

Fig. 2.7 illustrates the EC performance of the proposed model for different values of UAV angular deviations, i.e., $\sigma_x = \sigma_y = \sigma$. It is observed that increasing the UAV orientation fluctuation parameter σ progressively degrades the EC performance of the system. As σ increases, random UAV orientation fluctuations distort the effective RIS radiation pattern and introduce beam misalignment, which reduces the received signal power and achievable communication capacity. Specifically, at an average SNR of 25 dB, the EC values corresponding to $\sigma = 1^\circ$, 3.5° , 6° , and 7.5° are observed to be approximately 4.26, 4.17, 3.95, and 3.75 bits/s/Hz, respectively. It can therefore be observed that larger UAV angular deviations reduce the achievable EC performance due to degradation in directional beamforming

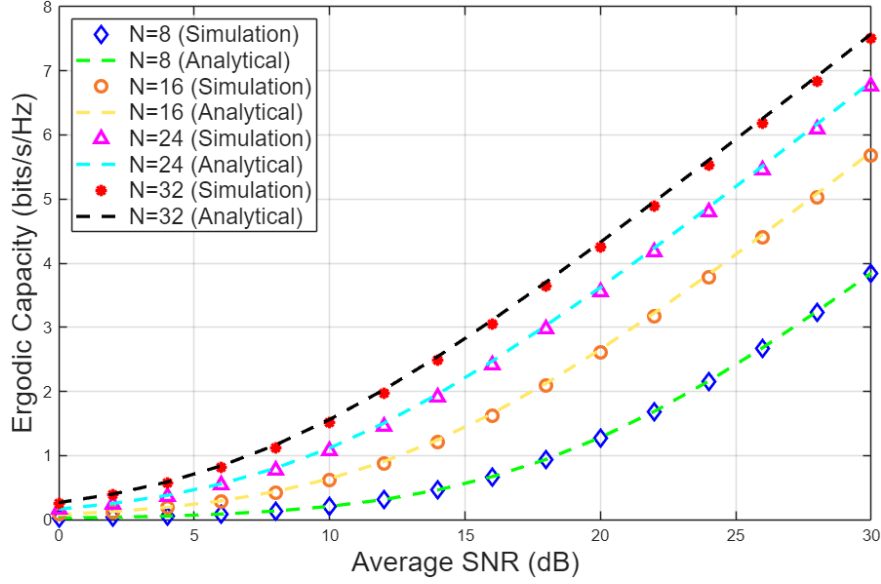


Figure 2.6: EC versus average SNR for varying N values.

efficiency. This behavior occurs because UAV hovering instability introduces random orientation variations in the RIS structure, thereby affecting the spatial beam-steering characteristics and coherent reflection performance.

Overall, the obtained numerical results demonstrate that practical impairments such as UAV orientation fluctuations, RIS phase estimation errors, and imperfect CSI significantly affect the performance of UAV-assisted RIS communication systems. Nevertheless, increasing the number of RIS reflecting elements substantially improves OP, ASER, and EC performance, thereby demonstrating the effectiveness of RIS-assisted beamforming for practical next-generation wireless communication systems.

2.6 Conclusions

In this chapter, the performance analysis of a UAV-assisted RIS communication system under practical impairments was presented. Tractable analytical expressions for OP, ASER and Ec were derived by incorporating UAV orientation fluctuations, RIS phase estimation errors, and imperfect CSI. Nakagami- m fading distribution was considered for modeling the wireless propagation channels, while UAV orientation fluctuations and RIS phase errors were modeled using Gaussian angular deviations and von Mises distribution, respectively. Furthermore, moment-based Gamma approximation was utilized to analytically characterize the equivalent cascaded channel under the combined impact of practical impairments.

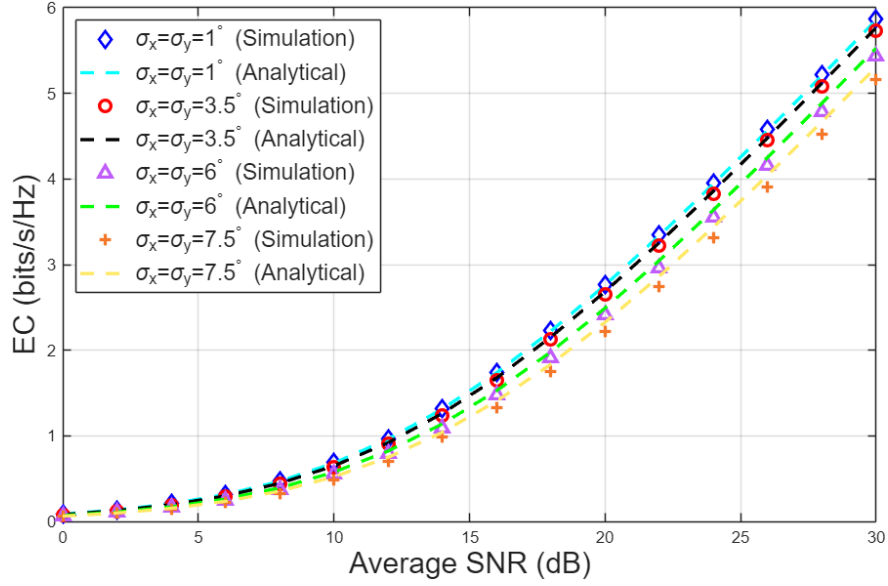


Figure 2.7: EC versus average SNR for varying UAV fluctuation severity.

Monte Carlo simulations were performed to validate the derived analytical expressions, and close agreement between simulation and analytical results was observed. The impact of UAV hovering instability, RIS phase uncertainty, imperfect CSI, fading severity, and the number of RIS reflecting elements on the system performance was investigated through numerical results. It was observed that practical impairments significantly degrade the communication reliability and achievable system capacity due to beam misalignment, inaccurate phase compensation, and channel estimation errors. However, increasing the number of RIS reflecting elements substantially improves the OP, ASER, and EC performance by enhancing passive beamforming gain and coherent signal combining capability.

Overall, the obtained results demonstrate the effectiveness of RIS-assisted beamforming for practical UAV-assisted wireless communication systems and provide useful insights for the design and deployment of next-generation RIS-enabled aerial communication networks.

Table 2.1: Simulation parameters

Parameter	Values
Antenna gain, A	10
Coordinates of source node, (x_s, y_s)	(0,0)
Coordinates of UAV-mounted RIS, (x_u, y_u)	(200,200)
Coordinates of destination node, (x_d, y_d)	(1000,1000)
Outage threshold SNR, γ_{th}	5 dB
Number of RIS reflecting elements, N	16
Uplink propagation constant, k_u	-1.7
Downlink propagation constant, k_d	-1.7
Uplink environment constant, w_u	0.12
Downlink environment constant, w_d	0.12
Concentration parameter (von Mises distribution), κ	7
Standard deviation of UAV angular fluctuations, σ	3.5°
CSI correlation coefficient, δ	0.9
Nakagami fading parameter, m	1
Nakagami fading spread parameter, Ω	1

Chapter 3

RIS Design and Electromagnetic Simulation

3.1 Introduction

Although several existing works have investigated RIS-assisted communication systems from analytical and system-level perspectives, unified frameworks combining theoretical analysis, practical realization, and experimental validation of RIS structures remain relatively unexplored. In practical deployment scenarios, RIS implementation requires accurate electromagnetic characterization of the unit-cell structure, reflection coefficient response, and phase controllability for effective wavefront manipulation and programmable reflection control. Furthermore, practical RIS design involves challenges associated with phase quantization, programmable beam steering, fabrication constraints, and experimental measurement validation.

Metasurfaces and phase-gradient structures have emerged as important technologies for realizing practical RIS implementations. By engineering the reflection phase response of periodic unit cells, phase-gradient metasurfaces enable anomalous reflection through engineered spatial phase distributions based on generalized Snell's law. In addition, digitally coded RIS structures employing quantized phase states have been widely investigated for programmable electromagnetic wave manipulation and deployable wireless communication applications. Motivated by these challenges, this chapter focuses on the electromagnetic design and simulation for the fabrication and experimental characterization of a practical RIS structure operating at 5 GHz.

3.2 Phase Gradient Metasurface Fundamentals

3.2.1 Metasurface-Based Wavefront Manipulation

Metasurfaces are artificially engineered two-dimensional electromagnetic structures composed of subwavelength unit cells capable of manipulating the amplitude, phase, and polarization of incident electromagnetic waves. In RIS-assisted wireless communication systems, metasurfaces operate by introducing programmable phase shifts across the reflecting surface such that the reflected electromagnetic wave can be redirected toward desired directions. This phase manipulation is achieved through appropriate design of the metasurface unit cells. Depending upon the unit-cell geometry and dimensions, different reflection phase responses can be obtained while maintaining sufficiently high reflection magnitude.

In this work, a square patch-based phase-gradient metasurface structure is considered for programmable RIS implementation. The proposed unit cell consists of a square metallic patch printed on a grounded dielectric substrate. By varying the patch dimensions, particularly the patch length, different reflection phase responses are achieved. The corresponding unit-cell geometry and simulation setup are implemented using Ansys HFSS software. The designed structure provides a wide phase tuning range while maintaining low reflection loss around the operating frequency of 5 GHz.

When an electromagnetic wave impinges on a conventional periodic reflecting surface, all unit cells exhibit nearly identical reflection phases, resulting in specular reflection according to classical Snell's law. However, when adjacent metasurface elements are designed to provide progressively varying reflection phases, the reflected wavefront experiences an additional spatial phase discontinuity. Consequently, the reflected electromagnetic wave can be redirected toward different reflection directions, thereby enabling programmable wavefront manipulation.

Practical RIS implementations generally utilize discrete phase quantization techniques instead of continuously varying phase responses. Accordingly, finite-bit coding schemes such as 1-bit, 2-bit, and 3-bit structures are commonly employed for programmable RIS realization. Increasing the number of quantization bits improves the phase resolution and enables more accurate phase-gradient implementation. In the proposed work, a 3-bit quantized RIS structure is utilized for practical programmable reflection control.

3.2.2 Generalized Snell's Law for Anomalous Reflection

Phase-gradient metasurfaces enable controllable manipulation of reflected electromagnetic waves by introducing spatially varying reflection phases across the metasurface aperture. Unlike conventional reflection governed by classical Snell's law, metasurfaces impose an additional phase discontinuity that modifies the reflection direction of the incident electromagnetic wave.

According to generalized Snell's law, the relationship between the incident angle, reflected angle, and the spatial phase gradient is expressed as

$$\sin(\theta_r) - \sin(\theta_i) = \frac{\lambda_0}{2\pi n_i} \frac{d\Phi}{dx}, \quad (3.1)$$

where θ_i and θ_r denote the incident and reflected angles, respectively, λ_0 represents the free-space wavelength, n_i denotes the refractive index of the surrounding medium, and $\frac{d\Phi}{dx}$ represents the phase gradient introduced across the metasurface interface.

It can therefore be observed that the reflected beam direction can be controlled by appropriately engineering the spatial phase distribution across the RIS aperture. To realize a desired anomalous reflection direction, adjacent unit cells are arranged such that a progressive phase variation is generated along the metasurface surface.

For practical implementation, the continuous phase profile obtained from generalized Snell's law is approximated using discrete quantized phase states. Accordingly, different unit-cell geometries corresponding to specific reflection phase values are spatially arranged across the RIS aperture to synthesize the required phase-gradient distribution. In the proposed work, the extracted reflection phase responses corresponding to different patch lengths are utilized to realize practical quantized RIS configurations in MATLAB and HFSS environments.

3.3 RIS Unit Cell Design

3.3.1 Geometry and Design Parameters

The proposed RIS unit cell is designed using a square patch geometry to achieve programmable reflection phase characteristics at the operating frequency of 5 GHz. The unit cell consists of a metallic square patch printed on the top surface of a grounded dielectric

substrate. The bottom layer of the structure is completely covered by a metallic ground plane to ensure full reflection of the incident electromagnetic wave.

The geometrical structure of the proposed RIS unit cell is illustrated in Fig. 3.1 and Fig. 3.2. The overall dimensions of the unit cell are selected as $L \times L$, where $L = 13$ mm denotes the side length of the square substrate. The substrate thickness is chosen as $h = 1.6$ mm. Further, the square metallic patch is centrally positioned on the substrate surface, and its side length P is varied to obtain different reflection phase responses.

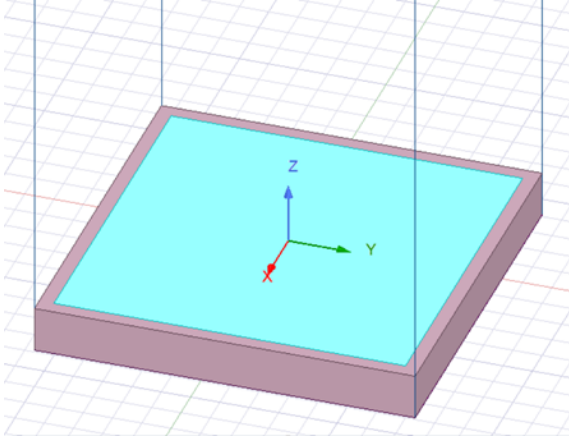


Figure 3.1: Isometric view of unit cell.

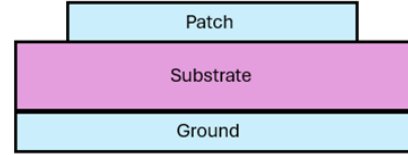


Figure 3.2: Side view of unit cell.

The reflection characteristics of the unit cell strongly depend upon the patch dimensions. Therefore, by varying the patch length parameter P , different reflection phase values are achieved while maintaining sufficiently high reflection magnitude around the desired operating frequency. This phase tunability enables the realization of discrete phase states required for practical RIS operation.

The proposed unit cell geometry is designed to provide a wide reflection phase coverage with relatively simple fabrication requirements. Owing to the symmetric square geometry, the structure also provides polarization-insensitive reflection characteristics for normally incident electromagnetic waves.

The RIS unit cell is implemented using an FR4 dielectric substrate due to its low fabrication cost, commercial availability, and ease of practical realization. The dielectric substrate possesses a relative permittivity of $\epsilon_r = 4.4$ and a thickness of 1.6 mm. Copper material is used for both the metallic patch and the ground plane.

The operating frequency of the proposed RIS structure is selected as 5 GHz considering potential wireless communication and programmable reflection applications. The dimen-

sions of the square patch are optimized to obtain a wide phase variation around the operating frequency while maintaining acceptable reflection coefficient magnitude characteristics.

Different patch lengths are considered to realize multiple discrete phase states required for quantized RIS implementation. The optimized patch lengths corresponding to the desired reflection phase values are extracted through full-wave electromagnetic simulations. These phase states are subsequently utilized for constructing phase-gradient RIS configurations for programmable reflection control.

The important design parameters of the proposed RIS unit cell are summarized in Table 3.1.

Table 3.1: Design parameters of the proposed RIS unit cell

Parameter	Value
Operating frequency	5 GHz
Substrate material	FR4
Relative permittivity (ϵ_r)	4.4
Substrate thickness (h)	1.6 mm
Unit cell dimension (L)	13 mm
Patch material	Copper
Ground plane material	Copper
Patch length (P)	Variable

3.3.2 HFSS Simulation Setup

The proposed RIS unit cell is modeled and simulated using Ansys HFSS software. To analyze the electromagnetic response of the RIS structure, master-slave boundary conditions are assigned along the lateral faces of the unit cell, while Floquet ports are utilized to excite the structure using a normally incident plane wave. The Floquet port configuration enables accurate extraction of the reflection coefficient magnitude and phase characteristics of the periodic RIS structure. The corresponding HFSS simulation setup used for electromagnetic characterization of the proposed RIS unit cell is illustrated in Fig. 3.3.

The simulation frequency range is selected around the operating frequency of 5 GHz to observe the variation of the reflection coefficient response with changing patch dimensions.

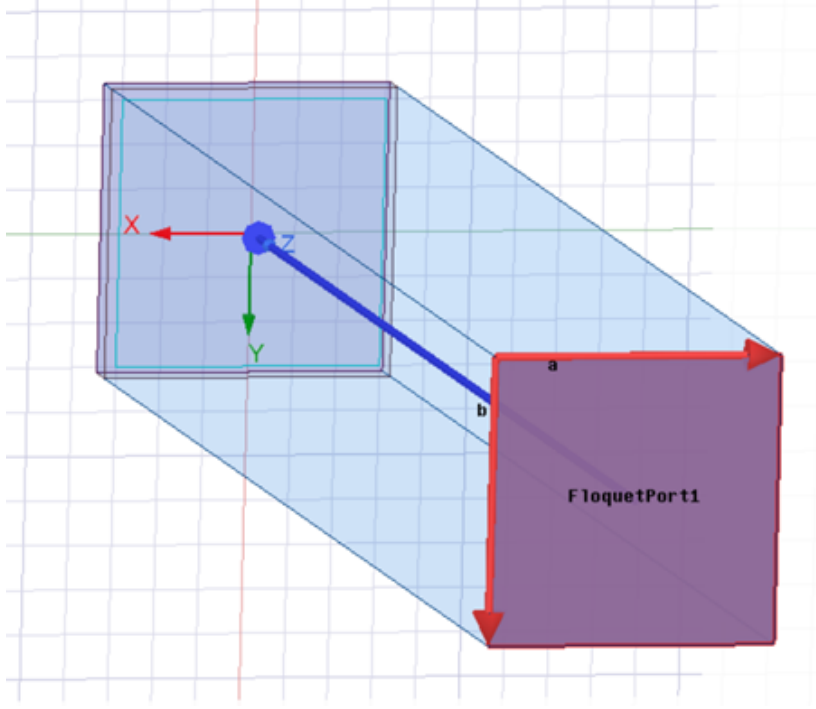


Figure 3.3: HFSS simulation setup of the proposed RIS unit cell.

The reflection coefficient parameter S_{11} is extracted for different values of patch length P to characterize the reflection magnitude and phase response of the RIS unit cell.

The extracted phase states are further implemented in MATLAB to realize programmable phase-gradient RIS configurations for beam-steering applications.

3.4 Reflection Characterization of RIS Unit Cell

3.4.1 Reflection Coefficient Magnitude (S_{11}) Analysis

The reflection characteristics of the proposed RIS unit cell are analyzed using the reflection coefficient parameter S_{11} . The parameter S_{11} represents the ratio of reflected power to incident power at the input port and therefore indicates the reflection performance of the metasurface structure. A higher magnitude of S_{11} corresponds to stronger electromagnetic wave reflection from the RIS surface.

Full-wave electromagnetic simulations are carried out in Ansys HFSS for different values of patch length P around the operating frequency of 5 GHz. The simulated S_{11} magnitude responses corresponding to various patch dimensions are illustrated in Fig. 3.4. It is observed that the proposed RIS unit cell exhibits high reflection characteristics near the

desired operating frequency while maintaining stable electromagnetic behavior for different patch dimensions.

The variation in patch length modifies the resonant behavior of the unit cell, thereby affecting both the reflection magnitude and the reflection phase response. However, despite changes in the patch dimensions, the reflection magnitude remains sufficiently high near the operating frequency, which is desirable for practical RIS-assisted beam-steering applications.

The obtained results verify that the proposed square patch-based RIS unit cell provides efficient electromagnetic wave reflection with relatively low reflection loss. Consequently, the structure becomes suitable for programmable RIS implementations and practical anomalous reflection applications.

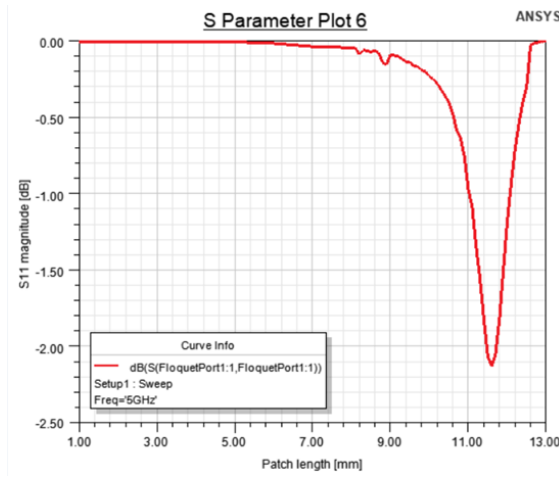


Figure 3.4: S_{11} magnitude response for different patch lengths at 5 GHz.

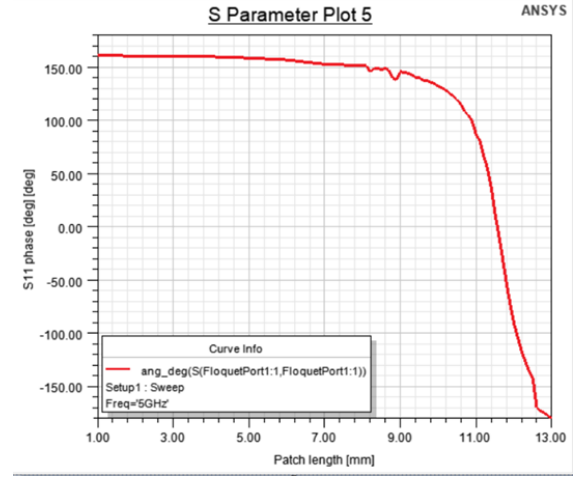


Figure 3.5: S_{11} phase response for different patch lengths at 5 GHz.

3.4.2 Reflection Phase Analysis

In addition to the reflection magnitude characteristics, the reflection phase response of the RIS unit cell plays a crucial role in wavefront manipulation and beam-steering implementation. Therefore, the reflection phase corresponding to different patch lengths is extracted through full-wave electromagnetic simulations using HFSS.

The simulated reflection phase responses for various values of patch length P are illustrated in Fig. 3.5. It is observed that varying the patch dimensions results in significant changes in the reflection phase response of the unit cell. Specifically, the proposed structure

achieves a wide phase tuning range of approximately 330° around the operating frequency of 5 GHz.

This wide phase coverage enables flexible phase control across the RIS aperture, which is essential for realizing phase-gradient metasurface configurations. The obtained phase variation demonstrates that the proposed RIS structure can effectively manipulate the reflected electromagnetic wavefront through appropriate geometrical tuning of the unit-cell dimensions.

Further, the reflection phase variation exhibits a monotonic relationship with the patch length parameter, thereby simplifying the implementation of practical phase-gradient RIS configurations. Hence, the extracted phase responses can be directly utilized for constructing quantized phase states required for digital RIS implementations.

3.4.3 Phase–Length Mapping for Quantized RIS Design

To realize practical programmable RIS implementations, a phase–length mapping framework is developed using the extracted reflection phase characteristics of the proposed unit cell. The relationship between the patch length and the corresponding reflection phase is utilized to construct discrete phase states for quantized RIS beam steering.

Different patch lengths corresponding to specific reflection phase values are selected from the simulated phase response data. In this work, a 3-bit quantized RIS structure is considered, resulting in eight discrete phase states distributed across the available phase tuning range. The optimized patch dimensions and their corresponding reflection phases are summarized in Table 3.2.

The extracted phase–length mapping enables practical implementation of digitally coded metasurfaces and programmable phase-gradient RIS configurations. By spatially arranging unit cells corresponding to different quantized phase states, desired phase distributions can be synthesized across the RIS aperture for programmable RIS implementations.

Further, the obtained phase mapping is implemented in MATLAB to realize phase-gradient RIS configurations based on generalized Snell’s law. Consequently, the proposed phase–length mapping framework provides an effective approach for practical realization of programmable RIS-assisted wireless communication systems.

Table 3.2: Patch length versus reflection phase characteristics

Patch Length (mm)	Reflection Phase ($^{\circ}$)
12.6	-169.88°
12.3	-126.48°
11.9	-73.57°
11.7	-30.04°
11.5	11.81°
11.3	54.07°
10.9	97.84°
9.0	145.03°

3.5 Phase-Gradient RIS Implementation

3.5.1 3-Bit RIS Coding Scheme

To realize practical programmable beam steering, the extracted reflection phase responses of the proposed RIS unit cell are utilized to implement a 3-bit quantized coding scheme. In a 3-bit RIS structure, eight discrete phase states are employed to approximate the desired continuous phase distribution across the RIS aperture. Each phase state corresponds to a specific patch length obtained from the phase-length mapping framework discussed in the previous section.

The use of quantized phase states simplifies practical RIS implementation while enabling practical phase-gradient implementation. Compared with lower-bit coding schemes, the 3-bit RIS configuration provides improved phase resolution and reduced quantization error for practical phase-gradient realization. Accordingly, the optimized unit-cell dimensions corresponding to the required discrete phase states are spatially arranged over the RIS aperture to synthesize the desired phase-gradient distribution for programmable anomalous reflection.

3.5.2 Generalized Snell's Law Based Phase Gradient Design

Phase-gradient design in the proposed RIS structure is implemented using generalized Snell's law by introducing a progressive reflection phase distribution across adjacent RIS elements. By engineering the spatial phase gradient, the reflected electromagnetic wave can be redi-

rected toward a desired anomalous reflection angle instead of conventional specular reflection. The required phase-gradient distribution for programmable anomalous reflection is designed using the generalized Snell's law discussed in Section 3.2.2. Accordingly, suitable discrete phase states are arranged across the RIS aperture to realize the desired spatial phase variation.

Using the extracted phase states from the phase-length mapping framework, suitable phase-gradient configurations are constructed for programmable anomalous reflection. Consequently, the proposed RIS structure enables controllable anomalous reflection through programmable phase manipulation.

3.5.3 MATLAB-Based RIS Array Implementation

The RIS array configuration is implemented in MATLAB using the extracted reflection phase characteristics obtained from HFSS simulations. The quantized phase states corresponding to different patch lengths are assigned across the RIS aperture to synthesize the required phase-gradient distribution. Based on generalized Snell's law, the desired steering angle is first selected, following which the required phase profile is calculated across the RIS array. The corresponding patch lengths are then assigned using the previously obtained phase-length mapping table.

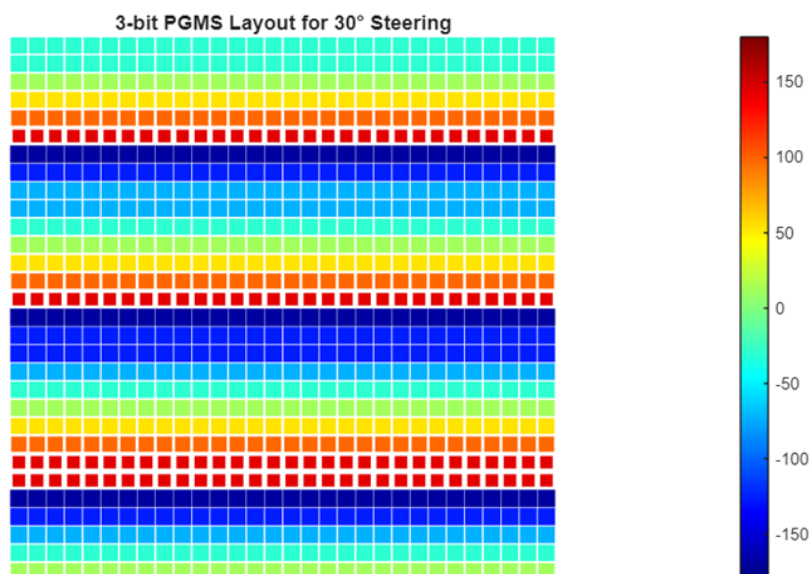


Figure 3.6: RIS structure simulated on MATLAB using the generalized Snell's law.

The MATLAB implementation is utilized to generate and visualize the required quan-

tized phase distributions across the RIS aperture. The obtained configurations are further utilized for RIS phase-distribution analysis based on the extracted phase–length mapping characteristics. An example of the generated 3-bit phase-gradient metasurface (PGMS) configuration corresponding to a steering angle of 30° is illustrated in Fig. 3.6.

3.6 Conclusions

In this chapter, the electromagnetic design and simulation of a practical RIS structure operating at 5 GHz were presented. A square patch-based RIS unit cell was designed and analyzed using Ansys HFSS to obtain suitable reflection magnitude and phase characteristics for programmable RIS implementation. Further, the reflection phase response corresponding to different patch dimensions was utilized to develop a phase–length mapping framework for quantized RIS realization.

In addition, generalized Snell’s law was employed to design phase-gradient RIS configurations for programmable anomalous reflection. A 3-bit quantized RIS coding scheme was implemented using the extracted phase states, and MATLAB-based RIS array configurations were developed for phase-gradient analysis. The obtained results demonstrate that the proposed RIS structure provides effective reflection phase controllability and practical feasibility for programmable RIS-assisted wireless communication applications.

Chapter 4

Experimental Validation of RIS-Aided UAV Communication System

4.1 Experimental Testing and Validation

4.1.1 Fabricated RIS Prototype

To validate the practical feasibility of the proposed RIS structure, the designed unit-cell configurations were fabricated on an FR4 dielectric substrate operating at the frequency of 5 GHz. The fabricated RIS prototype consists of square metallic patch elements printed on the top surface of the substrate, while the bottom surface is fully covered by a metallic ground plane to ensure complete electromagnetic wave reflection.

The fabricated RIS structure was realized using the optimized geometrical dimensions obtained from the HFSS-based electromagnetic simulations discussed in the previous sections. Different patch dimensions corresponding to the extracted quantized phase states were implemented to realize the required phase-gradient configuration for anomalous reflection and beam-steering applications.

The fabricated prototypes were designed considering practical implementation constraints such as fabrication simplicity, low-cost substrate availability, and ease of experimental characterization. The overall structures were lightweight and compact, thereby making them suitable for future UAV-mounted deployment scenarios. Fig. 4.1 and Fig. 4.2 illustrate two of the fabricated RIS prototypes corresponding to different anomalous reflection configurations with incident angle $i = 0^\circ$ and reflection angles $r = 30^\circ$ and $r = 20^\circ$, respectively.

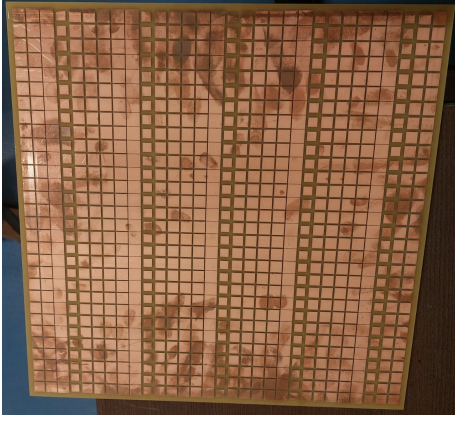


Figure 4.1: Fabricated RIS prototype for $(i = 0^\circ, r = 30^\circ)$ configuration.

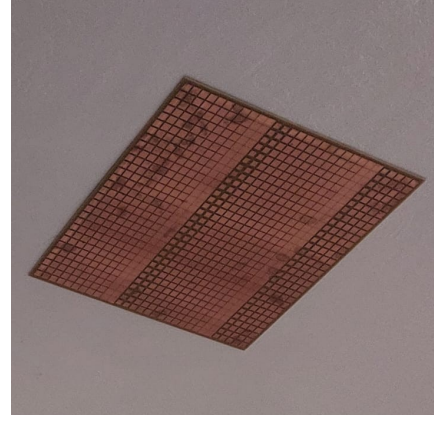


Figure 4.2: Fabricated RIS prototype for $(i = 0^\circ, r = 20^\circ)$ configuration.

4.1.2 Experimental Setup and Measurement Procedure

Experimental characterization of the fabricated RIS structure was carried out using a two-horn antenna and VNA-based measurement setup. The objective of the measurement setup was to experimentally evaluate the reflection characteristics and directional beam-steering capability of the fabricated RIS structure under practical operating conditions.

The experimental arrangement consisted of a transmitting horn antenna, a receiving horn antenna, the fabricated RIS prototype, and a VNA for measuring the transmission coefficient characteristics. The RIS structure was positioned between the transmitting and receiving antennas such that the reflected electromagnetic wave from the RIS surface could be captured at the desired observation angle.

To emulate practical UAV-mounted deployment conditions, the fabricated RIS structure was mounted overhead using a supporting arrangement. The transmitting horn antenna was positioned at a fixed incident angle toward the RIS surface, while the receiving horn antenna was placed at specific reflection angles corresponding to the desired anomalous reflection directions. The developed setup enabled controlled evaluation of the reflected electromagnetic signals and provided experimental verification of the beam-steering capability of the proposed RIS structure. The experimental measurement setup corresponding to the fabricated RIS characterization is illustrated in Fig. 4.3.

Two horn antennas were utilized for both signal transmission and reception due to their directional radiation characteristics and suitability for microwave frequency measurements. The transmitting horn antenna was connected to Port 1 of the VNA, while the receiving horn

antenna was connected to Port 2.

The VNA was configured to measure the forward transmission coefficient parameter $|S_{21}|$ over the operating frequency range around 5 GHz. The S_{21} parameter represents the amount of electromagnetic power transferred from the transmitting antenna to the receiving antenna after reflection from the RIS surface.

Measurements were primarily performed for configurations corresponding to an incident angle of 0° and reflection angles of approximately 20° and 25° . Although the fabricated RIS prototype was primarily designed for the $(i = 0^\circ, r = 20^\circ)$ anomalous reflection configuration, additional measurements were also performed at nearby observation angles, including approximately 25° , in order to investigate the directional reflection and beam-steering characteristics of the proposed RIS structure. Proper antenna alignment and separation distance were maintained to minimize unwanted scattering and ensure accurate measurement observations. The obtained measurements were subsequently utilized for comparison with reference metallic reflector configurations.

The experimental characterization procedure was carried out by measuring the scattering parameters of the fabricated RIS structure over the selected microwave frequency range. During measurements, the transmitting and receiving horn antennas were positioned at pre-determined incident and reflection angles with the fabricated RIS prototype placed between them.

The VNA recorded the scattering parameters S_{11} , S_{21} , S_{12} , and S_{22} corresponding to the RIS configuration. Among these parameters, the transmission coefficient magnitude $|S_{21}|$ was primarily utilized for evaluating the reflected signal characteristics of the fabricated RIS structure.

The measured data was analyzed over the frequency range around 5 GHz, particularly between approximately 4.9 GHz and 5.1 GHz, where the RIS structure exhibited significant reflection response characteristics. Further, measurements were performed for different receiving antenna positions corresponding to multiple reflection directions in order to analyze the directional reflection behavior of the fabricated RIS prototype.

The obtained scattering parameter data was subsequently post-processed for comparison and experimental performance evaluation of the fabricated RIS structure.

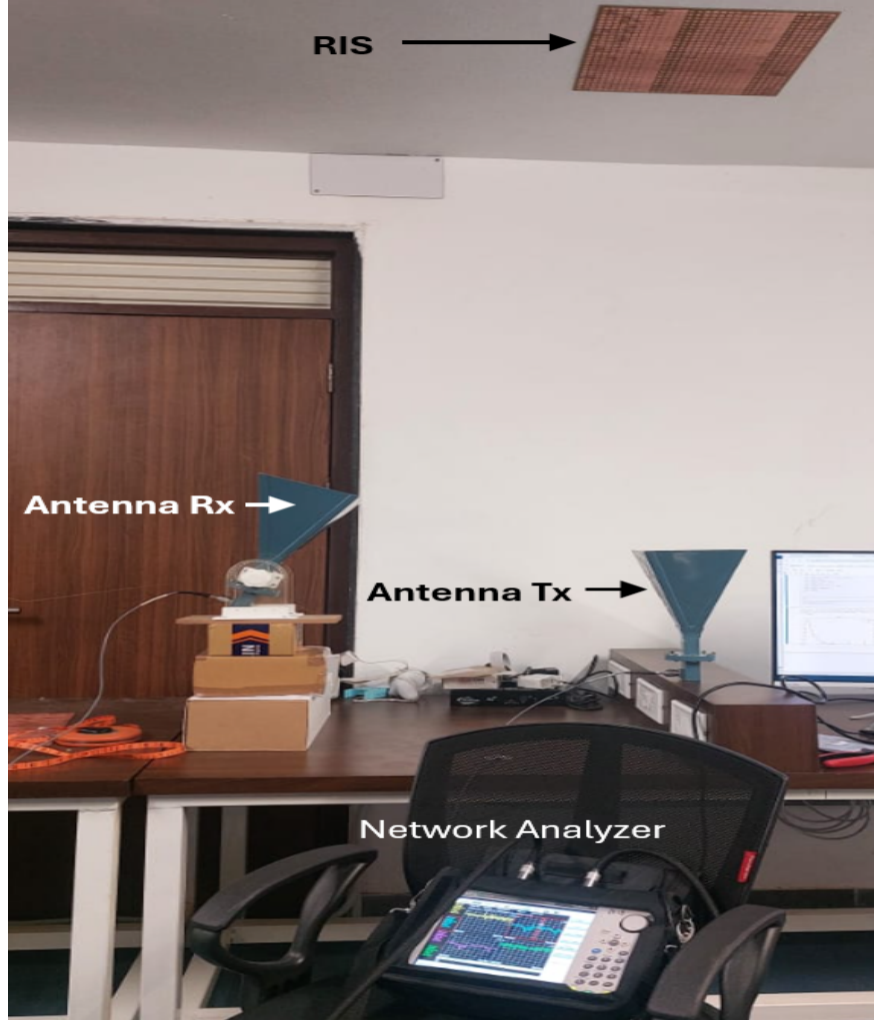


Figure 4.3: Experimental measurement setup for fabricated RIS prototype.

4.1.3 Reference Copper Plate Comparison

To evaluate the effectiveness of the fabricated RIS structure, experimental measurements were additionally performed using a metallic copper plate of dimensions similar to the RIS prototype. The copper plate acted as a conventional reflector producing specular reflection without programmable phase manipulation capability.

The same experimental setup and antenna configuration were maintained during both RIS and copper plate measurements to ensure fair comparison conditions. The corresponding $|S_{21}|$ magnitude responses obtained from the RIS structure and the copper reflector were compared over the operating frequency range.

Particular emphasis was given to the frequency region between approximately 4.9 GHz and 5.1 GHz, where noticeable variations in the measured $|S_{21}|$ magnitude responses were observed between the RIS and metallic reflector configurations. These differences in trans-

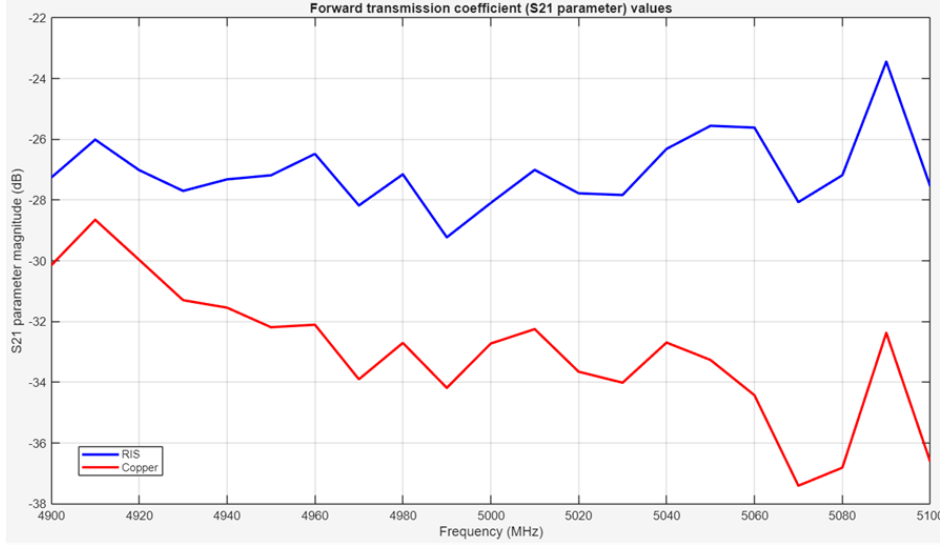


Figure 4.4: Measured $|S_{21}|$ response versus frequency for the fabricated RIS configuration with incident angle 0° and reflection angle 20° .

mission coefficient magnitude indicate the programmable reflection behavior introduced by the phase-gradient RIS structure.

The obtained experimental observations therefore demonstrate the practical feasibility of the proposed RIS design for programmable reflection and beam-steering applications in RIS-assisted wireless communication systems.

4.2 Experimental Outcomes and Discussion

4.2.1 Measurement Results

The experimental measurements obtained using the fabricated RIS prototype were analyzed through the measured scattering parameter responses acquired from the VNA. In particular, the transmission coefficient magnitude $|S_{21}|$ was utilized to evaluate the reflection characteristics of the proposed RIS structure around the operating frequency of 5 GHz.

The measured results corresponding to the fabricated RIS structure and the reference copper plate configuration are illustrated in Fig. 4.4 and Fig. 4.5 for reflection angles of approximately 20° and 25° , respectively, while maintaining an incident angle of 0° .

For the reflection configuration corresponding to $\theta_r \approx 20^\circ$, the fabricated RIS structure exhibited higher $|S_{21}|$ magnitude responses compared with the copper plate over a significant portion of the considered frequency range. In particular, a maximum magnitude difference

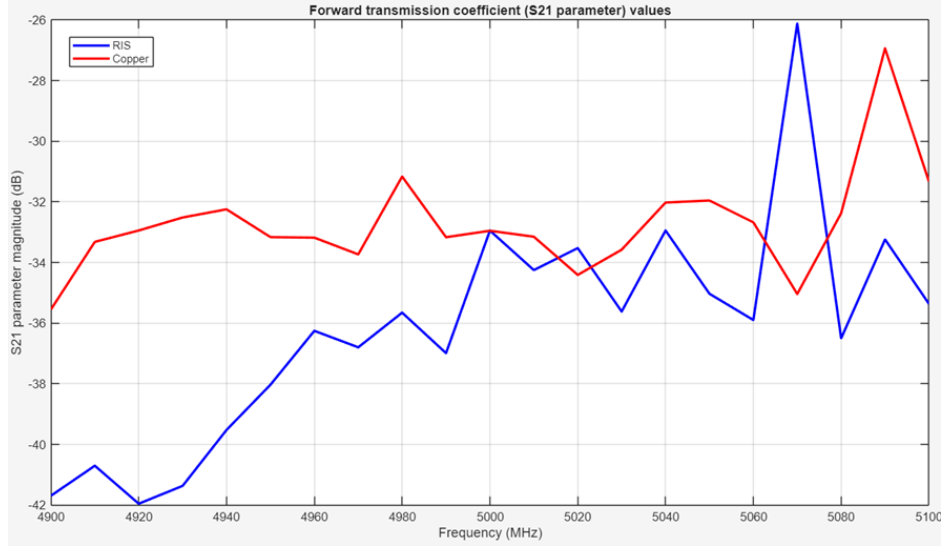


Figure 4.5: Measured $|S_{21}|$ response versus frequency for the fabricated RIS configuration with incident angle 0° and reflection angle 25° .

of approximately 9.63 dB was observed near 5.08 GHz, indicating enhanced directional reflection characteristics introduced by the phase-gradient RIS configuration.

Similarly, for the reflection configuration corresponding to $\theta_r \approx 25^\circ$, noticeable variations between the RIS and copper plate responses were observed across the measured frequency range. A maximum magnitude difference of approximately 9.01 dB was obtained near 4.92 GHz. These observations further demonstrate the programmable reflection behavior and directional scattering characteristics of the fabricated RIS structure.

The obtained experimental results demonstrate that the fabricated RIS prototype is capable of modifying the reflected electromagnetic wave characteristics compared with a conventional metallic reflector. Consequently, the proposed phase-gradient RIS structure shows practical feasibility for programmable beam manipulation and RIS-assisted wireless communication applications.

4.2.2 Practical Challenges and Limitations

Although the fabricated RIS prototype demonstrated programmable reflection characteristics, several practical challenges were encountered during the experimental characterization process. One of the major limitations involved maintaining accurate alignment between the transmitting horn antenna, receiving horn antenna, and the RIS structure during measurements. Small variations in antenna positioning and observation angle significantly affected

the measured scattering parameter responses.

Further, environmental reflections and multipath effects present in the measurement environment introduced additional uncertainty into the measured results. Since the experiments were performed under practical laboratory conditions rather than inside an anechoic chamber, unwanted electromagnetic reflections from surrounding objects could not be completely eliminated.

Fabrication tolerances associated with the RIS unit-cell dimensions, substrate properties, and practical assembly process may affect the overall reflection characteristics of the fabricated RIS structure. In addition, the use of quantized phase states introduces phase discretization errors, which can influence the achievable directional reflection performance of the practical RIS implementation.

Another practical limitation is associated with the operating bandwidth of the fabricated RIS structure. Since the unit-cell dimensions were optimized around a specific operating frequency, the reflection characteristics remain frequency dependent and may vary outside the designed operating range.

4.2.3 Discussion on UAV-Mounted Deployment Feasibility

The fabricated RIS prototype and the corresponding experimental observations demonstrate the potential feasibility of practical UAV-mounted RIS deployment for future wireless communication applications. Owing to the lightweight planar structure and passive reflecting configuration, the proposed RIS design can potentially be integrated with aerial platforms for adaptive wireless coverage enhancement and directional beam control.

The obtained experimental observations validate the practical reflection characteristics of the fabricated RIS structure and demonstrate its suitability for programmable electromagnetic wave manipulation applications. Further, the proposed phase-gradient RIS design provides flexibility for future implementation in UAV-assisted communication systems involving adaptive beam steering and intelligent wireless coverage enhancement. The analytical modeling, electromagnetic simulations, and experimental characterization presented in this work collectively establish a foundation for future development of practical UAV-mounted RIS platforms and real-time programmable wireless communication applications.

To further investigate the practical feasibility of UAV-assisted RIS deployment, prelimi-



Figure 4.6: Preliminary UAV-mounted RIS deployment setup.

nary outdoor integration and mounting experiments were also conducted using a UAV platform. Fig. 4.6 illustrates the experimental UAV-mounted RIS setup considered for practical deployment evaluation. The lightweight planar structure of the RIS prototypes enables integration with aerial communication platforms for wireless coverage enhancement applications.

4.3 Conclusions

In this chapter, the practical implementation and experimental characterization of the proposed phase-gradient RIS structure were presented. To validate the practical feasibility of the proposed RIS structure, fabricated RIS prototypes corresponding to different anomalous reflection configurations were experimentally characterized using a two-horn antenna and VNA-based measurement setup. The measured $|S_{21}|$ responses demonstrated noticeable differences between the fabricated RIS structure and a conventional copper reflector configuration, thereby validating the programmable reflection capability of the proposed RIS design.

The obtained simulation and experimental observations collectively demonstrate the feasibility of implementing practical RIS-assisted beam steering and programmable electromagnetic wave manipulation using quantized phase-gradient metasurfaces. Furthermore, the lightweight planar structure and passive reflecting characteristics of the fabricated RIS prototype indicate its potential suitability for future UAV-assisted wireless communication and intelligent beam-control applications.

Chapter 5

Conclusion and Future Scope

This thesis focused on the analytical modeling, electromagnetic design, fabrication, and experimental validation of UAV-assisted RIS communication systems under practical operating conditions. The major contributions of this thesis include performance analysis under practical UAV impairments, electromagnetic simulation and design of programmable RIS structures, and experimental verification of beam-steering RIS prototypes using horn antenna and VNA-based measurements.

5.1 Conclusions

In Chapter 2, the performance of the UAV-assisted RIS communication system was analyzed under practical aerial deployment impairments. Tractable expressions for key performance metrics were derived by incorporating the effects of UAV orientation fluctuations, RIS phase estimation errors, and imperfect CSI. Nakagami- m fading distribution was considered for modeling the wireless propagation channels, while the RIS phase errors were modeled using the von Mises distribution. Further, the impact of UAV hovering instability on the RIS radiation pattern was incorporated through a sectorized radiation gain model. The derived analytical expressions were validated using Monte Carlo simulations. From the numerical results, it was observed that increasing the number of RIS reflecting elements significantly improved the communication performance. Moreover, the system performance degraded under severe UAV orientation fluctuations, stronger phase estimation errors, and imperfect CSI conditions, thereby demonstrating the importance of considering practical impairments in UAV-mounted RIS communication systems.

In Chapter 3, the electromagnetic design and simulation of a practical RIS structure for beam steering applications were presented. A square patch-based RIS unit cell operating at 5 GHz was designed and optimized using Ansys HFSS software. The reflection coefficient magnitude and phase responses of the proposed RIS structure were analyzed for different patch dimensions. Further, a phase–length mapping framework was developed. A 3-bit phase quantized RIS structure was considered for realizing programmable phase-gradient metasurface configurations. Generalized Snell’s law was utilized to implement directional beam steering through appropriate spatial phase distributions. The obtained simulation results demonstrated wide reflection phase coverage and effective phase controllability suitable for practical RIS-assisted communication applications.

In Chapter 4, practical experimental validation of the proposed RIS structure was carried out using controlled measurement setups. The fabricated RIS prototype was experimentally evaluated through measured scattering parameter responses, particularly using the transmission coefficient magnitude $|S_{21}|$. Further, the experimental measurements were compared with those corresponding to a conventional copper plate reflector under identical measurement conditions. The obtained experimental results demonstrated noticeable differences in the measured reflection characteristics between the RIS and metallic reflector configurations, thereby validating the programmable reflection capability of the fabricated phase-gradient RIS structure.

Overall, the analytical modeling, electromagnetic simulation, and experimental characterization presented in this thesis collectively demonstrate the feasibility and effectiveness of UAV-assisted RIS communication systems for next-generation intelligent wireless communication applications. The presented work establishes a unified framework combining analytical modeling, electromagnetic simulation, and experimental characterization for UAV-assisted RIS communication systems.

5.2 Future Works

The scope for future work can be summarized as follows:

- More generalized wireless fading models such as κ - μ , α - μ , η - μ , or shadowed fading distributions can be considered for further realistic performance analysis of UAV-assisted RIS communication systems.

- Active RIS architectures can be explored to improve reflection gain, extend communication range, and enhance communication reliability under severe blockage or long-distance wireless propagation conditions. Such active RIS implementations may provide improved performance compared with conventional passive RIS structures for future aerial communication systems.
- The present work considered practical impairments for passive RIS such as UAV orientation fluctuations, RIS phase errors, and imperfect CSI within the analytical framework. Future work can investigate additional hardware impairments including non-linear amplifiers, mutual coupling effects, non-unity RIS reflection coefficients, and dynamic phase quantization effects.
- Energy harvesting-assisted UAV-RIS operation can also be investigated using radio-frequency (RF) energy harvesting and SWIPT techniques for improving UAV endurance and powering onboard RIS control circuitry during long-duration deployments.

Publications and Research Contributions

- Sourosmitta Das, Manojkumar B. Kokare, Prashant Sharma, Swaminathan R., Sumit Gautam, and Saptarshi Ghosh, “On the Joint Impact of UAV Orientation Instability and Phase Errors in UAV-Aided RIS Systems,” in *Proc. IEEE SPCOM 2026*, (**Submitted and under review**).
- Research proposal submitted to the DoT 5G Innovation Hackathon 2026 titled “Design and Development of UAV-Aided RIS Networks for Disaster Management Applications.”

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