RS-Assisted Wireless Communication: Use Cases, Benefits, and Integration

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Abstract: Intelligent Reflecting Surfaces (IRS) are gaining recognition as a passive, cost-effective, and environmentally friendly solution designed to tackle the challenges of high complexity, elevated hardware costs, and increased energy consumption in future wireless networks. These networks are expected to provide expansive connectivity services to an ever-growing number of devices globally. This paper outlines the benefits of IRS technology over alternative solutions and showcases the potential of IRS-assisted wireless communication in novel scenarios when integrated with complementary technologies. Specifically, it explores the application of IRS in relay scenarios, detailing how this approach can enhance the physical layer security of communication systems.

Keywords: Intelligent Reflective Surfaces (IRS); Wireless communication; Physical layer security.

1. Introduction

With the rapid development of new applications such as Artificial Intelligence (AI), Internet of things (IoT), Internet of things (IoE), virtual reality, three-dimensional media and autonomous driving, this will lead to a surge in data traffic. In 2010, the global mobile traffic volume was 7.462 EB/ month. It is expected that by 2030, the mobile communication network will connect tens of billions of wireless devices through the intensive deployment of multi-antenna base stations (BS) and access points, and the traffic volume is expected to be 5016 EB/ month in 2030 [2,3]. These statistics also show how fast the data surge has been. Society is moving towards a fully automated remote management architecture. Autonomous systems will be distributed in all fields of society, including industry, health, roads, oceans and space stations, and autonomous characteristics will become an inevitable trend. In this regard, millions of sensors are being integrated into cities, vehicles, homes, industries, food, toys and other environments to provide intelligent living and automated systems. Therefore, high data rates with reliable connections are needed to support these applications. Although 5G provides users with reliable communication connection services with its stable advantages, the rapid growth of data-centric automated systems may exceed the capabilities of 5G wireless networks, which will not be able to provide a fully automated and intelligent network, that is, provide everything services and a fully immersive experience. Although 5G communication systems will make significant improvements to existing systems, they will still be unable to meet the demands of emerging intelligent and automated systems in the future. 5G communications largely ignore the convergence of communication, intelligence, sensing, control and computing functions that will, however, be required for future IoT applications. Certain devices, such as virtual reality ones, are well beyond the rate range that 5G can offer, as they require data rates of at least 10 Gbps. Therefore, 5G will reach its limit in the near future [4,5] and cannot meet the needs of users.

The most critical requirement of the next-generation communication network, 6G, is the ability to process massive data with low delay and high rate, as well as to meet the very high data rate connection between devices, so as to overcome the limitations of 5G in facing new challenges. The key driver of 6G will be the convergence of all past features, such as network densification, high throughput, high reliability, low power consumption, and large-scale connectivity. The 6G system will also continue the trend of previous generations, including new services that incorporate new technologies. New services include AI, smart wearables, implants, autonomous vehicles, computational reality devices, sensing and 3D maps. The 6G communication network will be developed by introducing new synthesis of future services such as environmental sensing intelligence and novel human-computer interaction, the general introduction of AI, as well as terahertz, three-dimensional networks, quantum communication, holographic beamforming, backscatter communication, Intelligent reflective surface (IRS) to make up for the performance lag of 5G systems and bring better service quality.

Spectrum and energy efficiency have always been key considerations in the design of modern wireless communications. As 6G continues to meet performance requirements such as ultra-high data rate, ultra-low delay, ultra-high stability and ultra-high reliability, it means that more and more BS and wireless terminals will be deployed to support exponential growth of mobile services, large-scale wireless connectivity, ubiquitous computing power, precise sensing and driving, large-scale data fusion and massive data processing, at which time power and spectrum consumption and implementation costs will increase to prohibitive levels . Therefore, 6G must realize the efficient use of spectrum, use the same energy to provide data traffic more than a hundred times as before, lower cost network equipment, lower deployment cost and scalable backward network to provide high energy efficiency, high speed and high security services [10,11].

IRS, as a passive, low-cost and easy-to-deploy green communication technology, has attracted much attention. It can provide energy saving, economical and efficient communication support for future wireless networks, so it is regarded as one of the most promising 6G wireless communication technologies. IRS improves the efficiency of wireless power transmission by dynamically adjusting the phase shift of reflected signals to change the wireless propagation environment by using low-cost passive components based on a time-varying environment, resulting in high passive beamforming gains. Because IRS operates in full duplex mode and requires low power consumption, it is a candidate solution to improve energy and spectrum efficiency. Compared with traditional technologies such as active beamforming and relaying based on large-scale multiple input and multiple output (MIMO), IRS eliminates signal amplification and regeneration, resulting in lower hardware costs, energy consumption, and interference pollution. Also, IRS has effective short-range/local coverage that can be deployed intensively at a scalable cost, but does not require complex interference management as long as they are sufficiently separated from each other, in addition to IRS-assisted wireless communication technologies that have the advantage of being easy to deploy and sustainable to operate, IRS can be easily integrated into communications environments because of their very small hardware footprint, not only can it be easily and flexibly deployed in the exterior wall and interior of the building, but also can be embedded in the ceiling, furniture, computer cases, even clothes and other surfaces, which provides a high degree of flexibility and excellent compatibility for wireless communication and does not consume extra energy, so it has a broad application prospect in the future wireless communication network .

With the further development of the research, the application of IRS assisted wireless network in different scenarios and different technologies keeps emerging, and the transmission performance of the system is further improved by combining with other technologies. Based on this, this article considers IRS-assisted mobile communication and summarizes it.

2. IRS versus other communication technologies

IRS has the following advantages over existing related technologies, namely conventional reflective surfaces, AF relays, active intelligence surfaces, backscatter communications, and massive MIMO.

First, thanks to recent breakthroughs in Micro-electromechanical Systems and composites, IRS can reconfigure reflection coefficients in real time, whereas traditional reflective surfaces only have fixed reflection coefficients.

Second, IRS is a green and energy efficient technology that passively reflects incoming signals without additional energy consumption, whereas AF relays and active intelligence surfaces require active RF components. Active AF relays typically operate in half duplex mode and are therefore less spectral efficient than IRS operating in full duplex mode. Although AF relaying can also work in full duplex, it is inevitably subject to severe self-jamming, which requires effective jamming cancellation techniques.

Third, although both IRS and backscatter communications use passive communication, IRS can be equipped with a large number of reflecting elements due to complexity and cost limitations, whereas backscatter devices are usually equipped with single/few antennas.

Fourth, IRS only attempts to assist the intended transmission of signals between transmitter and receiver pairs, enhancing the performance of the existing communication link, and not its own information transmission, whereas traditional radio frequency identification devices tag backscatter communication (communication with the receiver by reflecting the signal sent from the reader) needs to support the transmission of information from the backscatter device. Thus, the direct path signal in backscatter communication (from reader to receiver) is an unwanted interference that needs to be eliminated/suppressed at the receiver. However, in IRS enhanced communication, both direct path and reflected path signals carry the same useful information and can therefore be added coherently at the receiver to maximize the total received power.

Fifth, massive MIMO uses large antenna arrays to improve spectrum and power utilization, which is more dependent on the utilization of each RF chain and powerful signal processing algorithms. Literature for the first time analyzed the capacity of IRS, demonstrating that the capacity per square meter of IRS is linear with the average transmission power, while the large-scale MIMO is logarithmic. In addition, IRS differs from massive MIMO based on active intelligence surfaces due to different array architectures (passive versus active) and operational mechanisms (reflection versus emission).

Sixth, other communication technologies, such as mm-wave communication, intensive networking, etc., these related technologies cannot control the wireless transmission environment and energy consumption.

Table 1. Comparison of IRS with other related technologies

Technology	Mechanism	Mode	Hardware cost	Energy consumption	Role
IRS	Passive, reflective	Full duplex	Low	Low	Helper
Backscatter	Passive, reflective	Full duplex	Very low	Very low	Source
Relay	Active，receive and send	Half/full duplex	High	High	Helper
MIMO	Active，receive and send	Half/full duplex	High	High	Helper
Massive MIMO	Active，receive and send	Half/full duplex	Very high	Very high	Source/Destination

3. IRS combines with other communication technologies

As shown in Table 2, applications of IRS-assisted wireless networks in different scenarios and technologies are emerging. For example, IRS assisted MIMO, IRS assisted massive MIMO, IRS assisted mobile edge computing, IRS assisted Unmanned Aerial Vehicle (UAV) communication, IRS assisted relay, IRS assisted physical layer security, robust beamforming design in IRS assisted MISO communication, IRS assisted Simultaneous Wireless Information and Power Transfer (SWIPT) and IRS enhanced Non-orthogonal multiple access (NOMA) transmission. The IRS functions like a relay, which is deployed on tall buildings. The antennas of the BS and receiver are at a relatively low elevation Angle. It can create a new link to assist communication under the coverage of blind areas or complex propagation environment. Provide wider coverage and higher performance communication for inaccessible areas, provide high strength signal for poor performance links, realize high gain of passive beamforming through intelligent regulation of IRS reflection phase, achieve additional diversity gain, and build battery-free Internet of Things network for difficult communication environment of battery replacement and energy supplement.

Table 2. Applications of IRS-assisted wireless networks in different scenarios and technologies

IRS combines with other technologies	Reference
IRS assists MIMO	[19-21]
IRS assists massive MIMO	
IRS assisted mobile edge computing	
IRS assisted UAV	[24,25]
IRS assisted physical layer security	[26,27]
Robust beamforming design in IRS assisted MISO communication	
IRS assisted SWIPT	[29-38]
IRS assisted NOMA	[39-41]
IRS assisted Internet of vehicles (IOV)	[42-44]
IRS assisted smart medical	

4. IRS assists relay

In this section, taking IRS assisted relay communication as an example, the advantages of this scenario and the significant features of improving physical layer security are elaborated in detail.

4.1. IRS combines with traditional relay

Considering the fact that the previous generations of mobile communication technologies have deployed a large number of relays in the actual communication environment, combined with the advantages provided by IRS to overcome the current communication challenges, this paper considers to integrate the two technologies, and proposes a widely deployed relays and IRS communication model, so as to provide more efficient, stable and reliable communication services for target users.

In terms of network architecture, compared with the traditional single-link network, the relay collaborative IRS communication network can effectively meet the network demand of the rapid growth of data traffic and user traffic, enhance the expected signal strength of the receiving node, reduce the wireless network access cost, effectively utilize the relay resources, expand the communication coverage, reduce the system power consumption, improve the system capacity and security performance. In line with the new development trend of future mobile communication, it can provide services for new application communication such as IoT, IOV, smart city and smart home in future mobile communication.

With the rapid deployment of relay collaborative IRS system, although the network architecture is heterogeneous and complex, its network coverage, data rate and network capacity are also improved.

To be specific, firstly, Alleviates the communication interruption caused by the small wireless coverage area of BS communication, limited BS resources and energy consumption, deployment in remote areas, or difficult battery replacement of equipment.

Secondly, it can strengthen the communication quality of users and the coverage range of indoor communication. In particular, for the scene where line of sight is blocked and the communication is blocked, a new type of non-line-of-sight link with good performance can be created to assist the communication. Specifically, in specific cases, the communication quality of densely populated cities can be expanded.

Third, for users on the edge of the cell, improve their communication quality, eliminate inter-cell interference, reduce the average load of single BS, reduce the average congestion of network capacity, and improve the data transmission rate of the network. Its passive, intelligent and passive characteristics improve the quality of the communication environment and improve the dynamic network capacity adjusted on demand. It also provides the possibility for further optimizing network security and enhancing anti-interference capability.

Fourth, rich relay nodes assist IRS communications, improve end-user service quality, and enhance security performance.

Fifth, by configuring different wireless technologies such as transmission power, antenna number, number of relays and coverage area, the system performance can be improved and personalized services can be provided to the vast number of users.

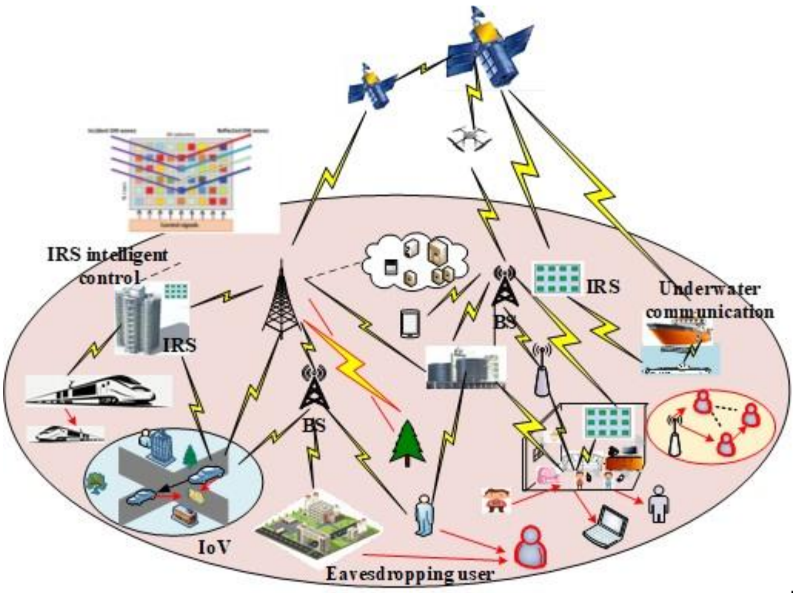

Figure 1. Relay cooperation IRS network architecture

As shown in Figure 1, the IRS system framework of relay collaboration is given. However, for any end user, it is very important to improve the quality of service and ensure safe transmission. Therefore, the development of the IRS network of relay collaboration is still mainly focused on the secure transmission of user information.

4.2. IRS assists physical layer security

The essence of wireless physical layer security, that is, the intrinsic security of wireless channel is utilized by physical layer. It is a technology that utilizes the intrinsic characteristics of wireless channel and noise to realize the safe transmission of wireless signal. By taking advantage of the diversity and time-variability of wireless channel as well as the uniqueness and reciprocity of both channels of legitimate communication, it starts from the objective law of wireless signal transmission. Mining the internal security elements of wireless channel. These security elements are naturally parasitic in the communication process and signal processing technology, which can evolve and integrate with the new air interface technology to promote the integration of security and communication. Different from the traditional security means that rely on key encryption, it is an endogenous security mechanism and manifestation of physical layer wireless communication. From the perspective of information theory, physical layer security provides another way to deal with the problem of communication security.

The traditional network optimization in wireless communication system is limited to the transmission control at the transceiver, but pays little attention to the wireless communication environment. This is mainly because the wireless propagation environment has long been regarded as an entity of uncontrollable and random behavior between transceivers. In addition to being uncontrollable, the environment usually adversely affects communication efficiency due to the introduced signal attenuation, fading, and interference. As a result, the propagation environment itself becomes the main limiting factor which hinders the further improvement of wireless network performance. Recently, there has been an increasing demand for new communication paradigms that can intelligently adjust the communication environment to improve communication efficiency or simplify transceiver architectures. In this regard, the IRS has received a great deal of attention for its ability to reconfigure the propagation environment through software-controlled reflection, so the IRS assists the physical layer secure communication model to reconfigure the wireless propagation environment to facilitate transmission to meet the new challenges posed by increasing performance requirements.

As shown in the figure 2, the transmission of the legitimate link is enhanced by optimizing the passive beamforming vector at IRS, and the signal reception of the listening link is offset, thus improving the security performance of the wireless network.

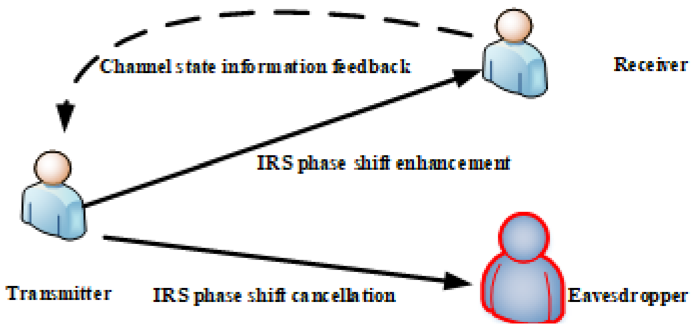

Figure 2. Enhancing physical layer security by optimizing IRS phase shift

5. Conclusion

With the explosion of wireless network data volume, how to achieve the balance between performance and energy efficiency in the next generation of mobile communication is a major challenge. This paper investigates one of the candidate technologies, IRS, respectively summarizes the advantages of IRS technology compared with other related technologies and the new scenarios of combining with other technologies. In particular, The IRS assisted relay communication technology is described in detail. This article envisages that IRS technology will be widely used in the future to solve resource-constrained wireless transmission.

References

[1] Huang C, Zappone A, Alexandropoulos G C, et al. Reconfigurable Intelligent Surfaces for Energy Efficiency in Wireless Communication[J]. IEEE Transactions on Wireless Communications, 2019, 18(8): 4157–4170.

[2] Mohsan S A H, Othman N Q H, Mohamed A F A, et al. A vision of 6G: technology trends, potential applications, challenges and future roadmap[J]. International Journal of Computer Applications in Technology, Inderscience Publishers, 2021, 67(2–3): 275–288.

[3] Sanusi J, Oshiga O, Thomas S, et al. A Review on 6G Wireless Communication Systems: Localization and Sensing[C]// 2021 1st International Conference on Multidisciplinary Engineering and Applied Science (ICMEAS), 2021: 1–5.

[4] Guo F, Yu F R, Zhang H, et al. Enabling Massive IoT Toward 6G: A Comprehensive Survey[J]. IEEE Internet of Things Journal, 2021, 8(15): 11891–11915.

[5] Calvanese Strinati E, Barbarossa S, Gonzalez-Jimenez J L, et al. 6G: The Next Frontier: From Holographic Messaging to Artificial Intelligence Using Subterahertz and Visible Light Communication[J]. IEEE Vehicular Technology Magazine, 2019, 14(3): 42–50.

[6] Wang M, Lin Y, Tian Q, et al. Transfer Learning Promotes 6G Wireless Communications: Recent Advances and Future Challenges[J]. IEEE Transactions on Reliability, 2021, 70(2): 790–807.

[7] Jain P, Gupta A, Kumar N. A vision towards integrated 6G communication networks: Promising technologies, architecture, and use-cases[J]. Physical Communication, 2022, 55: 101917.

[8] Akbar M S, Hussain Z, Sheng Q Z, et al. 6G survey on challenges, requirements, applications, key enabling technologies, use cases, AI integration issues and security aspects[J]. arXiv preprint arXiv:2206.00868, 2022.

[9] Yang P, Xiao Y, Xiao M, et al. 6G Wireless Communications: Vision and Potential Techniques[J]. IEEE Network, 2019, 33(4): 70–75.

[10] Chaoub A, Giordani M, Lall B, et al. 6G for Bridging the Digital Divide: Wireless Connectivity to Remote Areas[J]. IEEE Wireless Communications, 2022, 29(1): 160–168.

[11] Han S, Xie T, I C-L. Greener Physical Layer Technologies for 6G Mobile Communications[J]. IEEE Communications Magazine, 2021, 59(4): 68–74.

[12] Chen R, Liu M, Hui Y, et al. Reconfigurable Intelligent Surfaces for 6G IoT Wireless Positioning: A Contemporary Survey[J]. IEEE Internet of Things Journal, 2022, 9(23): 23570–23582.

[13] Wu Q, Zhang S, Zheng B, et al. Intelligent Reflecting Surface-Aided Wireless Communications: A Tutorial[J]. IEEE Transactions on Communications, 2021, 69(5): 3313–3351.

[14] Wu Q, Zhang R. Towards Smart and Reconfigurable Environment: Intelligent Reflecting Surface Aided Wireless Network[J]. IEEE Communications Magazine, 2020, 58(1): 106–112.

[15] Ji B, Han Y, Liu S, et al. Several Key Technologies for 6G: Challenges and Opportunities[J]. IEEE Communications Standards Magazine, 2021, 5(2): 44–51.

[16] Li Z, Chen W, Wu Q, et al. Joint Beamforming Design and Power Splitting Optimization in IRS-Assisted SWIPT NOMA Networks[J]. IEEE Transactions on Wireless Communications, 2022, 21(3): 2019–2033.

[17] Wu Q, Zhang R. Intelligent Reflecting Surface Enhanced Wireless Network via Joint Active and Passive Beamforming[J]. IEEE Transactions on Wireless Communications, 2019, 18(11): 5394–5409.

[18] Chen J, Liang Y-C, Pei Y, et al. Intelligent Reflecting Surface: A Programmable Wireless Environment for Physical Layer Security[J]. IEEE Access, 2019, 7: 82599–82612.

[19] Yan W, Yuan X, He Z-Q, et al. Passive Beamforming and Information Transfer Design for Reconfigurable Intelligent Surfaces Aided Multiuser MIMO Systems[J]. IEEE Journal on Selected Areas in Communications, 2020, 38(8): 1793–1808.

[20] Dong L, Wang H-M. Enhancing Secure MIMO Transmission via Intelligent Reflecting Surface[J]. IEEE Transactions on Wireless Communications, 2020, 19(11): 7543–7556.

[21] Hong S, Pan C, Ren H, et al. Artificial-Noise-Aided Secure MIMO Wireless Communications via Intelligent Reflecting Surface[J]. IEEE Transactions on Communications, 2020, 68(12): 7851–7866.

[22] Zhi K, Pan C, Ren H, et al. Statistical CSI-Based Design for Reconfigurable Intelligent Surface-Aided Massive MIMO Systems With Direct Links[J]. IEEE Wireless Communications Letters, 2021, 10(5): 1128–1132.

[23] Bai T, Pan C, Deng Y, et al. Latency Minimization for Intelligent Reflecting Surface Aided Mobile Edge Computing[J]. IEEE Journal on Selected Areas in Communications, 2020, 38(11): 2666–2682.

[24] Shafique T, Tabassum H, Hossain E. Optimization of Wireless Relaying With Flexible UAV-Borne Reflecting Surfaces[J]. IEEE Transactions on Communications, 2021, 69(1): 309–325.

[25] Li S, Duo B, Yuan X, et al. Reconfigurable Intelligent Surface Assisted UAV Communication: Joint Trajectory Design and Passive Beamforming[J]. IEEE Wireless Communications Letters, 2020, 9(5): 716–720.

[26] Lv L, Wu Q, Li Z, et al. Secure Two-Way Communications via Intelligent Reflecting Surfaces[J]. IEEE Communications Letters, 2021, 25(3): 744–748.

[27] Wu C, Yan S, Zhou X, et al. Intelligent Reflecting Surface (IRS)-Aided Covert Communication With Warden's Statistical CSI[J]. IEEE Wireless Communications Letters, 2021, 10(7): 1449–1453.

[28] Zhou G, Pan C, Ren H, et al. A Framework of Robust Transmission Design for IRS-Aided MISO Communications With Imperfect Cascaded Channels[J]. IEEE Transactions on Signal Processing, 2020, 68: 5092–5106.

[29] Zargari S, Khalili A, Zhang R. Energy Efficiency Maximization via Joint Active and Passive Beamforming Design for Multiuser MISO IRS-Aided SWIPT[J]. IEEE Wireless Communications Letters, 2021, 10(3): 557–561.

[30] Liu J, Xiong K, Lu Y, et al. Energy Efficiency in Secure IRS-Aided SWIPT[J]. IEEE Wireless Communications Letters, 2020, 9(11): 1884–1888.

[31] Wu Q, Zhang R. Joint Active and Passive Beamforming Optimization for Intelligent Reflecting Surface Assisted SWIPT Under QoS Constraints[J]. IEEE Journal on Selected Areas in Communications, 2020, 38(8): 1735–1748.

[32] Tang Y, Ma G, Xie H, et al. Joint Transmit and Reflective Beamforming Design for IRS-Assisted Multiuser MISO SWIPT Systems[C]// ICC 2020 - 2020 IEEE International Conference on Communications (ICC), 2020: 1–6.

[33] Li Z, Chen W, Wu Q, et al. Joint Beamforming Design and Power Splitting Optimization in IRS-Assisted SWIPT NOMA Networks[J]. IEEE Transactions on Wireless Communications, 2022, 21(3): 2019–2033.

[34] Khalili A, Zargari S, Wu Q, et al. Multi-Objective Resource Allocation for IRS-Aided SWIPT[J]. IEEE Wireless Communications Letters, 2021, 10(6): 1324–1328.

[35] Zargari S, Farahmand S, Abolhassani B, et al. Robust Active and Passive Beamformer Design for IRS-Aided Downlink MISO PS-SWIPT With a Nonlinear Energy Harvesting Model[J]. IEEE Transactions on Green Communications and Networking, 2021, 5(4): 2027–2041.

[36] Xu D, Yu X, Jamali V, et al. Resource Allocation for Large IRS-Assisted SWIPT Systems with Non-linear Energy Harvesting Model[C]// 2021 IEEE Wireless Communications and Networking Conference (WCNC), 2021: 1–7.

[37] Wu Q, Zhang R. Weighted Sum Power Maximization for Intelligent Reflecting Surface Aided SWIPT[J]. IEEE Wireless Communications Letters, 2020, 9(5): 586–590.

[38] Xu D, Jamali V, Yu X, et al. Optimal resource allocation design for large IRS-assisted SWIPT systems: A scalable optimization framework[J]. IEEE Transactions on Communications, 2022, 70(2): 1423-1441.

[39] Fu M, Zhou Y, Shi Y, et al. Reconfigurable Intelligent Surface Empowered Downlink Non-Orthogonal Multiple Access[J]. IEEE Transactions on Communications, 2021, 69(6): 3802–3817.

[40] Zheng B, Wu Q, Zhang R. Intelligent Reflecting Surface-Assisted Multiple Access With User Pairing: NOMA or OMA?[J]. IEEE Communications Letters, 2020, 24(4): 753–757.

[41] Zuo J, Liu Y, Qin Z, et al. Resource Allocation in Intelligent Reflecting Surface Assisted NOMA Systems[J]. IEEE Transactions on Communications, 2020, 68(11): 7170–7183.

[42] Chen Y, Wang Y, Zhang J, et al. Resource allocation for intelligent reflecting surface aided vehicular communications [J]. IEEE Transactions on Vehicular Technology, 2020, 69(10): 12321-12326.

[43] Huang Z, Zheng B, Zhang R. Roadside IRS-Aided Vehicular Communication: Efficient Channel Estimation and Low-Complexity Beamforming Design[J]. IEEE Transactions on Wireless Communications, 2023.

[44] Dampahalage D, Manosha K B S, Rajatheva N, et al. Intelligent reflecting surface aided vehicular communications[C]//2020 IEEE Globecom Workshops (GC Wkshps. IEEE, 2020: 1-6.

[45] Ji B, Wang Y, Xing L, et al. IRS-driven Cybersecurity of Healthcare Cyber Physical Systems [J]. IEEE Transactions on Network Science and Engineering, 2022.