Suez Canal Engineering Energy and Environmental Science Journal
Faculty of Engineering – Suez Canal University
Year, Volume 3, NO. 2, pages 76– 93

RIS for 5G Wireless Communications: A Survey

Maira Khafagy[1,2], Sherief Fathi[2], and Ahmed Magdy[2]

1 Department of Physics, School of Science and Engineering, The American University in Cairo, New Cairo, Egypt
2 Electrical Engineering Department, Suez Canal University, Ismailia, Egypt

**Corresponding author, Email address: mayra.mohamed@eng.suez.edu.eg*
DOI: 10.21608/sceee.2025.352875.1061

Article Info:

Article History:
Received: 26\02\2025
Accepted: 20\04\2025
Published: 30\04\2025

DOI: 10.21608/sceee.2025.352875.1061

Abstract

The increasing dependence on wireless technologies for communication, navigation, and data exchange has introduced several challenges, including limited data transmission rates, service quality issues, and rising security concerns. Reconfigurable intelligent surfaces have emerged as a promising solution to address these limitations, especially within the context of fifth-generation and future wireless communication systems. By dynamically controlling the behavior of electromagnetic waves, these surfaces enable enhanced signal quality, improved energy efficiency, and better network coverage. This survey presents a comprehensive overview of reconfigurable intelligent surface technology, focusing on its core principles, structural designs, control methods, and practical deployment considerations. The study also explores compact design approaches suitable for integration in environments with limited space, such as buildings and vehicles. Through comparative analysis of existing research, the paper highlights current trends, design trade-offs, and key directions for future development in intelligent surface-enabled wireless communication.

Keywords: *Reconfigurable intelligent surface, Beamforming, 5G networks, Reflection properties.*

Suez Canal Engineering, Energy and Environmental Science Journal (2025), ***Vol. 3***, NO.2

1. Introduction

As the demand for wireless communication systems grows, Fifth-generation (5G) networks are being expanded to deliver higher performance and faster data transmission. Researchers have increasingly focused on enhancing both the energy efficiency and spectral efficiency of these systems, particularly in complex and high-reliability environments that support diverse applications, such as autonomous vehicles, smart cities, and the Internet of Things (IoT). In recent years, massive Multiple Input-Multiple Output (mMIMO) (Ghoneim, Ghattas, Ghuniem, Abdelsalam, & Magdy, 2023), (Khan, Ahmad, & Choi, 2024), Millimeter-Wave (mmWave) communication (Roberts, Zhang, Osman, & Alkhateeb, 2024), (Elalaouy, Ghzaoui, & Foshi, 2024), (Shariff et al., 2024), beamforming (Azari, Skrivervik, & Aliakbarian, 2024), and network slicing (Hamdi, Ksouri, Bulut, & Mosbah, 2024), have been extensively investigated to improve the capabilities and overall performance of 5G networks.

Although these methods are effective in enhancing the performance of 5G networks, they face limitations in spatially complex environments characterized by high population density, dense infrastructure, and numerous buildings or physical obstacles. These challenges are further intensified by the reliance on highly active elements such as antennas and base stations, which increase the need for advanced surveillance and security mechanisms. To address these issues, the concept of the Reconfigurable Intelligent Surface (RIS) also known as the Intelligent Reflecting Surface (IRS) has recently emerged as a promising solution to improve the efficiency, coverage, and adaptability of wireless communication systems.

RIS is a metasurface composed of metallic or dielectric and consists of an array of passive elements that are integrated into the physical layer of the communication system. These elements can be dynamically controlled via software, such as a microcontroller, enabling the redirection of Electromagnetic (EM) waves, as shown in Fig. 1. By adjusting the phase of each scattering element in the array, the radiation pattern can be reflected toward the desired user. This dynamic control is particularly effective for serving mobile users, as RIS can steer beams toward the target direction (Y. Liu et al., 2021). Each RIS element can tune its reflection characteristics based on the metasurface properties, allowing the system to adapt to the environment and mitigate obstacles such as buildings (Mu, Xu, Liu, & Hanzo, 2024). By integrating active elements, RIS can further optimize beamforming toward the user (J. Hu et al., 2020), (Wang, Yang, Makki, & Shamim, 2024) , thereby enhancing Quality of Service (QoS) and reducing latency (Cao & Lv, 2019). Additionally, RIS can act as a relay node by minimizing interference in Device-to-Device (D2D) communication networks. Owing to these capabilities, RIS can eliminate undesired signals through passive beamforming design, which is especially beneficial for improving security at the physical layer (L. Yang et al., 2020), (Zhang, Huang, & Liu, 2024). Moreover, RIS can help mitigate interference from neighboring cells, thereby improving QoS and compensating for signal attenuation over long distances, making it suitable for both data transmission and energy harvesting applications (Wu & Zhang, 2019b), (Ampoma Affum et al., 2024).

An RIS typically consists of multiple layers, including a substrate, a circuit board to tune reflection coefficients, and tuning elements (such as diodes) that adjust EM waves based on Channel State Information (CSI) provided by the base station. These elements enable the RIS to adapt phase shifts to the desired user without altering the physical hardware (Wu & Zhang, 2019a). This allows the RIS to enhance the Signal-to-Noise Ratio (SNR) and reduce the number of required antennas (Gu et al., 2021). Additionally, as we move toward the smart applications of the 5G era, there are growing concerns about security and privacy. RIS can provide a smart solution for these challenges by exploiting the physical characteristics of the communication network. RIS security by controlling signal propagation to prevent eavesdropping, mitigate jamming attacks, and ensure secure transmission in both indoor and outdoor environments (Xing, Wang, & Yuan, 2023).

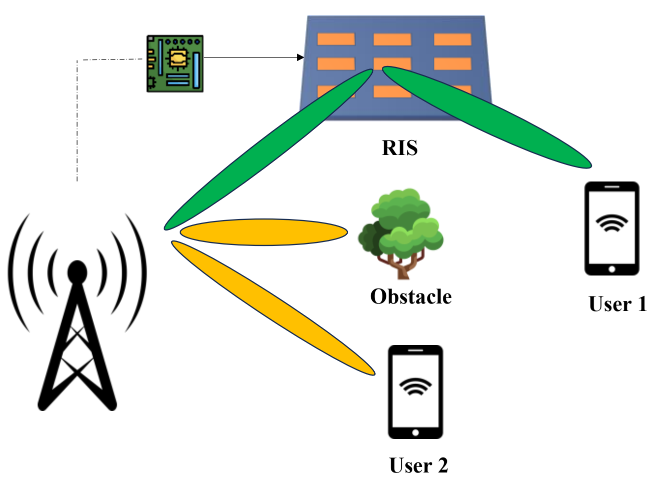

Figure 1: RIS control beamforming to desired user.

1.1. Related Work

RIS has been extensively explored in recent years as a means to improve wireless communication performance across various domains. Several survey studies have provided valuable insights into RIS applications, particularly in outdoor scenarios such as vehicular communications, terahertz networks, and Physical-Layer Security (PLS). However, these existing surveys often focus on general system-level enhancements or theoretical frameworks and rarely consider indoor deployments in confined environments. Table 1 summarizes several notable surveys, highlighting the environment studied, the application area, the type of RIS considered, and whether a specific case study was included. As shown, most of the surveyed works are focused on outdoor applications and lack detailed analysis or practical insights into RIS deployment for indoor environments such as office spaces and conference rooms. In contrast, this paper provides a focused examination of RIS for indoor use cases, addressing practical implementation challenges and reviewing recent contributions that consider spatial constraints, user distribution, and system-level optimization in confined areas.

Table 1. Summary of related surveys on RIS deployment and applications.

Ref.	Environment	Areas Covered Based RIS	Type of RIS	Case Study
(Naaz, Nauman, Khurshaid, & Kim, 2024)	Outdoor	Vehicular Network	✗	✗
(M. Ahmed et al., 2024)	Outdoor	THz Network	✓	✗
(Sharma, Chehri, & Fortier, 2021)	Outdoor	5G and beyond Wireless Communications	✓	✗
(Tarafder, Chun, Ullah, Kim, & Choi, 2025)	Outdoor	Channel Estimation in 5G	✗	✗
(Kaur et al., 2024)	Outdoor	PLS for 6G wireless communication	✗	✓
This work	Indoor	5G and beyond Wireless Communications	✓	✓

1.2. Research Motivation

The growing demand for reliable, high-speed wireless communication has led to the rapid development of advanced technologies such as massive multiple-input multiple-output systems, millimeter-wave communication, and beamforming. However, these solutions often face significant challenges in indoor environments due to signal blockages, reflections, and interference caused by walls, furniture, and other obstacles. While reconfigurable intelligent surfaces have emerged as a promising technology to address such limitations, most of the existing literature predominantly focuses on outdoor scenarios, aiming to extend coverage in large-scale cellular networks. Despite the potential benefits of reconfigurable intelligent surfaces in indoor spaces, there remains a noticeable gap in studies specifically targeting confined environments such as office buildings, conference rooms, or smart indoor infrastructures. These areas are critical for next-generation applications like real-time teleconferencing, indoor navigation, and intelligent workspace management, where signal reliability and quality of service are essential.

Motivated by this gap, our work presents a comprehensive survey of recent developments in RIS technology, with a particular emphasis on its role in enhancing indoor wireless communication. In contrast to studies that primarily optimize RIS placement and phase shift design for broad outdoor coverage, this paper focuses on compact and strategic deployment within indoor settings. By examining existing research and highlighting potential design strategies, our goal is to guide future work toward more effective and efficient RIS-assisted solutions for indoor use cases.

1.3. Scope and Research Question

As wireless communication systems continue to evolve, there is a growing interest in technologies that can support high data rates, low latency, and reliable connectivity—particularly in indoor environments where signal degradation due to reflections, obstacles, and interference is common. Reconfigurable intelligent surfaces have gained significant attention as a transformative solution, enabling dynamic manipulation of electromagnetic wave propagation to enhance signal strength and coverage. While the majority of existing research has concentrated on deploying RIS in outdoor settings to extend cellular coverage or support long-range communication, there remains a substantial gap in understanding how RIS can be effectively utilized in indoor spaces. Environments such as offices, conference rooms, and smart buildings pose unique challenges due to confined geometry, user mobility, and multipath effects, which require tailored RIS deployment strategies and design considerations.

This paper aims to address this gap by surveying recent advances in RIS-assisted communication and focusing on the specific case of indoor applications. Our objective is to explore how RIS technology can be integrated into indoor wireless systems to improve coverage, reduce interference, and enable efficient communication in complex enclosed environments. Through this survey, we seek to answer the following research question: "**How can reconfigurable intelligent surfaces be effectively deployed in indoor environments to enhance wireless communication performance and reliability, particularly in office and conference room scenarios?".** By synthesizing insights from current literature and identifying open challenges, our study provides a foundation for future research and development of RIS-based indoor communication systems.

1.4. Challenges and Limitations

While this survey aims to provide a comprehensive overview of RIS technology and its potential in enhancing indoor wireless communication, several challenges and limitations must be acknowledged. A key difficulty lies in the deployment and adaptation of RIS within confined and dynamic indoor environments. Unlike outdoor scenarios, indoor spaces present highly reflective surfaces, varying user positions, and frequent changes in physical layout, all of which complicate the effective placement and operation of RIS elements. Moreover, most of the existing literature on RIS technologies focuses on outdoor or large-scale deployments, with comparatively limited attention given to small-scale, indoor-specific use cases. This gap in research limits the availability of standardized frameworks, experimental results, or practical design guidelines for RIS in indoor scenarios such as offices or conference rooms. Another significant limitation arises from the reliance on idealized simulation models in many studies. Real-world deployments may face hardware limitations, phase tuning inaccuracies, latency in RIS control mechanisms, and constraints imposed by existing infrastructure. Additionally, integrating RIS into indoor environments may involve practical concerns such as cost, power supply for semi-passive or active elements, and compliance with building regulations.

Despite these challenges, this survey serves as a timely and necessary contribution by consolidating current knowledge and identifying opportunities for further exploration. By focusing on indoor applications, this work aims to encourage future research on practical deployment strategies, optimization techniques, and performance evaluation of RIS-based solutions tailored for enclosed environments.

1.5. Main Contributions

This survey paper aims to provide a structured overview of recent advances in reconfigurable intelligent surface technology, with specific emphasis on its application in indoor wireless communication environments such as office spaces and conference rooms. While much of the existing literature centers on outdoor RIS deployment and performance enhancement in large-scale networks, this work highlights the importance of optimizing RIS design and integration in confined, multipath-prone indoor scenarios.

The main contributions of this paper are as follows:

- **Comprehensive Literature Survey on Indoor RIS Applications:** We review and categorize recent research on RIS technology, with a particular focus on its deployment and effectiveness in indoor communication settings. This includes analyzing key performance parameters such as signal quality, energy efficiency, and interference mitigation.
- **Classification of RIS Use Cases for a different applications:** We propose a classification framework to organize existing RIS studies based on their target environments (indoor vs. outdoor), application objectives (coverage enhancement, security, energy efficiency), and deployment strategies (wall-mounted, ceiling-mounted, or embedded).
- **Case Study Analysis of RIS in Confined Environments:** We present a focused case study analysis that investigates how RIS can enhance communication within enclosed environments like meeting rooms and shared workspaces. This includes reviewing practical implementations and simulation-based findings that demonstrate the impact of RIS on indoor wireless performance.

Through these contributions, this survey aims to bridge the knowledge gap between theoretical research on reconfigurable intelligent surfaces and their practical applications in indoor communication systems. It offers a valuable resource for researchers and engineers seeking to develop and optimize RIS-based indoor solutions. A summary of the abbreviations used throughout this paper is provided in Table 2.

This survey is organized as follows: Section 2 discusses the fundamental concepts of RIS, Section 3 provides an in-depth review of diodes commonly used in RIS elements, such as PIN and varactor diodes, which serve as control mechanisms for dynamically adjusting reflection amplitude and phase. This section also explores their roles across various applications. Section 4 examines the role of RIS in wireless communication through real-world case studies, including unmanned aerial vehicle (UAV) networks, non-orthogonal multiple access (NOMA), the Internet of Things (IoT), and transportation systems, highlighting how RIS can provide intelligent solutions to persistent challenges. Section 5 focuses on RIS deployment in indoor environments such as offices and buildings, demonstrating how RIS can reflect signals in desired directions when signal strength is reduced or blocked by structural obstacles. Section 6 addresses the security enhancements that RIS can offer when integrated into various applications. Section 7 introduces the concept of compact RIS design and discusses limitations observed in recent studies, particularly concerning large-scale implementations. Finally, the conclusion summarizes the key findings and future directions.

Table 2. List of abbreviations used in this paper.

Abbreviation	Full Term	Abbreviation	Full Term
RIS	Reconfigurable Intelligent Surface	IRS	Intelligent Reflecting Surface
IoT	Internet of Things	UAV	Unmanned Aerial Vehicle
NOMA	Non-Orthogonal Multiple Access	PLS	Physical Layer Security
SNR	Signal-to-Noise Ratio	CSI	Channel State Information
QoS	Quality of Service	EM	Electromagnetic
5G	Fifth Generation	mmWave	Millimeter Wave
mMIMO	Massive Multiple Input Multiple Output	D2D	Device-to-Device Communication
LC	Liquid Crystal	PCM	Phase-Change Materials
V2V	Vehicle-to-Vehicle	V2I	Vehicle-to-Infrastructure
ML	Machine Learning	BS	Base Station

2. RIS Fundamentals

As the demand for wireless communication systems grows, 5G networks are being expanded to improve performance and, in this section, we focus on the fundamentals of the RIS, the operation principle and type of controlling element.

2.1 RIS Overview

Innovative technologies are set to transform advanced wireless communication systems. These surfaces dynamically adjust the propagation of electromagnetic waves on the meta-surface to minimize power consumption (Khalid et al., 2023). The RIS can be an intelligent signal processing with distinct input and output paths and multiple adaptable subsystems to meet diverse communication needs (Rasilainen, Phan, Berg, Pärssinen, & Soh, 2023). Table 3 provides a comprehensive overview of the various EM surface structures.

Table 3. Overview of the RIS.

Ref	Year	Control	Primarily Functionality
(Subrt & Pechac, 2012)	2012	PIN Diode	Reflection Surfaces
(Kaina, Dupré, Lerosey, & Fink, 2014)	2014	Phase Control Meta surface	microwave
(H. Yang et al., 2016)	2016	PIN Diode	Provides dynamic control over phase
(Tan, Sun, Jornet, & Pados, 2016)	2016	Varactor Diode	Reflection phase adjustments
(S. Hu, Rusek, & Edfors, 2018)	2018	Active Material	Substitute for MIMO

2.1 RIS Structure and Principle of Operation

RIS mainly consists of three basic layers that are responsible for controlling the interaction with incoming EM waves and directing the reflected wave directly to the receiver. As shown in Fig. 2, the first layer is composed of metallic elements embedded on a dielectric substrate, which interact with the incident EM waves. The response of each component can be controlled by designing the size, orientation, and arrangement of these elements. A copper layer is mounted as the middle layer to prevent any leakage of the incident signal power. The final layer contains a circuit board, such as a microcontroller, which enables remote control of the reflection characteristics (amplitude and phase) of the reflected signals.

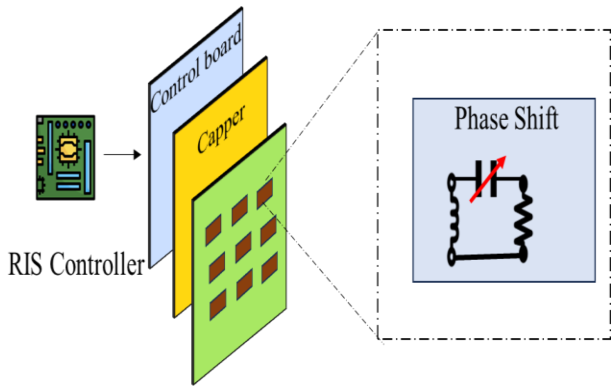

Figure 2: RIS Structure.

2.2 RIS Classification

RIS can be classified according to the working principle as described in Fig. 3, the distinction between types is dependent on the ability to manage the EM propagation with varying control levels and use power usage (S. Zhang et al., 2024). Passive RIS, in Fig. 3(a), excels in energy conservation by relying solely on the properties of the materials for wave processing, due to changes in the reflection characteristics and polarization of the incident wave (Inserra et al., 2024), leading very low power consumption (J. Wang et al., 2024). Active RIS brings adaptability through electronically adjustable elements, providing precise real-time control However, this capability increases power consumption due to the need for an external power source (Radpour et al., 2024) as shown in Fig. 3(b). The hybrid RIS appears as a middle ground, integrating the strengths of both approaches. It not only enhances wave control through active components but also preserves some of the energy-saving benefits of passive systems. This type of RIS uses a limited number of active elements to reflect and amplify the incident signals (A. K. Ahmed & Al-Raweshidy, 2024) as shown in Fig.3(c).

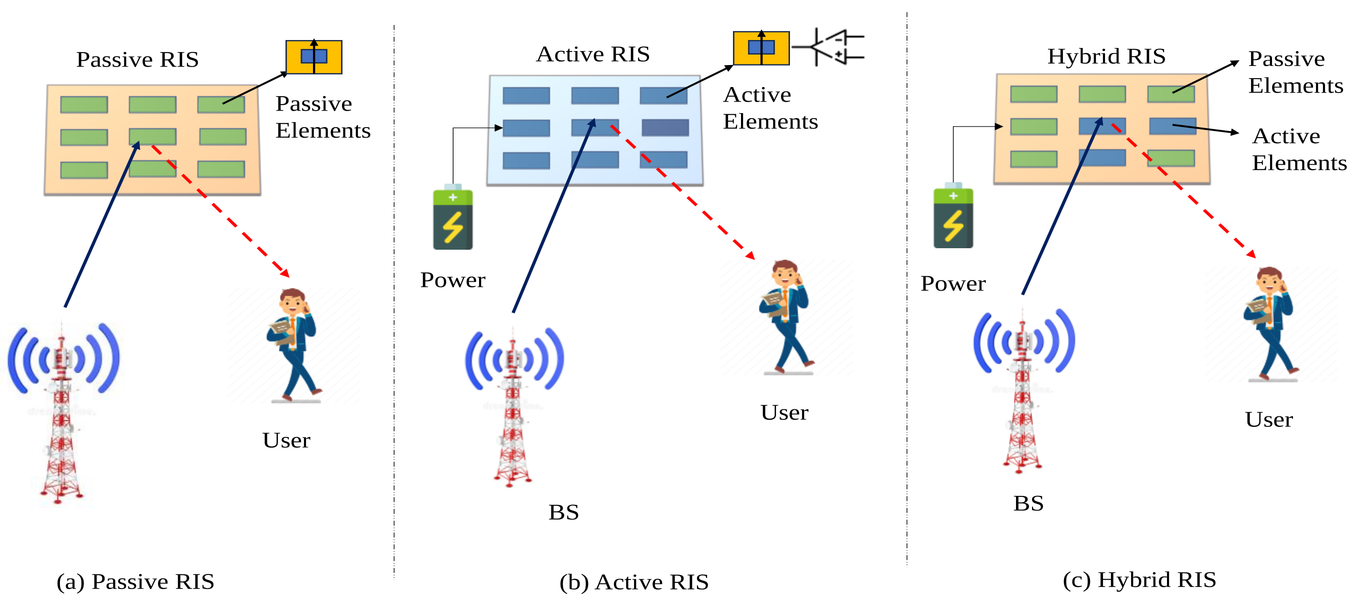

Figure 3: RIS Classification (a) passive, (b) active(c), hybrid.

2.3 RIS Control Mechanism

Fig. 4 represents different control mechanisms. These tuning elements can be integrated into the circuit, making them suitable for reconfigurable meta-surfaces to tune the unit cell, even across large-scale areas. Liquid Crystal (LC) is a tunable meta-atom that is especially effective in terahertz wave processing, making it extremely useful in imaging and telecommunications systems. Unfortunately, in some applications, LC exhibits a slow response time (Shen, Li, Jin, &

Zhao, 2024). Another tunable element is Phase-Change Materials (PCM), which can change their physical properties when excited by external stimuli such as heat or light. However, this capability makes them energy-intensive (Attuluri, 2024). Graphene is the most famous meta-surface and provides tuning over varying voltages as absorption or transmission (Dhote, Sharma, & Singh, 2023). Graphene is one of the most widely used meta-surfaces, offering tunability over varying voltages for applications such as absorption and transmission. Finally, diodes—such as PIN diodes and varactor diodes—enable phase shift control circuits, making them suitable for microwave applications (Zhu et al., 2024).

Table 4 represents the different studies-based control tuning of the RIS in varies application.

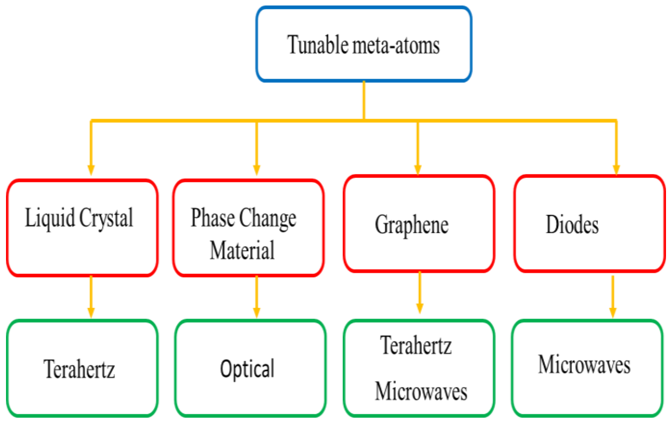

Figure 4: RIS different control mechanisms.

Table 4 . Different Control Mechanisms

Ref.	Control	Regime	Function
(Shen et al., 2024)	LC	THz	Beam steering
(Aboagye, Ndjiongue, Ngatched, & Dobre, 2022)	LC	Visible Light	light steering and amplification
(Attuluri, 2024)	PCM	sub-THz	Control EM waves
(Dhote et al., 2023)	Graphene	THz	controlling the chemical potential
(Islam & Eroglu, 2024)	*Graphene*	THz	phase gradients
(Zhu et al., 2024)	*Diode (Varactor)*	mm-wave	Beam steering
(C. Zhang et al., 2024)	*Diode (PIN)*	mm-wave	Beam steering
(Singh et al., 2023)	*Diode (PIN)*	Ratio Frequency	Sensing

3. Diodes Based RIS

The diodes are widely used as a control element for RIS, due to their properties to control the beamforming and dynamically adjust the amplitude and phase of the reflected signal.

These tuning diodes also provide an effective cost and reduce power consumption.

3.1 PIN Diodes Based RIS

The diodes are widely used as control elements for RIS due to their ability to manage beamforming and dynamically adjust the amplitude and phase of the reflected signal. The PIN diode, in particular, enables control of the EM wave at the level of a single unit cell. These diodes operate in two states—ON and OFF—in a 1-bit configuration, which allows the reflection of EM waves with a 180-degree phase shift between the ON and OFF states. For a 2-bit configuration, two PIN diodes are used, where each combination of diode states provides a unique phase shift. A PIN diode is in the ON state (forward bias), allowing current to pass through, and in the OFF state (reverse bias), blocking current. Table 5 presents several studies that utilize PIN diodes as tuning elements in RIS unit cells.

Table 5. Different studies use pin diodes.

Ref.	Year	Freq,	Control	Mark
(Gros, Popov, Odit, Lenets, & Lerosey, 2021)	2021	28.5 GHz	PIN	beamforming
(Trichopoulos et al., 2022)	2022	5.8 GHz	PIN	SNR gains of RIS
(Gharbieh, D'Errico, & Clemente, 2023)	2023	27 – 31GHz	PIN	beamforming
(Badisa, Boddapati, & Selvan, 2023)	2023	31.9 GHz	AlGaAs PIN	phase control
(Singh et al., 2023)	*2023*	*1.35 to 2.12.1 GHz*	PIN	Sensing
(R. Wang et al., 2024)	*2024*	*22.7 to 30.5 GHz*	PIN	beam scanning
(C. Zhang et al., 2024)	*2024*	*26.5 to 28.5 GHz*	PIN	Beam steering
(Machado, Abbasi, McKernan, Gu, & Zelenchuk, 2024)	*2024*	*26.50 29.45 GHz*	PIN	Beam steering

3.2 Varactor Diodes Based RIS

A varactor diode, also known as a tuning diode, is a specialized type of semiconductor designed to vary the capacitance of a reverse-biased P-N junction. The capacitance changes in response to the applied reverse voltage. This type of diode offers fine-tuned adjustment control with minimal power consumption. Table 6 summarizes several studies that utilize varactor diodes to control phase shifts through varying capacitance.

Table 6. Different studies use varactor diodes

Ref.	Year	Freq,	Control	Mark
(Araghi et al., 2022)	2022	35 GHz	Varactor	beamforming
(Rains et al., 2022)	2022	24.25 - 27.5 GHz	Varactor	beamforming
(Wolff et al., 2023)	2023	30.6 to 31.7GHz	Varactor	Phase tuning

(Q. Hu, Yang, Zeng, & Zhang, 2023)	2023	4.6 to 5.2 GHz	Varactor	Phase tuning
(Malau, Tong, & Wong, 2023)	2023	26 GHz and beyond	Varactor	Phase tuning
(Zhu et al., 2024)	2024	28 GHz	Varactor	Phase tuning
(Farashahi, Seet, & Li, 2024)	2024	5.3 GHz	Varactor	dual-polarized phase control
(Petrou, Antoniades, & Georgiou, 2024)	2024	-	MOS varactor	beamforming
(Dey, 2024)	2024	5.8 GHz	Varactor	Phase tuning
(Lang et al., 2024)	2024	3.55 GHz	Varactor	Phase tuning
(Sikder, Kumar, & Mohan, 2024)	2024	(3 GHz, 5.2 GHz, and 6.2 GHz	Varactor	Phase tuning

4. Integration RIS in Wireless Communication Systems

In this section, we discuss the impact of RIS on wireless communication systems and its integration into various applications to enhance performance. As illustrated in Fig. 5, RIS enhances communication by enabling intelligent beamforming, which dynamically adjusts the phase and amplitude of reflected signals directly toward the receiver.

4.1 RIS Assisted UAV Network

Recently, UAV networks have emerged as a promising technology network has become an upcoming technology for wireless communication systems (Ma, Ding, & Hassan, 2020). In [(S. Li, Duo, Di Renzo, Tao, & Yuan, 2021), the authors examined the performance of a secure UAV communication system with the help of RIS, which consists of a rotary-wing UAV.

To facilitate secure communication between the UAV and the ground user, a Time-Division Multiple Access Protocol (TDMA) is used. A building-mounted RIS system is used to enhance data transmission security further. It is assumed that all communication links undergo fading for the RIS fading, and the incomplete CSI of the eavesdropping are available in the transmitter. To maximize the average worst Secrecy Rate (SR), the authors propose a common uplink/downlink optimization algorithm. The simulation results show significant performance gains, attributable to the combined optimization of the drone's trajectory, which is the passive beam shaping of the RIS, and the transmission power of legitimate users.

In (Yao, Liu, Yu, Huang, & Yue, 2024), the UAV functions as an air base station, and performance metrics such as outage probability, ergodic rate, and energy efficiency are evaluated using Nakagami-m fading channels. To emphasize the benefits of air-ground networks supported by the RIS system, the study compares them with point-to-point connections, amplification, and forward relay schemes, traditional centralized deployments of the RIS system, and integration networks without hardware impairments.

4.2 RIS Assisted IOT and Smart Cities

With the growth of 5G networks, IoT has garnered significant research interest has become interesting research in many studies. This technology not only facilitates seamless communication among diverse devices, including sensors, autonomous vehicles, and smart systems, but also optimizes energy consumption and reduces network congestion. The systems supported by the RIS provide a flexible and low-cost solution to enhance network security and resilience in urban spaces, contributing to the creation of more efficient and sustainable smart cities.

Devices often face challenges related to signal blockage, interference, and various user requirements. By enabling intelligent control over electromagnetic wave propagation, RIS can dynamically reflect and redirect signals to overcome these obstacles. This ensures improved coverage and reduced latency across the smart city infrastructure.

In (Shahiri, Behroozi, Kuhestani, & Wong, 2024), the authors explore Physical Layer Key Generation (PLKG) to improve security in resource-limited networks such as IoT, where generating high Key Generation Rates (KGR) in semi-static channels, such as smart homes or remote sensing, poses challenges. To address this, the study investigates the use of RIS to introduce controlled randomness in the communication channel and mitigate the commonly neglected issue of spatial correlation between RIS elements.

4.3 RIS Assisted NOMA

NOMA is an interesting solution due to its ability to improve spectrum efficiency and throughput, especially in a complex environment with indirect communication links (Liu, Lin, Zhou, & Jia, 2021). NOMA can support multiple users with the same resources over different powers.

In (X. Li et al., 2024) the authors, referred to as the PRIS-ARIS-NOMA, assessment system, includes a passive RIS and an active RIS assessment system to enhance spectral efficiency and reliability. Closed and asymptotic expressions for the probability of interruption and the ergodic data rate of non-orthogonal users are derived under the schemes of complete and complete sequential deinterlacing. In (Sherif, Maher, & El-Mahdy, 2024), the author represents a Heterogeneous Network (HetNet), in which drones act as Small Base Station (SBS) serving ground users in microcells, while the Microcells Base Station (MBS) uses NOMA with the help of RIS.

The common optimization problem is formulated to maximize the sum rate by optimizing the powers assigned to all users and the phase shifts of the RIS system.

4.4 RIS Assisted Transportation Network

The most recent application is the concept of smart transportation which aims to improve the cellular user's QoS for cellular users, as well as enhance road safety, reduce traffic congestion, lower costs, and improve energy efficiency (Saarika, Sandhya, & Sudha, 2017). It focuses on adjusting the reflection characteristics of incident waves allowing the desired signal information to be intelligently reflected toward moving receivers (Wu, Zhang, Zheng, You, & Zhang, 2021).

During the deployment of strategic research and development systems, intelligent transmission technologies can enhance the reliability of communications and protect against eavesdropping attacks. To be effective, RIS units must be optimally positioned, accurately estimate Channel State Information (CSI), intelligently reflect signals, and adapt to different spectrum bands, as shown in Fig. 5.

In (Mensi, Rawat, & Balti, 2021), the authors discussed the RIS effect on Physical Layer Security (PLS) and used Machine Learning (ML) to provide the accurate result. In (Makarfi, Rabie, Kaiwartya, Li, & Kharel, 2020), the authors use RIS for PLS and Vehicle-to-Vehicle (V2V) communication. In (Ai et al., 2021), the authors represent two realistic scenarios, the first one is V2V with RIS, as shown in Fig.5, and the second one is Vehicle-to-Infrastructure (V2I).

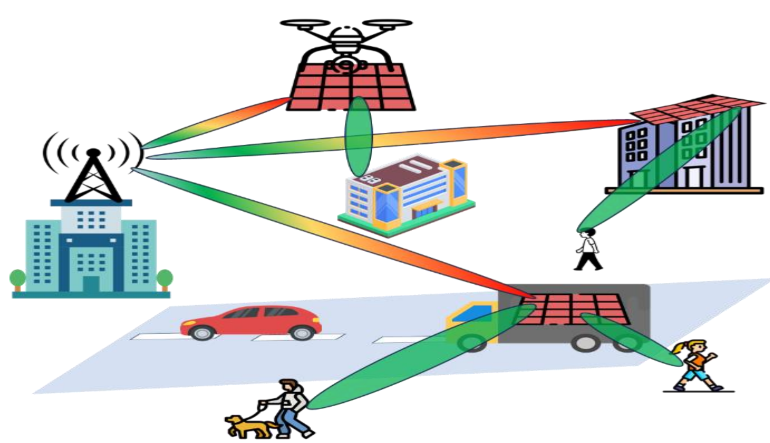

Figure 5: RIS integrated into wireless communication.

5. Integration RIS in Indoor Communication Systems

RIS is emerging as a promising technology to enhance indoor wireless communication. RIS can receive EM from the coming signal and dynamically control the phase and amplitude reflected signal digitally toward the receiver. RIS mitigate interference caused by obstacles such as concrete walls, which often attenuate incoming signals, as shown in Fig.6. Usually, indoor communication is difficult to ensure coverage for each limited space, which creates challenges. This RIS can take the main beam from the BS and reflect it inside the building to the target user and avoiding any obstacles.

In (Xu, Li, & Quek, 2024), the authors demonstrated an additional application of RIS for improving indoor performance. By dynamically controlling the phase-shift matrices of multiple RIS units, it is possible to generate distinct wireless fingerprints for different sub-regions within a localization area, even when using a single antenna. This method allows for the determination of optimal phase-shift configurations that minimize localization errors. In (Nielsen, Franek, & Zhinong, 2024), the authors investigated the impact of RIS on indoor radio propagation. By measuring the instantaneous Channel Impulse Response (CIR) between a transmitter (Tx) and a moving receiver (Rx) antenna in Non-Line-of-Sight (NLOS) scenarios, they observed that the RIS provided a power gain of up to 22 dB when strategically placed, and only around 1 dB at close distances. This analysis offers valuable insights into the distribution of instantaneous power levels and the variability of channel responses.

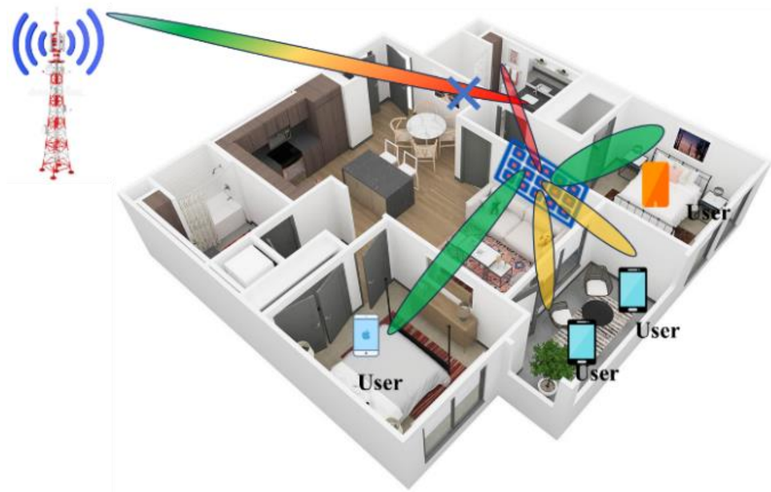

Figure 6: RIS in indoor wireless communication.

6. RIS in Physical Layer Security (PLS)

Security is an essential aspect in designing a network, especially for applications such as banking, social media platforms, and environmental surveillance. A promising approach gaining momentum in this area is Physical Layer Security (PLS), particularly as technology grows and expands into new areas. RIS provides the ability to optimize signals for legitimate users while simultaneously disrupting signals intended for unauthorized interceptors, as shown in Fig. 7.

In (B. Li, Wu, Li, & Zhao, 2021), the authors discuss the integration of Mobile Edge Computing (MEC) with RIS to enhance IoT security by amplifying user signals and suppressing signals received by eavesdroppers. They utilize RIS phase shifts and user scheduling strategies to minimize secure power consumption. This is achieved using Alternating Optimization (AO), Semi-Definite Relaxation (SDR), and Dinkelbach's method. In (Ngo, Nguyen, Dinh, Hoang, & Juntti, 2021), the authors present an analysis of a Hybrid Relay-RIS (HRRIS) system for a single-user MEC network. To reduce transmission latency and protect data from eavesdropping, HRRIS is implemented using a combination of active relays and passive reflecting elements, enabling simultaneous signal amplification and redirection. The AO approach is employed to minimize latency and enhance RIS performance. In (Yan, Wang, & Zheng, 2022), another scope is provided involving UAVs and RIS, where MEC systems are used to optimize the transmission efficiency and security of wireless networks. The UAV processes data and emits interference signals to mitigate eavesdropping attempts.

In (Tu et al., 2024), the authors introduce a dynamic RIS design to enhance mmWave applications by equipping RIS with special capabilities to counter jamming and eavesdropping attacks. The study proposes a hybrid fixed and mobile reinforcement learning algorithm with the aid of multiple RIS elements. The problem is decomposed into sub-problems and solved using fractional programming and linear block format methods via proxy to identify the optimal solution.

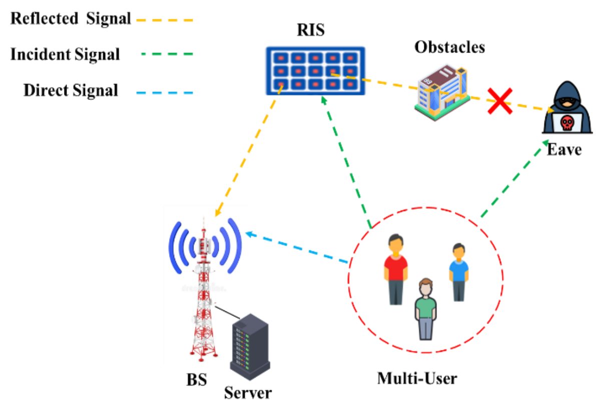

Figure 7: RIS in physical security.

7. Case Study: Compact Design of a RIS for 5G Applications

This section presents our compact RIS design to enhance wireless communication systems. Fig. 8 shows the flowchart of our workflow. The first step involves understanding the main challenges in 5G networks and how RIS can address these significant issues, such as enhancing Non-Line-of-Sight (NLoS) conditions in wireless networks, optimizing data transmission in IoT applications, and improving Physical Layer Security (PLS) in wireless communications. After collecting and analyzing this data, we propose solutions using a compact RIS, making it suitable not only for large-scale areas but also for critical and confined spaces where improved communication coverage is needed. Most existing studies focus on large-scale RIS designs for broad-area implementation. In contrast, our RIS unit is sized to allow easy integration into compact spaces—such as buildings, vehicles, or other environments with limited space. For the control mechanism, we use a varactor diode, which enables tuning of the capacitance to ensure the unit cell operates at the desired frequency with optimized reflection phase and amplitude. Additionally, we designed the unit cell using suitable materials to support tunability across the metasurface, allowing for dynamic adjustment of reflection characteristics. A properly sized array is then configured to maintain stability in real-world applications. Finally, the entire array is controlled using a microcontroller such as an FPGA (Field-Programmable Gate Array). We plan to fabricate this RIS and measure its performance characteristics.

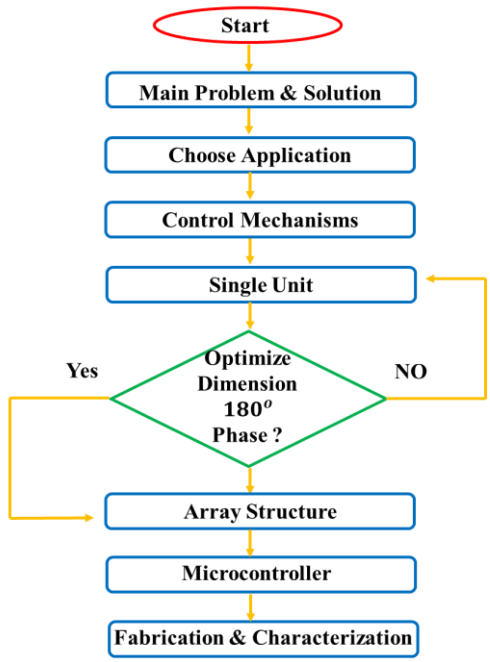

Figure 8: **RIS design chart.**

1.7 MATLAB Implementation of RIS Application

To demonstrate the practical feasibility of our proposed compact RIS design, a simplified MATLAB simulation is presented. This implementation focuses on beam steering using programmable phase shifts across the RIS unit cells. Beam steering is one of the fundamental applications of RIS, enabling intelligent redirection of EM waves toward a target receiver to overcome signal blockage or enhance signal strength in NLoS scenarios. The simulation assumes a uniform linear RIS array consisting of 16-unit cells. Each element can apply a specific phase shift to reflect the incident signal toward a desired direction. By calculating the required phase profile, we steer the reflected beam to a specific angle, for example, 30°, which demonstrates the RIS ability to dynamically control the EM propagation path.

As shown in Fig. 9, the main beam is effectively directed toward the specified target angle, verifying the steering capabilities of the RIS. This simulation validates that through simple electronic control, the phase of each unit cell can be adapted to achieve desired beam patterns.

This implementation can serve as a foundation for more advanced applications, such as RIS-assisted Internet of IoT environments, PLS enhancements, or UAV communication networks. Future studies can extend this model to include realistic channel effects, adaptive control algorithms, and energy efficiency optimization for practical deployment.

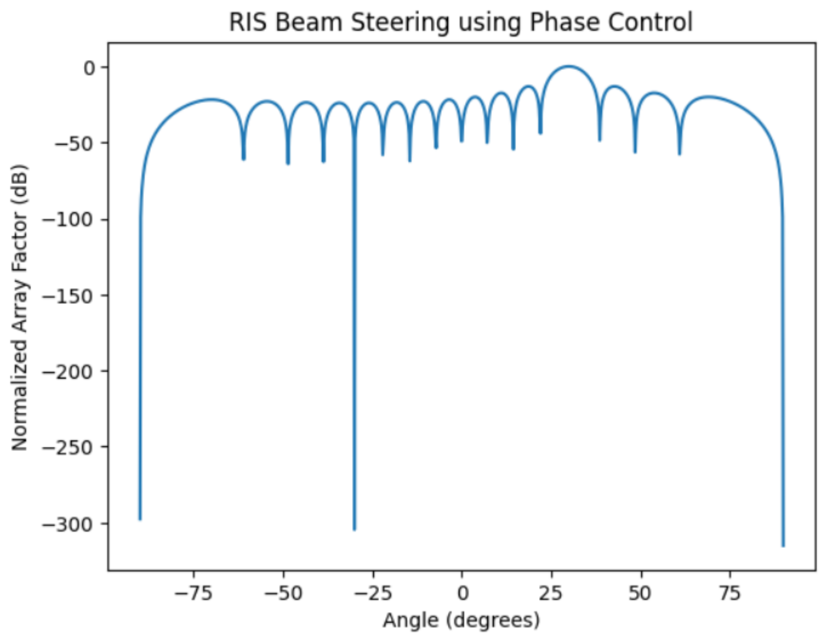

Figure 9: **RIS Beam Steering using Phase Control. The main lobe is directed toward the desired angle (30°), demonstrating the ability of the RIS to steer reflected signals by applying programmable phase shifts across unit cells.**

8. Conclusion

This survey has addressed the key challenges facing 5G wireless communication systems, including high data rate demands, Quality of Service (QoS), and security concerns, and has highlighted how Reconfigurable Intelligent Surfaces (RIS) offer a promising solution. The paper presents a comprehensive overview of the RIS concept, its control mechanisms, and its potential to enhance wireless communication performance in both outdoor (e.g., UAV networks and smart transportation) and indoor environments. Special attention was given to the role of RIS in overcoming signal blockages, improving coverage, and enabling secure and efficient communication. A structured examination of RIS applications was conducted, including their integration with emerging technologies such as Mobile Edge Computing (MEC), Physical Layer Security (PLS), and the Internet of Things (IoT). Furthermore, a MATLAB-based case study was presented to demonstrate the beamforming capability of RIS through phase control, offering practical insights into RIS performance. Finally, the limitations of large-scale RIS designs were discussed, and a compact RIS architecture was proposed. This compact design is suitable for integration into confined and critical environments, such as vehicles and smart buildings, where space and energy efficiency are essential.

9. References

Aboagye, S., Ndjiongue, A. R., Ngatched, T., & Dobre, O. (2022). Design and Optimization of Liquid Crystal RIS-Based Visible Light Communication Receivers. *IEEE Photonics Journal, PP*, 1-7. doi:10.1109/JPHOT.2022.3211730

Ahmed, A. K., & Al-Raweshidy, H. S. (2024). Highly Efficient Hybrid Reconfigurable Intelligent Surface Approach for Power Loss Reduction and Coverage Area Enhancement in 6G Networks.

Ahmed, M., Wahid, A., Khan, W. U., Khan, F., Ihsan, A., Ali, Z., . . . Han, Z. J. I. A. (2024). A survey on RIS advances in terahertz communications: Emerging paradigms and research frontiers.

Ai, Y., Felipe, A., Kong, L., Cheffena, M., Chatzinotas, S., & Ottersten, B. (2021). Secure vehicular communications through reconfigurable intelligent surfaces. *IEEE Transactions on Vehicular Technology, 70*(7), 7272-7276.

Ampoma Affum, E., Tweneboah-Koduah, S., Kubi Appiah, M., Gyamfi, E., Adeola Ajagbe, S., Agyeman Antwi, O., & Adigun, M. (2024). Maximization of sum rate for Wireless Powered Communication Network with Intelligent Reflecting Surface and NOMA in the nonappearance of uplink and downlink beamforming matrix, subject to transmit power and time. *International Journal of Communication Systems, 37*(16), e5911.

Araghi, A., Khalily, M., Safaei, M., Bagheri, A., Singh, V., Wang, F., & Tafazolli, R. (2022). Reconfigurable intelligent surface (RIS) in the sub-6 GHz band: Design, implementation, and real-world demonstration. *IEEE Access, 10*, 2646-2655.

Attuluri, B. T. (2024). *Design and simulation of reconfigurable intelligent surfaces for potential novel tuning-based method implementations.* BT Attuluri,

Azari, A., Skrivervik, A., & Aliakbarian, H. (2024). Design of a novel wide-angle Rotman lens beamformer for 5G mmWave applications. *Scientific Reports, 14*(1), 1245.

Badisa, A. B., Boddapati, T. P. M., & Selvan, K. T. (2023, 11-14 Dec. 2023). *An AlGaAs Diode-based Reconfigurable Intelligent Surface for mmWave Communication.* Paper presented at the 2023 IEEE Microwaves, Antennas, and Propagation Conference (MAPCON).

Cao, Y., & Lv, T. (2019). Intelligent reflecting surface enhanced resilient design for MEC offloading over millimeter wave links. *arXiv preprint arXiv:1912.06361*.

Dey, S. (2024). *A 3-bit Intelligent Reflective Surface with Reconfigurable Phase States, Polarization Insensitivity and Angular Stability for Wi-Fi and IoT applications.* Paper presented at the 2024 IEEE Wireless Antenna and Microwave Symposium (WAMS).

Dhote, C., Sharma, P. K., & Singh, A. (2023). *Graphene-Based Reconfigurable Intelligent Surface for 6G Wireless Communication.* Paper presented at the 2023 IEEE Microwaves, Antennas, and Propagation Conference (MAPCON).

Elalaouy, O., Ghzaoui, M. E., & Foshi, J. (2024). A high-isolated wideband two-port MIMO antenna for 5G millimeter-wave applications. *Results in Engineering, 23*, 102466.

Farashahi, M., Seet, B.-C., & Li, X. J. (2024). *Dual-Polarized Reconfigurable Intelligent Surface Unit Cell with Single Varactor Diode.* Paper presented at the 2024 IEEE International Mediterranean Conference on Communications and Networking (MeditCom).

Gharbieh, S., D'Errico, R., & Clemente, A. (2023). *Reconfigurable Intelligent Surface Design using PIN Diodes via Rotation Technique – Proof of Concept*.

Ghoneim, A., Ghattas, N., Ghuniem, A., Abdelsalam, A., & Magdy, A. (2023). Planar Antenna Arrays Beamforming Using Various Optimization Algorithms. *IEEE Access, PP*, 1-1. doi:10.1109/ACCESS.2023.3292792

Gros, J.-B., Popov, V., Odit, M., Lenets, V., & Lerosey, G. (2021). A Reconfigurable Intelligent Surface at mmWave Based on a Binary Phase Tunable Metasurface. *IEEE Open Journal of the Communications Society, 2*, 1055-1064. doi:10.1109/OJCOMS.2021.3076271

Gu, Q., Wu, D., Su, X., Jin, J., Yuan, Y., & Wang, J. (2021). *Performance comparisons between reconfigurable intelligent surface and full/half-duplex relays.* Paper presented at the 2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall).

Hamdi, W., Ksouri, C., Bulut, H., & Mosbah, M. (2024). Network slicing based learning techniques for iov in 5g and beyond networks. *IEEE Communications Surveys & Tutorials*.

Hu, J., Zhang, H., Di, B., Li, L., Bian, K., Song, L., . . . Poor, H. V. (2020). Reconfigurable intelligent surface based RF sensing: Design, optimization, and implementation. *IEEE Journal on Selected Areas in Communications, 38*(11), 2700-2716.

Hu, Q., Yang, H., Zeng, X., & Zhang, X. Y. (2023). Wideband reconfigurable intelligent surface using dual-resonance element. *IEEE Antennas and Wireless Propagation Letters, 22*(10), 2422-2426.

Hu, S., Rusek, F., & Edfors, O. (2018). Beyond massive MIMO: The potential of data transmission with large intelligent surfaces. *IEEE Transactions on Signal Processing, 66*(10), 2746-2758.

Inserra, D., Li, G., Dai, J., Shi, J., Wen, G., Li, J., & Huang, Y. (2024). Dual-orthogonal polarization amplifying reconfigurable intelligent surface with reflection amplifier based on passive circulator. *IEEE Transactions on Microwave Theory and Techniques, 72*(7), 4383-4394.

Islam, T., & Eroglu, A. (2024, 14-19 July 2024). *Design of Graphene-Based Reconfigurable Intelligent Surface for THz Applications.* Paper presented at the 2024 IEEE INC-USNC-URSI Radio Science Meeting (Joint with AP-S Symposium).

Kaina, N., Dupré, M., Lerosey, G., & Fink, M. (2014). Shaping complex microwave fields in reverberating media with binary tunable metasurfaces. *Scientific Reports, 4*(1), 6693.

Kaur, R., Bansal, B., Majhi, S., Jain, S., Huang, C., & Yuen, C. (2024). A Survey on Reconfigurable Intelligent Surface for Physical Layer Security of Next-Generation Wireless Communications. *IEEE Open Journal of Vehicular Technology, 5*, 172-199. doi:10.1109/OJVT.2023.3348658

Khalid, W., Rehman, M. A. U., Van Chien, T., Kaleem, Z., Lee, H., & Yu, H. (2023). Reconfigurable intelligent surface for physical layer security in 6G-IoT: Designs, issues, and advances. *IEEE Internet of Things Journal, 11*(2), 3599-3613.

Khan, D., Ahmad, A., & Choi, D.-Y. (2024). Dual-band 5G MIMO antenna with enhanced coupling reduction using metamaterials. *Scientific Reports, 14*(1), 96.

Lang, H.-D., Nyffenegger, M. A., Keller, S., Stöckli, P., Hoffman, N. A., Mathis, H., & Zhang, X. (2024). *Validating Convex Optimization of Reconfigurable Intelligent Surfaces via Measurements.* Paper presented at the 2024 18th European Conference on Antennas and Propagation (EuCAP).

Li, B., Wu, W., Li, Y., & Zhao, W. (2021). Intelligent reflecting surface and artificial-noise-assisted secure transmission of MEC system. *IEEE Internet of Things Journal, 9*(13), 11477-11488.

Li, S., Duo, B., Di Renzo, M., Tao, M., & Yuan, X. (2021). Robust secure UAV communications with the aid of reconfigurable intelligent surfaces. *IEEE Transactions on Wireless Communications, 20*(10), 6402-6417.

Li, X., Lian, X., Yue, X., Lu, Z., Huang, C., & Hou, T. (2024). Performance analysis of double reconfigurable intelligent surfaces assisted NOMA networks. *IEEE Transactions on Vehicular Technology*.

Liu, X., Lin, B., Zhou, M., & Jia, M. (2021). NOMA-based cognitive spectrum access for 5G-enabled Internet of Things. *IEEE Network, 35*(5), 290-297.

Liu, Y., Liu, X., Mu, X., Hou, T., Xu, J., Di Renzo, M., & Al-Dhahir, N. (2021). Reconfigurable intelligent surfaces: Principles and opportunities. *IEEE Communications Surveys & Tutorials, 23*(3), 1546-1577.

Ma, D., Ding, M., & Hassan, M. (2020). *Enhancing cellular communications for UAVs via intelligent reflective surface.* Paper presented at the 2020 IEEE Wireless Communications and Networking Conference (WCNC).

Machado, G. G., Abbasi, M. A. B., McKernan, A., Gu, C., & Zelenchuk, D. (2024). *Wideband dual-polarized 1-bit unit-cell design for mmwave reconfigurable intelligent surface.* Paper presented at the 2024 18th European Conference on Antennas and Propagation (EuCAP).

Makarfi, A. U., Rabie, K. M., Kaiwartya, O., Li, X., & Kharel, R. (2020). *Physical layer security in vehicular networks with reconfigurable intelligent surfaces.* Paper presented at the 2020 IEEE 91st vehicular technology conference (VTC2020-Spring).

Malau, H., Tong, K.-F., & Wong, K.-K. (2023). *Intelligent Reflecting Surfaces (IRS) Metasurface-based with Tunable Varactor Diodes for Advanced 6G Wireless Applications.* Paper presented at the 2023 29th International Conference on Telecommunications (ICT).

Mensi, N., Rawat, D. B., & Balti, E. (2021). *Physical layer security for V2I communications: Reflecting surfaces vs. relaying.* Paper presented at the 2021 IEEE Global Communications Conference (GLOBECOM).

Mu, X., Xu, J., Liu, Y., & Hanzo, L. (2024). Reconfigurable intelligent surface-aided near-field communications for 6G: Opportunities and challenges. *IEEE Vehicular Technology Magazine, 19*(1), 65-74.

Naaz, F., Nauman, A., Khurshaid, T., & Kim, S.-W. (2024). Empowering the Vehicular Network with RIS Technology: A State-of-the-Art Review. *24*(2), 337.

Ngo, K.-H., Nguyen, N. T., Dinh, T. Q., Hoang, T.-M., & Juntti, M. (2021). *Low-latency and secure computation offloading assisted by hybrid relay-reflecting intelligent surface.* Paper presented at the 2021 International Conference on Advanced Technologies for Communications (ATC).

Nielsen, J. Ø., Franek, O., & Zhinong, Y. (2024). *Indoor Propagation Measurements with a Reconfigurable Intelligent Surface at 3.5 GHz.* Paper presented at the 2024 18th European Conference on Antennas and Propagation (EuCAP).

Petrou, L., Antoniades, M. A., & Georgiou, J. (2024). *Dynamic Control of Reconfigurable Intelligent Surfaces: An IC-Based MOS Varactor Approach.* Paper presented at the 2024 IEEE International Symposium on Circuits and Systems (ISCAS).

Radpour, H., Hofer, M., Mayer, L. W., Hofmann, A., Schiefer, M., & Zemen, T. (2024). *Active reconfigurable intelligent surface for the millimeter-wave frequency band: Design and measurement results.* Paper presented at the 2024 IEEE Wireless Communications and Networking Conference (WCNC).

Rains, J., Kazim, J. U. R., Tukmanov, A., Zhang, L., Abbasi, Q. H., & Imran, M. (2022). *Varactor-based reconfigurable intelligent surface with dual linear polarisation at K-band.* Paper presented at the 2022 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/URSI).

Rasilainen, K., Phan, T. D., Berg, M., Pärssinen, A., & Soh, P. J. (2023). Hardware aspects of sub-THz antennas and reconfigurable intelligent surfaces for 6G communications. *IEEE Journal on Selected Areas in Communications, 41*(8), 2530-2546.

Roberts, I. P., Zhang, Y., Osman, T., & Alkhateeb, A. (2024). Real-world evaluation of full-duplex millimeter wave communication systems. *IEEE Transactions on Wireless Communications*.

Saarika, P., Sandhya, K., & Sudha, T. (2017). *Smart transportation system using IoT.* Paper presented at the 2017 international conference on smart technologies for smart nation (SmartTechCon).

Shahiri, V., Behroozi, H., Kuhestani, A., & Wong, K.-K. (2024). Reconfigurable-intelligent-surface-assisted secret key generation under spatially correlated channels in quasi-static environments. *IEEE Internet of Things Journal, 11*(9), 15808-15822.

Shariff, B. P., Ali, T., Kumar, P., Pathan, S., Simha, G. G., Mane, P. R., . . . Boulogeorges, A.-A. A. (2024). Dual-band compact six-element millimeter wave mimo antenna: Design, characterization, and its application for v2v communication. *IEEE Access*.

Sharma, T., Chehri, A., & Fortier, P. (2021). Reconfigurable Intelligent Surfaces for 5G and beyond Wireless Communications: A Comprehensive Survey. *14*(24), 8219.

Shen, Z., Li, W., Jin, B., & Zhao, D. (2024). A liquid crystal-based multi-bit terahertz reconfigurable intelligent surface. *APL Photonics, 9*(1).

Sherif, D. M., Maher, E. A., & El-Mahdy, A. (2024). *Reconfigurable Intelligent Surface Assisted UAV in Heterogeneous Networks with NOMA.* Paper presented at the 2024 International Telecommunications Conference (ITC-Egypt).

Sikder, A., Kumar, V., & Mohan, A. (2024). *A 2-bit Polarization-Insensitive Unit Cell for Triple Band Reconfigurable Intelligent Surface.* Paper presented at the 2024 IEEE Wireless Antenna and Microwave Symposium (WAMS).

Singh, K., Saikia, M., Thiyagarajan, K., Thalakotuna, D., Esselle, K., & Kodagoda, S. (2023). Multi-Functional Reconfigurable Intelligent Surfaces for Enhanced Sensing and Communication. *Sensors*, *23*, 8561. doi:10.3390/s23208561

Subrt, L., & Pechac, P. (2012). *Controlling propagation environments using intelligent walls.* Paper presented at the 2012 6th European Conference on Antennas and Propagation (EUCAP).

Tan, X., Sun, Z., Jornet, J. M., & Pados, D. (2016). *Increasing indoor spectrum sharing capacity using smart reflect-array.* Paper presented at the 2016 IEEE International Conference on Communications (ICC).

Tarafder, P., Chun, C., Ullah, A., Kim, Y., & Choi, W. (2025). Channel Estimation in 5G-and-Beyond Wireless Communication: A Comprehensive Survey. *14*(4), 750.

Trichopoulos, G., Theofanopoulos, P., Kashyap, B., Shekhawat, A., Modi, A., Osman, T., . . . Alkhateeb, A. (2022). Design and Evaluation of Reconfigurable Intelligent Surfaces in Real-World Environment. *IEEE Open Journal of the Communications Society, 3*, 1-1. doi:10.1109/OJCOMS.2022.3158310

Tu, Q., Dong, Z., Zou, X., Wei, N., Li, Y., & Xu, F. (2024). Dynamic reconfigurable intelligent surface deployment for physical layer security enhancement in mmWave systems. *IET Communications, 18*(5), 365-374.

Wang, J., Tang, W., Liang, J. C., Zhang, L., Dai, J. Y., Li, X., . . . Cui, T. J. (2024). Reconfigurable intelligent surface: Power consumption modeling and practical measurement validation. *IEEE Transactions on Communications*.

Wang, R., Yang, Y., Makki, B., & Shamim, A. (2024). A wideband reconfigurable intelligent surface for 5G millimeter-wave applications. *IEEE transactions on antennas and propagation, 72*(3), 2399-2410.

Wolff, A., Franke, L., Klingel, S., Krieger, J., Mueller, L., Stemler, R., & Rahm, M. (2023). Continuous beam steering with a varactor-based reconfigurable intelligent surface in the Ka-band at 31 GHz. *Journal of Applied Physics, 134*(11).

Wu, Q., & Zhang, R. (2019a). Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network. *IEEE communications magazine, 58*(1), 106-112.

Wu, Q., & Zhang, R. (2019b). Weighted sum power maximization for intelligent reflecting surface aided SWIPT. *IEEE Wireless Communications Letters, 9*(5), 586-590.

Wu, Q., Zhang, S., Zheng, B., You, C., & Zhang, R. (2021). Intelligent reflecting surface-aided wireless communications: A tutorial. *IEEE Transactions on Communications, 69*(5), 3313-3351.

Xing, Z., Wang, R., & Yuan, X. (2023). Reconfigurable intelligent surface aided physical-layer security enhancement in integrated sensing and communication systems. *IEEE Transactions on Vehicular Technology, 73*(4), 5179-5196.

Xu, Y., Li, Y., & Quek, T. Q. (2024). Distributed Reconfigurable Intelligent Surfaces–Enabled Indoor Localization Based on Wireless Fingerprinting. *IEEE Wireless Communications Letters, 13*(4), 1039-1043.

Yan, L., Wang, C., & Zheng, W. (2022). Secure efficiency maximization for UAV-assisted mobile edge computing networks. *Physical Communication, 51*, 101568.

Yang, H., Cao, X., Yang, F., Gao, J., Xu, S., Li, M., . . . Li, S. (2016). A programmable metasurface with dynamic polarization, scattering and focusing control. *Scientific Reports, 6*(1), 35692.

Yang, L., Yang, J., Xie, W., Hasna, M. O., Tsiftsis, T., & Di Renzo, M. (2020). Secrecy performance analysis of RIS-aided wireless communication systems. *IEEE Transactions on Vehicular Technology, 69*(10), 12296-12300.

Yao, Y., Liu, Q., Yu, K., Huang, S., & Yue, X. (2024). Performance Analysis of Distributed Reconfigurable-Intelligent-Surface-Assisted Air–Ground Fusion Networks with Non-Ideal Environments. *Drones, 8*(6), 271.

Zhang, C., Yang, X. X., Feng, Q., Lou, T., Yi, Z., Tan, G., . . . Gao, S. (2024). Millimeter-Wave Large-Angle Dual-Polarization Reconfigurable Intelligent Surface for 6G Communication Relay. *IEEE Antennas and Wireless Propagation Letters, 23*(10), 2900-2904. doi:10.1109/LAWP.2024.3413695

Zhang, S., Huang, W., & Liu, Y. (2024). A systematic survey on physical layer security oriented to reconfigurable intelligent surface empowered 6G. *Computers & Security*, 104100.

Zhu, Y., Vilenskiy, A. R., Iupikov, O. A., Krasov, P. S., Emanuelsson, T., Lasser, G., & Ivashina, M. V. (2024). *A varactor-based reconfigurable intelligent surface concept for 5G/6G mm-wave applications.* Paper presented at the 2024 18th European Conference on Antennas and Propagation (EuCAP).