Status and Prospect of Intelligent Reflecting Surfaces for Green Communication System

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Abstract: *With the further evolution of communication technology, the era of the Internet of Everything is becoming a visible future. In Sixth-Generation (6G) communication networks, in addition to higher communication rates, lower latency, and more intelligent network management, larger system capacity, wider coverage, lower energy consumption, and lower costs are also required. The combination of Reconfigurable Intelligent Surface (RIS) technology and Simultaneous Wireless Information and Power Transfer (SWIPT) technology can not only ensure the communication quality, but also provide reliable technical support for 6G communication in terms of low power consumption, low cost and wide coverage. This paper presents an overview of the development process and existing problems of RIS-assisted SWIPT systems, aiming to discuss the application potentials and challenges of these systems in 6G communication. Firstly, the new demands in 6G communication are discussed, and by comparing Wireless Power Transfer (WPT) technology and SWIPT technology, the advantages and unresolved issues of SWIPT technology in wireless communication scenarios are elaborated. Then, the characteristics and research status of RIS technology were introduced. The paper points out that RIS assisted SWIPT systems will achieve improvements in spectral and energy efficiency, and analyzes the technical challenges currently present in the system. Finally, the future research directions and application prospects of RIS assisted SWIPT systems are discussed.*

Keywords: *Wireless communication technology; Reflecting Intelligent Surface (RIS); Simultaneous Wireless Information and Power Transfer (SWIPT)*

1. Introduction

In recent years, the global development of 5G technology has advanced rapidly, while 6G technology has already entered the research and exploration phase. The vision for the future is to create an all-encompassing, ubiquitous, intelligent digital world. As tens of thousands of wireless devices connect to the network, there is a growing demand for higher performance in wireless communication, including global seamless coverage, greater spectral efficiency, higher intelligence, enhanced security, and lower energy consumption. To meet these goals, ultra-dense networks must be established while minimizing the number of nodes in the signal transmission path. However, building ultra-dense networks not only increases the cost of network construction, energy consumption, and hardware complexity, but it also causes significant issues with signal transmission due to obstructions in the path [1]. Therefore, the development of new communication technologies is crucial for addressing the demands of low-power, low-cost, and lightweight networks.

Wireless Power Transfer (WPT) technology offers a novel solution to the energy limitations of communication networks. WPT transmits electrical energy from the transmitter to the receiver through intangible media in space, such as electric or magnetic fields. This eliminates the challenges associated with traditional wired connections and addresses issues like wire aging and corona discharge in wired energy transmission [2]. However, using only wired lines for energy transfer reduces spectral efficiency. To overcome this, Simultaneous Wireless Information and Power Transfer (SWIPT) technology has drawn significant attention from researchers. SWIPT technology uses Radio Frequency (RF) signals to transmit both information and green, clean, sustainable energy simultaneously. The receiver decodes the information and harvests energy, obtaining both the desired data and the energy needed to power the system. This enables continuous energy supply while maintaining effective communication [3]. By reducing the need for wiring, SWIPT eliminates the frequent need for battery replacements in wireless devices, extends communication cycles, and reduces the size and cost of terminal devices. As a result, SWIPT has garnered widespread interest among researchers globally.

To minimize losses in the signal and energy transfer paths, Reconfigurable Intelligent Surface (RIS) technology has garnered significant attention from researchers. RIS is a large, thin metasurface composed of passive sub-wavelength scattering elements with specially designed physical structures made from metallic or dielectric materials. These elements can be controlled via software to adjust their phase. The unique design of RIS makes it nearly passive and easy to deploy. When combined with Simultaneous Wireless Information and Power Transfer (SWIPT) technology, RIS can effectively reduce system construction costs while enhancing both communication and energy harvesting capabilities. Moreover, since RIS only reflects signals without amplifying them, it does not introduce additional thermal noise, thereby preventing interference in the system. Given these advantages, integrating RIS with SWIPT technology can make wireless communication systems more energy-efficient and environmentally friendly. It offers significant benefits in improving spectral efficiency and reducing energy consumption, showcasing tremendous potential for future applications in wireless communication systems.

This paper aims to provide a comprehensive and in-depth exploration of RIS-assisted SWIPT systems, which optimize the quality of information signal transmission while effectively improving energy transfer efficiency. The paper starts with an introduction to SWIPT technology, covering the development history of energy transfer and simultaneous wireless information and power transfer technologies, along with current research directions. It then discusses the combination of SWIPT and RIS technologies, highlighting their application scenarios. Building on this, the paper delves into the existing challenges within these systems and outlines future research directions. It also examines the potential applications of these systems across various fields and concludes with a summary of key insights.

2. SWIPT Technology

Traditional energy transfer technologies primarily refer to Wireless Power Transfer (WPT), which involves transmitting electrical power or energy without any physical connection between the load and the power source. This technology converts electrical energy into other forms, such as electromagnetic fields, lasers, microwaves, or mechanical waves, and transmits it wirelessly through space. At the receiving end, a receiver converts these different forms of energy back into electrical power, thereby achieving wireless energy transfer.

Wireless power transfer (WPT) technology is generally divided into four types: magnetic coupling, electric coupling, electromagnetic induction, and microwave radiation. Magnetic coupling wireless power transfer is based on the principle of magnetic coupling resonance, using resonant coils for transmission. It is suitable for medium-range power transmission and is unaffected by non-magnetic obstacles, commonly used in charging scenarios for electric vehicles and robots. Electric coupling power transfer generally refers to capacitive coupling, where wireless power is transferred through electric fields. It is suitable for short-range transmission, such as in smart homes. Electromagnetic induction wireless power transfer is based on Ampere's law and Faraday's principle of electromagnetic induction, and it is currently the most widely used wireless power transfer technology, widely applied in short-range energy transmission such as in electric toothbrushes and wireless charging for smartphones. Microwave radiation power transfer converts DC power into microwave energy for transmission, making it suitable for long-range, high-power transmission, although it suffers from higher path loss. Overall, wireless power transfer technologies have their own advantages and applicability in different scenarios, providing convenience for wireless charging, smart homes, electric vehicles, and other fields.

Compared to Wireless Power Transfer (WPT) technology, Simultaneous Wireless Information and Power Transfer (SWIPT) technology not only enables energy transfer but also facilitates simultaneous information transmission, improving the spectral efficiency of communication systems. It enhances the integration of wireless charging and data transmission, playing a crucial role in increasing the convenience of wireless networks and extending device battery life. SWIPT holds broader application prospects and greater technical challenges in the field of wireless communication. The concept was first introduced by scholar Lav R. Varshney in 2008 [4], who proposed the idea of simultaneously transmitting both information and energy using a single RF signal. He also introduced a new function to measure the balance between the information transmission rate and energy transfer efficiency within the RF signal. Later, scholars Grover and Sahai [5] extended this concept to communication systems, highlighting the trade-off between signal transmission rate and energy transfer efficiency. In 2013, the literature [6] first proposed Time Switching (TS) receivers and Power Splitting (PS) receivers based on practical scenarios. The former uses time slot rotation to separately demodulate the received signal for information decoding and energy harvesting, while the latter splits the received signal into two energy flows for information demodulation and energy harvesting. Subsequently, researchers began to explore how to balance information transmission quality and energy transfer efficiency in system design, aiming to find the equilibrium point where both information transmission rate and energy transfer efficiency are optimized. During this process, the focus gradually shifted towards system optimization and performance enhancement.

Currently, the reception architecture of SWIPT technology can be broadly classified into four types [7-8], as shown in Figure 1:

1) Separate Receiver Architecture: In this architecture, two independent receivers are used for information decoding and energy harvesting. Each receiver is equipped with a dedicated antenna and operates without interference from the other. One receiver is solely responsible for energy harvesting, while the other focuses on information decoding.

2) Time-Switching Receiver Architecture: This architecture employs a single receiver, which performs both information decoding and energy harvesting functions. The receiver's antenna switches between energy harvesting and information decoding modes based on a predefined time allocation factor. In this setup, the transmitter is responsible for calculating and assigning the transmission time ratio for each frame. This design requires precise time synchronization, possibly involving accurate timing control and synchronization mechanisms to ensure no conflicts or data loss during switching.

3) Power-Switching Receiver Architecture: Power switching combines wireless power transfer and information decoding. In this architecture, the signal is split according to a certain power ratio, with part of it directed to the energy harvester and the other part sent to the information decoder for decoding.

4) Antenna-Switching Receiver Architecture: This architecture typically involves using multiple antennas, each capable of both information decoding and energy harvesting. The receiver switches between antennas based on a certain strategy to optimize signal reception. The system can monitor the signal quality received by each antenna and use the best-performing antenna for information decoding, while the others naturally collect energy. This approach has the advantage of lower antenna switching complexity.

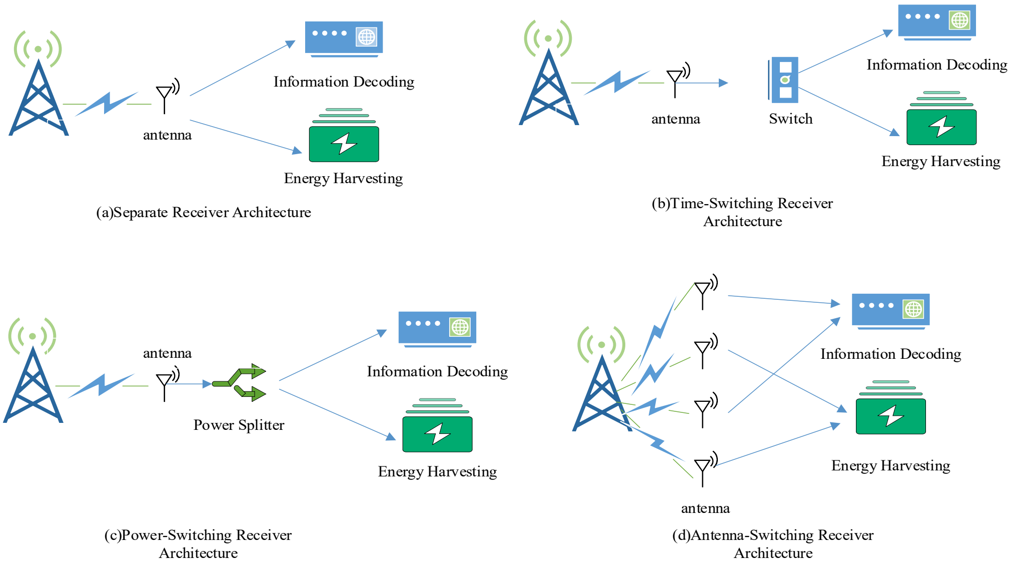
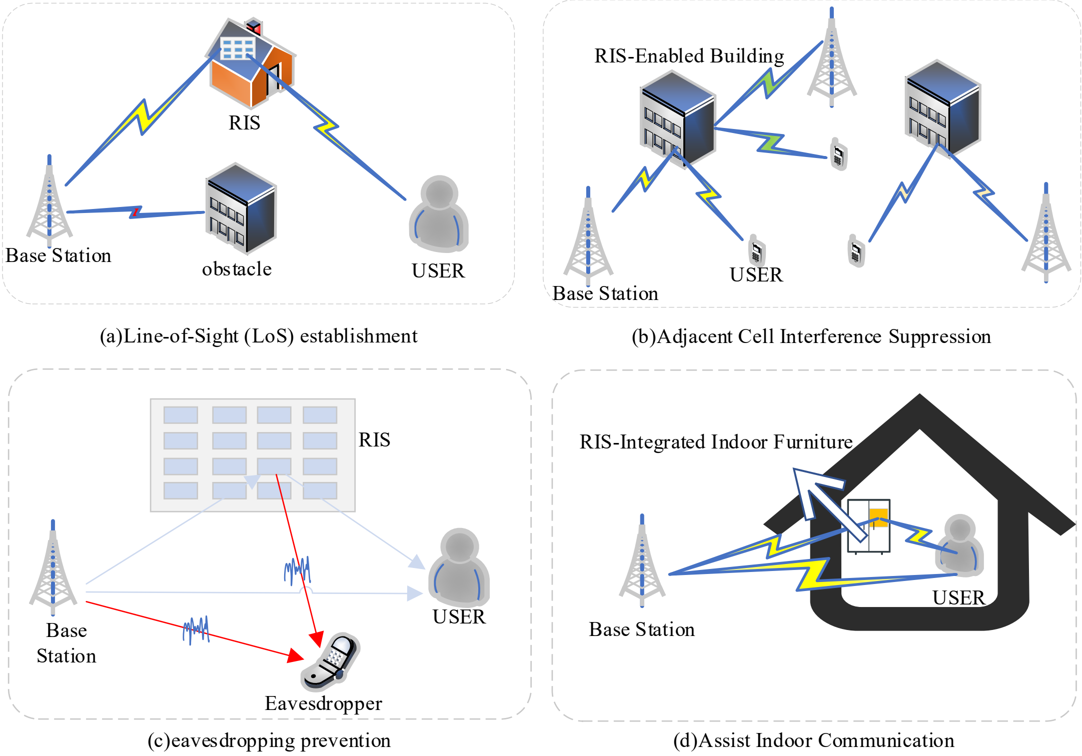


Figure 1: Classification of SWIPT Receiver Architectures.

The advantage of SWIPT technology is its ability to achieve efficient energy utilization, but its disadvantage lies in the limited transmission range. In [9], it is pointed out that in long-distance transmission, SWIPT systems are affected by various conversion losses during the energy transmission and reception processes, which impacts energy transmission efficiency. In [10], it is mentioned that low energy transmission efficiency and range limitations are key constraints of SWIPT systems. In [11], near-field transmission methods such as inductive coupling are studied, and the results show that wireless power transfer performs well at short distances, but as the distance between the transmitter and receiver increases, energy transmission efficiency decreases sharply. On the other hand, far-field transmission methods, although offering longer transmission distances, have low transmission efficiency and safety concerns. How to effectively expand coverage, enhance signal transmission quality and communication efficiency, and improve overall system performance and user experience becomes a key issue that SWIPT systems need to address.

3. RIS-assisted wireless communication system

Due to its unique characteristics and advantages, RIS (Reconfigurable Intelligent Surface) can optimize communication links by dynamically adjusting its structure, thereby improving the performance of communication systems. As shown in Figure 2, for signal transmission paths with obstacles, RIS can establish a line-of-sight environment by flexibly adjusting the signal reflection direction, optimizing channel transmission characteristics. This not only enhances spectral efficiency but also increases data transmission rates while reducing the energy consumption of the communication system. RIS can cover hard-to-reach areas by adjusting the signal reflection direction, compensating for weak coverage zones, and simultaneously reducing costs. RIS-assisted communication systems also offer interference resistance advantages. Since RIS is passive, it does not introduce noise and can intelligently adjust the reflection angle to weaken interference signals and enhance the propagation of desired signals, improving communication quality and reliability. Moreover, RIS can alter the signal propagation direction, making it useful for anti-eavesdropping purposes. By intelligently changing the amplitude and phase of RIS, the signal strength along legitimate paths can be enhanced while suppressing illegal signal links or concealing legitimate communication paths, thus achieving anti-eavesdropping and enhancing communication reliability and security. This also helps protect user privacy and prevent information leakage. Additionally, because RIS is easy to deploy, it can be conveniently installed indoors to assist with indoor communication needs, improving signal transmission efficiency and reducing energy consumption.



(a)Line-of-Sight (LoS) establishment

(b)Adjacent Cell Interference Suppression

(c)eavesdropping prevention

(d)Assist Indoor Communication

Figure 2: Applications of RIS in Communication Systems.

In recent years, the research directions for RIS-assisted wireless communication systems have mainly focused on system performance analysis and optimization, channel estimation, and physical layer security, among others. Table 1 summarizes and compares the research directions and key technologies used in different studies.

Research aimed at improving the performance of RIS-assisted wireless communication systems primarily involves jointly optimizing the transmit beamforming and the RIS reflection coefficient matrix to maximize spectral efficiency, total signal transmission rate, received energy at the receiver, or minimize transmit power, bit error rate, and other objectives [9-13], thereby improving various performance metrics of the communication system. Reference [12] investigates a RIS-assisted MISO system, utilizing the Majorization-Minimization (MM) method and alternating optimization of transmit power and RIS reflection coefficients to maximize the overall communication rate while ensuring Quality of Service (QoS). Under the constraint of signal-to-noise ratio (SNR), reference [13] employs a maximum ratio transmission algorithm and Block Coordinate Descent (BCD) algorithm for optimization to minimize base station transmit power and obtain a suboptimal solution using a penalty algorithm. Reference [14] combines total power constraints and the maximum interference level constraint at the receiver, using BCD and Semi-Definite Programming (SDP) algorithms to improve the system's spectral efficiency. In addition, the optimization objectives of the system include scenarios such as MIMO systems and IoT communication systems, where algorithms like alternating optimization and BCD are used to maximize received power or minimize transmit power [15,16].

Table 1: Summary of Key Technologies in RIS-Assisted Wireless Communication Systems.

References	Research Directions	Optimization Objectives	Key Technologies
[12]	MISO System Performance Optimization	Maximization of Total Communication Rate	MM, Alternating Optimization
[13]	MISO System Performance Optimization	Minimization of Transmit Power	MRT, BCD, Penalty Algorithm
[14]	MISO System Performance Optimization	Maximization of System Spectral Efficiency	BCD, SDP
[15]	MISO System Performance Optimization	Maximization of Received Power	BCD, Alternating Optimization
[16]	MISO System Performance Optimization	Minimization of Transmit Power	MMSE, ZF, Fixed-point method
[17]	Channel Estimation	Perform Channel Estimation	ON/OFF Protocol
[18]	Channel Estimation	Improve Channel Estimation Accuracy	MMSE, Fourier Transform
[19]	Channel Estimation	Consider Channel Estimation in Mobile Scenarios	MMSE
[20]	Channel Estimation	High-Mobility Scenario Channel Estimation	MMSE, Fourier Transform
[21]	Enhance Secure Communications	Minimization of Transmit Power	Penalty Algorithm
[25]	Enhance the Confidentiality Outage Probability Performance of Communication Systems	Minimize the Eavesdropping Link Signal-to-noise ratio	Heuristic Algorithm
[26]	Wireless Anti-Jamming Communication	Minimize transmission power and improve anti-jamming capability	Alternating Optimization, SDR, Lagrangian Dual Method, MRT
[27]	Enhancing Physical Layer Security in Sensing and Communication Systems	Maximizing Approximate Secrecy Rate	MRT, SCA

Due to the passive nature of RIS and its lack of signal processing capabilities, channel estimation becomes particularly important. Current research focuses on reducing the computational cost of channel estimation and the overhead of pilot signals. Scholars have employed various strategies, such as ON/OFF protocols, Fourier transform-based cascaded channel estimation schemes, and low-cost channel estimation methods, to improve the accuracy and efficiency of channel estimation [17,18]. Additionally, some researchers have utilized methods like channel time correlation and Kalman filters to achieve superior channel estimation in mobile scenarios [19,20].

RIS-based secure communication primarily revolves around optimizing the signal transmission of legitimate links, reducing the leakage of signals towards eavesdroppers, or minimizing the signal-to-noise ratio (SNR) of eavesdropper links. Various algorithms, including alternating optimization, SDR, Lagrange dual functions, MRT, and Successive Convex Approximation (SCA), have been adopted to optimize system performance and enhance communication security. Some studies focus on weakening the signals received by eavesdroppers by adjusting the RIS reflection, thus ensuring information-theoretic security. Other studies focus on adjusting the RIS phase to conceal the legitimate communication link, making it impossible for eavesdroppers to access the information of the legitimate link [21]. Reference [22] discusses the impact of electromagnetic interference on the physical layer security of RIS-assisted communication systems and points out that the uncertainty of electromagnetic interference capability has a decisive impact on the system's confidentiality performance. Moreover, research has found that the physical layer security of RIS-assisted systems is influenced by several factors, such as the position and size of the RIS, the distribution of eavesdroppers [23], and power constraints. These factors must be considered comprehensively when designing the system to optimize performance and improve the confidentiality of the communication system. Currently, research also addresses the physical layer security issues in RIS-assisted satellite communication systems. By leveraging channel similarity to enhance the confidentiality of satellite communications, an air-assisted full-duplex cooperative interference scheme has been proposed. Under the constraints of data rate, satellite power, and secrecy rate, the proposed scheme demonstrates superior performance compared to traditional methods by minimizing total power [24].

3.1. RIS-assisted WPT System

Due to the inevitable energy loss during long-distance energy transmission, the efficiency of wireless power transfer (WPT) systems over long distances is limited. To reduce energy transmission losses, researchers have started to focus on integrating multiple antennas and beamforming technologies to improve the system's energy transfer efficiency [28]. By utilizing large-scale antenna arrays for wireless energy transfer, the range of wireless energy transmission can be expanded, and energy transfer efficiency can be enhanced. However, each antenna in a multi-antenna array requires a dedicated RF chain to adjust the amplitude and phase of each antenna, along with amplifiers, phase shifters, and other RF components. This leads to excessively high hardware costs, implementation costs, as well as increased system complexity and energy consumption [29]. Although multi-antenna array systems are theoretically feasible, in practice, due to cost and other considerations, this approach is not practical. As a result, RIS (Reconfigurable Intelligent Surface) has begun to attract the attention of researchers. RIS consists of multiple reflective units and is nearly passive, requiring no additional active components to implement beamforming, making it superior to multi-antenna arrays in terms of both cost and construction complexity.

Literature [30] considered an RIS-assisted SISO WPT system and derived an exact approximation for the end-to-end cascaded fading channel's probability density function, ultimately verifying the superior performance of RIS in WPT systems. Literature [31] studied the charging time of an RIS-assisted WPT system and found that the distance between the RIS and the RF energy collection point affects the charging time, with shorter distances resulting in faster charging speeds. Literature [32] investigated an RIS-assisted MIMO WPT system and used a constant envelope simulated beamformer. By simplifying and reducing a set of phase shifters in the front end, the research further reduced hardware costs. An algorithm was proposed that maximizes total received power, subject to the constraint of the minimum received power of individual users. Literature [33] explored a multi-RIS-assisted WPT system and found that, compared to non-cooperative schemes, the joint collaboration of multiple RISs significantly improves network coverage and enhances system performance. Literature [34] applied RIS to power Internet of Things (IoT) devices and proposed a multi-RIS beam scanning algorithm to maximize received power. Considering the hardware implementation issues of IoT, the proposed algorithm only requires power information to achieve RIS beam focusing, greatly improving power transfer efficiency. Literature [35] studied a self-powered RIS-assisted WPT system and designed an independent beamforming algorithm that is simpler and performs comparably to joint beamforming algorithms. The study also considered multi-user scenarios and validated the effectiveness of the solution.

In the context of UAV (Unmanned Aerial Vehicle) wireless energy transfer, Literature [36] primarily discussed base station beamforming, RIS phase adjustment, and UAV energy harvesting. The research explored the optimal positioning of RIS and energy transfer efficiency in a dual UAV scenario. The results showed that RIS helps to improve energy transfer efficiency but requires a certain scale. Moreover, Literature [37] studied an RIS-assisted UAV wireless power supply network and proposed an alternating optimization algorithm based on the SCA (Successive Convex Approximation) and SDR (Semidefinite Relaxation) algorithms. This approach comprehensively considered user transmission power, UAV horizontal positioning, transmission time allocation, and RIS passive beamforming, ultimately minimizing the ground user throughput. Literature [38] utilized non-real-time CSI (Channel State Information) to configure RIS for maximizing UAV wireless power communication throughput. A dual-time scale active-passive beamforming framework was proposed, optimized using the GSS (Golden Section Search) and Dinkelbach algorithms, and the results showed that this algorithm outperforms the golden section search in terms of convergence speed.

3.2. RIS-assisted SWIPT System

Despite the significant advantages of SWIPT systems in improving device autonomy and energy utilization, they also face numerous challenges, such as channel fading, instability, information transmission security, low energy transfer efficiency, and complex hardware implementation. By comparing the applications of RIS (Reconfigurable Intelligent Surface) and relays in communication systems from different perspectives, it can be concluded that, compared to traditional relay nodes, RIS can be viewed as a passive, self-interference-free, full-duplex MIMO relay, capable of achieving energy efficiency performance comparable to or even better than full-duplex relays [39]. Introducing RIS can address some of the inherent issues in SWIPT systems to a certain extent.The combination of RIS and SWIPT technologies enables smarter and more efficient energy transfer. Specifically, RIS can adjust the direction and power distribution of the information and energy signals by designing its reflection parameters, ensuring that the desired information and energy signals accurately reach the destination. Meanwhile, during the information and energy transmission process, RIS can also adjust the phase and amplitude of the signals to maximize spectral efficiency and energy transfer efficiency. The integration of RIS and SWIPT technologies is a hot research topic, mainly focused on: optimizing allocation strategies to balance the trade-off between information transmission and energy harvesting, maximizing energy collection at the receiver; designing corresponding beamforming and precoding techniques to improve signal quality and achieve optimal performance; adopting robust encryption and privacy protection schemes to address security vulnerabilities unique to the RIS environment and ensure secure system communication; and developing adaptive algorithms to accommodate dynamic environments and user mobility.

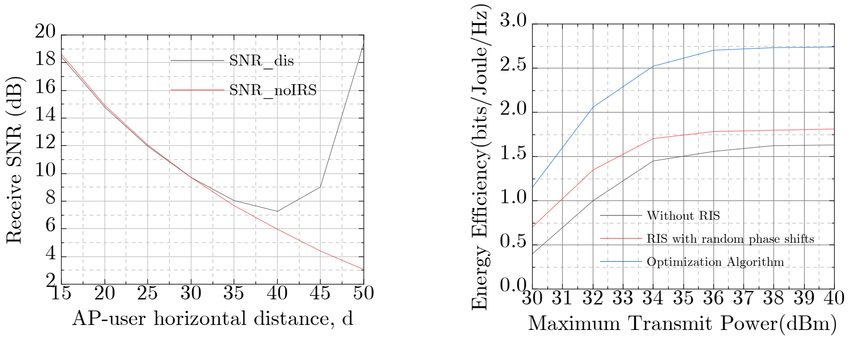
In literature [40], RIS was first applied to SWIPT systems with the aim of improving the rate-energy trade-off. By using a semidefinite relaxation algorithm, the transmission precoding matrix at the transmitter and the passive phase-shift matrix of the RIS were jointly optimized alternately. The study, with signal-to-noise ratio as a constraint, proposed an algorithm with low complexity but superior performance. The results showed that the RIS-assisted SWIPT system outperforms the system without RIS assistance. In literature [41], the objective was to maximize the weighted sum rate, with the maximum transmit power at the base station and the minimum total energy collection power at the receiver as constraints. The beamforming matrix and passive RIS reflection matrix were jointly optimized. The problem was decoupled into three sub-problems, and an algorithm based on the Successive Convex Approximation (SCA) method was proposed to handle the energy harvesting constraint. The alternating direction method of multipliers (ADMM) was applied to solve the constant modulus constraint of the RIS reflection phase. In literature [42], the goal was to maximize the minimum rate of the information receiver. The algorithm alternately optimized the beamforming and RIS phase shifts using sorting and Golden Section Search (GSS). Literature [43] focused on improving network energy efficiency by decoupling the problem into two sub-problems: optimizing the precoding matrix and the phase shift matrix separately. Using the SCA algorithm and a binary search-based algorithm, suboptimal solutions were obtained for both sub-problems, and the BCD algorithm was used to alternately optimize the sub-problems to find the optimal solution. These studies emphasize the importance of RIS in SWIPT systems.Additionally, literature [44] and literature [45] extended the research to the performance optimization of active RIS-assisted SWIPT systems. In literature [44], it was noted that compared to passive RIS, active RIS can reduce the power required for energy transfer by 50%-60%. Literature [46] incorporated secrecy rate as a constraint and investigated the RIS SWIPT system with CSI errors, using an alternating optimization framework and Shur complement to minimize transmission power. The results demonstrated the effectiveness of RIS deployment and the robustness of the proposed algorithm. Literature [47] proposed an innovative secure communication scheme in which the information receiver uses full-duplex technology with the help of RIS to transmit signals. This scheme concentrates interference signals on the eavesdropper to disrupt unintended reception while eliminating self-interference at the receiver. Compared to traditional self-interference cancellation technologies, this approach significantly enhances the security communication performance.

In addition, as shown in Table 2, significant progress has been made in the research of RIS-assisted SWIPT systems across different application scenarios. The optimization methods in the literature provide valuable guidance for improving system performance and efficiency. The introduction of RIS into SWIPT systems can effectively enhance the balance between spectral efficiency and energy efficiency, while also increasing the total power received for energy harvesting. This holds great significance for the design of future communication systems. The optimization algorithms in the literature aim to achieve system performance optimization by jointly optimizing parameters such as the base station's transmit beamforming matrix, RIS reflection coefficients, and user power allocation ratio. These studies demonstrate that RIS-assisted SWIPT systems can achieve significant performance improvements in spectral efficiency and energy harvesting, offering new development opportunities for future communication technologies. Therefore, the application of RIS technology in SWIPT systems holds promising prospects and is of great importance for improving the efficiency and reliability of communication systems.

Table 2: A Summary of Research on RIS-assisted SWIPT Systems in Different Application Scenarios

References	System Model	Research Content	Key Technologies
[48]	RIS-assisted SWIPT Internet of Things (IoT)	Maximizing Energy Efficiency and Energy Harvesting Power	Dinkelbach Method, S-Lemma, CCP, SDP
[49]	RIS-assisted SCMA-based SWIPT System	Minimizing Transmission Power	SCA, Alternating Optimization
[50]	RIS-UAV SWIPT System	Maximizing Total Collected Energy	DDPG
[51]	Active RIS-UAV SWIPT	Minimizing the Total Energy Cost of UAV	SCA
[52]	STAR-RIS SWIPT MISO System	Balancing Spectral Efficiency and Energy Efficiency	DDPG
[53]	STAR-RIS-based SWIPT under Imperfect Channel	Minimizing Transmission Power	S-Lemma, Shur Complement
[54]	STAR-RIS SWIPT MIMO System	Maximizing Weighted Sum Power	Energy Splitting Protocol, MMSE

Figure 3(a) illustrates a comparison of the system performance of a SWIPT system before and after the deployment of RIS, specifically showing the relationship between the received signal-to-noise ratio (SNR) and the user's distance from the base station. As clearly shown in the figure, after the RIS is deployed, even users farther away from the base station can receive signals with minimal loss.Figure 3(b) demonstrates the relationship between the energy efficiency performance of the SWIPT system with and without RIS and the base station’s maximum transmit power. It can be observed that as the base station's maximum transmit power increases, the system's energy efficiency also increases and eventually stabilizes, meaning that further increases in power no longer result in higher efficiency. Clearly, with the RIS configuration, the system's energy efficiency is significantly improved compared to the system without RIS.In conclusion, the deployment of RIS significantly enhances the performance of the SWIPT system, improving the signal reception quality for users at greater distances and boosting the system's energy efficiency. These findings provide important insights for the design and optimization of SWIPT systems and demonstrate the promising potential of RIS technology in wireless communication systems.



(a) SNR with/without RIS in SWIPT *(b) System Energy Efficiency with/without RIS in SWIPT*

Figure 3: Performance Comparison of SWIPT System with/without RIS.

3.3. Challenges of RIS-assisted SWIPT System

The RIS-assisted SWIPT system is considered an excellent green communication solution. However, in practical applications, several limitations and key issues remain to be addressed, such as hardware design, channel estimation, multipath fading, high-dimensional optimization, security and privacy concerns, and half-space coverage.

1) Hardware Design

In practical applications, many hardware parameters have a significant impact on the performance of communication systems. For example, the density of the unit elements on the RIS and the maximum number of elements that can be integrated onto the substrate directly affect system performance. If the RIS is deployed outdoors, harsh weather conditions over months or even years must be considered.

Therefore, when selecting materials for RIS components and associated control circuits, factors such as reliability, corrosion resistance, and durability are crucial to withstand long-term exposure to severe weather conditions.

Additionally, the deployment of RIS may be constrained by size and weight limitations, so careful consideration must be given to how the size and weight of the RIS impact its adaptability to real-world applications. The performance of the RIS is closely related to the density of its surface elements; to enhance performance, larger sizes and higher element densities are required. However, this increases the challenges of manufacturing and deployment, leading to higher energy consumption and costs, and requiring solutions to additional engineering problems. Overcoming these challenges may necessitate interdisciplinary collaboration. At the same time, for the receiving devices, exploring ways to achieve more efficient energy harvesting and storage to further improve system performance and reliability remains a key challenge for RIS-assisted SWIPT systems.

2) Channel Estimation

The passive nature of RIS introduces challenges in obtaining channel state information (CSI), as the amplitude and phase of each RIS element need to be accurately estimated. Acquiring CSI requires processing large-scale data, which undoubtedly increases computational and communication overhead. Furthermore, RIS inevitably introduces complex channel conditions such as multipath propagation and multiple reflections. After the signal reflects and scatters off the RIS surface, the number of signal propagation paths may increase significantly, making the channel model more complex and CSI acquisition more difficult.

On the other hand, in a wireless communication environment, the signal propagation path from the RIS to the user is dynamic, uncertain, and unstable. These reflection paths are influenced by environmental changes and mobility, which inherently lead to instability in the channel state. Traditional CSI acquisition techniques, which require frequent channel measurements and estimations to achieve a certain level of accuracy, are no longer applicable to RIS-assisted wireless systems. This is because such methods would result in significant delays and power consumption, making them unacceptable for real-time applications.

3) Dual-path Fading

When a signal passes through the RIS surface, multiple reflections and scattering occur, creating several propagation paths. The length and phase differences of these paths lead to signal superposition and interference effects, resulting in multipath effects at the receiver. Different parts of the RIS surface may have varying reflection coefficients, causing uneven signal strength across different paths. This unevenness exacerbates the dual-path loss issue. In complex propagation environments, multipath effects become more pronounced. These effects can also lead to interference, degrading communication quality and energy transfer efficiency. Therefore, interference cancellation techniques or intelligent scheduling algorithms are needed to mitigate interference. Addressing multipath effects is a key challenge in current research. On one hand, optimization algorithms can be designed to reduce dual-path loss. On the other hand, hardware improvements can be made by optimizing the RIS surface to ensure more uniform reflection coefficients across different regions, thereby reducing signal variability and mitigating dual-path loss.This section must be in one column.

4) High-dimensional Optimization

The RIS reflection units require complex configurations, with each unit's phase and amplitude needing adjustment based on the environment. In practical applications, the number of RIS reflection units typically reaches thousands or even tens of thousands, making the configuration variables for each unit amount to tens of thousands. Considering the high computational complexity of traditional optimization algorithms, current research is primarily limited to small-scale RIS. Furthermore, the signal transmission environment is continuously changing, and RIS needs to adjust its configuration in real-time. However, due to the large computational load, traditional optimization algorithms cannot respond quickly to these environmental changes, posing challenges in high-dimensional optimization.

To address this issue, algorithms such as deep learning and particle swarm optimization can be considered. Deep learning algorithms, through large-scale sample training, can learn optimization models with complex mapping relationships, reducing computational complexity. Particle swarm optimization, on the other hand, can simulate the optimization process of bird flocks in the search space, offering good global search capabilities. Integrating these algorithms into RIS configuration optimization is expected to enhance system performance and better adapt to the dynamic and complex communication environment.

5) Security and Privacy

During communication, there is a risk that the RIS could be maliciously exploited to interfere with or eavesdrop on legitimate communications. The SWIPT communication system operates in an open environment, where energy is transmitted alongside information. Signals can be received by any energy-limited device within the coverage area. If an eavesdropper masquerades as a legitimate energy-limited device, there is a possibility of information being intercepted, thereby increasing the likelihood of malicious interception.

Furthermore, the configuration of RIS relies on precise CSI, and under certain conditions, these configuration parameters may inadvertently leak user location information, threatening user privacy. Attackers could exploit the reflective properties of RIS to steal information or inject malicious data, compromising the confidentiality and integrity of signals and endangering the normal operation of the communication system.

6) Half-space Coverage

The physical properties of RIS cause it to primarily focus on signal reflection and refraction within a half-space, leading to the issue of half-space coverage. The back side of the RIS may suffer from inadequate coverage and limited enhancement, resulting in reduced signal quality for users located on the backside, which negatively impacts communication quality and energy reception efficiency. Similarly, obtaining channel state information for users on the back side becomes more challenging, further diminishing optimization performance. Addressing these issues requires a comprehensive approach that considers both security and communication quality, implementing appropriate technical measures during the design and configuration of the RIS to ensure the smooth operation of the communication system.

4. Future Research Directions for RIS-assisted SWIPT Systems

RIS-assisted SWIPT systems still have several limitations, but they show tremendous potential across various application scenarios. There are numerous possible applications and research directions to explore in the future.

1) System Architecture and Optimization

The RIS faces the issue of half-space coverage, which calls for research into multi-RIS coordination, the design of rotating RIS or curved RIS, and the development of multifunctional RIS that can simultaneously reflect and transmit signals to enhance coverage and system performance. The challenges include: effectively addressing the coordination communication problem between multiple RIS, and developing fast and efficient algorithms for the dynamic configuration of RIS. These solutions should adapt to changing environments, ensure communication quality, and minimize computational and communication overhead.

2) Physical Layer Security Research

The characteristics of RIS give rise to security and privacy concerns, and there are two potential approaches to address this issue. The first approach is covert communication, which ensures efficient transmission of both information and energy while protecting the privacy of legitimate users. The second approach is counteracting illegal users, as malicious users may gain control of the RIS and disrupt legitimate communication links. Therefore, new technological methods need to be designed to detect and expel illegal users as soon as they attempt to access legitimate communication channels. Research in this area will provide more effective safeguards for the security of RIS systems.

3) Multidisciplinary Integration

By integrating disciplines such as materials science, the challenges in the hardware of RIS-assisted SWIPT systems can be addressed. Developing comprehensive solutions through interdisciplinary collaboration and innovation can overcome barriers and challenges across different fields, such as mitigating multipath effects. Combining intelligent algorithms and machine learning techniques can lead to the development of new algorithms and models to process massive data in complex environments, optimize RIS configuration and system performance, and realize a more intelligent RIS-assisted simultaneous wireless information and power transfer system.

4) Integration of Energy Harvesting and Energy Efficiency

In SWIPT systems, energy harvesting and transmission are crucial issues. The key to achieving simultaneous transmission of energy and signals through the integration of RIS and energy harvesting technology lies in the reasonable design of the RIS operation mode and the structure of the energy harvester, ensuring efficient energy collection while transmitting signals. Future research could explore how to more effectively combine RIS and SWIPT technologies to achieve simultaneous transmission of both signals and energy, while optimizing the system's energy utilization efficiency.

5) Expansion of Application Scenarios

RIS-assisted SWIPT systems have broad application prospects in various fields. As the technology continues to develop and mature, these systems will play a significant role in multiple areas. For example: In smart cities, they can improve the communication quality and energy transmission efficiency of public facilities such as smart streetlights and environmental monitoring stations, thereby enhancing urban management efficiency and intelligence. In public safety and surveillance, they can provide wider coverage and higher image transmission quality while offering a stable power supply to widely distributed sensor nodes, thus improving the effectiveness and reliability of public safety monitoring. In smart homes and IoT, they can reduce the reliance on cables, improving user convenience and experience. In healthcare, they can provide high-quality and reliable telemedicine services, support real-time patient monitoring and remote diagnostics, and offer stable, continuous energy supply to wearable health devices, extending their lifespan. In defense and security, they can enhance the reliability and coverage of battlefield communications. When combined with drones, they provide wireless energy transmission for military UAVs and UGVs, extending mission duration, improving operational capabilities, and supporting complex tasks in challenging environments.

5. Conclusion

The RIS-assisted SWIPT system represents a new paradigm for signal transmission in the 6G era. This system not only ensures the stability and security of information transmission but also enhances the efficiency of energy transfer, offering a broad range of application prospects. This paper provides a detailed introduction to the development of energy transfer technology and RIS technology, deeply explores the current research status and application prospects of the RIS-assisted SWIPT system, and discusses its advantages as well as the existing unresolved issues. Based on these challenges, future research directions for the RIS-assisted SWIPT system are proposed, with a view to its application advantages in areas such as smart cities, healthcare, and national defense. Through continuous innovation and progress, it is believed that this technology will unlock greater potential in various communication scenarios and make significant contributions to societal development and advancement.

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