Reconfigurable Intelligent Surface for 6G Communications: Overview, Control Mechanism, Application, and Opportunities

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Abstract- Reconfigurable Intelligent Surfaces (RIS) represent a transformative technology for next-generation wireless networks (e.g., 6G), addressing persistent challenges such as power consumption, spectrum scarcity, interference, and security vulnerabilities. RIS dynamically manipulates electromagnetic wave propagation through programmable phase, amplitude, and polarization adjustments, enabling control over wireless environments without active signal amplification. It's hardware architecture comprising passive, active, or hybrid elements offers cost-effective, energy-efficient, and easily deployable solutions compared to traditional massive MIMO systems. Key applications include coverage extension, spectral/energy efficiency enhancement, physical-layer security, beamforming management, and localization accuracy. RIS integrates seamlessly with emerging technologies like IoT, UAVs, vehicular networks, VLC, mmWave, and MEC networks. Despite its promise, challenges remain in hardware imperfections, channel-state information acquisition, mobility management, and security optimization. Future research directions focus on AI integration, RF sensing, hybrid VLC/RF networks, and scalable deployment strategies, positioning RIS as a cornerstone for sustainable, high-performance future communications.

Index Terms- 5G, 6G, AI, FSS, IoT, IRS, MEC, SER, UAV, mmWave

I. Introduction

Wireless systems continue to evolve, yet persistent challenges remain, including significant power consumption constraints, the fundamental inability to control the unpredictable wireless environment (leading to interference, path-loss, and fading), increasing spectrum scarcity, growing security vulnerabilities, the demand for massive device connectivity, the need for ultra-low latency Addressing these interconnected issues, particularly through intelligent management of electromagnetic wave interactions with surrounding objects, is crucial for mitigating negative effects and enabling future advancements. Over years of research, Reconfigurable Intelligent Surfaces (RIS) have generated substantial scientific literature and novel concepts [1]. Investigations have expanded to encompass deep learning integration, physical layer security solutions, and RIS applications in free-space optics (FSO), visible light communication (VLC), and millimeter-wave (mmWave) systems. Notably, RIS technology demonstrates seamless compatibility with existing wireless infrastructure, offering significant potential for performance enhancement. RIS, also known as intelligent reflecting surface (IRS) [2], reconfigurable smart surface (RSS) [3], software-controlled meta surface (SCM) [4], large intelligent surface (LIS) [5], and frequency-sensitive surface (FSS), Reconfigurable Intelligent Surfaces (RIS) represent an innovative technological paradigm that empowers 6G communication systems with unprecedented wireless capabilities [6]. To address spectrum scarcity, communication systems increasingly utilize higher-frequency bands with abundant unused spectrum. Nevertheless, the inherent stochastic unpredictability of wireless propagation persists. Conventional approaches treat the wireless channel as an uncontrollable stochastic link, countering its unreliability through advanced transmitter/receiver signal processing—including diversity techniques, beamforming, and adaptive modulation—to maximize capacity. Recently, reconfigurable intelligent surfaces (RIS) and smart radio environments [7], [8] enable partial control over the channel itself.

II. INTELLIGENT REFLECTIVE SURFACE

Per established definitions [9], [10], a Reconfigurable Intelligent Surface (RIS) is an electromagnetic meta-device engineered to dynamically control radio wave propagation through programmable phase manipulation. Structurally, an RIS comprises a two-dimensional planar array of passive sub-wavelength elements (termed IRS in [11]). These metamaterial-based units feature configurable phase-shifting capabilities, enabling programmatic redirection of incident electromagnetic waves to regulate signal behavior in wireless environments [12]. Reconfigurable Intelligent Surfaces (RIS) offer superior cost and energy efficiency compared to massive MIMO systems, which require dedicated RF chains per antenna element—significantly increasing hardware complexity, expenses, and power consumption [13]. One key feature of metasurfaces is their ability to support a wide range of electromagnetic (EM) functionalities [14]. Some common examples are briefly described below:

- **Reflection**: This function defines the reflection of an impinging wave, with a given direction of arrival, towards a custom direction.
- **Refraction**: This function defines the refraction of an impinging radio wave towards a specified direction that may not necessarily coincide with the direction of incidence.
- **Absorption**: This function ensures minimal reflected and/or refracted power for impinging waves.
- **Polarization**: This function changes the oscillation orientation of the wave's electric and magnetic field.

III. SURVEY METHODOLOGY

The survey methodology of this article is primarily divided into two sections. The following discussion elaborates on these parts in detail.

A. *Study Selection Criteria*

This section highlights the study selection criteria and research activities related to RIS. The criteria clarify the procedures used to select studies for this review, offering detailed guidance on the selection process. The review also discusses previous and ongoing research topics, key focus areas, and notable contributions in RIS-assisted communication.

1. **Briefly Review**: Choosing studies published between 2020 and 2025 that are free from contradictions. Begin by scanning the titles and abstracts to determine if the study is relevant. Once relevant studies are identified, proceed to the next step, which involves a thorough review of the full text
2. **Full Text Analysis:** Performing a detailed examination of the entire content, considering each sentence carefully. Decisions regarding inclusion or exclusion were made based on this analysis. Recent works in related areas published in academic journals, conferences, books, and accessible through ArXiv were also reviewed. In cases where authors have multiple similar publications, priority was given to the most significant work in the analysis. In summary, by reviewing the study title and abstract, readers can gain a clear understanding of the study's scope, since these components were explored in detail earlier. The core aspects of these two methods are briefly summarized in **Error! Reference source not found.**, which provides an overview of the main topics covered in the paper.

TABLE 1: General Overview of the Sorting Study's Topic

Prominence	**Category**
Publication	Renowned journal studies, scientific magazines, international conferences, scientific books, and research studies.
Year	2020-2025
Criteria for evaluating study choices	Initially, the primary focus of this scholarly document pertains to the title and abstract. Subsequently, select the suitable document and thoroughly peruse its entirety.
Exclusion	Similar works were recently published in journals, periodicals, and at prestigious scientific conferences and were accessible on ArXiv.
Inclusion	Focus on RIS working principles, architecture, communication, drawbacks, and new concepts.
The categorization of the study choice	This study discusses various aspects of RIS-assisted communication, including typical communication scenarios, the operational principles of RIS, challenges faced in RIS-assisted communications, hardware architecture, and signal propagation. It also explores current trends, potential opportunities, and application scenarios for RIS-assisted communication.

B. *Research Activities on RIS*

In recent years, numerous research projects, experiments, and studies on RIS systems have been carried out worldwide. Several important studies have been conducted, with their key contributions, research directions, and focus areas summarized in Table 3. This table offers an overview of the latest research on RIS technology and communication systems.

IV. SYESTEM OVERVIEW

This section provides an overview of the RIS system, highlighting some of the essential terms related to it. These terms will be organized clearly and systematically to ensure easy comprehension.

A. Hardware Architecture

As depicted in Fig. 1, a standard RIS design features three primary layers and a controller [11]. The outermost layer contains an array of metallic patches mounted on a dielectric substrate, which interfaces directly with incoming signals. Positioned beneath this layer, a copper plate minimizes signal leakage. The innermost layer houses the control circuit board, responsible for communicating with the controller and adjusting the phase shift and reflection coefficient of each individual reflective element.

No.	Ref.	Year	Contribution	Key Focus rea
1	[15]	2020	Radio localization and mapping with RIS	Radio localization and RIS-assisted mapping
2	[16]	2020	Comparison between RIS and relay technologies	Difference between RIS and relay
3	[17]	2020	Analysis of distance effects on RIS reflection in free-space communication	Bridging gap analysis of RIS
4	[18]	2020	Experimental analysis of phase shifts under various data rates	Phase shifts technique
5	[19]	2021	2021 RIS-aided MISO system with reflection pattern modulation	Reflection pattern modulation for beamforming
6	[20]	2021	Rayleigh fading modeling for RIS-aided communications	Channel hardening and Rayleigh fading modeling
7	[21]	2021	Optimization of data rate and energy efficiency using RIS phase shifts	Design of RIS
8	[22]	2021	Modeling and analysis of RIS for indoor/outdoor localization	Modeling and analysis of a RIS
9	[23]	2022	RIS-assisted non-terrestrial networks with system optimization	RIS-aided non-terrestrial networks communication
10	[24]	2022	Mathematical modeling of space-time digital metasurfaces	Architecture of RIS
11	[25]	2022	Performance evaluation of 160-element RIS at 5.8 GHz	RIS model design and analysis
12	[26]	2022	Optimization of wireless networks using RIS communication models	Develop a mathematical model for RIS-assisted
13	[27]	2022	Signal processing for beam shaping and SNR improvement	Signal processing approach for RIS-assisted
14	[28]	2022	Industrial perspective on RIS impact on smart radio environments	Impact of RIS on SRE
15	[29]	2022	Challenges and applications of RIS-based wireless sensing localization	Sensing and localization
16	[30]	2022	Survey of RIS hardware design and channel models	RIS hardware and channel model
17	[31]	2023	RIS hardware design and research gaps	RIS hardware
18	[32]	2023	Fundamentals of RIS sensing/communication for future deployment	RIS-assisted sensing and communication
19	[33]	2023	Capacity optimization for large RIS (LIS)	RIS and its capacity optimization
20	[34]	2023	Introduction to SRE, RIS-assisted performance, and next-gen systems	RIS-aided wireless communication
21	[35]	2023	Near-field MIMO channel multiplexing with RIS	MIMO channel with RIS
22	[36]	2023	Security design for RIS-assisted communication	Security for RIS-assisted
23	[37]	2023	Omni-digital RIS for indoor visible light communication	Omni-digital RIS

24	[38]	2023	Integration of active RIS components into UAV technology	RIS aided UAV communication
25	[39]	2023	Optimization of NGBS beamforming and RIS phase shifts	Energy efficient beamforming optimization in RIS
26	[40]	2023	Performance analysis of RIS-assisted backscatter communication with crypto holographic tags	Crypto holographic RIS aided backscatter communications
27	[41]	2024	Closed-form global optimization of beyond diagonal RIS	Beyond diagonal RIS optimization
28	[42]	2024	Static grouping strategy design for beyond diagonal RIS	Grouping strategy for beyond diagonal RIS
29	[43]	2024	RIS designs for physical layer security in 6G-IoT	Physical layer security for 6G-IoT
30	[44]	2024	Opportunities/challenges of RIS-aided near-field communications for 6G	Near-field communications for 6G
31	[45]	2024	Secure transmission design for RIS-UAV networks using deep reinforcement learning	Secure UAV communication with RIS and DRL
32	[46]	2024	Beamforming vector optimization in RIS-based non-terrestrial systems	Beamforming optimization in non-terrestrial systems
33	[47]	2024	Power consumption modeling and validation for RIS	RIS power consumption modeling
34	[48]	2024	Sum-rate maximization in STAR-RIS assisted RSMA via PPO algorithm	STAR-RIS assisted RSMA networks
35	[49]	2024	Hybrid DRL for localization/communication efficiency in RIS-aided ISAC	RIS-aided ISAC systems
36	[50]	2025	Transformation of ISAC with STAR-RIS: Design challenges and opportunities	STAR-RIS for ISAC
37	[51]	2025	Energy-efficient design of active STAR-RIS aided SWIPT systems	Active STAR-RIS for SWIPT
38	[52]	2025	Sustainability framework for RIS vs. relays power efficiency	Sustainability of RIS vs. relays
This study			This paper presents a comprehensive review of Reconfigurable Intelligent Surfaces (RIS) technology. It covers key aspects such as hardware architecture, essential features, control mechanisms, and modes of operation. The study also examines the control panel, deployment methods. Additionally, it explores the application of RIS in wireless communication.	A complete overview of RIS system, deployment, control panel, operating environment, advantages and so on.

The RIS controller itself typically employs either a microcontroller unit (MCU) or a field-programmable gate array (FPGA). This controller acts as a communication gateway, connecting the RIS to the NGBS and other network elements via dedicated wired or wireless links. The NGBS generally computes the optimal phase shifts for the RIS and transmits these configurations through the controller. FPGA devices are particularly suitable for high-speed 6G applications due to their superior clock frequency, enabling rapid switching operations [55].

Accounting for different wave propagation types, the RIS circuit diagram can be categorized into three distinct sections, as outlined below. • Active RIS • Passive RIS • Hybrid RIS The specifics of these component elements for the RIS:

1. **ACTIVE RIS:** Active RIS incorporates sequential signal processing units and high-power RF circuitry, distinguishing it from passive designs. Unlike passive RIS, active RIS can transmit and receive signals across its entire surface or employ selected components to achieve expanded functionality. These systems represent an evolution from traditional massive MIMO, enabling denser integration of software-controlled antenna elements on a confined two-dimensional plane. Semi-active RIS, conversely, feature structures where only a portion of the components possess transmit and/or receive capability. The discrete photonic antenna array exemplifies active RIS, integrating active optoelectronic detectors, converters, and modulators for optical or RF communication.
2. **Passive RIS:** A passive RIS is constructed from numerous passive components, each capable of reflecting incoming waves with a controllable phase shift. Typically, each component features a reflecting patch linked to a phase-changing circuit with adjustable impedance [56]. Due to the absence of active RF elements, a passive RIS component rarely requires direct current power and typically generates negligible thermal noise [57].
3. **Hybrid RIS** A hybrid RIS simultaneously reflects an impinging signal wave while detecting a portion of it. This approach enhances coherent communications while retaining the energy efficiency and coverage extension advantages of passive RIS. One

implementation method fully loads the surface with varactors, altering their capacitance via an external DC signal. This phase modulation steers the reflected beam in the desired direction.

B. *Physical Design*

Intelligent surfaces are constructed from meta-atoms arranged in a repeating pattern across a substrate. Metasurfaces typically contain several hundred meta-atoms, with a minimum size requirement of approximately 30×30 elements [58]. Designs can utilize either static meta-atoms or dynamic ones. Dynamic meta-atoms incorporate phase-switching components capable of altering the meta-atom's structure. Although all intelligent surface types are based on metamaterials, each type necessitates a distinct design solution.

RIS design relies primarily on three key factors. The first factor is the two-dimensional structure of the RIS, meaning the transverse size of the model is significantly larger than its thickness. The second factor is the composite layers based on meta-atoms. Fig. 2 shows that the RIS is composed of a composite material layer made of patches printed on a dielectric substrate. These patches are responsible for the macroscopic behavior of the surface.

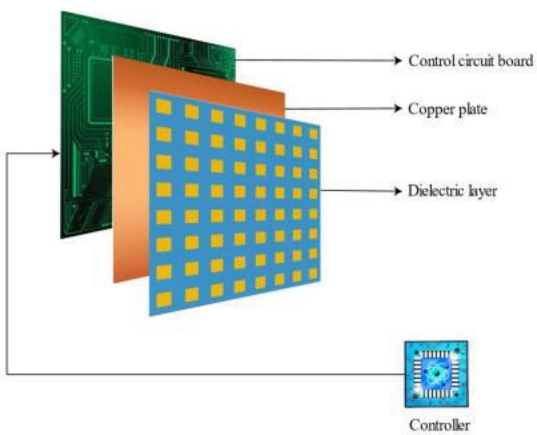


Fig. 1: Hardware architecture of RIS.

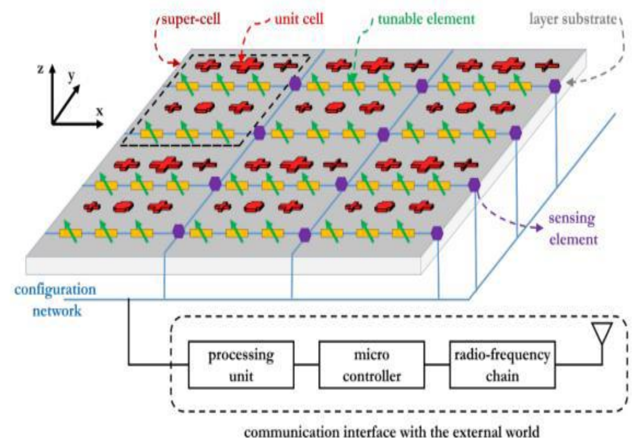


Fig. 2: Conceptual structure of a reconfigurable intelligent surface [14].

Last element is the phase reconfiguration controller. Dynamic operation of the RIS is enabled by low-power electronic components like Positive Intrinsic Negative (PIN) diodes.

A PIN diode is a three-layer semiconductor (P-I-N) that functions as a smart electrical switch: When forward-biased (+), charge carriers flood the middle intrinsic layer, making it conductive. When reverse- biased (-), carriers deplete, restoring insulation. This enables real-time control over the phase of electromagnetic waves reflected by Reconfigurable Intelligent Surfaces (RIS), acting as a "tunable mirror.

C. *Key Characteristics*

While RIS implementations vary across research groups, they maintain consistent core structural and communication principles. The key characteristics of RIS are outlined below.

1. **Nearly Passive**: Unlike systems that amplify reflected signals, the IRS modifies wireless channels by controlling signal reflections. This is accomplished using minimal electrical power to program phase shifts. Crucially, IRS avoids the analog-to-digital/digital-to-analog conversions and power amplification required in traditional wireless systems, both during setup and operation. This positions IRS as a more energy-efficient and cost-effective solution for wireless communication.

2. **Reconfigurable**: RIS enables independent control over the frequency, amplitude, phase, and polarization of the signal reflected from each element. This inherent reconfigurability allows real-time shaping of signals across the entire surface, making dynamic adaptation essential given its continuous aperture nature.

3. **Easy to Deployment**: RISs are light and flat surfaces that can be easily mounted on the outer walls, ceilings, or windows of buildings. The hardware structure of RISs is illustrated in **Error! Reference source not found.**. The design of RIS includes two main components: the sensing component and the control component, which is an electronic device. The sensing part consists of three elements: the reflective panel, the circuit board, and the copper backplane. The reflective panel is densely populated with two-dimensional adjustable metamaterial elements that can be controlled individually to interact with the source signals and modify the

reflected signal. To minimize signal loss, a copper backplane is utilized. Beneath the copper backplane in the control layer, there is a 6G intelligent control system and a circuit board.

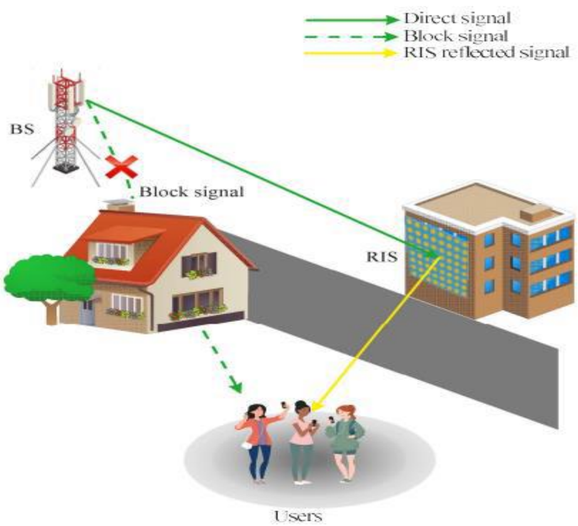


Fig. 3: Deployment of RIS in a building for communication.

D. Control Mechanism

The tuning mechanism of an RIS is primarily governed by its hardware implementation and geometry. Based on these factors, RIS phase shift control is broadly classified into three tuning approaches. These include:

- Circuit tuning
- Geometric tuning
- Material Tuning

Detailed explanations of these tuning mechanisms follow in the next section.

1. **Circuit Tuning**: Unit cell circuit design modifies specific impedance characteristics, achieved by integrating variable capacitors and switches embedded within the unit cell structure.

2. **Geometric Tuning**: This approach physically reshapes the unit cell, enabling significant signal phase shifts through corresponding changes in its circuit model.

3. **Material Tuning**: Altering the properties and behavior of a substrate layer or unit cell sub-component requires changing its material characteristics. Additional control mechanisms can be used alongside these tuning methods to achieve RIS-assisted communication goals, necessitating proper component configuration.

E. Communication Duplex Mode

A duplex communication system enables bidirectional communication between connected devices. Essential for modern networks, it provides continuous two-way data exchange, allows remote modification of field equipment, and supports bidirectional monitoring. The three primary duplex modes are Time Division Duplex (TDD), Frequency Division Duplex (FDD), and Full Duplex. These modes are applicable in RIS-aided communication systems.

TDD Mode: it is common knowledge that channel reciprocity exists between the Downlink (DL) and Uplink (UL) channels that share the same frequency band. The preservation of channel reciprocity by RIS depends on the manufacturing methods employed. In situations where reciprocity is valid for RIS TDD systems, the same RIS configuration, including phase shifts, amplitudes (or beam directions), can be utilized for both DL and UL transmissions. Specifically, in TDD mode, RIS can receive downlink signals from the network, reflect them to User Equipment (UE) in one time frame (e.g., one or multiple OFDM symbols), and then receive uplink signals from UE(s) and reflect them back to the network in another time frame. While the UL and DL reception/reflection may occur on the same frequency, they happen in different time frames. A guard period may be set up for RIS during DL/UL switching to prevent interference between UL and DL reflection/reception at the RIS. TDD can involve two modes: reciprocity-constrained mode and reciprocity-non-constrained mode. Generally, channel reciprocity can be maintained in most RIS hardware setups. However, depending on the fabrication techniques used for RIS, reciprocity may not always be guaranteed. To operate in the reciprocity-constrained mode, channel reciprocity can be ensured by configuring RIS element phase shifts to reflect UL/DL signals towards Base Stations (BS)/UEs, enabling them to transmit and receive signals using the same beams. In the reciprocity-non-constrained mode, channel reciprocity may not be necessary, and RIS phase shifts can be set independently of UE/BS UL/DL beams. **Error! Reference source not found.**(a) and **Error! Reference source not found.**(b) provide illustrations for both reciprocity-constrained and reciprocity-non-constrained modes.

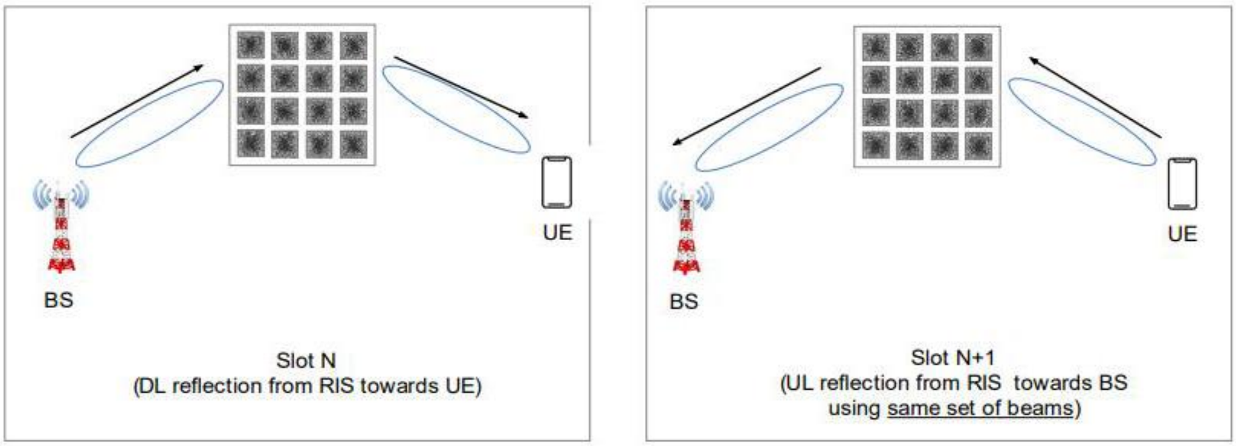
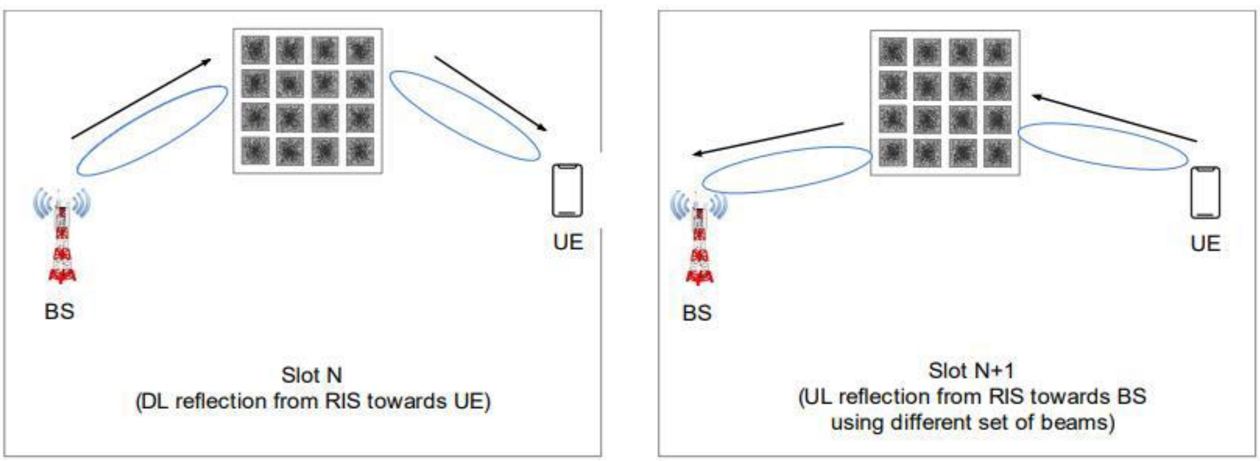


Fig. 4(a): TDD communication with reciprocity-constrained mode at UE using same set of phase shifts for UL and DL at RIS



(b) ITDD communication with reciprocity-non-constrained mode at UE using . different set of phase shifts for UL and DL at RIS

FDD Mode: downlink (DL) and uplink (UL) channels operate on separate frequency bands. Consequently, channel reciprocity does not apply to RIS-aided FDD systems. Using identical RIS configurations—such as phase shifts, amplitudes, or beam directions—for both DL and UL can degrade performance. Thus, RIS design and operation for FDD bands demand specific strategies.

FULL DUPLEX Mode: RIS simultaneously reflects downlink (DL) and uplink (UL) signals on the same frequency band. Compared to half-duplex systems, this introduces additional interference challenges. Consequently, specialized design considerations are essential to mitigate interference while leveraging full-duplex advantages.

F. Operating Mode

There are six operating modes in RIS-assisted wireless communication [59]. They are given below:

- Transmitting mode
- Receiving mode
- Reflection mode

- Reflection mode
- Absorption mode
- Backscattering mode

The rest of the description of this operating mode is discussed beneath.

1. **Transmitting Mode**: By incorporating RIS into radio transmitters, the shape of transmitted radio waves can be reconfigured. Dynamic Metasurface Antennas (DMAs) offer an efficient realization of large antenna arrays for this purpose. DMAs enable beam tuning and analog signal processing for both transmitted and received signals, operating with simpler, dynamically programmable transceiver hardware. DMA-based systems consume significantly less power and cost less than traditional antenna arrays, potentially eliminating the need for complex corporate feeds or active phase shifters. Furthermore, DMAs comprise densely packed, tunable metamaterial-based elements within compact physical spaces, supporting a wide range of operating frequencies. A typical reflecting RIS uses a DMA structure with multiple waveguide-fed element arrays, each connected to a single input/output port. These waveguides manage numerous radiating elements, and sub-wavelength spacing allows each port to feed many potentially coupled radiators. In two-dimensional waveguides, waves disperse from each element in all directions. However, the proposed one-dimensional waveguide is simpler to analyze, typically designed for single-mode operation where signals propagate along a single line. Port isolation is also more manageable in one-dimensional waveguides compared to two-dimensional structures.

2. **Receiving Mode**: In receiving mode, RIS can capture and process radio signals. This is achieved by integrating wavelength guides within individual RIS elements or element groups, directing incoming waves to receiving hardware. This hardware typically includes a low-noise amplifier, an RF-to-baseband mixer, and an analog-to-digital converter.

3. **Reflection Mode**: Early RIS concepts focused on passive systems with near-zero power consumption per element. These elements are vital as they modify how electromagnetic (EM) waves are reflected, enabling diverse wave reception adjustments. Precise beamforming—essential for quasi-free-space beam manipulation—requires exact control over reflected EM fields. Sub-wavelength meta-atoms, despite inherent strong reciprocal coupling and grayscale-tunable EM properties, are well-suited for this. In dense scattering environments, signal energy disperses evenly, causing rays to strike the RIS from all directions ("ray pandemonium"). The goal shifts from directional beamforming to manipulating numerous ray paths: altering rays for constructive superposition at a target location and directing the EM field efficiently. RIS equipped with half-wavelength meta-atoms effectively controls multiple rays using a fixed number of electrical components.

4. **Refraction Mode**: In refraction mode, EM waves passing through the RIS are redirected in multiple directions via phase alteration. Unlike reflection mode, no shielding layer exists beneath the RIS panel, permitting wave transmission. This mode is particularly useful for outdoor-to-indoor transitions. RIS can function as window glass, focusing incoming EM waves on specific indoor target areas to enhance coverage within buildings.

5. **Absorption Mode**: In absorption mode, incident radio waves within a specific center frequency and bandwidth are entirely absorbed, producing no reflection. This operation offers significant benefits for interference mitigation, privacy, and information security. A common application involves deploying RIS on building facades to block EM waves, isolating indoor/outdoor areas or internal rooms. The RIS plane absorbs incident signals, preventing penetration through walls. Bias voltage can regulate switching between refraction, absorption, and reflection modes. For example, graphene-based RIS can achieve nearly 100% absorption in designated bands based on device design [79]. Electrically tuning the meta-atom response via graphene's chemical properties enables perfect absorption.

6. **Backscattering Mode**: Backscattering mode produces a reflected wave that spreads over a wide area instead of focusing on a specific point. Achieving wide-angle blind-spot coverage thus requires balancing gain and effective area. This mode is utilized by passive RIS [79], which reflects incident EM waves in predetermined directions.

G. Operating Frequency

The following section specifies suitable frequency bands for RIS in wireless networks. There are two frequency ranges (FR): FR1 and FR2. The frequency range for FR1 is 410 MHz to 7,125 MHz, while FR2 covers a range of 24,250 MHz to 71,000 MHz [79]. The following are the frequency bands suitable for RIS-aided wireless communications.

1. **SUB-6GHZ Band**: FR1 spans 410 MHz to 7,125 MHz, initially designated as sub-6 GHz but extended to 7,125 GHz through additional spectrum licensing [79]. This range incorporates authorized TDD and FDD bands for RIS operations. These bands support significant cellular traffic (e.g., LTE, NR) and deliver extensive coverage in cellular networks.

2. **mmWAVE Band**: FR2 (24,250–71,000 MHz) is termed the mmWave band. It permits RIS operations via TDD and FDD bands [97]. Networks like NR prioritize FR2 for ultra-high throughput owing to its substantial bandwidth potential.

3. **THZ Band**: THz bands cover 0.1–10 THz, with sub-THz bands occupying 0.1–0.3 THz [80]. Current evaluations focus solely on TDD implementations at these frequencies. While 3GPP-directed RIS applications target FR1/FR2, THz/sub-THz bands are emerging for 6G networks due to high bandwidth and channel capacity. Communications in these ranges are inherently short-range, unstable, and prone to obstruction/absorption, necessitating consistent line-of-sight (LOS) links. RIS mitigates these issues by adapting propagation environments to sustain LOS connectivity. Deploying multiple RIS units enriches multipath characteristics in single-rank channels, enhancing spatial multiplexing. RIS also extends coverage for sub-THz/THz bands and can leverage synergies with lower FR1/FR2 bands (similar to 5G NR) to maximize network coverage.

4. **Unlicensed Band**: Unlicensed bands in FR1/FR2 are increasingly utilized worldwide. RIS operation at specific unlicensed frequencies may require channel access techniques. Depending on local regulations and deployments, methods analogous to cellular networks (e.g., LTE/NR) could be adopted—e.g., active RIS using Listen-Before-Talk (LBT) for channel access, configured by controlling nodes (e.g., gNB, UE). Compliance with power constraints (e.g., regulatory maximum Equivalent Isotopically Radiated Power limits) is also critical for RIS in unlicensed bands.

V. CONTROL PANEL

The RIS control plane governs the meta surface element group and optimizes channel quality for designated uplink, downlink, and NGBS links within a specified area. Its functionalities include:

- Channel measurements are performed between the network nodes and RIS, as well as between mobile devices and RIS
- Measurement for positioning.
- Mode selection by controlling RIS
- Selection of RIS configuration and providing the desired configuration to RIS.
- Obtaining and communicating essential information and control plane status information to the RIS controller.

Comprising diverse functions, the control plane activates RIS configurations across various timeframes and retrieves real-time RIS states. Control plane functions are categorized by RIS management approach:

- Centralized management of NGBS.
- Distributed management of NGBS.
- Autonomous RIS.
- User controlled RIS.

The descriptions of these approaches are follow:

1. **Centralized Management of NGBS**: Network-layer centralized RIS administration allocates/modifies one or more NGBSs to provide appropriate RIS configurations. The control plane resides at a central node, which analyzes measurements/feedback to determine RIS configuration adjustments. After deciding updated settings, the central node communicates them to the NGBSs, instructing delivery to the RIS. Collaboration between NGBSs is unnecessary.

2. **Distributed Management of NGBS**: Contributing NGBSs handle distributed RIS management on the network side, hosting the RIS control plane. The NGBS interfacing with the RIS analyzes measurements/feedback and decides configuration changes. When multiple NGBSs interact with the RIS, collaboration is essential to prevent conflicts. Cooperative techniques can optimize network metrics (e.g., performance) when multiple distributed NGBSs manage numerous RIS.

3. **Autonomous RIS**: Autonomous RIS technology optimizes reflected beam gain between NGBS and user equipment without dedicated control plane capabilities, often classified as hybrid RIS and potentially requiring power-sensing. By sequentially activating probing beams, it obtains a power profile. It identifies angular locations of the NGBS and user equipment by detecting power profile peaks, computes the optimal configuration locally, and activates it automatically based on these locations.

4. **User Controlled RIS**: RIS can be deployed in personal/local access networks (e.g., indoor), operating in unlicensed spectrum (like Wi Fi) or licensed spectrum (like 3GPP Customer Premises Network - CPN or Personal IoT Network - PIN). In CPN/PIN (small-

scale personal networks within public coverage), management is handled by elements like the Evolved Residential Gateway (eRG) for CPN or the PIN element for PIN. For Wi Fi, management is by WiFi APs [18]. User equipment (UEs) in these networks may have direct/indirect connections. Within a RIS-integrated CPN, the eRG may enable a UE to manage the RIS, establishing/maintaining links with other CPN UEs. Similarly, in a RIS-integrated PIN, a PIN component (3GPP/non-3GPP device) can control the RIS to connect other PIN components. The eRG or PIN element sets the RIS operating frequency. Operation in licensed spectrum requires initial network authorization.

VI. ADVANTAGES

Reconfigurable Intelligent Surfaces (RIS) offer key advantages for wireless communication systems, including:

1. **Coverage Enhancement**: Uneven wireless signal coverage may occur due to obstacles such as tall buildings or trees, resulting in insufficient coverage in specific areas of the cellular network. These areas with weak coverage can lead to significant issues as devices in these locations may not receive adequate quality-of-service levels. One proposed solution to mitigate this challenge involves deploying additional Access Points (APs) in the poorly covered areas. However, this solution can be costly and inefficient. An alternative, cost-effective, and straightforward approach is to utilize Reconfigurable Intelligent Surfaces (RIS). By strategically placing RIS in suitable locations, Line-of-Sight (LOS) propagation paths can be established between APs and RIS, as well as between RIS and the devices in the areas with limited coverage. For example, Fig. 5 illustrates the blockage issue that arises when the Next-Generation Base Station (NGBS) is located in one corridor but needs to serve User Equipments (UEs) in an adjacent hallway. The use of RIS can help overcome this obstacle, enabling the connection despite significant penetration loss.

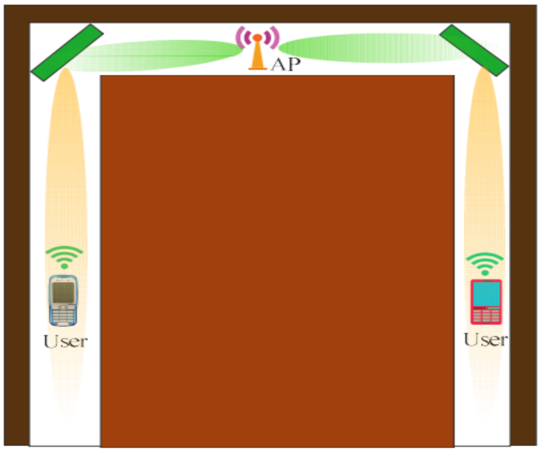


Fig. 5: Coverage enhancement of RIS.

2. **Spectral Efficiency**: In wireless communication systems, the channels between transmitting and receiving antennas may exhibit high correlation, which can limit the available eigenchannels for concurrent data transmission. However, this issue of channel correlation can be addressed by integrating Reconfigurable Intelligent Surfaces (RIS). RIS implementation can enhance spatial multiplexing benefits and spectrum efficiency by expanding the pool of eigenchannels accessible for data transmission. By boosting received signal strength, RIS can enhance coverage and elevate spectral efficiency simultaneously. Furthermore, RIS can increase degrees of freedom in the channel and spatial multiplexing rank, particularly in scenarios where a few dominant pathways exist, often seen at higher frequencies. Additionally, RIS can mitigate disruptions like channel and inter-cell interference.

3. **Energy Efficiency**: In cases where communication between transmitters and energy-harvesting users faces challenges, Reconfigurable Intelligent Surfaces (RIS) can play a pivotal role in facilitating power transfer between Next-Generation Base Stations (NGBSs) and users. An additional benefit of RIS is that users can not only receive the transmitted signal but also gain from the accumulated energy provided by the RIS, resulting in decreased transmission power and enhanced energy efficiency. The evolving demands of future networks beyond 6G, with their high data rate requirements, have highlighted energy consumption as a significant concern. To promote environmentally conscious and sustainable wireless networks, several energy-efficient technologies have been developed. The implementation of RIS holds the promise of substantially enhancing network efficiency in terms of coverage and data rates. The RIS-assisted framework necessitates lower NGBS transmit power and a reduced number of NGBSs to attain specific coverage or data rate objectives. Relative to traditional amplify-and-forward relay solutions, RIS-assisted deployments present an appealing choice for enhancing network performance, decreasing network energy usage, and elevating network energy efficiency. Similarly, the integration of RIS can enhance user energy efficiency through RIS-assisted uplink transmission. The mostly

passive behavior of RISs has been identified as a key benefit in terms of energy; however, it also limits the rate performance that a RIS-aided network can provide [60], [61], particularly if there is no direct channel available [62].

4. **Beamforming Management**: Beam management is a widely used technique in wireless communication networks, such as NR, to reduce signal losses during transmission. It involves creating and maintaining a network of beam pair connections between the sender and the receiver to optimize network performance and ensure reliable coverage, especially in high-frequency bands. Beamforming with Reconfigurable Intelligent Surfaces (RIS) is achieved by adjusting the reflecting angle of each element, allowing multiple groups of elements to point to different users with signal strength proportional to the number of elements. Compared to massive Multiple Input, Multiple Output (MIMO) systems, RIS requires less power to achieve the same beamforming gain. A multi-element RIS, similar to MIMO, can generate beams to direct signals towards individual users or specific directions. The reflective elements on RIS can produce signals with similar wavelengths, resulting in increased signal intensity in a specific direction for targeted beams.

5. **Physical Layer Security**: The physical layer can impact the security of communication systems due to the unpredictable dispersion of confidential signals through electromagnetic propagation channels. However, Reconfigurable Intelligent Surfaces (RIS) can help establish a controlled wireless propagation environment to prevent the leakage of sensitive signals to eavesdroppers and improve communication privacy. Without RIS, data transmitted to user equipment is easily vulnerable to exposure through ordinary reflections off surfaces such as walls and ceilings. By using RIS, these reflections can be directed towards a "trusted region," thereby reducing data leakage to potential eavesdroppers and enhancing communication security. Nonetheless, it is important to recognize that RIS can also be exploited maliciously. An eavesdropper might deploy RIS to leverage its ability to create a strong wireless link with a legitimate system, enabling successful decoding of transmitted data. In such scenarios, broadcasting artificial noise by the legitimate system may not suffice to ensure secrecy, necessitating consideration of the legal deployment of RIS.

6. **Localization Accuracy**: By leveraging Reconfigurable Intelligent Surfaces (RIS), communication networks can enhance spatial resolution and achieve precise positioning, capabilities that traditional wireless networks may struggle to deliver due to limitations in precision stemming from factors such as position, Line-of-Sight (LOS) availability, and the number of Base Stations (BS). The deployment of RIS is not only more flexible but also more cost-effective than deploying additional BS. Furthermore, RIS has the potential to enhance location accuracy in indoor environments.

7. **Link Management**: RIS can be positioned on the rear side of shelves and walls to streamline automated intra-rack connectivity management and inter-rack connectivity management for unconnected racks, leveraging THz or mmWave technologies. Machine learning algorithms can play a pivotal role in automating the various tasks involved in setting up and supervising such a system. This system based on RIS technology presents a fresh level of automated data center reconfiguration, along with resilience against hardware failures and alterations.

VII. RIS-AIDED WIRELESS COMMUNICATIONS

Numerous recent research studies indicate that incorporating Reconfigurable Intelligent Surfaces (RIS) enhances both the spectral and energy efficiency of wireless signals, while also expanding the signal coverage area of wireless networks. This research delves into the emerging advantages of integrating RIS with various evolving communication technologies such as vehicular ad hoc network communications, Visible Light Communication (VLC), millimeter-wave communication, railway communication systems, Terahertz (THz) communications, Mobile Edge Computing (MEC) networks, underwater wireless communication, backscatter communication, UAV communication, IoT networks, and more.

1. **RIS-Aided IoT Communication**: The interconnection of various devices and gadgets through the Internet of Things (IoT) network is captivating as it enables data exchange for purposes like smart homes, industrial automation, healthcare monitoring, and more. Despite significant progress in this field, there are fundamental challenges that must be addressed for the full potential of IoT networks to be realized. One critical issue is the limited range of low-power IoT devices, necessitating efficient power solutions for densely deployed devices. Additionally, the scarcity of radio spectrum poses a challenge to IoT network performance. Innovative approaches such as Simultaneous Wireless Information and Power Transfer (SWIPT) and backscatter communication have emerged to tackle the energy constraints of IoT devices, while cognitive radio technology addresses spectrum scarcity. However, these solutions alone may not suffice for the requirements of future IoT networks beyond 6G. To meet the demands for energy harvesting, data reliability, channel capacity, energy and spectrum efficiency, and operating frequency range, Reconfigurable Intelligent Surfaces (RIS) can be leveraged to coherently integrate signals and optimize received signal strength, enhancing overall system performance.

2. **RIS-Aided UAV Communication**: Unmanned Aerial Vehicles (UAVs), or drones, offer diverse applications including relaying, data collection, and secure data transport when equipped with modern batteries, receivers, and transmitters [63], [64], [65]. Their significant mobility and flexibility make them suitable aerial platforms for wireless communication using existing technologies like cellular networks [66], [67]. Integrating Reconfigurable Intelligent Surfaces (RISs) with UAV-based wireless communication can improve signal performance. For example, in dense urban environments or during mmWave communications, the direct Line-of-

Sight (LOS) RIS path between the UAV and ground node can be blocked, degrading communication [68], [69]. In these scenarios, RIS can enhance signals by establishing alternative communication links. Furthermore, RIS can address inter-cell interference in future beyond-6G UAV networks by destructively combining wireless signals. This interference arises from favorable channel conditions between terrestrial Next-Generation Base Stations (NGBSs) and UAVs in adjacent cells. Furthermore, within UAV-assisted relay communication networks, the adoption of airborne Reconfigurable Intelligent Surfaces (RIS) can notably enhance network coverage and signal connectivity when compared to terrestrial RIS. The adaptable reflection capabilities of RIS can enhance the established cellular link of UAVs, which initially stems from Next-Generation Base Stations (NGBSs) with downward-tilted antennas. The diagram clearly illustrates the coherent integration of direct and RIS-reflected connections of UAVs, resulting in a collective increase in signal strength.

3. **RIS-Aided Vehicular Networks Communication**: Intelligent Transport Systems (ITS) and autonomous vehicles represent cutting-edge technological paradigms for 6G wireless networks. Vehicle-to-Everything (V2X) technology is emerging as a viable approach to enhance road safety, traffic efficiency, fuel conservation, and road management. However, the dynamic nature of the wireless signal propagation environment renders vehicular communication links highly unreliable. To address this challenge, Reconfigurable Intelligent Surfaces (RIS) can be integrated into vehicular communication. By intelligently manipulating signal wave reflections, RIS enhances channel stability, thereby improving communication performance and extending coverage. Fully realizing the potential of RIS in V2X communication requires optimizing RIS phase-shifts alongside resource management and vehicular arrangement. Recently, the authors introduced an iterative resource allocation algorithm designed for next-generation RIS-aided vehicular communication to optimize resource allocation [70].

4. **MEC Network For RIS-Aided Wireless Communication**: IoT networks enable diverse applications such as automated home appliances, smart cities, autonomous vehicles, digital healthcare monitoring, intelligent transportation, industrial automation, and disaster management [71]. However, the reliance on low-power wireless devices in these networks imposes significant strain, as such devices lack the computational capacity for resource-intensive applications. Multi-access Edge Computing (MEC) offers a viable solution by offloading processing tasks to servers at the network edge. These MEC servers share the computational load among devices, reducing latency for real-time networks by performing processing near wireless nodes. Yet, effectively leveraging MEC in practice faces challenges, particularly in highly dynamic network environments where communication links change rapidly. Furthermore, severe path loss significantly increases offloading delays when mobile devices are distant from MEC nodes, limiting overall network performance. Integrating Reconfigurable Intelligent Surfaces (RIS) into MEC communication systems can help mitigate these issues.

5. **RIS-Aided VLC**: Visible Light Communication (VLC) is an advanced technology that transmits signals using visible light wavelengths (380 nm to 750 nm). Recognized as one of the most promising indoor communication solutions within Optical Wireless Communication (OWC) [72], VLC is poised for widespread adoption due to its high channel capacity and enhanced connectivity [73]. Notably, VLC can achieve data rates dramatically exceeding those of traditional RF systems—by more than 10,000 times [74]. The operational principles of the conventional Visible Light Communication (VLC) system and the RIS-enhanced VLC system exhibit similarities. Nevertheless, the RIS-enhanced VLC system offers a distinctive advantage through the utilization of an intelligent metallic surface.

6. **RIS-Aided mmWAVE Communication**: Reconfigurable Intelligent Surfaces (RIS) have the potential to provide effective alternate paths for communication in millimeter-wave (mmWave) transmissions, particularly in scenarios where direct communication between the base station and end user is impeded by obstacles. The wide bandwidth range of mmWave frequencies allows for gigabits-per-second (Gbps) transmission speeds, meeting the data rate requirements of wireless applications. Nonetheless, the escalation in the number of active antennas and radio frequency (RF) chains in mmWave communications leads to increased hardware costs and energy consumption. Furthermore, the channels utilized in mmWave communication are more susceptible to obstructions and exhibit higher overall propagation losses. By integrating RIS between Next-Generation Base Stations (NGBSs) and end users, the reflective and refractive properties of RIS can be leveraged to address dead zone concerns by establishing connections among Line-of-Sight (LOS) channels, the Access Point (AP), and client devices, consequently resulting in enhanced Spectral Efficiency (SE) and throughput [75].

VIII. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

RIS is a promising technology for the forthcoming 5G communication systems. Although it provides several benefits, such as improved signal strength and extended coverage, it also presents certain limitations that must be considered during its deployment for communication purposes. In this context, some of the challenges related to RIS are discussed in detail below.

A. Hardware Imperfection

Historically, a majority of the research concerning RIS-assisted networks in communication has concentrated on theoretical scenarios, neglecting the influence of hardware imperfections and channel anomalies. Yet, in real-world implementations, hardware imperfections can notably constrain the efficacy of RIS-supported systems. Hence, evaluating system performance without acknowledging these factors might lead to inaccurate outcomes. Furthermore, exploring the underlying reasons for these imperfections is advantageous for enhancing system functionality.

B. PHY-Layer Security

Enhancing PHY-layer security is crucial for securing future wireless networks. This can be achieved by manipulating random signal noise in distributed systems, securing eavesdropping links, utilizing channel dissipation against legitimate interference, and implementing Wyner's wiretap coding [67]. When existing PHY-layer security methods prove insufficient, Intelligent Reflecting Surfaces (IRS) offer a promising technology to boost the secrecy rate of wireless networks.

C. RF Sensing and Localization

RIS technology holds potential for RF sensing and localization. Its large aperture and ability to manipulate the propagation environment can significantly enhance RF sensing capabilities [77]. Research in demonstrates promising applications in energy-saving surveillance, assisted living, and remote health monitoring. However, designing RIS setups to optimize RF sensing remains an open challenge. A viable approach involves precisely creating and monitoring a suitable sensing condition by modifying the wireless channel.

D. RIS-Aided OWC

In contrast to RF technology, Optical Wireless Communication (OWC) is renowned for its cost-effective hardware and high data transmission speeds. Nevertheless, optical communications can encounter challenges from environmental obstructions, hindering direct wireless use. Establishing a clear Line of Sight (LOS) between the transmitter and receiver is essential for effective OWC functionality. Leveraging RIS technology enables the precise directing of optical beams to mitigate LOS obstacles and surmount this restriction. Furthermore, integrating RIS technology into OWC can foster new connections and significantly extend the scope of optical communication. Through strategic placement of multiple RIS elements, alternate paths can be created, enhancing system efficiency and reducing outage risks.

E. Channel State Information Acquisition

For modern wireless systems incorporating RIS, swift and accurate acquisition of Channel State Information (CSI) is pivotal, particularly in Multiple-Input Multiple-Output RIS (MIMO-RIS) and Multiple-Input Single-Output RIS (MISO-RIS) networks. Extensive research has been conducted on achieving flawless CSI for Next-Generation Base Stations (NGBS), RIS controllers, and users. However, acquiring CSI in RIS-enabled contemporary wireless networks is a complex endeavor that entails substantial training overhead. Furthermore, in RIS-assisted Non-Orthogonal Multiple Access (NOMA) networks, device users within each cluster must cooperate regarding CSI and mutual interference cancellation. Due to the passive nature of RIS elements, CSI acquisition and exchange pose challenges. Deep Learning (DL) methodologies have been proposed to leverage CSI structures and advance solutions beyond linear dependencies.

F. RIS-Aided Mec Networks

Execution of computationally intensive tasks like image and video processing, along with real-time virtual reality applications, necessitates Mobile Edge Computing (MEC) networks. However, most Virtual Reality (VR) systems encounter limitations in remote task execution due to hardware and power constraints. To address these constraints, potent processing units positioned near the network edge can offload the tasks. Nonetheless, in certain scenarios, when all components are distantly located from MEC network communication devices, reduced data transfer speeds may occur due to severe signal attenuation, resulting in notable offloading delays. To mitigate this challenge, a specialized RIS-supported MEC architecture can mitigate path loss, low data rates, and latency concerns.

G. RIS-Aided VLC/RF Hybrid Networks

RIS introduces an economical and low-power consumption approach that can revolutionize the physical propagation environment into a fully customizable, computational, and adaptable space. RIS-assisted Visible Light Communication (VLC) systems have emerged as a prominent technology in 6G systems, making a mark in the technological landscape for their unique applications. The efficacy of VLC systems heavily relies on effectively overcoming LOS obstacles in highly dynamic settings, like vehicle, Unmanned

Aerial Vehicle (UAV), and Optical Wireless Communication (OWC) applications, where LOS challenges can compromise wireless communication reliability. Integrating RIS into LiFi-supported networks assists in alleviating congestion while enabling intricate network system interactions. Moreover, RIS-enhanced hybrid VLC-RF networks exhibit remarkable channel capacity, spectral efficiency, and expanded coverage attributes. This integration holds promise for delivering substantial solutions for future 6G networks and communication systems, offering significantly low latency, ultra-reliability, energy efficiency, and seamless connectivity.

H. RIS-Aided UAV Communication

RIS-empowered Unmanned Aerial Vehicle (UAV) communication has emerged as a crucial component of wireless communication networks, with UAVs playing a pivotal role in delivering rapid connectivity in regions with inadequate communication infrastructure. In addition to their mobility and compact size, UAVs can establish ad hoc networks in remote areas such as deserts and mountains where traditional communication methods may be lacking. With the potential to enhance energy efficiency and spectral efficiency in 6G communications, RIS has garnered considerable attention in diverse application scenarios within automotive and Internet of Things (IoT) network communication systems.

I. Using AI in RIS-Aided Wireless Communication

The Internet of Things (IoT) holds significance in forthcoming wireless communication networks. The future 6G cellular networks are anticipated to leverage millimeter-wave (mmWave) channels, necessitating robust antenna gains for dependable high-data-rate communications. However, certain Internet of Everything (IoE) devices may be too compact to accommodate the requisite antenna arrays for proper beamforming to connect to a remote Next-Generation Base Station (NGBS).

J. Platform of IRS For Aerial Relaying

Various transportation companies are leveraging Unmanned Aerial Vehicles (UAVs) for package delivery due to their cargo-carrying capabilities. The advancement of metamaterials has enabled the shrinking of Intelligent Reflecting Surfaces (IRS), facilitating their installation on UAVs or other aerial vehicles for enhanced adaptability. UAV mobility grants IRS the ability to fly near targeted user devices, ensuring reliable connections, especially in disaster-affected areas. Incorporating IRS on UAVs can convert the conventional Rayleigh fading channel into a Rician fading channel by leveraging the latest LOS channel performance analysis. Planar IRSs situated on buildings or the ground cater only to customers directly facing them. Conversely, when placed on UAVs, they can offer three-dimensional service as UAVs can maneuver and rotate 360 degrees. Specially designed spherical IRSs, when mounted on UAVs, can enhance communication coverage and positioning accuracy.

K. Wireless Power Transfer

Effective passive beamforming of IRS in Wireless Power Transfer (WPT) and Simultaneous Wireless Information and Power Transfer (SWIPT) relies on accurate Channel State Information (CSI) acquisition. However, CSI acquisition consumes energy resources, posing a limitation. Short channels necessitate a pilot-assisted approach to channel allocation in the uplink direction, striking a balance between precise channel estimation and power transfer in the downlink direction. Inadequate or inaccurate channel estimation, driven by minimizing channel training time, may lead to diminished gains in energy beamforming. Conversely, excessive training drains considerable energy at the energy receiver, reducing available harvesting time. The introduction of IRS can significantly impact WPT and SWIPT systems' performance, warranting further exploration.

L. RIS-Aided mmWAVE Communication

Millimeter-wave (mmWave) communication encompasses the 24 GHz to 100 GHz portion of the RF spectrum, offering untapped potential to amplify available bandwidth significantly. Nevertheless, wireless communication using mmWave faces substantial challenges, with path loss standing out prominently. Penetration loss, rain attenuation, and other factors impede mmWave, restricting coverage for deploying post-5G wireless mobile communication systems. Despite these obstacles, the substantial array gain from a concentrated antenna array can help surmount limitations. mmWave transmissions are hindered by obstacles like individuals, foliage, structures, and vehicles. The dynamic nature of 5G mmWave beamforming presents a challenge, with massive antenna arrays falling short in handling extensive penetration loss. RIS utilization can serve as a backup transmission channel when the direct channel is inaccessible.

M. RIS-Aided Massive MIMO Network

Massive Multiple-Input Multiple-Output (MIMO) technology involves deploying multiple antennas to enhance communication between transmitters and receivers. This technique, termed massive MIMO, boosts channel capacity, data transmission rates, and transmission medium quality. Within a massive MIMO network, spatial multiplexing and diversity methods are employed to transmit distinct encoded data "streams". Serving as an extended form of MIMO technology, massive MIMO substantially heightens the system's spectrum efficiency and transmission gain. As the need for integrated intelligent applications in communication networks rises, MIMO stands out as a pivotal technology in 6G communication networks. Massive MIMO facilitates numerous connections, enriches spatial degrees of freedom, and bolsters signal energy and spectrum efficiency.

N. Beam Tracking

To facilitate the integration of RIS technology with mobile User Equipments (UEs) in dynamic scenarios, precise beam tracking is paramount. The 3GPP 5G beam refinement technique entails the UE monitoring a received signal beam, while the Next-Generation Base Station (NGBS) conducts beamforming sweeps across a subset of transmitting signal beams. Subsequently, the mobile UE relays data for beam measurement and the selected accurate beams to the NGBS. However, direct application of this beam refinement method to RIS operations is not feasible. Due to the limited information available to the RIS regarding certain source signal messages exchanged between the NGBS and mobile UE, signaling between the evolving RIS technology and the NGBS or mobile UE is vital for beam refinement. Moreover, the sensing capabilities of the advancing RIS technology can facilitate beam tracking for transparent RIS deployment.

O. Configuration of RIS Under Mobility

Numerous studies on wireless communication networks assume channels are piecewise time-invariant, enabling the application of linear time-invariant (LTI) system theory to mobile devices. However, wireless communication channels are time-variant due to the mobility of the sender or receiver [81].

I. CONCLUSION

In recent decades, there has been a significant increase in the number of users of communication systems. However, technological advancements in future communication systems beyond 6G may not be able to meet the growing expectations for network security. To address these challenges, a new approach known as Reconfigurable Intelligent Surface (RIS) has emerged, introducing innovative features to communication systems. This study presented the definition of RIS, including a system overview, architecture, working principles, key characteristics, control mechanisms, communication duplex modes, operating modes, and frequency ranges, as well as the control panel and operating environment. The study demonstrated that RIS provides significant performance enhancements in communication systems, especially in applications such as the Internet of Things (IoT), unmanned aerial vehicles (UAVs), vehicular networks, visible light communications (VLC), and more. The potential applications of RIS in future communication systems have also been discussed, with a focus on ongoing research challenges and future directions.

RIS is characterized by its nearly passive physical nature and the diversity of its possible implementations. It can be used as a covering material to enable smart cities, smart vehicles, or even smart clothing, but its primary goal remains to enhance wireless communication efficiency. Promising applications include supporting UAVs and enabling wireless power transfer (WPT) to deliver energy and information to hard-to-reach areas. Moreover, RIS technology is relatively low-cost, easy to deploy, and more sustainable, making it an attractive option for the development of current and future wireless networks.

Overall, this study provides a valuable reference for understanding RIS technology in terms of system overview, operating environment, advanced applications, and future research prospects, paving the way for the development of smarter and more efficient communication systems in the future.

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