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Reconfigurable intelligent surface for wireless communication network

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Abstract The future of wireless communication looks promising, thanks to its various applications and the demanding needs of upcoming 6th generation (6G) and subsequent wireless networks. Since the advent of modern wireless technology, the propagation channel has been seen as an unpredictable factor in the communication process that degraded the quality of the received signal. With the recent emergence of reconfigurable intelligent surfaces (RIS), network providers can now control the way radio waves are scattered, reflected, and refracted, improving the performance of wireless communication systems. RIS provide a potential solution for creating a software-configurable smart radio environment. By controlling the communication environment, the quality of service and the spectrum efficiency will be increased. According to its features, RIS is one of the most important enablers for 6G and promising candidate in the future of wireless networks. This paper seeks to offer a thorough overview of RIS, while also discussing the key differences from relays and highlighting the most pressing open research challenges to address.

Keywords 6G; reconfigurable intelligent surface (RIS); wireless communication system; smart radio environment

1.Introduction

6G networks will incorporate entirely new technologies that were not taken into account over the design and development of fifth generation (5G) along with improvements to existing technologies from earlier generations of wireless cellular networks to achieve the require performance. There are many enablers to achieve 6G broadband connectivity with data rates reaching up to tera bits per second (Tbsp) range such as Enablers at the infrastructure level, Enablers at the spectrum level and Enablers at the protocol/algorithmic level. One of the most important infrastructure level enablers is RIS. RISs are utilized to enhance the radio environment by shaping and completely

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prevalent electromagnetic waves (EM). Structurally, a RIS is a versatile, cost-effective meta-surface composed of numerous programmable elements. These elements can individually control the phase of incoming waves, guided by a smart controller. Consequently, the RIS can steer the incoming wave towards the receiver (Rx) by modifying the phase shifts of each element, eliminating the need for conventional transmitter (Tx) modules [1]. RIS is lightweight and small size which enable them to be attached to walls and building, or mounted in unmanned aerial vehicles (UAV), thus providing high flexibility for their practicality. Additionally, the RIS power gain follows the quadratic scaling law instead of the linear power scaling law of conventional active antenna arrays. In RIS-aided communication, both the reflected and direct paths carry valuable information. Therefore, by intelligently combining these paths, we can boost the received signal strength at the Rx compared to backscattering communication, where the direct path is considered interference[2]. The RIS consists of numerous sub-wavelength elements with highly adjustable properties such as impedance that can control the scattering of incoming signals[3]. The incoming waveform can be reflected as a focused beam, with its direction established by the phase-shift pattern across the reflecting elements. RIS can not only manipulate the direction of the reflected wave but also its shape, making it a reconfigurable lens rather than merely a mirror. Beyond amplifying the signal strength for individual users, RIS can enhance channel quality by mitigating interference and improving multicasting performance [4].

The reminder of this paper is outlined as follows; Section 2 explores the RIS. Section 3 gives the comparison between RIS and relays. Meanwhile, Section 4 introduces the research directions. Section 5 introduces the conclusion.

2. Reconfigurable Intelligent Surfaces (RISs)

The potential of RIS to arbitrarily manipulate wireless channel characteristics has sparked significant interest within academia and industry. Higher carrier frequencies result in increased propagation challenges due to amplified penetration losses, diminished scattering, and a reduced number of viable propagation paths. Furthermore, the shrinking size of antenna elements at these frequencies complicates coherent antenna array design. By introducing RIS, the wireless propagation environment, once statically adaptable, becomes dynamically controllable, thereby facilitating the construction of a smart radio environment (SRE)[5]. By establishing a customizable and controllable wireless environment, RIS introduces innovative opportunities for optimizing wireless networks, complementing traditional transceiver design. Its metamaterial-based design enables large-scale deployment at low cost and energy consumption due to the absence of complex

Radio frequency (RF) components. RISs can be unobtrusively integrated into building facades or indoor environments, offering low-complexity deployment and a visually discreet profile. The RISs simple fabrication enables mounting on various surfaces, facilitating seamless integration into diverse applications. Its integration into wireless networks as user-transparent, enhancing flexibility and compatibility. The RIS concept originates from reflect array antennas, a type of directive antenna that functions as a flat parabolic reflector or RF lens[6]. RIS offer real-time reconfigurability, enabling dynamic adaptation to rapidly changing channel conditions. RIS comprise numerous sub-wavelength elements with dynamically adjustable properties, such as impedance. This enables precise control over reflected signal characteristics, including phase shift, amplitude, and polarization. As a result, an incoming waveform can be reflected as a focused beam, with its direction controlled by the phase-shift pattern across the reflecting elements. By jointly optimizing reflection coefficients (e.g., phase shifts) with transmitter and receiver parameters, RISs can significantly enhance overall system performance, such as spectral efficiency (SE) and energy efficiency (EE)[7]. RIS represent a distinct departure from existing wireless technologies, such as relays, MIMO beamforming, and backscatter communication. Hence, there are some RIS features:

- RISs operate in a nearly passive manner and ideally require no dedicated power source.
- RISs can be conceptualized as a continuous surface capable of independently manipulating incident waves at each point, akin to software-defined control (soft programming).
- Unlike conventional wireless components, RISs operate passively without requiring analog to digital converters (ADCs), digital to analog converters (DACs), or power amplifiers. This eliminates noise amplification and enables inherent full-duplex operation.
- RISs exhibit a full-band response, theoretically operating across a wide range of frequencies.
- RISs can be readily deployed in a variety of environments, including building facades, indoor ceilings, and even wearable applications.

2.2.1 RIS structure

RISs are customizable surfaces that can control wireless signals to improve reception. These surfaces are made up of many inexpensive, passive elements that can manipulate incoming radio waves in ways that go beyond the limitations of natural materials. A prime example is a meta surface based RIS that functions as a programmable reflector shown in Figure1. RISs are sometimes called software-defined surfaces (SDSs), similar to software-defined radio (SDR) where physical layer functions are controlled by software. The authors in [8] introduced intelligent walls incorporating frequency-selective surfaces. These surfaces feature a flat design with PIN diodes integrated into the metal connections of each element. PIN diodes in each surface element can be switched between conducting and non-conducting states using an external bias, enabling the intelligent wall to alternate between transmission and reflection modes, as shown in figure 1. Intelligent walls can selectively transmit or reflect electromagnetic waves. varactor-tuned resonators provide an alternative approach to creating reconfigurable and intelligent reflect-arrays introduced in [9] as shown in figure 2. The idea behind this implementation is that the varactor-tuned resonators allow for electronic adjustment of patch resonant frequencies, offering a dynamic alternative to the fixed dimensions of traditional reflect-arrays. Each reflector unit incorporates a varactor diode, allowing for dynamic phase shift control through adjustments in bias voltage, which in turn modifies the varactor's capacitance. A smart reflector with 48 patch elements was built using this method in [10]. A more sophisticated reflect-array featuring 224 programmable patches was introduced in [11]. A reflect-array designed for 60 GHz Wi-Fi employs electronically dominance relay switches. Each reflector element may be hold on or off depending on the switch's position.

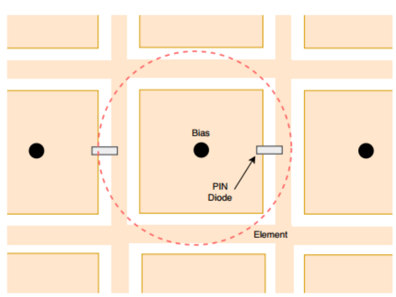

Figure 1.RIS which made of frequency selective structure.

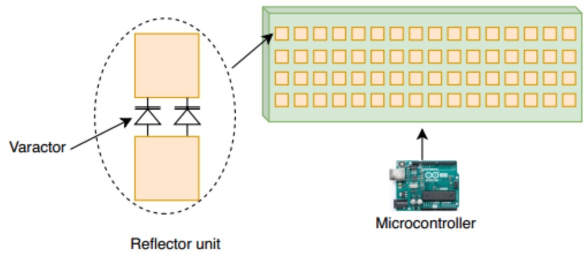

Figure 2. RIS with tunable resonator.

2.2.2 Application of RIS for future wireless network

A combination of RIS integrated communication, localization, and sensing, millimeter wave/terahertz and visible light communications, mobile edge computing, and simultaneous wireless information and power transfer is emerging. By integrating RIS with these complementary technologies, we can leverage new opportunities to enhance communication system performance[12].

- **Massive connectivity communications**

In addition to Enhanced Mobile Broadband (EMBB) and Ultra-Reliable Low-Latency Communication (URLLC), Massive Machine Type Communication (MMTC), also referred to as Massive Connectivity, is recognized as one of the three primary use cases for 5G wireless networks. This recognition stems largely from the extensive adoption of the Internet of Things (IoT). A significant challenge in massive Machine Type Communication (MMTC) is ensuring reliable connectivity for infrequent, short-packet exchanges among the base station and a vast number of IoT devices. Due to obstacles and environmental challenges, many IoT devices operate in areas with obstructed line-of-sight communication, commonly referred to as "dead zones." Due to the precarious nature of signals from IoT devices, achieving precise device detection is a significant hurdle for base stations. Dead zone conditions degrade link reliability for active devices. RIS can address these challenges. In[13] the investigation centers on the challenges of detecting active devices and estimating channel parameters in RIS-assisted massive IoT networks. Due to the sparse scattering environment between the RIS and BS, the corresponding channel is modeled accordingly.

To tackle this issue, a sparse matrix factorization model is used, taking advantage of the inherent sparsity in both sporadic device activity and the channel between the RIS and the base station. The authors proposed an approximate message passing (AMP)-based algorithm that utilizes a Bayesian inference framework to simultaneously detect active devices and know the two separate channels: the RIS-to-BS link and the RIS-to-device link.

- **THz communications**

Given the limited availability of radio spectrum, THz communications, spanning 100 GHz to 10 THz, emerge as a key technology for enabling EMBB in future wireless networks. Due to severe penetration loss and limited diffraction at high frequencies, RIS is essential for overcoming THz communication challenges. To enhance sum-rate performance in RIS-aided THz MIMO systems, a joint hybrid precoding approach was developed in [14]. To alleviate the computational burden of channel estimation and data transmission, a hierarchical search codebook design was introduced in [15]. A theoretical error rate analysis was conducted in [16] for a RIS-assisted LEO satellite network operating in the THz band.

- **Localization, Positioning, and Sensing**

merging location-based applications, such as virtual reality, robot navigation, and autonomous driving, are essential for future wireless communication networks. These applications need more tough requirements for both communication and sensing in modern wireless systems, including ultra-high data rates, widespread and uninterrupted coverage, frequently high reliability and ultra-low latency, and high precision/resolution sensing. To achieve the demanding requirements of future 6G systems for both communication and sensing, a new RIS-based self-sensing system was introduced in [17]. In this system, the RIS controller sends out probing signals, and specialized sensors mounted on the RIS determine the target's location and angle using the reflected signals.

- **Mobile edge computing**

To facilitate low-latency services with high-performance edge computing, a cornerstone of 6G networks, decentralizes computing and storage resources by deploying them near end users. Despite their advantages, mobile edge computing (MEC) systems face restrictions due to the length of the offloading link. To overcome the limitations of long-distance offloading, RIS can be deployed to improve signal transmission via passive beamforming RIS-aided MEC systems were investigated in[18] [19].The aim is to improve uplink offloading by jointly designing active and passive beamforming, RIS deployment, and resource allocation in RIS-aided MEC systems.

- **Air-ground communications**

To create robust and adaptable wireless networks, researchers are focusing on air-to-ground systems utilizing Unmanned aerial vehicles (UAVs), which will revolutionize industries such as package delivery and public safety. To enhance performance, a joint optimization framework was proposed in [20] that considered active and passive beamforming, RIS placement, and resource allocation for multi-user air-ground communications. To further improve SE and EE, the aerial user trajectory was optimized within the system in [21].

3. RIS Vs. Relays

Relays are generally considered active components that require external power. To enhance their versatility, relays may include additional components such as mixers, power amplifiers for signal transmission, and low-noise amplifiers for signal reception. The deployment of relays often incurs significant costs and power consumption, especially when implementing multiple-antenna systems at millimeter and submillimeter wave frequencies[22]. Due to the presence of active components, relays are susceptible to generating additive noise, thereby deteriorating the overall performance of relaying systems. To counteract the adverse effects of additive noise, decode and forward (DF) relaying can be utilized, albeit at the expense of increased signal processing complexity, power consumption, and the need for signal regeneration at relay nodes. Residual loopback self-interference further degrades the performance of DF relaying systems. Different duplexing protocols exhibit varying degrees of impact on the SE of relay-assisted communication systems. The achievable rate in half duplex (HD) relaying systems is inherently limited to half that of an ideal system due to the necessity of using separate resources for the source and relay signals. By leveraging advantageous propagation paths for the relayed signal and employing optimal signal integrating techniques, HD relaying can achieve significant gains in end-to-end signal to noise ratio (SNR). While full duplex (FD) relaying offers the potential for higher SE compared to HD, it faces significant obstacles in the form of loopback self-interference at the relay and combined interference from both the transmitter and relay at the receiver. To enable signal amplification and processing, relays require a dedicated power source to support their operational functions. Furthermore, the implementation of maximum ratio combining in a multi-antenna relay results in a linear growth of average end-to-end SNR as the number of antennas increases[23].

On the other hand, RISs consist of composite layers featuring metallic or dielectric patches printed onto a grounded dielectric base. The adjustable nature of RISs is made possible through the integration of low-power electronic circuitry, including switches or varactors[24]. The hardware simplicity of RISs, which often eliminates the need for power amplifiers, mixers, and DACs/ADCs, positions them as a potentially lower-complexity alternative to relays, especially in large-scale deployments[25], [26]. While additive noise poses no threat to RISs configured as anomalous reflectors, the presence of phase noise can impair their performance[26]. By operating as anomalous reflectors, RISs avoid the challenges associated with half-duplex transmission and loopback interference, which commonly affect relay-based systems. By carefully designing the surface reflection coefficient, RISs can effectively combine signals from both the transmitter and the reflected path, leading to enhanced signal quality. Moreover, the ability to control the power reflected and scattered by an RIS hinges on optimizing its transmittance, which is achieved through careful design of the meta surface[24]. Under ideal circumstances, a RIS exhibits perfect power conservation, reflecting the entire incident radio wave energy.

4. Research directions

Many researchers have conducted various studies and developed innovative solutions concerning RISs. Researchers have concentrated on several areas including theoretical derivations of SNR, channel estimation, signal-to-interference-plus-noise ratio (SINR) maximization, and the optimization of joint active and passive beamforming. They have also examined the Utilization of machine learning tools, explored security solutions at the physical layer, and assessed the potential of intelligent surfaces for millimeter-wave/terahertz, free-space optical, and visible light communication systems. Moreover, early efforts to Combine RISs with orthogonal frequency division multiplexing (OFDM) and space shift keying (SSK) schemes have been recorded. In [27] Examines the use of Passive Intelligent Mirrors (PIMs) for a multi-user Multiple-Input Single-Output (MISO) downlink communication. The approach involves optimizing transmit powers and mirror reflection coefficients to maximize the total sum-rate while ensuring individual quality-of-service (QoS) guarantees for each mobile user. In [28] Consider a multi-user MISO communication system where a multi-antenna base station simultaneously communicates with several single-antenna mobile users in the downlink. This setup is supported by a Large Intelligent Surface (LIS) equipped with numerous nearly passive antenna elements, which can be adjusted to meet specific objectives. In this study shown that RIS outperform the AF relaying in term of EE. In[29] The authors investigate the use of a RIS for downlink multi-user communication from a multi-antenna base station. In this approach, energy-efficient methods have been introduced for allocating transmit power and adjusting the phase shifts of the RIS's elements, ensuring that each mobile user's individual link budget is met. The author in[30] aim to leverage the advantages of both cascaded and parallel topologies through a hybrid RIS network structure. The cascaded topology helps reduce path loss and improve multiplicative gain, while the parallel topology enhances the scattering signatures within the target region (or cluster). The author in [31] propose a RIS selection strategy to choose the appropriate RISs as a preliminary step before the joint beamforming optimization between the BS and RISs, aiming to reduce the complexity associated with the joint beamforming process. The problem of joint active passive beamforming has been investigated in [32], [33], [34], [35], [36].In [32] introduce a RIS with a limited number of phase shifts for each element is implemented to facilitate communication from a multi-antenna access point (AP) to a single-antenna user. In this setup, the user receives signals directly from the AP and those reflected by the RIS. The goal is to improve the received signal strength at the Rx by Collaboratively optimizing the active beamforming at the AP and the passive reflection beamforming through RIS reflecting elements. In[33] proposed a RIS-assisted single-cell wireless system where an IRS facilitates communication among a multi-antenna AP and multiple single-antenna users. They analysis and address an optimization problem aimed at reducing the power at the AP. Optimizing both the active beamforming at AP and the passive beamforming with phase shifters at the RIS simultaneously, while ensuring that each user's individual (SINR) constraints are satisfied. Most previous studies on RIS assume that each reflecting element can continuously adjust its phase shift, which is difficult to achieve in practice due to hardware limitations. In contrast, the authors in [34] examines an RIS-assisted wireless network since the RIS has a limited set of phase shifts available for each element. The RIS facilitates communication among a multi-antenna AP and a single-antenna user and aiming to reduce the AP's power while optimizing both the continuous transmit beamforming at the AP and the discrete reflect beamforming at the RIS, ensuring that the user's receiver achieves a desired SNR. In [35], the author investigates a point-to-point RIS-aided MISO communication system. The goal is to jointly optimize the beamformer at the AP and the RIS to maximize SE. To solve the resulting non-convex optimization problem, the authors develop two efficient algorithms: one based on fixed point iteration and the other utilizing manifold optimization techniques. In [36] The authors Proposed a method that integrates the transmitted signal information with the RIS reflections to improve system SE. The authors in[37] [38][39] addressed the challenges associated with RIS assisted UAV. In [37], The authors employed RIS to enhance integrated satellite high-altitude platform terrestrial networks (IS-HAP-TNs) by leveraging the RIS's reflective capabilities. The RIS is strategically placed on the side of the high-altitude platform (HAP) to bounce signals from multiple ground user equipment (UE) to the satellite. To improve the data rate for all system, the transmit beamforming matrix of the UEs and the phase shift matrix of the RIS are optimized together. The authors in [38]improves the performance of UAV-terrestrial networks by combines it with RIS. In this approach, RIS utilize to reflect the signal from ground to UAV. In [39] , an optimization of numerous- RIS-aided integrated satellite-unmanned aerial vehicle-terrestrial networks (IS-UAV-TN) has been conducted. In this approach, RIS has been placed on the UAV to restructure the wireless transmission path and implemented non-orthogonal multiple access (NOMA) protocols to tackle spectrum limitations and enhance the system performance. In[40] focuses on improving the sum rate in an RIS-aided MIMO system. An algorithm is proposed to optimize the RIS phase shifts while considering large-scale fading effects.

For channel estimation problem with present of RIS, the author in [41]examined a large-scale antenna system supported by an RIS, where a base station communicates with a user that has a single antenna. In line with previous studies, the system assumes that the base station is aware of both the channel state information (CSI) and the RIS phases. Precoding stage can then be utilized, and the system ergodic capacity is optimized by adjusting the phase shift of RIS. A channel estimation protocol was introduced in [42] for RIS as a cost-effective, environmentally friendly alternative to massive antenna systems for achieving high energy beamforming (EB) gains. To reduce training overhead in the existence of passive RIS elements, the authors in[43] explored two significant methods for RIS design when channel knowledge is unknown: one approach utilizes compressive sensing, while the other leverages deep learning. In this work, a new RIS system is introduced that incorporates sparse channel sensors. In this setup, some RIS elements are active and connected to a baseband processor. The challenge of cascaded channel estimation with fully passive RIS elements for multi-antenna devices communicating via RIS has been addressed in [44]. In this scheme, a general approach is proposed for estimating the cascaded MIMO channel involving the source, RIS, and destination.

For the search based on RIS and SM, the author in [45] explored the use of RIS to enhance SE by proposing two schemes: RIS-SM and RIS-SSK. These schemes integrate the optimization of intelligent surface phases with IM to enhance received signal strength and SE. In this approach, a unified framework is proposed to calculate the theoretical average bit error probability. In both techniques, RIS was utilized as an access point, it was integrated into the Tx to direct the signal toward the Rx based on the input data bits. the authors in [46]utilize the Tx indices instead of

Rx antenna indices, which are utilized in[45] to leverage SSK. In [47] the author proposed a new modulation scheme for RIS , where the RIS is portioned into two segments to make the in phase (I) and quadrature (Q) signal components. In this approach, effectively doubling the SE compared to the approach introduced in[45]. In[48], the authors introduced a RIS-based generalized SM scheme to improve the SE of the RIS-based system. In this approach, this scheme involves modulating the transmit signals jointly through both the Tx and RIS, while allowing for more flexible design of the receive antenna patterns. However, in this scheme, the SE was improved, but at the other hand the BER performance was degraded. In [49], a precoding stage was developed at the Tx grounded in a signature constellation to minimize the correlation among the channels, which is increased from the short distance among the reflected elements of RIS. In [50], Two algorithms have introduced to improve the BER and throughput performance of the system. However, the main drawback of these proposed schemes is the highly computational complexity. The authors in [50] employed the concept of SM with both Tx and Rx antennas to boost SE, but this method resulted in a deterioration of BER performance.

Recently, the researcher begun to study the integration of RIS with NOMA. In [51]the authors proposed RIS aided orthogonal multiple access (OMA) and RIS aided NOMA with comparing between two proposed. In this scheme, the authors indicated that RIS aided NOMA outperform the RIS assisted OMA. The authors in [52] proposed RIS assisted downlink NOMA intended to minimize the total transmit power by jointly optimizing the transmit beamforming vectors at the base station and the reflection coefficient vector at the RIS. The authors in [53] introduced downlink multi input single output RIS assisted NOMA, where seek to increase the sum rate for all users and focused on jointly optimizing both the active beamforming at the BS and the passive beamforming at RIS. In [54]the authors investigated downlink RIS assisted NOMA. In this work, a novel resource allocation algorithm with three steps was proposed to maximize the throughput of the system. In [55]the authors proposed a low complexity phase selection scheme to enhance the reliability of random phase shifting design. In [56] the authors approved that using RIS can enhance secrecy performance compared to traditional NOMA systems.

5.Conclusion

In this paper, we have shown the important of RIS in wireless networks. The ability of the reflected elements in RIS to control and reshape the incoming signal make it as one the most promising technologies in 6G networks. Moreover, introduce the structure of RIS which is small and lightweight. This feature makes the RIS easy to fix in building and walls. We also discuss the important applications of RIS in THz communication. Furthermore, we show the difference between RIS and relays and illustrate the superiority of RIS. Finally, we introduce the challenges and the research directions about RIS.

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