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Wireless Communications beyond Antennas: The Role of Reconfigurable Intelligent Surfaces †

Moazzam Shah Bukhari Syed [1,*], Hafiz Muhammad Attaullah [2], Sundus Ali [2] and Muhammad Imran Aslam [2]

1 School of Information & Communications Engineering, Xi'an Jiaotong University, Xi'an 710049, China
2 Department of Telecommunication Engineering, NED University of Engineering Technology, Karachi 75270, Pakistan; attaullahshafiq10@gmail.com (H.M.A.); sundus@neduet.edu.pk (S.A.); iaslam@neduet.edu.pk (M.I.A.)
* Correspondence: moazzam@stu.xjtu.edu.cn
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Abstract: Reconfigurable intelligent surfaces (RISs) are a new and emerging technology that has the potential to revolutionize the way that wireless communication systems are designed and implemented. These surfaces are made up of a large number of small, individually controllable elements, each of which can be used to manipulate the phase and amplitude of the electromagnetic waves that pass through it. This allows them to perform a wide range of functions, including wireless power transfer, beamforming, and cloaking. In this work, we provide an overview of the principles and applications of reconfigurable intelligent surfaces, and we discuss the advantages and challenges of these surfaces in wireless communications. We also provide an overview of the current state of research in this area. Moreover, we outline the future directions for the development of these surfaces.

Keywords: 5G; 6G; reconfigurable intelligent surfaces; next generation wireless systems; wireless communications

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1. Introduction

Reconfigurable intelligent surfaces (RISs), also known as smart surfaces, are a relatively new type of technology that has the potential to revolutionize the field of wireless communications. These surfaces are made up of a large number of small, individually controllable elements that can be used to manipulate electromagnetic waves in a desired manner. By changing the shape and orientation of these elements, reconfigurable intelligent surfaces can be used to reflect, absorb, or transmit electromagnetic waves, allowing them to perform a variety of different functions.

Wireless communications have become an integral part of modern society, with an increasing number of devices relying on wireless connections to communicate with one another and access the internet. The demand for wireless data is expected to continue to grow in the coming years, and new technologies will be needed to meet this demand [1]. Traditional wireless communication technologies, such as multiple-input multiple-output (MIMO) systems, have been successful in increasing the capacity and coverage of wireless networks, but they have reached their limits in terms of performance [2].

RISs have the potential to be a key technology for next-generation wireless communications, as they offer several advantages over traditional antennas. These surfaces can be made much smaller and more compact than traditional antennas, making them more suitable for use in devices with limited space [3]. They also have the ability to adapt their shape and configuration to the specific needs of the wireless communication system, allowing them to perform a wider range of functions than traditional antennas [4]. In addition, RISs can be integrated into a variety of different materials and surfaces, making them more versatile and easier to deploy in a variety of different environments.

This paper aims to provide a comprehensive overview of RISs as a next-generation wireless technology. The paper begins by discussing the technical background of these surfaces, including their basic principles and the concept of metasurfaces. It will then explore the various applications of RISs in wireless communications, including their use in wireless power transfer, beamforming, and cloaking. The paper also discusses the advantages and challenges of using these surfaces in wireless communications and concludes with a discussion of the potential impact of these surfaces on the future of wireless communications.

2. Technical Background

Wireless communications rely on the transmission and reception of electromagnetic waves, which are often generated and detected using antennas. Antennas come in a variety of shapes and sizes, and each type is designed to operate over a specific range of frequencies and to provide a specific level of performance. The design and placement of antennas play a critical role in the performance of a wireless communication system, as the antennas are responsible for converting electrical signals into electromagnetic waves and vice versa.

RISs are a new type of technology that can be used in place of traditional antennas to transmit and receive electromagnetic waves. These surfaces are made up of a large number of small, individually controllable elements, each of which can be used to manipulate the phase and amplitude of the electromagnetic waves that pass through it. By changing the shape and orientation of these elements, RISs can be used to reflect, absorb, or transmit electromagnetic waves, allowing them to perform a variety of different functions.

The basic principles behind RISs are rooted in the concept of metasurfaces. A metasurface is a two-dimensional structure that is composed of a large number of subwavelength-sized elements, each of which can be individually controlled to manipulate the phase and amplitude of the electromagnetic waves that pass through it [5]. These elements can be made from a variety of different materials, including metals, dielectrics, and semiconductors, and can be arranged in a variety of different patterns to achieve specific electromagnetic properties [6].

Metasurfaces have been used in a variety of different applications, including antennas, filters, polarizers, and beamformers [7]. However, the concept of RISs takes the idea of metasurfaces one step further by adding the ability to control the shape and orientation of the elements in real time. This allows RISs to adapt their shape and configuration to the specific needs of the wireless communication system, making them more versatile and efficient than traditional antennas [3].

In addition to their ability to adapt their shape and configuration, RISs have several other advantages over traditional antennas. These surfaces can be made much smaller and more compact than traditional antennas, making them more suitable for use in devices with limited space [2,8].

Reconfigurable intelligent surfaces have recently gained significant attention as a promising solution for enhancing the performance of wireless communication systems. RISs are passive, reconfigurable metasurfaces that can manipulate the phase, amplitude, and polarization of impinging electromagnetic waves. The ability to intelligently control the reflection of impinging waves enables the RIS to act as a programmable reflector, allowing for the tailoring of the wireless propagation environment to improve the performance of wireless communication systems.

The research on RISs has so far been focused on three main application areas:

Spectrum efficiency: by judiciously controlling the phase shifts of the RIS elements, the interference level between different transmission links can be minimized, leading to improved spectrum efficiency;

Energy efficiency: by directing the signal energy towards the intended receiver, the energy efficiency of wireless communication systems can be improved;

Physical layer security: by creating a favorable propagation environment for the legitimate users and a hostile environment for eavesdroppers, the physical layer security of wireless communication systems can be enhanced.

Table 1 summarizes the main research challenges [5] and opportunities in the field of RIS-aided wireless communication systems.

Table 1. List of open research challenges and opportunities within RISs.

Research Challenges	Research Opportunities
Channel modeling	Spectrum efficiency
Protocol design	Energy efficiency
Complexity	Physical layer security
Synchronization	Cooperation and coordination among multi-RIS systems
Energy efficiency	Potential for use in Millimeter Wave and Terahertz communications
Security and privacy	Integration with other technologies such as MIMO and NOMA
Deployment and maintenance	Ability to enhance coverage and capacity in indoor and outdoor environments
Interference management	Feasibility for integration in 5G and beyond cellular networks

As RIS-aided wireless communication systems continue to evolve, there is a growing need for further research to fully understand their potential and to develop practical solutions for their implementation. This includes the development of efficient algorithms for the design and control of RISs, the investigation of novel application areas for RISs, and the implementation of large-scale experimental testbeds to validate the performance of RIS-aided wireless communication systems.

While the field is currently in its infancy and many research opportunities are available, there are also some challenges that need to be resolved in order to fully realize the potential of RISs in wireless communication systems.

3. Application of Reconfigurable Intelligent Surfaces

RISs have a wide range of potential applications in wireless communications, and researchers are actively exploring the use of these surfaces in a variety of different scenarios. Some of the most promising applications of these surfaces include wireless power transfer, beamforming, and cloaking.

Wireless power transfer is the process of transferring electrical energy from a power source to a device without the use of physical cables. This is typically performed using electromagnetic waves, which can be generated and received using antennas. Reconfigurable intelligent surfaces can be used in place of traditional antennas to transfer power wirelessly, and they offer several advantages over traditional methods. For example, they can be made much smaller and more compact than traditional antennas, making them more suitable for use in portable devices [9,10].

In Figure 1 [11], some examples of how RISs can be used in various new sub-6 GHz systems with the help of primary and secondary transmitters and receivers (PUs, SUs) include:

a. Utilizing RISs to enhance the performance of multi-cell networks;
b. Using RISs to improve the performance of simultaneous wireless information and power transfer (SWIPT) systems;
c. Implementing RISs in mobile edge computing (MEC) networks to improve network performance;
d. Enhancing the performance of multi-group multicast systems using RISs;
e. Utilizing RISs to improve the performance of physical layer security (PLS) systems;
f. Using RISs to enhance the performance of cooperative relaying (CR) networks.

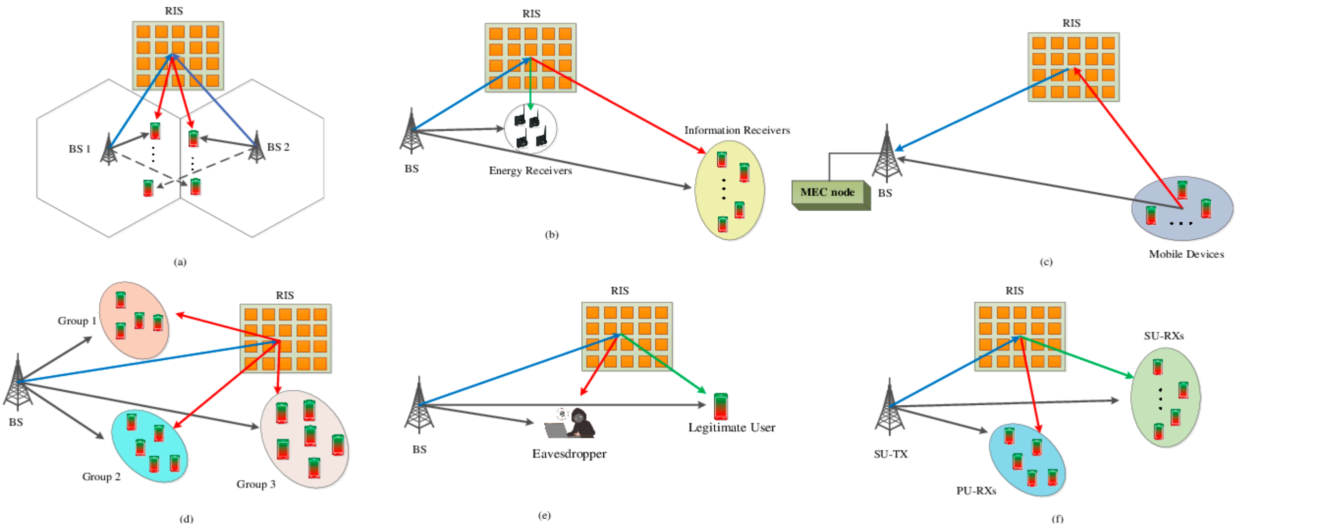

Figure 1. Exploring the potential of reconfigurable intelligent surfaces in emerging sub-6 GHz systems [12].

Beamforming is a technique that is used to direct electromagnetic waves in a specific direction, and it is commonly used in wireless communication systems to increase the range and capacity of the network. Reconfigurable intelligent surfaces can be used to shape the beam of the electromagnetic waves, allowing them to be directed towards specific devices or to avoid obstacles [13]. This can be particularly useful in environments where the signal is prone to interference or where there are multiple devices that need to be connected.

Cloaking is the process of making an object or area invisible to electromagnetic waves, and it is a technique that has been of interest to researchers for many years. Reconfigurable intelligent surfaces can be used to create cloaking devices that can make an object or area invisible to electromagnetic waves over a specific range of frequencies [14]. This could have a wide range of practical applications, including military, security, and medical applications. Additionally, it can enable the deployment of machine learning algorithms to the edge device where the data are generated.

In addition to these applications, reconfigurable intelligent surfaces have also been used in a variety of other scenarios, including radar systems, wireless charging, and wireless sensing. As research in this area continues to progress, it is likely that new and innovative applications for these surfaces will be discovered.

4. Advantages and Challenges in Reconfigurable Intelligent Surfaces

RISs have several advantages over traditional antennas in wireless communications, including their size, versatility, and adaptability. These surfaces can be made much smaller and more compact than traditional antennas, making them more suitable for use in devices with limited space [3,10]. Additionally, these surfaces have the ability to adapt their shape and configuration to the specific needs of the wireless communication system, allowing them to perform a wider range of functions than traditional antennas [4].

Despite these advantages, there are several challenges to the widespread adoption of reconfigurable intelligent surfaces in wireless communications. One of the main challenges is the cost of these surfaces, as they require a large number of individually controllable elements, which can be expensive to manufacture and maintain [11]. Another challenge is the complexity of these surfaces, as they require sophisticated control algorithms to optimize their performance and adapt to changing conditions [14]. Additionally, there are regulatory and standards issues that need to be addressed before these surfaces can be deployed on a large scale [15].

There are several challenges that may occur in a scenario that is discussed in Figure 2 [16], which must be addressed when implementing an RIS-empowered smart radio network [17], such as:

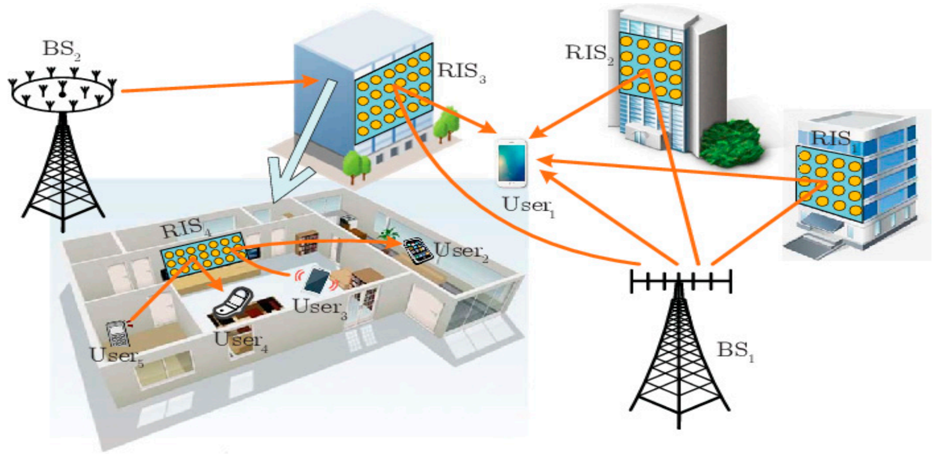

Figure 2. Scenario for challenges of implementing a reconfigurable intelligent surface (RIS)-empowered smart radio network [16].

Channel modeling: the behavior of the signal propagation in the presence of an RIS is not well understood, which makes it difficult to accurately model the channel;

Protocol design: the integration of RISs into a radio network requires the development of new protocols to manage the RIS and coordinate its operation with other network elements;

Complexity: the control and management of a large number of RIS elements can be computationally complex and may require advanced algorithms to optimize the performance of the network;

Synchronization: the RIS elements must be synchronized to work together effectively, which can be a challenging task especially when the network is highly dynamic;

Energy efficiency: the operation of an RIS-empowered network can be power-hungry, and as a result, it is important to design energy-efficient algorithms to manage the RIS;

Security and privacy: the use of a large number of RIS elements can pose security risks, and it is important to implement robust security mechanisms to protect the network from malicious attacks;

Deployment and maintenance: the deployment and maintenance of an RIS-empowered network can be costly and requires careful planning to ensure that the network is deployed in the most efficient and effective manner;

Interference: introducing an RIS can introduce more interference in the network due to the reflecting of the signals, which can lead to more difficulty in managing it.

In order to overcome these challenges and realize the full potential of reconfigurable intelligent surfaces in wireless communications, further research and development is needed. This includes the development of new materials and manufacturing techniques that can reduce the cost and complexity of these surfaces, as well as the development of new control algorithms and protocols that can optimize their performance and adaptability.

5. Future Research Directions for Reconfigurable Intelligent Surfaces

RISs have the potential to revolutionize the way that wireless communication systems are designed and implemented, and research in this area is actively ongoing. In the future, it is likely that these surfaces will be used in a wide range of different applications, including wireless power transfer, beamforming, and cloaking.

One area of particular interest is the use of RISs in 6G wireless networks. The next generation of wireless networks is expected to be significantly faster and more efficient than previous generations, and RISs have the potential to play a key role in achieving these goals [13]. Researchers are exploring the use of these surfaces to improve the capacity and coverage of 6G networks, as well as to reduce the energy consumption and latency of these systems [4].

Another area of focus is the integration of RISs into existing infrastructure. Many of the current applications of these surfaces require the deployment of additional hardware, which can be expensive and complex. However, it is possible to integrate these surfaces into existing infrastructure, such as walls, windows, and ceilings, which could greatly simplify the deployment process [16,17]. This could have a significant impact on the cost and feasibility of using these surfaces in a variety of different settings.

Researchers have been exploring various applications of RISs, including in 5G and beyond networks, radar systems, and satellite communications. They have also been investigating the design, optimization, and implementation of RISs using advanced materials, signal processing, and machine learning techniques. Despite the challenges, the field of wireless communications beyond antennas is rapidly evolving, and RISs are expected to play a crucial role in the future of wireless technology.

Overall, the future of RISs is bright, and it is likely that these surfaces will play a major role in the development of future wireless communication systems.

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