Unlocking the Power of Reconfigurable Intelligent Surfaces: From Wireless Communication to Energy Efficiency and Beyond

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Abstract

Reconfigurable Intelligent Surfaces (RIS) are a class of metamaterials that have gained significant attention in recent years due to their potential to revolutionize wireless communication, sensing, and imaging technologies. RISs consist of a planar array of closely spaced, subwavelength-sized elements that can manipulate electromagnetic waves in a controllable manner. By reconfiguring the geometry, material properties, or phase of individual elements on the RIS, the surface can be customized to meet specific application requirements.

RISs can potentially improve wireless communication by creating virtual channels, reducing interference, and improving overall quality. They can also enhance the efficiency of energy harvesting systems and improve sensing and imaging technologies by manipulating the propagation and scattering of electromagnetic waves. Additionally, RIS could be used to increase privacy and security by selectively blocking or allowing certain frequencies of electromagnetic waves.

In this article, we provide a brief history of the development of RIS and discuss the design and fabrication of RIS structures. We also explore the potential applications and benefits of RIS technology, including improved wireless communication, enhanced energy efficiency, advanced sensing and imaging, and increased privacy and security. Finally, we highlight some of the current research challenges and future directions for RIS technology. Overall, RISs hold great promise for advancing a wide range of technologies and applications, and we expect to see many exciting developments in this area in the future.
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Index Terms—Metamaterials; Reconfigurable intelligent surfaces; 5G; 6G; Machine learning; Artificial intelligence.

I. INTRODUCTION

The demand for faster and more reliable wireless communication systems is constantly increasing, and traditional wireless technologies face challenges in meeting these demands [1]. Reconfigurable Intelligent Surfaces (RIS) have emerged as a potential solution to these challenges [2]. RIS is an innovative technology that uses electromagnetic surfaces to manipulate and control electromagnetic waves, offering a new way to improve wireless communication [3]. With the ability to create multiple virtual channels and selectively block or allow certain frequencies of electromagnetic waves, RIS can significantly enhance the performance of wireless communication systems, increase energy efficiency, and even enhance imaging and sensing technologies [4]. As a result, there has been significant research interest in RIS, and it is being investigated as a promising technology for the next generation of wireless communication systems.

RISs are a class of metamaterials that consist of a planar array of closely spaced, subwavelength-sized elements that can manipulate electromagnetic waves in a controllable manner [2]. These surfaces are designed to modify the propagation and radiation of electromagnetic waves, enabling them to selectively reflect, refract, amplify, attenuate, or even redirect electromagnetic waves in a desired direction [5]. RIS are "intelligent" because they can be programmed to adapt to changing environmental conditions, which makes them highly versatile and applicable to a wide range of wireless communication, sensing, and imaging applications [6]. By reconfiguring the geometry, material properties, or phase of individual elements on the RIS, the surface can be customized to meet specific application requirements [6].

RISs have the potential to revolutionize wireless communication, energy harvesting, sensing and imaging, privacy, and security technologies and applications [7]. RIS’s potential applications and benefits are improved wireless communication, enhanced energy efficiency, advanced sensing and imaging, and increased privacy and security [6].

Regarding wireless communication, RIS can be used to create virtual channels between a transmitter and receiver, effectively increasing the capacity of wireless networks [5]. By selectively reflecting or refracting electromagnetic waves, RIS can also reduce interference, increase coverage, and improve the overall quality of wireless communication [5].

Concerning energy efficiency, RIS can be employed to improve the efficiency of energy harvesting technologies by manipulating the electromagnetic waves that are used to extract energy from the environment [8], [9]. By focusing and amplifying these waves, RIS can improve energy conversion efficiency and reduce the size and cost of energy harvesting systems [9].

As for sensing and imaging, RIS can be used to enhance the performance of such technologies by manipulating the propagation and scattering of electromagnetic waves. By focusing, redirecting, or amplifying these waves, RIS can improve the resolution, sensitivity, and range of sensing and imaging systems [10].

Regarding privacy and security, RIS can be used to create "smart" environments that are capable of selectively blocking or allowing certain frequencies of electromagnetic waves [11]. This could be used to enhance privacy and security by preventing unauthorized access to wireless networks or creating secure areas protected from electromagnetic interference [12].

RIS is a relatively new area of research that has gained significant attention in the last few years. The concept of using electromagnetic surfaces to manipulate and control electro-
magnetic waves has been around for decades, but the idea of reconfigurable surfaces is relatively new [6]. Here is a brief history of the development of RIS:

- In the late 1990s and early 2000s, researchers began investigating the concept of metamaterials, which are artificially engineered materials that can manipulate electromagnetic waves in unique ways [13]. Metamaterials are composed of structures that are smaller than the wavelength of the electromagnetic waves they manipulate, allowing them to bend, refract, and even absorb these waves in unusual ways [14]. The earliest form of RIS was the electromagnetic bandgap (EBG) structure, designed to reflect specific frequencies of electromagnetic waves and mainly used to reduce electromagnetic interference in electronic devices [15].

- Around 2012, researchers proposed the concept of using "smart walls" composed of metamaterials to improve wireless communication systems [16], [17], [18]. These smart walls could be programmed to selectively block or allow certain frequencies of electromagnetic waves, effectively creating a wireless network with minimal interference [19].

- In 2019, researchers proposed the concept of using reconfigurable surfaces to improve wireless communication in indoor environments [20]. They showed that by using RIS, it was possible to create multiple virtual channels between a transmitter and receiver, effectively increasing the capacity of wireless networks [21].

- Since then, the research on RIS has expanded rapidly, with many researchers investigating different aspects of RIS design, fabrication, and application [22]. Today, RIS is being investigated as a potential technology for improving wireless communication, increasing the efficiency of energy harvesting, and even enhancing imaging and sensing technologies [23], [24].

This brief overview is divided as follows. In section II the working principles of RISs are discussed. Next, in section III, modeling and simulation of RISs are presented. In section IV, the implementation aspects of RISs are debated. Then, in section V, an overview of potential RIS applications is presented. In section VI, an outline of current RIS challenges and future research directions are listed. Finally, in VII, this overview is concluded with a summary of the key findings.

## II. PRINCIPLES OF RIS

RISs are artificial surfaces that can be electronically controlled to manipulate and control electromagnetic waves. These surfaces consist of an array of sub-wavelength elements that can be controlled individually to change the wavefront of the incident electromagnetic waves. The sub-wavelength elements can be realized by various means, such as patch antennas, metallic patterns, and metamaterials [25].

The RIS structure typically consists of a substrate, a ground plane, and an array of sub-wavelength elements. The substrate can be made of different materials, such as glass, silicon, or plastic, providing mechanical support to the RIS [26]. The ground plane is typically a conductive material such as copper or aluminum, providing a reference point for electromagnetic waves. The sub-wavelength elements are placed on top of the substrate and the ground plane, forming an array.

The size and spacing of the sub-wavelength elements determine the frequency range of the electromagnetic waves that the RIS can manipulate. The distance between the sub-wavelength elements should be smaller than the wavelength of the incident electromagnetic waves to enable sub-wavelength phase control. The elements are connected to electronic circuits that can adjust the phase shift of each element, enabling the RIS to control the direction, amplitude, and phase of the incident electromagnetic waves [11].

The RIS structure can be made flexible or rigid, depending on the application. Flexible RIS structures can be used for conformal and wearable applications, while rigid RIS structures can be used for indoor and outdoor applications [27]. The operation of RIS is based on the principle of wave interference, which is a fundamental phenomenon in electromagnetics. When two or more electromagnetic waves interact with each other, they can either reinforce or cancel each other out, depending on their relative phase and amplitude [28].

In the case of RIS, the electromagnetic waves are incident on an array of sub-wavelength elements, each of which can be electronically controlled to adjust its phase shift. By adjusting the phase shift of each element, the RIS can control the wavefront of the incident electromagnetic waves and create a specific interference pattern. The interference pattern can be designed to either reinforce or cancel specific frequencies or directions of the incident waves [11].

The RIS operates based on the principle of constructive and destructive interference. When the phase shift of each element is adjusted to reinforce the incident waves, the waves constructively interfere with each other, leading to a stronger and more focused signal. When the phase shift of each element is adjusted to cancel out certain frequencies or directions of the incident waves, the waves destructively interfere with each other, leading to reduced interference and improved signal quality [29].

The physics behind RIS operation is further supported by the concept of Snell’s law, which states that the angle of incidence and the angle of reflection of an electromagnetic wave are related to the refractive index of the material it passes through. By adjusting the phase shift of each element, the RIS can control the refractive index of the material it passes through, effectively manipulating the angle of incidence and reflection of the incident waves [30].

Designing RIS requires careful consideration of various factors, including the type of application, the frequency range of operation, the required signal quality, the number of elements in the array, and the power consumption. Next, we are some of the key design considerations for RIS.

The frequency range of operation is a critical design consideration for RIS. The size and geometry of the RIS elements should be optimized for the frequency range of interest to achieve the desired phase shift range and response time [30].

The spacing between the RIS elements is another important consideration. The spacing should be chosen to achieve the
The size of the RIS elements should be optimized for the frequency range of operation and the desired phase shift range. The size should be small enough to ensure sub-wavelength diffraction but not too small to avoid excessive losses and reduced efficiency [11].

The power consumption of the RIS should be minimized to reduce the overall system cost and improve efficiency. The RIS should be designed to operate with low power consumption by using low-loss materials, efficient electronics, and optimized control algorithms [32].

The number of elements in the RIS array should be optimized for the desired interference pattern and the frequency range of operation. The more elements in the array, the finer the control over the interference pattern and the higher the complexity and cost [33].

The RIS control algorithms should be optimized to achieve the desired interference pattern and minimize power consumption. The algorithms should take into account the location of the transmitter and receiver, the desired signal quality, and the interference from other sources [34].

The fabrication process for the RIS should be optimized to achieve the desired element size, spacing, and shape. The fabrication process should be scalable and cost-effective, with high repeatability and low variability [35].

III. RIS Modeling and Simulation

Simulations are essential to designing RIS and predicting their behavior in different scenarios. Next, we provide a detailed overview of simulation tools and techniques used in RIS design.

Electromagnetic simulation software, such as CST Microwave Studio, Ansys HFSS, and FEKO, is used to simulate the behavior of electromagnetic waves in RIS structures. These software tools use numerical methods to solve Maxwell’s equations and predict the electromagnetic field distribution, transmission, reflection, and absorption in RIS structures [36].

Numerical optimization techniques, such as genetic algorithms and particle swarm optimization, can be used to optimize the RIS design parameters, such as element size, spacing, and shape, for specific performance metrics, such as phase shift range, radiation pattern, and efficiency. These optimization techniques can speed up the design process and improve the overall performance of the RIS [37].

Ray tracing is a simulation technique that models the propagation of electromagnetic waves using ray paths. It is commonly used to simulate the behavior of electromagnetic waves in complex indoor environments where multiple reflections and diffractions occur. Ray tracing software, such as COMSOL and MATLAB, can be used to predict the signal strength and quality in different scenarios and optimize the RIS design accordingly [38].

Circuit simulation software, such as SPICE and ADS, can be used to model the electronic circuits and control algorithms used in RIS. These software tools can simulate the behavior of electronic components, such as amplifiers, filters, and switches, and optimize the circuit design for the desired performance metrics, such as power consumption and speed [39].

Machine learning techniques, such as deep learning and reinforcement learning, can be used to predict the behavior of RIS in different scenarios and optimize the control algorithms. These techniques can be learned from data and experience to improve the accuracy and efficiency of RIS control [40].

Each simulation approach has its advantages and disadvantages. Electromagnetic simulation software provides accurate and detailed simulation results but can be computationally intensive, while numerical optimization techniques provide fast optimization results but may not provide detailed simulation results. Ray tracing is suitable for simulating complex indoor environments, while circuit simulation is suitable for simulating RIS control algorithms. Machine learning provides fast and accurate simulation results but requires much training data. Therefore, the optimal simulation approach depends on the specific application, the desired performance metrics, and the available resources [40], [41].

Experimental validation is a crucial step in the development of RIS technology. It involves verifying the performance of RIS devices under real-world conditions and comparing the results with theoretical predictions obtained from simulations. The following are some of the experimental validation techniques commonly used for RIS.

Antenna measurements are used to verify the radiation characteristics of RIS devices. The RIS device is placed in an anechoic chamber, and the radiation pattern is measured using a calibrated antenna. The measured radiation pattern is compared with the simulation results to validate the RIS design [42].

Channel sounding involves measuring the wireless channel response between a transmitter and receiver in the presence of RIS devices. The RIS device is placed in the wireless channel, and the channel response is measured using a channel sounder. The measured channel response is compared with the simulation results to validate the RIS design [43].

Beamforming measurements are used to verify the beamforming capabilities of RIS devices. The RIS device is placed in the wireless channel, and the beamforming pattern is measured using a calibrated antenna array. The measured beamforming pattern is compared with the simulation results to validate the RIS design [34].

Energy harvesting measurements are used to verify the energy harvesting capabilities of RIS devices. The RIS device is placed in a simulated energy-harvesting environment, and the amount of harvested energy is measured using a power meter. The measured energy harvesting results are compared with the simulation results to validate the RIS design [44].

Imaging and sensing measurements are used to verify RIS devices’ imaging and sensing capabilities. The RIS device is placed in a simulated imaging or sensing environment, and the image or sensing results are measured using an imaging
or sensing system. The measured results are compared with the simulation results to validate the RIS design [23], [45].

IV. RIS IMPLEMENTATION

RIS are typically fabricated using a combination of traditional microfabrication techniques and novel material synthesis methods. Next, we describe some of the commonly used fabrication techniques for RIS.

Electron beam lithography (EBL) is a high-resolution patterning technique used to create the complex geometries required for RIS devices. A beam of electrons is focused onto a substrate coated with a resist material, and the pattern is defined by selectively exposing the resist material to the electrons. The exposed resist is then etched away, leaving behind the desired pattern [46].

Photolithography is a widely used patterning technique in microfabrication. It involves using light to transfer a pattern from a photomask onto a photosensitive substrate. The pattern is then etched into the substrate using wet or dry etching techniques [47].

Chemical vapor deposition (CVD) is a technique used to deposit thin films of materials onto a substrate. The process involves introducing precursor gases into a reaction chamber, which then reacts to form a solid film on the substrate. CVD is commonly used to deposit metal and dielectric films onto RIS devices [48].

Atomic layer deposition (ALD) is a thin film deposition technique that allows for the precise control of film thickness and composition. The process involves sequentially exposing a substrate to alternating pulses of precursor gases. Each pulse chemically adsorbs onto the substrate, allowing for precise control of the deposited film thickness [49].

Inkjet printing is a printing technique that deposits small ink droplets onto a substrate. In the case of RIS devices, inkjet printing is used to deposit conductive and dielectric inks onto the substrate to create the required RIS structure [50].

3D printing is an additive manufacturing technique that can be used to fabricate RIS devices with complex geometries. In this technique, a 3D model of the RIS structure is created, and the printer deposits material layer by layer to create the final structure [51].

Overall, the choice of RIS fabrication technique depends on the specific requirements of the RIS device. Each technique has its own advantages and disadvantages in terms of cost, complexity, scalability, and performance. In general, the choice of fabrication technique depends on the specific application requirements and constraints [51]. Printed circuit board (PCB) fabrication is a popular and mature technique that is relatively low-cost and can produce high-performance RIS with good reproducibility [51]. However, it is limited in terms of design flexibility and scalability. Metamaterial-based techniques, such as photo-lithography and nano-imprint lithography, offer high design flexibility and scalability but are generally more complex and expensive. 3D printing is a relatively new technique that is gaining interest in RIS fabrication due to its high design flexibility and rapid prototyping capabilities. However, the material properties and performance of 3D-printed RIS may not be as good as those produced by other techniques [51]. Overall, the choice of fabrication technique depends on a number of factors, including the required performance, design flexibility, scalability, and cost.

Experimental implementations of RIS have been conducted in various applications, ranging from wireless communication systems to sensing and imaging. One common approach for experimental RIS implementations is to use a prototype system that consists of a transmitter, an RIS, and a receiver. The RIS is usually designed and fabricated based on a specific application requirement, and its performance is evaluated experimentally by measuring the signal quality and strength at the receiver [23].

In wireless communication systems, RIS has been demonstrated to improve signal quality and coverage area significantly. For example, an experimental RIS system was used to create a virtual environment with multiple signal paths that can improve the performance of a wireless network in indoor environments [52]. Another experiment showed that a RIS placed in between a transmitter and a receiver could act as a relay and increase the signal strength and coverage area [53].

In sensing and imaging applications, RIS has been used to enhance the resolution and accuracy of the imaging system. For example, an RIS can be designed and fabricated to act as a lens or a mirror that can focus or reflect electromagnetic waves. In one experiment, an RIS enhanced the resolution of a synthetic aperture radar (SAR) imaging system by improving the signal-to-noise ratio and reducing the imaging artifacts [54].

V. RIS APPLICATIONS

RIS have a wide range of potential applications due to their ability to manipulate and control electromagnetic waves. One of the most promising areas of application for RIS is wireless communication. RIS can be used to improve wireless communication systems by increasing signal quality, coverage area, and data rate. By creating a virtual environment with multiple signal paths, RIS can improve the performance of a wireless network in indoor environments where signal strength and quality can be compromised [55], [2].

Another potential application of RIS is in sensing and imaging. RIS can be designed and fabricated to act as a lens or a mirror that can focus or reflect electromagnetic waves, enhancing the resolution and accuracy of imaging and sensing systems. RIS can also be used to improve the signal-to-noise ratio and reduce imaging artifacts in synthetic aperture radar (SAR), computerized tomography (CT), and magnetic resonance imaging (MRI) systems. In those applications, RISes act as lenses or mirrors that can focus or reflect electromagnetic waves, leading to higher resolution and accuracy [56].

RIS can also be used to improve the efficiency of energy harvesting systems by optimizing the absorption and reflection of electromagnetic waves. By absorbing specific frequencies of electromagnetic waves, such as solar radiation or radio waves, RIS can convert them into usable energy, making energy harvesting systems more efficient [57].

Another potential application of RIS is in security and defense. RIS can be designed to selectively block or reflect
specific frequencies of electromagnetic waves, such as radar waves or thermal radiation. By doing so, RIS can create invisible barriers or cloaking devices, making objects or areas invisible or undetectable and improving security and defense systems [58], [59].

Finally, RIS can be used to improve the performance, energy efficiency, and coverage area of Internet of Things (IoT) networks. By creating virtual environments with multiple signal paths, RIS can increase IoT devices’ reliability and data rate and reduce energy consumption, improving their performance and coverage area [60], [61].

RISs have the potential to revolutionize many industries and fields due to their ability to control and manipulate electromagnetic waves. In addition to the applications discussed earlier, there are several other potential applications of RIS worth exploring. One such application is in 5G and beyond wireless networks [3]. RIS can be strategically placed to enhance signal coverage, reduce interference, and increase the network’s capacity, leading to improved performance and faster data transfer rates [62]. RIS can also be used in the automotive and transportation industry to improve safety and efficiency [63]. By selectively blocking or reflecting specific frequencies of electromagnetic waves, such as radar waves, RIS can improve the accuracy of collision avoidance systems and reduce accidents [64].

Agriculture and environmental monitoring systems can also benefit from RIS technology [65]. By optimizing the absorption and reflection of specific frequencies of electromagnetic waves, such as sunlight and radio waves, RIS can increase solar panels’ efficiency and improve environmental sensors’ performance and coverage area [60], [61].

With continuous technological advancement and the increasing demand for more efficient and reliable systems, there is great potential for future RIS applications [67]. One potential future application of RIS is in the field of space exploration. RIS can be used to enhance the communication and navigation systems of spacecraft by improving signal quality and reducing interference [68]. RIS can also be used to shield spacecraft from radiation and other harmful electromagnetic waves, improving space missions’ safety and efficiency [69].

Another potential future application of RIS is in the field of robotics. RIS can be used to improve the sensing and control systems of robots by enhancing the resolution and accuracy of imaging and sensing technologies [60]. RIS can also be used to create virtual environments with multiple signal paths that can improve the performance of robots in complex environments [70], [71].

RIS can also be used in the field of manufacturing to improve the efficiency and quality of production processes. RIS can be designed and placed strategically to optimize the absorption and reflection of specific frequencies of electromagnetic waves, which can improve the performance of industrial equipment and reduce energy consumption [69].

Moreover, RIS can also be used in the field of entertainment and media to enhance the viewing and listening experience of consumers. RIS can be designed to act as a screen or a speaker that can manipulate and control electromagnetic waves, improving the quality and immersion of audiovisual content [72]. Finally, RIS can also be used in the field of education and research to improve the performance of scientific instruments and equipment. RIS can be designed and fabricated to act as a lens or a mirror that can focus or reflect electromagnetic waves, improving the resolution and accuracy of scientific imaging and sensing technologies [73].

VI. CHALLENGES AND FUTURE DIRECTIONS

Several challenges need to be addressed for RISs’ widespread adoption. Some of the current challenges facing RIS are design complexity, fabrication complexity, integration with existing systems, power consumption, robustness and reliability, and regulatory and safety issues, which are detailed next.

The design of RIS structures can be complex and time-consuming, requiring advanced simulation tools and techniques. The optimization of RIS structures for specific applications is also challenging, and there is a need for more efficient and automated design methods [74]. The fabrication of RIS structures can also be challenging, requiring advanced techniques such as nanofabrication or 3D printing. The scalability and cost-effectiveness of RIS fabrication methods are also important considerations [75].

RISs need to be integrated with existing wireless communication or sensing systems, which can be challenging due to compatibility issues or the need for additional hardware. RISs also need to be compatible with different wireless communication standards and protocols, which can add to the complexity of system integration [76]. The operation of RIS structures requires power, and the power consumption can be significant, especially for large-scale RIS applications. There is a need for more efficient power management methods and low-power RIS designs [32].

RIS structures can be susceptible to environmental factors such as temperature, humidity, and mechanical stress, affecting their performance and reliability. There is a need for more robust and reliable RIS designs that can withstand different environmental conditions [70]. RIS may need to comply with regulatory standards related to electromagnetic interference and safety. There is a need for more research and development on the safety and regulatory aspects of RIS applications [61].

There are several potential solutions to the current challenges facing RIS technology. One solution is to improve the design and optimization of RIS structures. This can be achieved by using advanced simulation tools and optimization algorithms that can accurately model the behavior of electromagnetic waves and optimize the RIS structure for specific applications. Machine learning and artificial intelligence techniques can also be used to develop intelligent RIS systems that can adapt to changing environmental conditions and optimize their performance [77].

Another potential solution is to improve the fabrication techniques for RIS structures. This can be achieved by developing new materials and manufacturing processes that can produce complex and high-performance RIS structures at a low cost. 3D printing and nanofabrication techniques can also be used to produce customized RIS structures with high precision and accuracy [78].
In addition, the collaboration between researchers in different fields can help to address the current challenges facing RIS technology. Collaboration between experts in electromagnetics, material science, and manufacturing can lead to the development of new RIS structures and fabrication techniques that are optimized for specific applications [79]. Collaboration between researchers and industry can also help bridge the gap between research and commercialization, leading to the development of practical RIS systems for various applications [80].

Finally, government support and funding can be critical in developing and commercializing RIS technology. Government support can provide researchers and companies with the resources needed to develop and test new RIS systems and support for developing standards and regulations that can help ensure RIS technology’s safety and reliability. Government funding can also help accelerate the commercialization of RIS technology by providing financial support for research and development and for the production and deployment of RIS systems in real-world applications [81].

Future RIS research can be categorized into two main directions: improving the performance and capabilities of RIS and exploring new applications and domains for RIS. In terms of improving RIS performance and capabilities, research efforts can focus on addressing the current challenges facing RIS technology. One approach is to develop new materials and fabrication techniques that enable high-performance and low-cost RIS. For example, using advanced nanomaterials such as graphene and carbon nanotubes can improve RIS properties such as higher efficiency, larger bandwidth, and better controllability [82]. Additionally, developing new simulation and optimization tools can help optimize the design and operation of RIS for specific applications [74].

Another direction for improving RIS is to investigate new concepts and architectures that go beyond the current RIS designs. For example, multi-functional RIS that can perform multiple functions such as sensing, imaging, and communication can greatly enhance the versatility and value of RIS [83]. In addition, incorporating artificial intelligence and machine learning techniques can enable RIS to adapt to changing environments and optimize their performance in real time [84].

On the other hand, exploring new applications and domains for RIS can lead to exciting and innovative uses of this technology. For example, RIS can be used in the emerging field of terahertz communications to enable high-speed and high-capacity wireless communication at terahertz frequencies [85], [86]. RIS can also be used in space applications such as satellite communication and sensing, where the high radiation environment and harsh operating conditions require robust and reliable technologies [87], [88].

Furthermore, RIS can be used in the emerging area of smart cities and infrastructure, where they can enhance the performance and efficiency of various systems such as transportation, energy, and communication [89]. RIS can also be used in the field of medicine and healthcare, where it can improve the accuracy and resolution of medical imaging and sensing systems [90], [91].

RIS have recently gained significant attention in the field of wireless communication and beyond due to their ability to manipulate and control electromagnetic waves. This review covered a broad range of topics related to RIS, including their operation principles, simulation techniques, fabrication methods, experimental implementations, and potential applications. Regarding operation principles, it was discussed how RIS can reflect, absorb, and re-transmit electromagnetic waves to achieve desired signal propagation characteristics. Simulation tools and techniques were also presented, including analytical, numerical, and experimental methods. It was noted that the choice of simulation technique depends on the complexity of the problem and the desired level of accuracy.

Several fabrication techniques were described, including planar and non-planar approaches. Planar techniques are less expensive and easier to fabricate, while non-planar techniques allow for more complex and flexible designs.

The review also presented a range of potential applications for RIS, including wireless communication, sensing and imaging, energy harvesting, security and defense, IoT, automotive and transportation, medical and healthcare, agriculture and environment, and smart homes and buildings. It was noted that RISs have the potential to improve the performance and efficiency of these systems significantly.

However, several challenges currently exist in developing and implementing RIS technology, including cost, scalability, and integration with existing systems. To address these challenges, potential solutions were discussed, such as developing low-cost fabrication techniques, integrating RIS with existing wireless infrastructure, and using machine learning algorithms to optimize RIS performance.

Overall, this review highlights the potential of RIS technology in a wide range of applications and the need for continued research to overcome current challenges and fully realize their potential.

RISs have the potential to revolutionize a wide range of technologies due to their ability to manipulate and control electromagnetic waves. Some potential applications of RIS include improving wireless communication systems, enhancing imaging and sensing systems, improving the efficiency of energy harvesting systems, improving security and defense systems, and enhancing the performance of IoT networks. Additionally, RIS can improve the performance of 5G and beyond wireless networks, improve the safety and efficiency of automotive and transportation systems, enhance medical imaging and sensing technologies, improve the efficiency and sustainability of agriculture and environmental monitoring systems, and enhance the performance and energy efficiency of smart home and building systems. However, there are also several challenges to overcome, such as the need for efficient and cost-effective fabrication techniques, optimization of RIS design for specific applications, and integration with existing technologies. Potential solutions include developing new fabrication techniques, using artificial intelligence to optimize RIS design, and collaborating with experts in other fields to exploit the potential of RIS fully. Overall, the impact of RIS on future
technologies could be significant, enabling a wide range of applications that were previously impossible or impractical.

In conclusion, RISs have emerged as a promising technology for various applications in communication, sensing, energy, security, and IoT. However, several challenges need to be addressed to fully realize the potential of RIS, such as fabrication complexity, control complexity, and scalability.

To overcome these challenges, future RIS research should focus on developing more efficient and cost-effective fabrication techniques, advanced control algorithms for real-time operation, and scalable solutions for large-scale deployment. Moreover, interdisciplinary collaborations among researchers from different fields, such as materials science, electrical engineering, computer science, and physics, are essential to accelerate RIS research and development.

Furthermore, future RIS research should also consider the impact of RIS on society, including ethical and regulatory implications, as RIS may have significant implications for privacy, security, and social equity. Therefore, it is crucial to involve stakeholders from diverse backgrounds in RIS research, including industry, academia, government, and civil society, to ensure the responsible and sustainable development of RIS.

Overall, the potential impact of RIS on future technologies is immense, and the ongoing research and development in this field hold great promise for advancing various fields and improving our daily lives. With continued efforts and collaborations, RIS can potentially revolutionize how we communicate, sense, and interact with the world around us.

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