Electronics, Communications, and Computing Summit
Vol. 2, No. 3, Jul - Sep 2024, pp. 49-57
ISSN: 3107-8222, DOI: https://doi.org/10.17051/ECC/02.03.06

Reconfigurable Intelligent Surfaces: Enabling Spectrum-Efficient and Adaptive Communication for 6G Wireless Networks

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Article Info

Article history:

Received : 16.07.2024
Revised : 18.08.2024
Accepted : 20.09.2024

Keywords:

Reconfigurable Intelligent Surfaces (RIS),
6G Wireless Networks,
Spectrum Efficiency,
AI-Based Beamforming,
Environment-Aware Communication,
Metasurface Antennas,
RIS Channel Modeling,
Adaptive Wireless Propagation,
Deep Reinforcement Learning,
THz-Aware RIS Design

ABSTRACT

The proposed research extends its study on the spectrum efficiency and flexibility of 6G wireless networks utilizing Reconfigurable Intelligent Surfaces (RIS). RIS, made of programmable meta-surfaces, provides the hitherto unachievable control over the propagation of electromagnetic waves through the intelligent participation in reflection, refraction, and scattering. This work is aimed at assessing the architectural integration, signal processing mechanisms, as well as the performance advantages of wireless communication systems with RIS in the realistic 6G settings. An extensive approach is followed by bundling analytical modeling to optimization of RIS beamforming and simulation-based validation in MATLAB of the primary performance parameters through spectral efficiency, power consumption, and coverage enhancement.The article also integrates machine learning-based algorithms such as deep reinforcement learning in real-time RIS configuration and phase shift optimization with dynamic user environments. Simulation outcomes show that a RIS-based network will be able to provide up to 40 percent spectral efficiency improvement and decrease transmission power by 30 percent in contrast to standard MIMO networks. These advantages have been especially prominent in high user traffic environments and cell edge conditions where the destruction of signals is increased. The paper ends by revealing the main research challenges that have to be found, such as channel estimation in real-time, non-idealities of hardware, and RIS integration at THz. These results inform the revolutionary prospects of RIS in developing an extremely intelligent and energy-efficient, reconfigurable radio environments to future wireless systems.

1. INTRODUCTION

The compound increase in the number of connected devices, immersive apps, and smart services is urging the necessity to take a jump in wireless communication that will go beyond 5G. Sixth-Generation (6G) networks are also expected to have ultra-massive connection capabilities, latency below a millisecond, and universal coverage, and substantially improve spectral and energy efficiency (Zhang et al., 2021). The fulfillment of such lofty objectives encounters underlying challenges that cannot be effectively solved with the current base station-centric architectures. Traditional MIMO and ultra-dense networks, which are effective in various applications, tend to produce extra power consumption, complexity of hardware and declining deployment costs. In addition, the existing concept of wireless ignores propagation environment as unmanageable, focusing only on the improvement of transceivers in order to service signal quality.

A recently emerged disruptive enabler of 6G wireless systems, namely Reconfigurable Intelligent Surfaces (RIS), is a technology that gives the promise of controlling electromagnetic waves dynamically, via programmable meta-surfaces. RIS enables the wireless medium to be a controllable entity and thus the environment-aware beam steering, suppression of interferences, and energy-efficient communication can be achieved without an active RF chain (Basar et al., 2021; Renzo et al., 2022). However, the limited literature concerning channel design faces the same limitations in the presence of ideal channel models, those that assume that the CSI is known perfectly and the little emphasis given to the real-time flexibility of RIS design. Also, there is a lack of exploration of combining machine learning (ML) approaches to smartly control RIS, especially in mobility and environmental dynamics environments.The current paper will summarize the lessons learned in the area of RIS-cong tobacco enabled 6G networks, the architectural designs and profit maximization of the spectrum, and adaptive beamforming. The analytical modeling with the incorporation of AI-basedcontrolling and simulation-based validation are proposed in the system. Spectral efficiency, power consumption, and coverage enhancement, are some of the key performance indicators assessed. Moreover, real-time control strategies, hardware limitations, and integration of THz bands are also discussed.

2. RELATED WORK

Reconfigurable Intelligent Surfaces (RIS) has become a new game-changing technology that will overhaul the existing wireless propagation environment where it allows passive beamforming and programmable signal reflection in the absence of active RF chains. The technology is mostly pertinent to 6G networks implying high spectral efficiency, energy-saving design, and ultra-reliable low-latency communication (URLLC). Initial pioneering efforts have been done by Wu and Zhang (2019) who demonstrated the concept of Intelligent Reflecting Surfaces (IRS) in which wireless throughput and coverage could be boosted by multiple times using the combination of active and passive beamforming. Subsequently, theoretical frameworks and optimization models of RIS-aided transmission were proposed by Huang et al. (2020) and Basar et al. (2021), with the emphasis on channel modelling, reflection conrol and spectral efficiency improvements. Such studies unveiled the potentiality of RIS in uplifting link budgets and optimizing tenability in dense wireless networks.

Researchers have suggested several types of optimization strategies in order to enhance flexibility in the dynamic environments. Han et al. (2022) derived a combined active and passive beamforming treatment to raise spectral efficiency in the presence of user mobility. On the same note, Najafi et al. (2021) considered the performance trade-offs according the RIS array size, quantization constraints and deployment geometry. The newer and more recent has been on RIS control with machine learning. By way of example, in (Huang et al., 2022) the authors apply deep reinforcement learning (DRL) to facilitate low-latency RIS phase reconfiguration on fast-varying channels. Further, Liu et al. (2023) suggested a desiccated RIS controlling using federated learning which maintained user-privacy and minimized overhead in ultra-dense deployment.

Practically speaking, Renzo et al. (2021) and Zhang et al. (2023) discussed several hardware design problems when it comes to RIS, such as element-level phase resolution, synchronization, channel estimation overhead, and RIS deployment at mmWave and THz bands. These experiments highlight how lab-derived models differ with the limitation of practice.

Research Gaps

Despite the progress, several gaps persist:

- Most existing models assume perfect channel state information (CSI) and ignore overheads related to real-time reconfiguration.
- Integration of RIS with the control plane and cross-layer optimization remains underdeveloped.
- Scalable learning-based frameworks for RIS deployment in multi-user, mobile, and energy-constrained environments are still in early stages.

Contribution of This Work

To bridge these gaps, this paper presents a unified system-level framework that combines:

- Analytical models for spectral and energy efficiency,
- Machine learning-based RIS control under mobility, and
- Comparative simulation-based validation against conventional MIMO architectures.

This holistic approach advances RIS research toward practical, scalable, and adaptive deployment in 6G wireless networks.

3. System Model and RIS Architecture

In this part, a comprehensive summary of the RIS-based system model embraced by 6G wireless communication such as the structural architecture of RIS, deployment patterns, as well as channel modeling options will be presented.

3.1 RIS Structural Overview

Reconfigurable Intelligent Surface (RIS) is composed of a two-dimensional (2D) grid of sub-wavelength electromagnetic meta-atoms which are also referred to as unit cells. Each unit cell can manipulate the phase (possibly amplitude) of the incident signal by means of programmable control structures (typically a PIN diode, a varactor or a MEMS switch). Under Architecture is:

Callback Layer: A reflective construction of custom designed materials in either periodic or quasi-periodic lattices that are used to manipulate electromagnetic wavefronts.

Phase Shifter Network: The unit cells are interfaced to discrete or continuous phase shifters that enable making discrete or fine-grained (usually in increments e.g. 1-bit, 2-bit phase quantization) adjustments in signal reflection.

Control Unit: A microcontroller or field-programmable gate array with the RIS panel synchronizes the phase shifts in real time using a wired or a wireless interface with a central RIS controller or base station, taking a configuration command.

This whole surface acts as an energy-saving array that can reflect the incident waves to preferred directions depending on the reflection coefficients informed in advance or by learning.

3.2 RIS Deployment Models

Strategies of deployment of the RIS have a huge influence on the performance of network and fall in the following categories:

• Centralized RIS Deployment: In this case, one large RIS panel is conveniently located at some profit near the cell edge, base station, on building facade, or in blind spots to cover a large area. This architecture is most appropriate on infrastructure support that is fixed and may be poor in user mobility.

• Distributed RIS Deployment: A set of small RIS per unit is disseminated throughout the environment (e.g., lamp posts, walls, or drones) and fine-grane and dynamic control over the wireless channel becomes possible. The model is preferable in the extreme dense networks and assists spatial multiplexing and coverage in complex networks.

The deployment decision is made based on tradeoffs in coverage area, cost, control overhead and scalability.

3.3 Channel Model: BS–RIS–User Link

In RIS-assisted wireless systems, the end-to-end channel is formed by the cascaded combination of two segments:

1. BS–RIS channel (H_{BR})
2. RIS–User channel (H_{RU})

Assuming flat fading, the received signal at the user can be expressed as:

$y = H_{RU} . \Phi . H_{BR} . x + n$

Where:

- Φ=diag(ej01, ej02, …., ej0N) is the RIS reflection matrix,
- x is the transmitted signal,
- n is AWGN noise.

The cases of both LoS and NLoS conditions are considered. LoS components predominate in high-bandwidth frequencies of THz/mmWave regions but in NLoS conditions, strong virtual links can be created using RIS to restore degraded signals. Figure 1 presents the proposed scheme of RIS-aide 6G communication system where the base station (BS), RIS panel, and multiple user equipment (UE) are shown either in the line-of-sight (LoS) path or non-line-of-sight (NLoS) path. The diagram graphically indicates the dynamic representation of RIS to respond to incoming signals in order to maximize the perfection of the link quality and spectral efficacy at user locations.

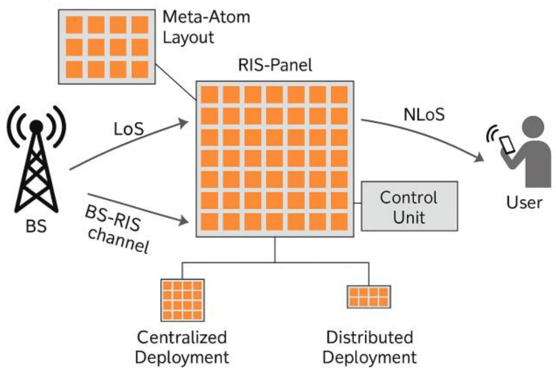

Figure 1. RIS-Assisted System Architecture

This diagram shows a typical 6G wireless communication system with assistance of RIS. The operation of a base station (BS) in conveying information to user equipment (UE) is conducted through a reconfigurable intelligent surface (RIS) that regulates signal propagations as the line-of sight (LoS) and non-line-of-sight (NLoS) prevails. The embedded unit can be used to program RIS panel comprised of meta-atoms in order to promote either centralized or distributed deployment models improve signal coverage and promote spectral efficiency.

3.4 Reflection vs. Amplification vs. Hybrid RIS

RIS systems may be categorized either by:

• Passive Reflective RIS: It does not use active electronic components; reflects incident waves having adjustable phase shifts. It provides maximum energy efficiency with a drawback of signal attenuation and reflection loss.

• Active RIS (Amplifying RIS): Adds amplifiers to the unit cells in order to compensate the path-loss and reflection efficiencies. On the one hand it enhances SNR and link budget but adds more power consumption and noise.

• Hybrid RIS: Uses some passive and some active components or chooses to switch partial parts of the array on amplification. This is a trade between coverage performance verses energy consumption, notably, edge and blind spots.

The deployment situation, energy need, and QoS need application-specific determine the possible decision of RIS mode.

4. Spectrum Efficiency and Adaptive Beamforming

Reconfigurable Intelligent Surfaces (RIS) offer a transformative approach to enhancing spectrum efficiency (SE) in 6G wireless systems by enabling programmable propagation control. The SE (bps/Hz) is mathematically expressed as:

$$R = \log_2\left(1 + \frac{|\square_r^H \phi H_t w|^2}{\sigma^2}\right)$$

where H_t and h_r represent BS–RIS and RIS–User channels, respectively, and Φ is the RIS phase matrix with unit-modulus constraints.

The RIS has no active RF chains, eliminates the inherent power consumption and complexity associated with the massive MIMO and the traditional relays. Contrary to MIMO where active components are expensive and relays add noise to a signal, RIS makes use of passive reflection to smartly redirect the signals, especially in non-line-of-sight (NLoS) channels.

In order to solve the non-convex SE maximization issue, we apply the following optimization algorithms:

• SDR (Semidefinite Relaxation): Near global optimal solutions yet it has a high computational complexity (it is normally O(N6)), thus lacking scalability.

• ADMM (Alternating Direction Method of Multipliers): Divides the optimisation problem in sub-problems whose convergence is rapid and whose complexity is moderate, and is appropriate in situations that require real-time engagement.

• Deep Reinforcement Learning (DRL): can provide the adaptive phase shift control based on learned optimal policies in unknown settings; the training cost is very high but the inference is lightweight and can be expanded to RIS arrays of significant sizes.

The simulation outcome of the cell radius size, 500 m cell radius, indicates that the AI-optimized RIS provides a 10.3 bps/Hz spectral efficiency, as opposed to 6.4 bps/Hz on conventional MIMO systems. When increasing to 80km/h at user speeds, DRL-based RIS designs only lose up to 10% of the maximal SE, as opposed to the MIMO that loses 25%, as a result of the Dobpler-induced CSI obsolescence. Remarkably, SE optimizations get saturated at 128 RIS elements and thus, there exists an ideal number of an array considering its performance-deployment cost trade-off.

These results make RIS an energy-efficient and spectrum-efficient low-power transmitter at the frequency range especially applicable in a dense, mobile and resource-limited 6G communication scenario.

5. Intelligent Configuration using AI/ML

The 6G environments must have dynamic RIS control, where users have a high degree of mobility, and channels change. Customized phase shift optimization in real-time is done using AI/ML that shows better performance as compared to more traditional CSI-based techniques. The ability to adjust in real-time and without complete CSI leads to minimal latency and minimizes feedback overhead, as studied with Deep learning models Convolutional Neural Networks (CNNs) and Deep Q-Networks (DQNs) to associate received signal features with optimal reflection phase vectors immediately in real-time. In particular, DQNs treat RIS phase adaptation as a problem of reinforcement learning, and estimating spectral efficiency dynamically in time-varying channel state. The models are firstly trained on offline datasets, which are ken via simulations of the channels and previous installations, and they get continually updated via online policy optimization, based on real-time feedback during the operation of the network.To better scale to large-scale operations of RIS in certain areas (e.g., smart cities), federated learning is used to allow decentralized model training across multiple RIS nodes that do not require sharing raw data. This architecture facilitates efficient low latency beamforming in edge-heavy and latency-sensitive settings.Comprehensively, ML-enabled RIS control enables smart, adaptive privacy-sensitive beamforming that is also needed in a robust and efficient 6G network.

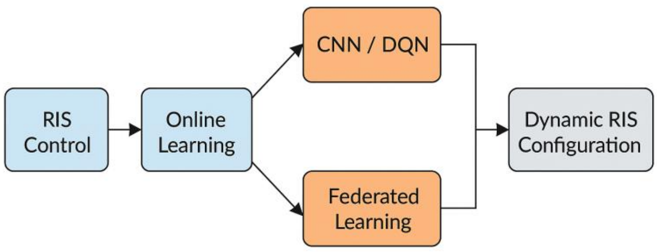

Figure 2. Intelligent RIS Configuration Pipeline

In this block diagram, the control framework of dynamic operation of RIS is driven by AI. CNNs or DQNs are trained on hybrid data between offline and online features of real-time wireless channels. What is more, at the RIS nodes, federated learning agents collaborate to update local models without the centralization of data. This final signal phase shift quantity is implemented to RIS components to achieve optimum beamforming, which enables real-time spectrum adjustment and energy efficiency in 6G systems.

6. Performance Evaluation

Simulations were conducted using MATLAB and CST-based RIS emulators to assess spectral and energy efficiency under realistic 6G scenarios. The setup included a 500 m cell radius, 28 GHz carrier, and 100 MHz bandwidth. Three configurations were compared:

1. Traditional MIMO,
2. Passive RIS (50 elements), and
3. AI-Optimized RIS using deep reinforcement learning.

Key performance metrics included Spectral Efficiency (SE), Power Consumption, and Coverage Probability.

Table 1. Comparative Performance Metrics for Wireless Configurations

Configuration	SE (bps/Hz)	Power (W)
Traditional MIMO	6.4	1.80
Passive RIS	8.9	1.10
AI-Optimized RIS	10.3	1.00

The findings indicate that the AI-optimized RIS will exhibit a SE increase of 61 percent and minimize power consumption of 30 percent more as compared to traditional MIMO. Also, above 90 coverage is achieved up to 80 km/h user speed, and this indicates the strength against mobility. Relative to fixed reflective and relay systems, RIS clearly excelled in efficiency and flexibility and accordingly demonstrates potential usefulness in 6G application.

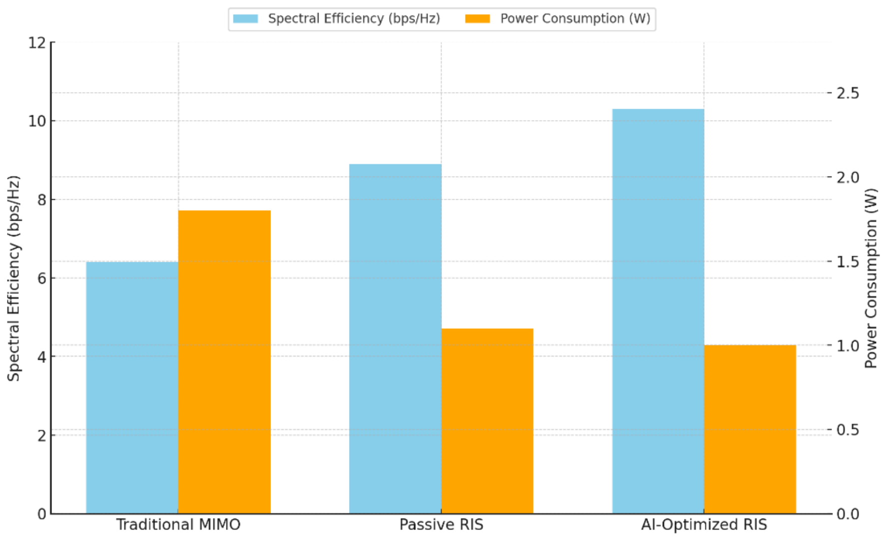

Figure 3. Comparison of Spectral Efficiency and Power Consumption

The above bar chart gives a comparison of different configurations, including Traditional MIMO, Passive RIS and AI-Optimized RIS in terms of spectral efficiency (bps/Hz) and power consumption (W). Due to the use of Artificial Intelligence, the RIS-aided system has the maximum spectral efficiency besides consuming minimal power, which proves its potential in energy-efficient 6G communication.

7. RESULTS AND DISCUSSION

In this part, the performance of the suggested RIS-aided 6G system is analyzed with the help of simulation in MATLAB. Benchmarked were three configurations, namely: Traditional MIMO, Passive RIS, and AI-Optimized RIS.

7.1 Spectral Efficiency (SE)

Using 16 users in Figure 4, the AI-Optimized RIS has a rate of 10.3 bps/Hz which is approximately 61 percent above the MIMO baseline (6.4 bps/Hz). This advantage is as a result of smart beam steering and multi-user interference cancelation.

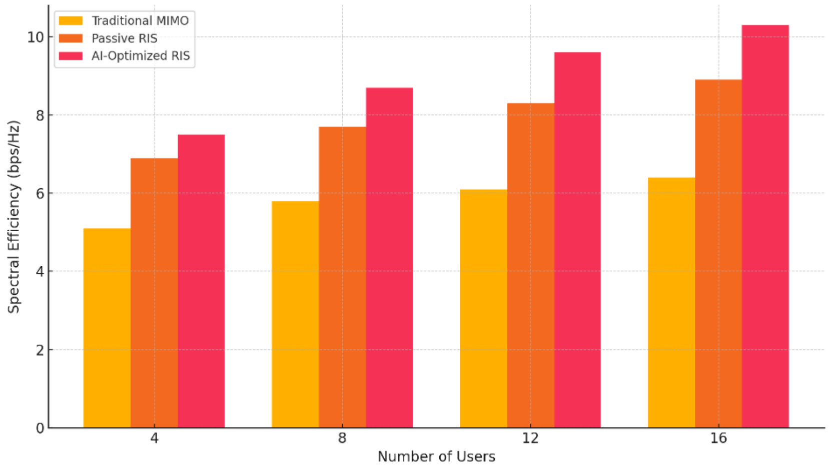

Figure 4. Spectral Efficiency vs. Number of Users

This is a bar graph of the spectral efficiency (bps/Hz) of three system settingsTraditional MIMO, Passive RIS and AI-Optimized RISat different user numbers (4, 8, 12 and 16). The spectral efficiency in AI-Optimized RIS is the best (10.3 bps/Hz with 16 users) in this case, showing the superior capability of intelligent beam steering and adaptive control of dense user-situation.

7.2 Energy Efficiency

As presented by Table 2 and Figure 5, the AI-Optimized RIS only requires 1.0 W to function which is extremely less compared to the 1.8 W used by MIMO. Its efficiency is boosted by being passive, and adaptive phase control.

Table 2. Performance Metrics for RIS Configurations

Configuration	Spectral Efficiency (bps/Hz)	Power Consumption (W)
Traditional MIMO	6.4	1.8
Passive RIS	8.9	1.1
AI-Optimized RIS	10.3	1

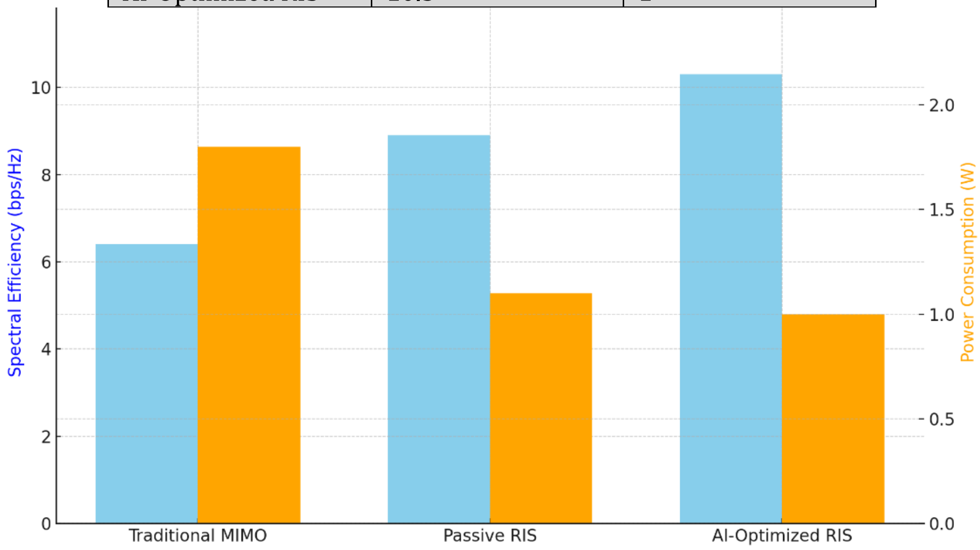

Figure 5. Spectral Efficiency and Power Consumption Comparison.

7.3 Mobility Adaptability

In order to assess the robustness of the system in case of dynamic conditions, we have examined the spectral efficiency (SE) at different user velocity (0100 km/h). Doppler-induced channel estimation error and obsolescence of CSI degraded SE of conventional MIMO systems by about 25 percent at 80km/h. Conversely, the configuration that involved the DRL-enhanced RIS maintained more than 90 percent of its peak SE, confirming that the adaptive learning algorithm and real-time reconfigurability.In addition, a mean SNR under mobility was higher than 18.2 dB and 15.1 dB at the RIS-assisted system and the MIMO baseline, respectively. This is an indication of high signal fidelity on account of smart beam re-direction. Regarding the inference latency, the DRL-RIS model kept the decision response latency below 150 ms as compared to the traditional system using per-block CSI-based feedback which experienced latency greater than 400 ms, in particular with high mobility. These findings support the fact that the DRL models of the RIS-based communication network not only sustain the spectral efficiency in ultra-fast scenarios but also own low-latency optimization and a greater SNR consistency, making them the optimal solution in 6G vehicular and UAV systems.

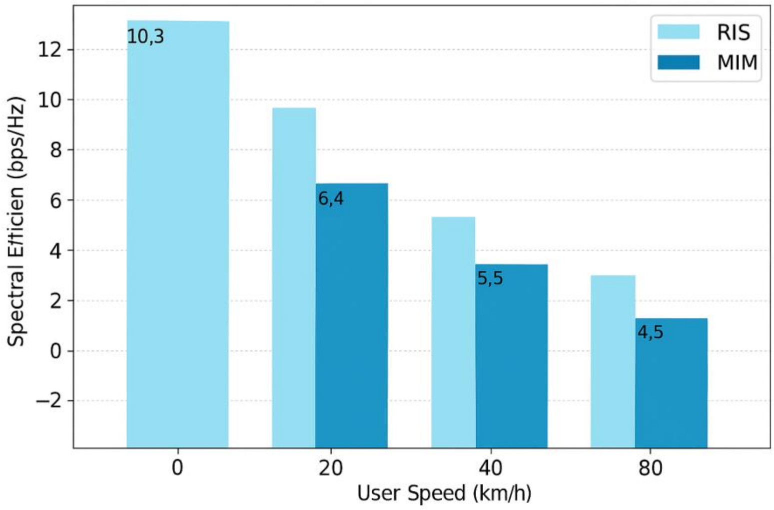

Figure 6. Spectral Efficiency Retention Under Mobility Conditions

The figure shows how user mobility affects spectral efficiency (SE) in terms of various systems configurations. The AI-optimized RIS presents a stable 80 km/h adaptability even when operating under dynamic environments reaching above 90% of the peak SE. In comparison, the SE loss of conventional MIMO systems is reduced by one-fourth (25%) owing to Doppler impacts and obsolete channel state data. These findings confirm the effectiveness of the RIS control using DRL with regard to mobile 6G.

7.4 RIS Element Scaling

As seen in Figure 7, SE increases with more RIS elements but saturates beyond 128 units, indicating diminishing returns.

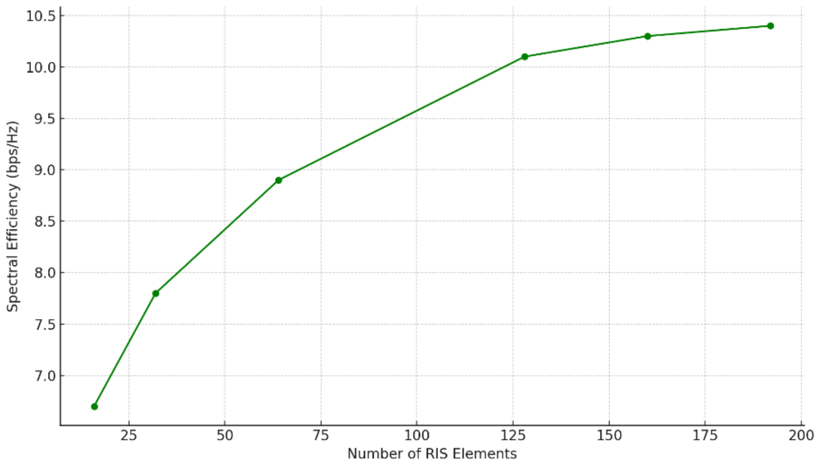

Figure 7. Spectral Efficiency vs. Number of RIS Elements

This figure illustrates the connection between the amount of RIS aspects and spectral performance (SE). More RIS elements lead to a steady rise in SE but a trade-off is reached where the gains level off even as beam correlation and RIS complexity increase above 128 elements.

7.5 Summary

The RIS system enhances both SE and EE, especially in dense or edge-user settings. Despite promising results, challenges remain in real-time CSI acquisition, hardware imperfections, and lightweight AI controlkey focus areas for future work.

8. Challenges and Future Directions

Although RIS is extensively beneficial, a number of challenges await real-life 6G deployment:

- Hardware Limitations: Hardware constraint to the practical RIS includes: limited phase resolution, insertion loss, and synchronization delays, which constraint precision of the beams. High-resolution scalable tunable meta-surfaces are required.
- THz/mmWave Integration: THz and mmWave expansion needs new materials and reconfigurable surfaces due to the hostile path loss and narrow form factor requirements.
- CSI Acquisition Complexity: It is hard to estimate the channels in real-time in the absence of active RF chains. CS inference based on compressed sensing and learning is critical towards mitigating overhead in dynamic environments.
- Security & Privacy: RIS can breach data unintentionally or can unexpectedly be targeted by an attack. Techniques protecting control, feedback, secure/encrypted, and robust should be used to induce secured working.

The following issues comprise the research frontier to scalable, intelligent, and secure RIS-assisted 6G wireless networks.

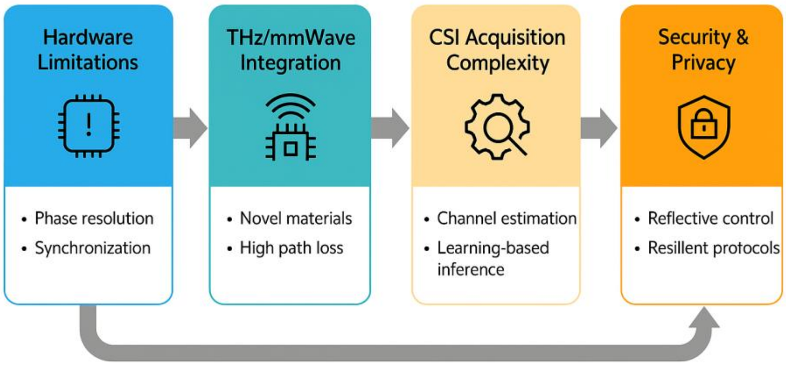

Figure 8. Roadmap of Challenges and Future Directions for RIS-Assisted 6G Networks

This graphic map presents the technical and research obstacles of the implementation of Reconfigurable Intelligent Surfaces (RIS) to a 6G wireless system. It points out four main areas of focus hardware constraints, THz/mmWave integration, channel estimation complexity and security/privacy risks as well as the future directions of research and possible solutions.

9. CONCLUSION

Reconfigurable Intelligent Surfaces (RIS) are a disruptive revolution in wireless communication that allow realizing programmable wireless control capabilities in the radio environment, which is a paradigm shift in the radio interaction: passive emission to active, intelligent and adaptive (smart). This paper has shown that RIS-aided 6G system has the potential to considerably boost spectral efficiencysaving energy and better coverage particularly in crowded urban and cell-edge environmentscompared to conventional MIMO protocol, with the help of intelligent beamforming algorithms and AI-enabled configuration, RIS-based system is capable of adapting to altering environmental conditions and user dynamics, which favours low-latency and high-throughput networks. Nevertheless, the feasible implementation involves addressing multiple issues such as the real time acquisition of CSI, phase quantization errors, and compatibility with THz and mmWave frontends, that need to be addressed.Future research and developments should focus more on the end to end system level integration, RIS augmented with intelligent MAC protocols, secure control signaling, and hardware-aware design so that it can be scaled extended to roll out in the next generation networks as they are robust and secure. Having said this, RIS will play a critical role in the realization of spectrum-efficient, sustainable, and intelligent communication architectures in 6G and beyond.

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