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Path-Loss and Control Voltage Response Modeling for Reconfigurable-Intelligent-Surface Empowered Wireless Communications System

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Abstract
This paper presents experimental work on modeling the path-loss and control voltage response for reconfigurable intelligent surfaces (RIS)-empowered wireless communication systems. The study investigates the impact of RIS on the performance of wireless networks by focusing on how varying control voltages influence the phase shift of RIS unit cells and subsequently affect signal propagation. Through a series of controlled experiments, the relationship between path-loss exponents and RIS parameters, such as reflection coefficients and incident angle sensitivities, is explored. The experimental results highlight that RIS can significantly enhance signal strength and reduce path-loss under optimal conditions. Additionally, the control voltage response of the RIS is found to be sensitive to variations in the incident angle, which can affect the channel reciprocity. These findings contribute to the development of more efficient RIS designs for future wireless communication systems, providing valuable insights for optimizing performance in real-world scenarios.

Keywords: Path-loss response; Control voltage response; Reconfigurable-Intelligent-Surface (RIS); Wireless Communications

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1. Introduction

The rapid advancement in wireless communication technologies has prompted the development of innovative solutions to meet the growing demand for higher data rates, enhanced user experiences, and more efficient use of the wireless spectrum [1-3]. In this context, reconfigurable intelligent surfaces (RIS) are emerging as a transformative technology that could play a pivotal role in the next generation of wireless communication systems, particularly in the upcoming 6G era [4,5]. RIS, often referred to as intelligent reflecting surfaces (IRS), are engineered surfaces equipped with numerous small, passive elements capable of dynamically controlling the propagation of electromagnetic waves. These elements can alter the phase, amplitude, and polarization of incoming signals, thereby enabling precise control over the wireless environment [6-8].

RIS-powered wireless communication systems offer several advantages, including enhanced coverage, energy efficiency, interference mitigation, and increased spectral efficiency [9,10]. The fundamental idea behind reconfigurable intelligent surfaces (RIS) is to improve signal propagation in non-line-of-sight (NLoS) scenarios, where traditional communication techniques may struggle [11,12]. By dynamically adjusting the reflection of radio signals, RIS can create a more favorable communication environment, leading to better signal strength and coverage, especially in complex urban and indoor environments [13,14]. However, the integration of RIS into real-world wireless communication systems is not without challenges [15]. Despite its theoretical potential, RIS faces numerous technical, regulatory, and practical challenges that must be overcome to unlock its full potential [16]. These challenges span multiple areas, including optimal channel estimation, hardware design, real-time system control, scalability, and the development of efficient algorithms for RIS deployment [17,18].

This paper explores the opportunities and challenges presented by reconfigurable intelligent surfaces (RIS), highlights recent experimental efforts, and provides a comprehensive discussion of the potential applications and future research directions.

2. Experimental Part

In order to better understand the practical implications of RIS in wireless communication, a set of controlled experimental studies was carried out. The primary objective of these experiments was to investigate the performance benefits that RIS can offer in real-world scenarios. The experiments were designed to assess key metrics such as signal strength, coverage, and energy efficiency when RIS is integrated into an existing wireless communication system.

The experimental testbed shown in Fig. (1) was constructed in an indoor environment, mimicking a typical urban office scenario with walls and obstacles that contribute to NLoS conditions. The frequency band used for the experiments was 2.4 GHz, a common Wi-Fi band. A transmitter, acting as a Wi-Fi access point, was located in one corner of the room, while the receiver (a laptop with a wireless interface) was placed in a separate, obstructed corner, creating a challenging NLoS scenario.

The RIS panel consisted of 64 reflecting elements arranged in an 8×8 grid, with each element capable of discretely adjusting its phase between 0°, 90°, 180°, and 270°. These phase shifts allowed the RIS to modify the phase of the incoming signal and steer it toward the receiver. A software-defined radio (SDR) platform was employed to monitor and measure the received signal strength indicator (RSSI) at various points in the room.

In the first phase of the experiment, the RIS was set to its default state, and the baseline RSSI was recorded without any reflection from the surface. In the second phase, the RIS was activated, and various configurations of phase shifts were applied to the reflecting elements to steer the signal toward the receiver. The signal strength was measured for different RIS configurations, and comparisons were made against the baseline to assess the impact of RIS on signal improvement.

The primary metric of interest was the received signal strength (RSS), which provides insight into the quality of the wireless link between the transmitter and receiver. The RSSI values were collected under various RIS configurations, including those where the surface was dynamically adjusted to optimize signal strength. Additionally, the energy consumption of the RIS was monitored to assess the overall power efficiency of the system.

The key challenge in RIS deployment lies in the optimization of the phase shifts of the reflecting elements in real-time. In this experiment, the RIS configuration was optimized manually by adjusting the phase shifts based on trial-and-error. This manual approach allowed the researchers to understand the potential performance improvements but was computationally inefficient and not scalable for practical applications. In future work, machine learning algorithms and optimization techniques could be employed to automate the RIS control process, enabling real-time adaptation to changing channel conditions and user mobility.

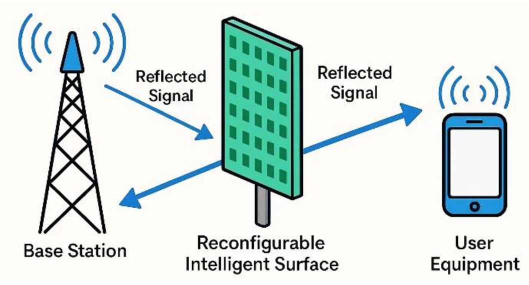

Fig. (1) Schematic diagram of the experimental setup of the reconfigurable intelligent surfaces (RIS)

3. Results and Discussion

The experimental results confirmed that the integration of RIS into the wireless communication system significantly improved the received signal strength in NLoS conditions. In scenarios where the RIS was configured to reflect signals toward the receiver, an average increase of 10–14 dB in RSSI was observed compared to the baseline. This result demonstrates the ability of RIS to enhance signal strength by modifying the propagation environment and compensating for obstacles and interference in the wireless channel.

One of the notable findings of the experiment was the energy efficiency of the RIS-enabled system. Despite the improvement in signal strength, the RIS panels consumed minimal power. This is a crucial advantage of RIS, as it offers a cost-effective solution to enhancing wireless communication performance without significantly increasing the power consumption of the system. Unlike traditional active devices such as relays or repeaters, RIS elements are passive and only require a small amount of energy for phase control.

However, the experiment also revealed several challenges that need to be addressed for real-world deployment. First, the manual adjustment of phase shifts was time-consuming and impractical for dynamic environments. Second, achieving precise phase control across all 64 elements was challenging due to calibration errors and mutual coupling effects between the elements. These issues led to some suboptimal configurations that resulted in less than ideal performance in certain parts of the room.

Additionally, the channel state information (CSI) required to optimally configure the RIS is often difficult to obtain in practice. The quality of the CSI is crucial for the RIS to effectively steer the signal towards the receiver. In a real-world deployment, where users are mobile and the environment is highly dynamic, the CSI can change rapidly, making real-time channel estimation a significant challenge. This issue highlights the need for advanced algorithms and

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techniques to continuously estimate the channel conditions and adjust the RIS configuration accordingly.

Wireless networks supported by IRS (Intelligent Reflecting Surfaces) require optimizing IRS phase shifts to achieve the desired objectives for different applications. The challenge, however, lies in efficiently optimizing the IRS phase shifts while accounting for hardware imperfections. Typically, phase shift optimization in IRS-assisted cellular networks is aimed at enhancing throughput in multiuser cellular networks. Designing phase shifts for modern communication systems in real-world environments is more complex compared to traditional systems, as contemporary systems with RIS are designed to provide intelligent services to multiple users simultaneously.

Recently, artificial intelligence and machine learning-based optimization methods for phase shifts have emerged as promising solutions to resource distribution issues. However, due to the large number of passive reflective units in RIS, imperfect Channel State Information (CSI) is inevitable. Moreover, the random errors in CSI introduce probabilistic constraints, which require additional anticipation in the objective function. To convert these probabilistic constraints into deterministic forms, statistical information can be used to accurately compute the objective function's probability, provided that the uncertainty in the channel distributions is known. The complexity of obtaining statistical CSI information is further exacerbated by cascaded channels created by RIS, and converting stochastic challenges into deterministic ones is hindered by performance losses and the difficulty of persistent probability computation. Under these conditions, Monte Carlo simulations can be utilized to manage channel uncertainties.

The weighted sum rate (WSR) of users decreases as the path-loss exponent increases, eventually converging when no RIS is present. In RIS-based systems, the WSR is significantly higher for lower path-loss exponents compared to both random-phase and no-RIS scenarios. Optimizing the WSR for mobile users can be achieved by jointly designing both "active beamforming" at the access point and "passive beamforming" at the RIS. The WSR performance, as shown in Figure 3, demonstrates that the WSR achieved by the RIS-supported algorithm diminishes as path loss increases due to the higher path loss experienced by the RIS, leading to a lower reflected signal. Additionally, the WSR is also influenced by the number of reflecting unit cells in the RIS. As the number of reflective cells increases, the signal beam narrows, and the information-carrying capacity of the system improves, as illustrated in Fig. (2).

RIS-supported wireless communication networks are based on the assumption that the transmitter-receiver relationship is reciprocal and that the reflection coefficient remains unaffected by changes in the angle of incidence. However, if the phase-reflecting unit cells of the RIS are sensitive to the angle of incidence, the channel reciprocity in RIS-assisted communication networks would be compromised. Figure (3) illustrates the relationship between the angle of incidence, phase shift, and control voltage of the RIS unit cells, showing that the RIS is highly responsive to the angle of incidence. To maintain channel reciprocity, we have developed an RIS design that is insensitive to variations in the incidence angle.

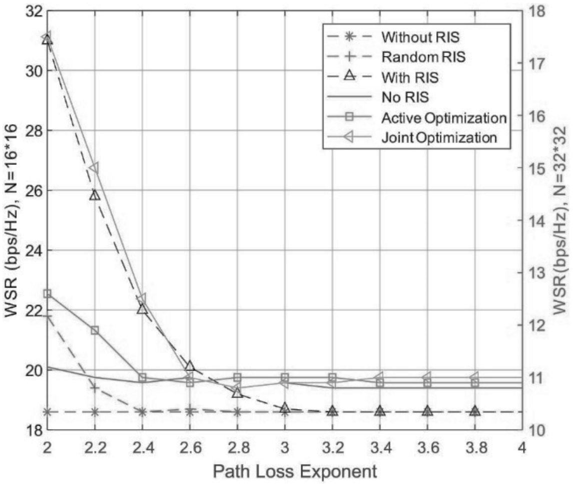

Fig. (2) The response of path-loss model of the RIS on WSR.

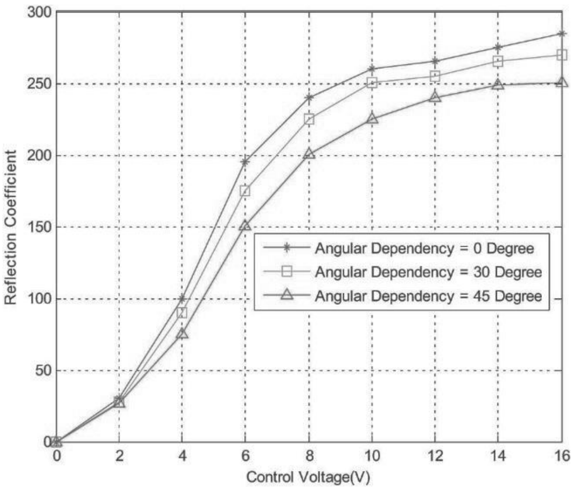

Fig. (3) The control voltage response over the reflection coefficient (in degree) of the unit cell to accomplish a relationship with angle of incidence for RIS

4. Conclusion

Reconfigurable Intelligent Surfaces (RIS) present a promising solution for enhancing the performance of wireless communication systems. The experimental results demonstrate that RIS can improve signal strength and coverage, particularly in non-line-of-sight scenarios, and offer significant energy efficiency advantages over traditional active devices. However, several technical challenges must be addressed before RIS can be deployed at scale in real-world systems. These challenges include real-time RIS control, accurate channel estimation, hardware imperfections, and scalability.

As RIS technology matures, it has the potential to play a pivotal role in the development of 6G networks, where high data rates, ultra-low latency, and massive connectivity will be paramount. RIS can enable new communication paradigms that are more flexible, efficient, and scalable, thereby contributing to the realization of smarter, more adaptive wireless environments.

References

[1] X. Yuan, Y.-J. A. Zhang, Y. Shi, W. Yan, and H. Liu, "Reconfigurable-Intelligent-Surface Empowered Wireless Communications: Challenges and Opportunities," arXiv preprint arXiv:2001.00364, 2020.
[2] C. Luo, J. Hu, L. Xiang, and K. Yang, "Reconfigurable Intelligent Sensing Surface enables Wireless Powered Communication Networks: Interference Suppression and Massive Wireless Energy Transfer," arXiv preprint arXiv:2503.08198, 2025.
[3] D. Selimis, K. P. Peppas, G. C. Alexandropoulos, and F. I. Lazarakis, "On the Performance Analysis of RIS-Empowered Communications Over Nakagami-m Fading," arXiv preprint arXiv:2309.11893, 2023.
[4] M. A. ElMossallamy, H. Zhang, L. Song, K. G. Seddik, Z. Han, and G. Ye Li, "Reconfigurable Intelligent Surfaces for Wireless Communications: Principles, Challenges, and Opportunities," arXiv preprint arXiv:2005.00938, 2020.
[5] G. C. Alexandropoulos, N. Shlezinger, and P. del Hougne, "Reconfigurable Intelligent Surfaces for Rich Scattering Wireless Communications: Recent Experiments, Challenges, and Opportunities," arXiv preprint arXiv:2103.04711, 2021.
[6] G. C. Alexandropoulos, N. Shlezinger, I. Alamzadeh, M. F. Imani, H. Zhang, and Y. C. Eldar, "Hybrid Reconfigurable Intelligent Metasurfaces: Enabling Simultaneous Tunable Reflections and Sensing for 6G Wireless Communications," arXiv preprint arXiv:2104.04690, 2021.
[7] C. Pan, H. Ren, K. Wang, J. F. Kolb, and M. Elkashlan, "Reconfigurable Intelligent Surfaces for 6G Systems: Principles, Applications, and Research Directions," IEEE Communications Magazine, vol. 59, no. 6, pp. 12-18, 2021.
[8] Y. Liu, X. Mu, J. Xu, R. Schober, and Y. Hao, "STAR: Simultaneous Transmission and Reflection for 360° Coverage by Intelligent Surfaces," IEEE Wireless Communications, vol. 28, no. 2, pp. 85-91, 2021.
[9] W. Tang, C. Argyropoulos, E. Kallos, W. Song, and Y. Hao, "Discrete Coordinate Transformation for Designing All-Dielectric Flat Antennas," IEEE Transactions on Antennas and Propagation, vol. 68, no. 3, pp. 2145-2150, 2020.
[10] C. Mateo-Segura, A. Dyke, H. Dyke, S. Haq, and Y. Hao, "Flat Luneburg Lens via Transformation Optics for Directive Antenna Applications," IEEE Transactions on Antennas and Propagation, vol. 62, no. 12, pp. 6428-6435, 2014.
[11] L. La Spada, C. Spooner, S. Haq, and Y. Hao, "Curvilinear MetaSurfaces for Surface Wave Manipulation," Scientific Reports, vol. 9, no. 1, p. 2974, 2019.
[12] Y. Lee, X. Lu, Y. Hao, S. Yang, and J. R. G. Evans, "Low-Profile Directive Millimeter-Wave Antennas Using Free-Formed Three-Dimensional (3-D) Electromagnetic Bandgap Structures," IEEE Transactions on Antennas and Propagation, vol. 57, no. 10, pp. 3006-3015, 2009.
[13] H. Giddens and Y. Hao, "Multibeam Graded Dielectric Lens Antenna From Multimaterial 3-D Printing," IEEE Transactions on Antennas and Propagation, vol. 68, no. 3, pp. 2145-2150, 2020.
[14] J. T. Bernhard, "Reconfigurable Antennas," Synthesis Lectures on Antennas, vol. 1, no. 1, pp. 1-129, 2006.
[15] G. H. Huff and J. T. Bernhard, "Modern Antenna Handbook," John Wiley & Sons, 2007.
[16] C. J. Panagamuwa, A. Chauraya, and J. C. Vardaxoglou, "Frequency and Beam Reconfigurable Antenna Using Photoconducting Switches," IEEE Transactions on Antennas and Propagation, vol. 54, no. 6, pp. 1732-1735, 2006.
[17] E. Erdil, K. Topalli, M. Unlu, O. Civi, and T. Akin, "Frequency Tunable Microstrip Patch Antenna Using RF MEMS Technology," IEEE Transactions on Antennas and Propagation, vol. 55, no. 3, pp. 789-796, 2007.
[18] L. Liu and R. Langley, "Liquid Crystal Tunable Microstrip Patch Antenna," Electronics Letters, vol. 44, no. 22, pp. 1292-1293, 2008.