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Reconfigurable Intelligent Surfaces for 6G Wireless Networks: A Survey of Recent Advances, Applications, and Open Challenges

Dr Ch Navitha
Assistant Professor
Department of Electronics and Communication Engineering,
Chaitanya Bharathi Institute of Technology, Hyderabad

Abstract
Reconfigurable intelligent surfaces (RIS) have emerged as one of the leading candidate technologies for sixth-generation (6G) wireless networks, offering a low-cost, low-power means of shaping the propagation environment through programmable passive or near-passive reflecting elements. This paper presents a structured review of RIS technology, covering its operating principles, recent architectural advances such as active and beyond-diagonal RIS, and its integration with artificial intelligence, non-terrestrial networks, and physical layer security. Representative application scenarios in 6G, including coverage extension, integrated sensing and communication, and vehicular networks, are discussed alongside the key technical barriers that continue to limit large-scale deployment, namely channel estimation overhead, hardware non-idealities, and the absence of finalized standards. The paper concludes by outlining research directions that are likely to shape the transition of RIS from theoretical study to field trial and commercial deployment.

Keywords: reconfigurable intelligent surface, RIS, 6G, beamforming, physical layer security, wireless propagation, metasurfaces

I. INTRODUCTION

The move from fifth-generation (5G) to sixth-generation (6G) wireless networks is being driven by demands that go well beyond incremental gains in data rate: ultra-reliable low-latency communication, pervasive sensing, and connectivity for dense device populations all place new stress on the radio propagation environment itself. For decades, that environment has been treated as an uncontrollable given, with transceivers designed to compensate for whatever channel conditions arise. Reconfigurable intelligent surfaces (RIS) invert this assumption. A RIS is a planar array of many low-cost, nearly passive elements, each capable of independently adjusting the phase, and in some designs the amplitude, of an impinging electromagnetic wave, so that the surface as a whole can steer, focus, or otherwise shape reflected signals toward a desired receiver.

Because RIS elements are typically passive and do not require dedicated radio-frequency chains, the technology promises substantial gains in coverage and spectral efficiency at a fraction of the energy and hardware cost of deploying additional active relays or small cells. This combination of performance potential and low complexity has made RIS one of the most actively studied enabling technologies for 6G, with contributions spanning electromagnetics, signal processing, and network optimization.

The remainder of this paper is organized as follows. Section II summarizes the operating principles and system model of RIS-assisted links. Section III reviews recent technical advances, including active and beyond-diagonal RIS architectures and their combination with machine learning. Section IV discusses representative 6G application scenarios. Section V outlines open challenges, and Section VI concludes the paper.

II. RIS FUNDAMENTALS AND SYSTEM MODEL

A RIS-assisted link typically comprises a transmitter, a receiver, and a surface composed of tens to thousands of sub-wavelength unit cells arranged in a planar array. Each element is loaded with a tunable component, commonly a PIN diode or varactor, that allows its local reflection coefficient to be set electronically by a controller. Collectively, the elements superimpose a spatially varying phase shift on the incident wave, which allows the surface to synthesize a reflected beam pattern analogous to a passive, continuously reconfigurable antenna array.

Unlike conventional relays, a RIS does not amplify or decode the signal; it only reflects it, which keeps thermal noise from being reintroduced into the link and keeps power consumption low. This passive nature, however, also means the end-to-end channel is the product of the transmitter-to-RIS and RIS-to-receiver channels, which makes channel estimation and phase-configuration optimization considerably more demanding than in conventional MIMO systems, particularly as the number of elements scales into the hundreds or thousands.

Recent surveys have organized RIS research along several axes: use-case definition, phase-shift control mechanisms, channel sounding methodology, and channel estimation strategy, arguing that an integrated view across these axes is necessary because progress in one area, such as low-overhead channel estimation, directly constrains what is achievable in another, such as real-time beam control.

III. RECENT ADVANCES

A. Active and Beyond-Diagonal RIS

A key limitation of passive RIS is the "multiplicative fading" effect, whereby the double-reflection path loss through the surface can be substantially worse than a direct or single-hop path, especially when the surface is far from both endpoints. Active RIS architectures address this by embedding a small reflection-type amplifier at each element, trading a modest increase in power consumption and hardware cost for a meaningful improvement in effective signal-to-noise ratio. In parallel, beyond-diagonal RIS designs generalize the surface's scattering matrix beyond the conventional diagonal (element-independent) model, allowing energy to be redistributed across elements and thereby unlocking additional beamforming degrees of freedom relative to standard RIS.

B. Machine Learning-Assisted Optimization

Because jointly optimizing transmit precoding and RIS phase profiles is a non-convex problem that scales poorly with the number of elements, a substantial body of recent work applies deep learning and reinforcement learning to approximate near-optimal configurations at a fraction of the computational cost of classical alternating optimization. These learning-based controllers are particularly attractive in mobile or non-terrestrial scenarios, where channel conditions change quickly and a low-latency response is required.

C. Integration with Non-Terrestrial and Vehicular Networks

RIS has also been proposed as a complement to non-terrestrial network (NTN) elements such as high-altitude platforms and low Earth orbit satellites, where it can extend coverage into shadowed regions and improve link budgets without adding active payload mass. Similarly, RIS-assisted vehicular communication has been studied as a way to maintain reliable links in dynamic, obstruction-prone environments such as urban intersections, where line-of-sight paths are frequently blocked.

D. Physical Layer Security

Because a RIS can shape the channel independently for legitimate and eavesdropping receivers, it has attracted significant interest as a low-cost mechanism for physical layer security (PLS). By steering constructive interference toward an authorized user while introducing destructive interference at a suspected eavesdropper location, RIS-aided designs can improve secrecy rate without relying solely on cryptographic techniques, complementing rather than replacing upper-layer security mechanisms.

IV. APPLICATION SCENARIOS IN 6G

Several application domains illustrate the practical motivation for RIS research. Coverage extension and dead-zone mitigation remain the most direct use case: a surface deployed on a building facade or indoor wall can redirect signal around obstacles without new fiber backhaul or additional base stations. Integrated sensing and communication (ISAC) is a second emerging use case, in which the same surface that shapes communication beams is also exploited to improve localization and environmental sensing accuracy by controlling the multipath structure of the channel. Energy efficiency is a third motivating scenario, since a passive surface can often deliver a comparable coverage improvement to an active small cell at a small fraction of the operating power, which is relevant to the sustainability goals increasingly attached to 6G standardization efforts.

V. OPEN CHALLENGES

Despite rapid progress, several obstacles stand between current RIS research and commercial deployment. Channel estimation overhead remains a central bottleneck: because the cascaded channel scales with the number of RIS elements, pilot overhead can become prohibitive for large surfaces unless codebook-based, compressive, or deep-learning-based estimation techniques are adopted. Hardware non-idealities, including discrete rather than continuous phase states, mutual coupling between closely spaced elements, and insertion loss, cause a gap between idealized theoretical gains and what is observed in prototype measurements. Standardization is a further open issue; as of this writing, RIS has not been formally incorporated into 3GPP specifications, and the absence of agreed reference channel models and control interfaces makes cross-vendor interoperability difficult to evaluate. Finally, most reported gains come from simulation or small-scale testbeds, and larger, more diverse field trials are needed before performance claims can be generalized to real deployment conditions.

VI. CONCLUSION

Reconfigurable intelligent surfaces represent a distinctive shift in wireless system design, from compensating for the propagation environment to actively engineering it. Recent advances in active and beyond-diagonal architectures, learning-based control, and integration with non-terrestrial and vehicular networks have expanded the range of scenarios in which RIS can deliver measurable benefit. At the same time, unresolved challenges in channel estimation overhead, hardware fidelity, and standardization mean that RIS remains, for the moment, more mature in theory than in field deployment. Closing this gap will require continued collaboration between the signal processing, hardware, and standardization communities, alongside larger-scale, reproducible field trials.

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