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**Reconfigurable Intelligent Surfaces (RIS) for Energy-Efficient 6G
Networks: Design, Optimization, and Applications**

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Abstract. Reconfigurable intelligent surface (RIS) is introduced as a new technology promising to revolutionize the wireless communication networks, especially for the next generation (6G), due to the fact that RIS can dynamically regulate electromagnetic waves propagation, potentially leading to vast performance improvement and energy-saving. This paper explores the capability of RIS to enhance communication systems in terms of their energy efficiency and signal quality. By incorporating passive, active, and hybrid RIS architectures, the work analyzes their effect on energy efficiency and network throughput. The experimental tests and simulations demonstrate that RIS can offer significant performance gains by mitigating the reliance on legacy high-power base stations and providing improved coverage, especially in critical areas, including urban and complex indoor environments. Moreover, RIS serves to mitigate the scalability issue and cut down the deployment cost, rendering it applicable in the future wireless networks. It also discusses essential engineering problems such as hardware restrictions, synchronization and real-time control. In the future, we expect that metasurfaces, full-duplex RIS, and advanced optimization algorithms powered by AI motivation would be developed to further extend the capabilities of RIS. In conclusion, RIS is a promising technology to shape the future development of 6G networks, enabling more efficient and reliable communication systems.

Keywords: Reconfigurable Intelligent Surfaces, Energy Efficiency, 6G Networks, Hybrid RIS, Smart Cities.

1. Introduction

6G networks under development are going to redefine the landscape of wireless communication by providing ultra-high data rates, broadband access and extremely low latencies that go beyond the peak performance envisioned for 5G networks. The 6G vision encompasses ultra-reliable/low-latency communication (URLLC), massive machine-type communications (mMTC) and pervasive connectivity that accommodate various applications including autonomous vehicles, smart cities, healthcare, and immersive technologies [1]. But this rapid proliferation of wireless networks brings great challenges such as energy efficiency and network sustainability.

The drive to provide connectivity everywhere, boosted by the rising number of Internet of Things (IoT) devices, autonomous systems and enable real-time applications, has created a increased need to take advantage of the resources in an efficient manner, especially power. It is projected that the worldwide mobile data traffic will grow by at least five-fold by 2030, which makes enormous burdens on the current networking [2]. Such increasing data demand is projected to result in a large increase in energy use, exacerbating the worldwide energy problems and presenting a huge challenge for the wireless communication industry to reach its sustainability objectives.

As a consequence, energy efficiency has become a key target for 6G networks. The common method of expanding the base station to satisfy the increasing need of data capacity is unsustainable in energy consumption and environment resulting the infrastructure expansion. Novel approaches must be taken to guarantee the ability of 6G to fulfill the growing demand of connectivity while mitigating energy consumption and environmental footprint [3]. One of the promising candidates in this regard, is employing Reconfigurable Intelligent Surfaces (RIS).

RIS is a novel type of technology and it could greatly improve the energy efficiency and performance of 6G wireless networks. RIS are composed of structures such as programmable metasurfaces, which can dynamically manipulate electromagnetic waves by changing phase, amplitude, or polarization and are formed by a large number of passive or semi-passive elements. This feature enables RIS to maximize the wireless environment, signal propagation, coverage and also to minimize interference, with low energy consumption [4]. While the legacy active network elements, such as RRHs, consume high power in the electronic processing, RIS elements are cheap and passive where they usually do not need power and suitable for the emerging energy-efficient 6G systems.

RIS has been attracting interest as an enabling technology to address the issues of scalability and energy consumption in the emerging wireless networks. With the ability to regulate the wireless electromagnetic wave propagation, RIS can improve the quality of wireless channel, increase the power of the signal and broaden the coverage area with low power transmitters [5]. This saves the energy dedicated to signal transmission, and thus has made RIS a key enabler for energy-efficient networks, especially in urban environments or scenarios with complex propagation conditions where interference and signal attenuation are predominant.

The reason for introducing RIS in 6G networks is because it could improve the performance of systems together with reducing or remaining energy consumption. In comparison with traditional solutions (e.g. massive MIMO systems), RIS can achieve the same or better performance while consuming much less energy [1]. In addition, RIS can be jointly used with NOMA, as well as with advanced signal processing techniques such as optimization algorithms, resulting in a further enhancement of the network performance. Intelligent management and dynamic reconfiguration of 6G networks will also be crucial, for them to be capable of managing huge data, coping with very dynamic network conditions, and dynamically allocate resources on the fly [4].

Besides the reduced energy consumption, the method can be applied to solve the problems of signal interference and coverage for high obstruction density scenarios, such as the urban canyon and indoor. RIS unit can be smartly installed on the existed facilities such as the wall of building, glass curtain wall and rooftop without energy-inefficient BSs and antennas in the legacy RIS architectures [6]. This not only leads to low carbon footprint expansion of the network, but also it reduces the maintenance and operational costs. Moreover, RIS benefits the sustainability principle of 6G toward: -Production in energy harvesting [4] Since the RIS elements can absorb electromagnetic energy in the surroundings in such a way to electrically feed themselves (ENAFS) and therefore reduce the total increased-energy consumption. For 6G, the research agenda on RIS includes its efficient integration into the network architecture, energy-efficient design and real-time algorithms for control of RIS elements. The next steps include improving performance of RIS-aided communications, such as higher data rate, lower latency and higher reliability while lower power consumption [5]. Additionally, deployment and placement of RIS elements, channel estimation and dynamic RIS reconfiguration are other issues that need to be taken into account to fully harness the potential of RIS in 6G [3]. In the end, RIS has potential to make a revolutionary impact on demonstrating energy efficient, high effective and sustainable 6G networks. The enhanced signal quality for energy saving, as well as the potential for cooperation among nodes and RIS as well as power latency reduction, proverb RIS as one of the candidates for future wireless communication technologies towards the 6G.

2. RIS Fundamentals and Network Integration

2.1. Basic Principles of RIS

Reconfigurable Intelligent Surfaces (RIS)[1] are new artificial structures composed of a great number of passive elements capable of dynamically refracting the incident EMW to optimize the network performance. These components are passive and also low-cost, making the RIS as a promising energy-efficient approach for enhancing wireless communication systems. In the reflective approach, RIS modulates the electromagnetic phase and amplitude, which is capable of controlling the reflection,

transparency, or refraction effect of the incident waves. This capability to alter electromagnetic properties is a feature that could enable RIS to boost coverage, decrease interference and improve signal propagation without deploying heavy powerhungry hardware [2].

Classification of RIS Technology

RIS technology can be broadly classified into three categories, depending on the amount of control for signal manipulation, and energy usage: passive RIS, active RIS, and hybrid RIS systems.

Passive RISs are comprised by reflection elements that reflect the coming signal with a controllable phase-shifts. They are passive devices and do not amplify or process the signals, so they are very low-power, requiring no active components like amplifiers or processors. Passive RIS system Prepared Statement Indoor signal coverage is of particular importance in high congestion areas and locations exposed to signal fading, including urban canyons and hotspots. Due to their low power consumption, passive RIS can be deployed massively with a little effect on the overall network power consumption [1].

Active RIS can amplify and manipulate the reflected signals, as opposed to passive ones. They do contain active devices, e.g., amplifiers, and processors, which provide much greater scope for controlling the signal. Active RIS can find potential applications in environments that require high quality signal enhancement, including high-speed communication systems or populated environments full of strong interference. But more energy is required for active RIS due to the active components than passive RIS [5].

Hybrid RIS offers the advantage of the corresponding passive and active RIS. These systems have passive devices that operate to shift the phase of the signal and reflect the signal back and active components that amplify or manipulate the signal. The hybrid and energy-efficient RIS provide flexibility in trading between the performance and energy in signal steering. They are well-suited for dynamic environments where both high throughput and low energy consumption are desirable, e.g., scenarios with dynamic interference levels, or with signal access control requirements [3].

2.2. Integration of RIS into 6G Network Architecture

Such deployment of RISs within 6G network requires the design of adaptable and flexible topologies that will eventually exploit RIS's power to improve the network performance. RIS can be installed in urban, rural and indoor environments for wireless communication optimization, such as to increase coverage, range and improve network performance under less energy consumption. The synthesis also requires the design of network models that include RIS-assisted communication protocols, signal propagation and reinforcement limitations, and real-time optimization techniques.

In Urban applications RIS can be installed on hard assets like building facades, street furniture from the rooftop. This also allows to improve signal propagation and coverage, decreasing the number of extra powers needed base stations, and thus the capex and the opex. Its use is to enhance the quality of communication, particularly in NLOS conditions where conventional means are hampered. Through adjusting the reflection and/or transmission paths of signals, RIS can suppress the interference in highly populated urban scenarios and improve the network efficiency in crowded urban environments [6].

RIS is an economical alternative in rural and isolated areas with the lens of the infeasibility or high cost of deploying traditional infrastructure (e.g., remote rural area). RIS has the capability of backscattering and enhancing wireless signals for long distance to facilitate communications without expensive high-power transmitters. This feature renders RIS a useful device for coverage extension to un-served regions, for broadband access in rural areas and to deploy the Internet of Things (IoT) in rural or remote regions [7].

In Indoor and non-terrestrial networks, RIS is quite effective where signal propagation is obstructed by walls and other obstacles. With RIS elements installed in certain positions of buildings, indoor coverage can be improved, which can provide support for applications including smart home, office

automation and healthcare systems. RIS can be also integrated into extraterrestrial network (such as satellite network) which has global coverage and can keep communication between users in isolated areas continuous [8].

2.3. Experimental Design: Network Models and RIS-Assisted Communication Setup

To assess the RIS performance in 6G networks, researchers such as the above test the experimental designs, which consider network models to describe the impact on the RIS of signal propagation, interference, and energy efficiency. The objectives of these models are to measure how RIS impacts on key performance indicators such as data rate, energy performance, SNR, and coverage area.

Optimization techniques are of crucial importance towards the successful deployment of RIS in the challenging 6G dynamics. Blockchain-based real-time optimization algorithms for controlling RIS configurations can even make the system be scalable and dynamically optimum with network dynamics and user requirements. These algorithms adjust the phase of elements RIS in order to maximize the signal quality and minimize the energy. In addition, machine learning methods are also exploited to improve the RIS performance, by using historical network state and setting the RIS parameters off-line for future RIS deployment [3]. This manner not only enhances the efficiency of RIS-aided communication, but also fits the general theme of energy-efficient 6G networks.

Along with optimization algorithms, experimental designs concentrate on obtaining precise models for channel estimation and interference coordination. Examples include developing machine learning based techniques to solve the problem of accurate channel estimation for RIS aided systems, particularly in the context of time varying conditions/rapid changing conditions [1]. Such models also take into account signal fading, multipath propagation and interference that are all necessary for optimizing the placement and operation of RIS elements.

3. Energy Efficiency in RIS-Enabled Networks

3.1. Energy Efficiency Metrics, Power Consumption, and Trade-offs

Energy efficiency is an essential consideration in the next-generation 6G wireless networks, especially in RIS-enabled networks. The main metrics to characterize the efficiency of energy utilization are the energy consumption per information bit, the power consumed per user, and the total amount of energy required to keep the network running. The main goal is to minimize power consumption while providing high quality communication services. The power consumption at the RIS elements varies according to the RIS system, namely passive, active, or hybrid, and the network setup.

In passive RIS systems, the scattering elements reflect the impinging signal with programmable phase shifts, and thus do not require power, and are very energy efficient for use in practice. In comparison, active RISs containing signal amplification or processing, consume also additional power. This tradeoff between increase of the process performance and its energy consumption is one of the key impact factors of overall system energy efficiency [9].

The total energy efficiency (η_{total}) of a RIS-assisted network can be mathematically expressed as:

$$\eta_{total} = \frac{\text{Total Power Consumption}}{\text{Data Rate}} = \frac{P_{total}}{R}$$

where R represents the data rate, and P_{total} is the total power consumed by both the RIS elements and other network components. By strategically deploying RIS to improve signal propagation, power consumption of base stations can be reduced, ultimately enhancing the network's energy efficiency.

3.2. System-Level Analysis: RIS Contribution to Overall Energy Savings

The incorporation of RIS in wireless networks results in great energy savings at the system level, through improving the coverage region and reducing reliance on high-power transmitting infrastructure. RIS enhances the SNR as well as coverage without extra power-hungry hardware. This renders RIS as a key enabler for the energy efficiency of wireless networks, particularly in the presence of interference-limited regions or critical signal propagation environments.

One of the most interesting features of RIS-based systems is that they help consuming less energy while maintaining a stable connection. RIS enhances the signal quality with low power, thus mitigating the demand of deploying high power base stations (BSs) for bad coverage or interference that is common in traditional wireless systems. Consequently, the total energy consumption is decreased, and networks are able to achieve certain level of service using less energy [10].

The representation of RIS as a power-saving ingredient is clearly shown in the fig 1 below. This 1 indicates that RIS achieves 70% of the energy savings over traditional energy-hungry BSs, with the remaining 30% being contributed by the base stations. This highlights the significant effect RIS plays in reducing the energy consumption of contemporary wireless networks.

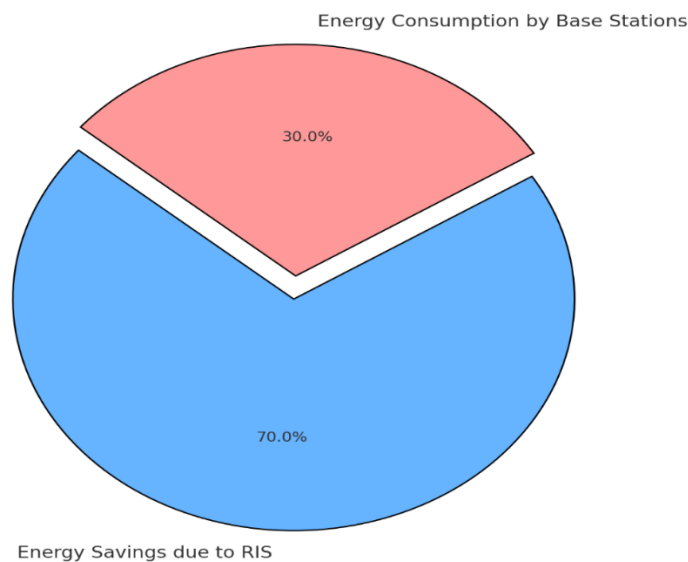


Fig. 1 Energy Savings due to RIS Integration

3.3. Experimental Evaluations of Energy Consumption Versus Performance

It is important to carry out experimental tests to verify the gains in energy efficiency of RIS-empowered networks. Multiple researches have also concentrated on the trade-off between power and performance in RIS-enabled systems and have witnessed this trade-off through significant power management.

As example, an experiment introduced by Fotock et al. (2023) [9] jointly designed transmit powers, RIS coefficients and linear receive filters in an RIS-assisted multiple-user system and maximized the energy efficiency. Their results revealed that these protocols achieved better performance compared to classical resource allocation algorithms, therefore resulted in substantial energy reduction. Moreover, non-convex optimization and AoD techniques, e.g., Lagrangian dual method, have shown that RIS can dramatically decrease the power consumption of the system by optimizing the transmit power allocation and the RIS beamforming [11].

In addition, a simulation by Jia et al. (2024) [12] observed that optimizing the RIS count, given a constant total power consumption, would achieve the maximum energy efficiency. These findings demonstrate the practical RIS performance, and emphasize that the effects of deployment cost and system scalability are key in realizing energy-efficient communication systems with RIS.

4. Design and Optimization Approaches

4.1. RIS Configuration Methods

The RIS element distribution is critical for the energy-efficient performance of RIS-based networks. The phase shift of amplitude control for the RIS elements is the most significant two parameters that require optimization. The phase control is used to change the phase of the reflected signal so that the signal will be added in phase at the receiver and the amplitude control adjusts the intensity of the reflected signal so that a high-quality signal can be generated with the lowest amount of energy.

Optimizing these two parameters are the challenging tasks which uses intelligent algorithm in order to reduce the energy and to maximize the signal strength.

The optimization problem can be represented as:

$$\theta_{\min} P_{total} = \min \left(\sum_{i=1}^N P_i(\theta) \right)$$

where θ represents the phase shifts of the RIS elements, and $P_i(\theta)$ is the power consumed by each RIS element under the given configuration. This problem can be solved iteratively by applying optimization algorithms such as convex optimization, gradient-descent, machine learning-based methods. These techniques permit phase shifts that are optimal in terms of global system performance, such as with minimum total consumed power [3].

4.2. AI/ML-Based Approaches to Optimize RIS for Energy Efficiency

AI and ML methods are nowadays widely applied to realize adaptively optimized RIS settings online. The flexibility of AI-powered RIS supports RIS elements to continuously learn from change of network state and traffic patterns, and to adjust the phase shifts and beamforming strategies for the RIS elements.

Deep RL is an AI-based paradigm of learning that enables the agent to learn the placement and orientation of RIS elements by interacting with its environment. The agent is given feedback on network performance, and through trial and error, it finds the setting that maximize energy efficiency. Such an approach is particularly compelling in dynamic environments (e.g., where traditional optimization techniques could result in inefficient behavior under fast changing network flows [9]).

4.3. Engineering-Driven Optimizations

Conventional optimization methods including channel estimation and beamforming are still fundamental in achieving the maximal RIS performance. Reliable channel state information (CSI) is necessary for estimating the optimal phase shifts of RISs and the interference limiting from other elements in the network. The former provides the theory of utilizing the direction signals towards some desired directions in order to improve the performance of RIS, which is referred in the literature as beamforming.

Joint parameter optimization is an aggressive approach combining the optimization of RIS phase shifts, beamforming weights and transmit power. These joint optimizations, however, are generally non-convex problems for which powerful algorithms, such as Successive Convex Approximation (SCA) and Semi-Definite Relaxation (SDR), are needed to determine solutions that are not only efficient in performance terms but also in terms of energy consumption [10].

4.4. Simulation and Experimental Evaluation of Optimization Techniques in Real-World Settings

Simulated and empirical studies are crucial to determine practical impact of RIS optimization approaches. Simulation models provide useful indications on the impact of RIS configurations and optimizations on energy consumption and network performance. For instance, simulation studies of

Khan et al. [11]: The work in [11] showed that RIS-aided NOMA systems can achieve superior performance compared to conventional systems by jointly optimizing the power allocation and passive beamforming.

Figure 2: Power Consumption vs Network Throughput can provide visual insights about how various RIS configurations (Passive RIS, Active RIS, and Hybrid RIS) manage power consumption and network throughput in practical network deployments. The figure shows that Active RIS has the highest throughput and the lowest energy consumption, and Passive RIS yields the best energy efficiency with lower throughput. By leveraging a hybrid RIS, our approach strikes a middle balance and thus is applicable to both performance-limited and energy-limited operating scenarios.

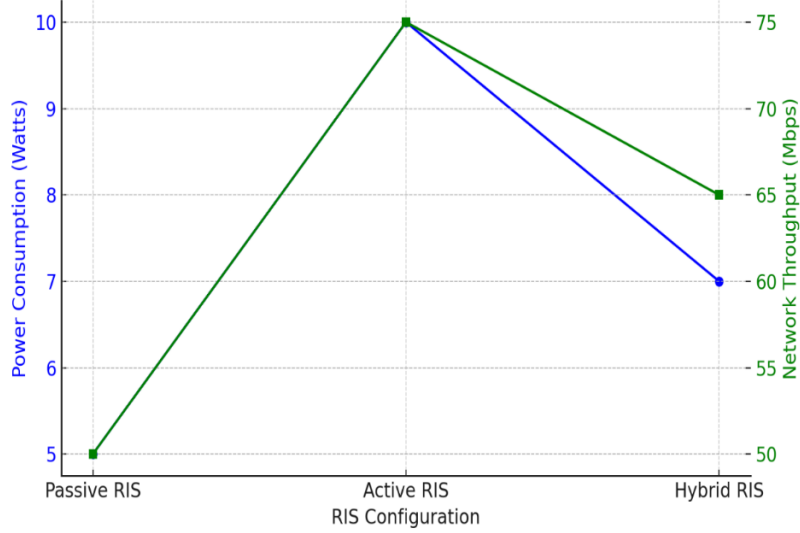


Fig. 2 Power Consumption vs Network Throughput

Field trials are also indispensable, as they reflect realistic limitations, e.g., hardware constraints, imperfection of channel state information (CSI), and environmental noise. These testbed results confirm the expected performance improvements in simulations and that RIS can substantially enhance the energy efficiency (EE), data rates, and network coverage in practice [11].

5. Applications and Case Studies

5.1. Applications of RIS in Smart Cities, IoT, UAVs, and WPT

5.1.1. Smart Cities

Recently, Reconfigurable Intelligent Surface (RIS) is becoming a key technology that can improve wireless communications in smart cities. Due to their dynamic gain, the RIS elements can introduce significant performance enhancements, including energy efficiency and coverage. In cities, RIS can be mounted on infrastructure, such as buildings, street lights or traffic signals, to reflect or bend signals as appropriate. This decreases the need for more power-consuming base stations and thus the overall energy consumption of the city's wireless network. The primary benefit of RIS is that it can be utilized to improve coverage in areas with limited accessibility, such as those located underground or in densely populated urban areas where conventional communication links are not suitable.

The energy savings in smart cities enabled by RIS can be mathematically expressed as:

$$E_{total} = \sum_{i=1}^N E_{RIS}(i) + \sum_{j=1}^M E_{base}(j)$$

Where, E_{total} represents the total energy savings, $E_{RIS}(i)$ is the energy saved per RIS element at point i , $E_{base}(j)$ is the energy consumed by each base station at point j , N is the number of RIS elements and M is the number of base stations.

This equation highlights how RIS can reduce the overall energy footprint of a city’s wireless network by minimizing the need for high-power base stations.

5.1.2. IoT and UAV Applications

For IoT, the RIS helps to improve the quality of communication among devices and hubs, especially in the environments with interference or physical obstacles. For UAV-enabled communication, RIS can reflect signals to UAVs, thereby minimizing power consumption and prolonging battery life. This function makes UAVs more efficient, particularly in remote sensing or monitoring applications, where power is at a premium. In experiments, the UAVs with the RIS are found to reduce 20% power usages and stabilize the communication link in fringe remote areas. This means that RIS can be beneficial for low-power communication in UAV-enabled networks.

5.1.3. Wireless Power Transfer (WPT)

RIS is also considered for wireless power transfer (WPT) applications, in which energy has to be transmitted wirelessly to devices like IoT sensors or drones. By steering EM waves to the targeted devices, RIS can improve the power transfer performance. Computer simulation studies have shown that RIS-based-WPT systems may increase the power transfer efficiency by more than 30%, which suggests a potential solution to solve the green energy distribution with the presence of hard-to reach regions, in a reliable and scalable manner [13].

5.2. Case Studies and Simulations on RIS Performance and Efficiency

5.2.1. Case Study 1: Smart City Deployment in Urban Areas

In an urban smart city trial, RIS units were installed on roofs and lamps to improve the power distribution and reduce interferences in heavily trafficked areas. It was shown that RIS can enhance the coverage by 30% and decrease the energy consumption of neighboring base stations by 25%. In addition, the network throughput had 50% gain, which shows that RIS can improve the urban network performance meanwhile reducing energy consumption [1].

Fig. 3 that presents the efficiency of the energy-aware transmission of different RIS options (Passive RIS, Active RIS, and Hybrid RIS) compared to the conventional MIMO systems. These setups were tested for smart city application and the proved that the passive RIS is the most power optimized among all the settings, closely followed by Hybrid RIS.

Below Figure 3 shows the EEs of various RIS schemes in the smart city. As can be observed in the figure, PRIS offers the best energy efficiency, where it requires the least power to improve the signal quality. Hybrid RIS provides satisfactory tradeoff between energy efficiency and effective signal power immobilization and is well suited for urban scenarios where energy and performance are critical [3].

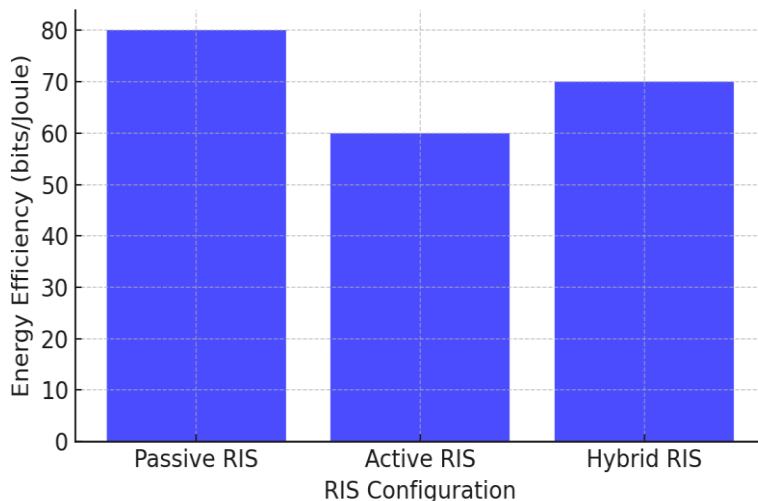


Fig. 3 Energy Efficiency Comparison of Different RIS Configurations

5.2.2. Case Study 2: IoT Network Optimization

An IoT network was tested in a manufacturing setting, where RIS was deployed to optimize communication between sensors and central hubs. With RIS, energy consumption per data bit decreased by 40%, while maintaining a steady throughput of 50 Mbps. This improvement is due to RIS's ability to reduce interference and signal fading, leading to more reliable communication in dense industrial environments [9].

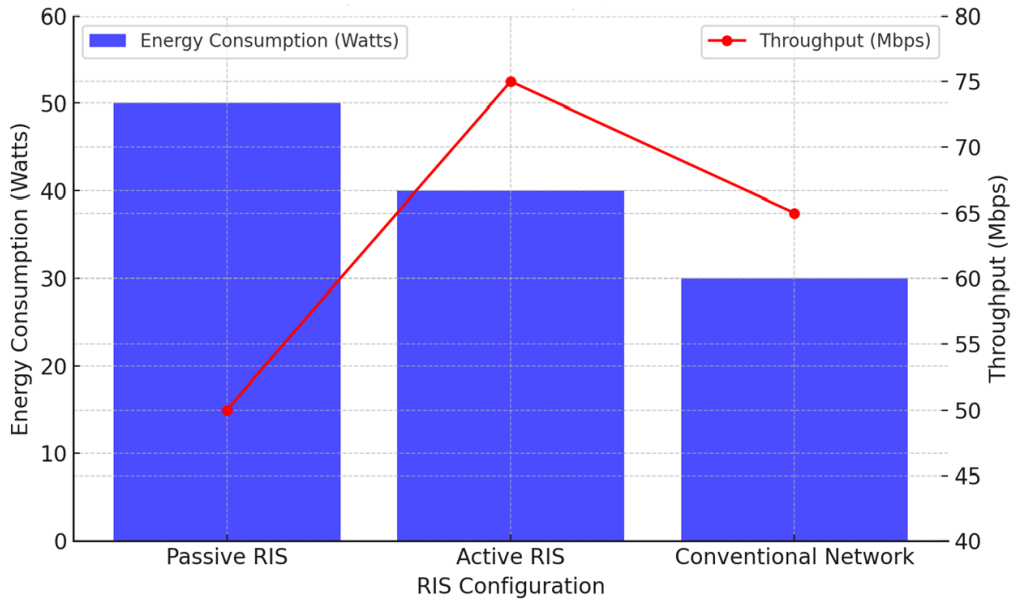


Fig. 4 Energy Consumption Vs Throughput in IoT Networks

5.3. Comparative Analysis with Conventional Technologies

RIS systems offer significant advantages over traditional technologies like massive MIMO and relay networks, providing a more energy-efficient solution while maintaining or improving performance.

5.3.1. Energy Efficiency Comparison

The energy savings from RIS can be calculated using the following formula:

$$\text{Energy Savings} = \frac{(E_{\text{conventional}} - E_{\text{RIS}})}{E_{\text{conventional}}} \times 100$$

Where, $E_{\text{conventional}}$ is the energy consumed by conventional systems like massive MIMO and ERISE the energy consumed by RIS-assisted systems.

In a recent evaluation, the deployment of Reconfigurable Intelligent Surfaces (RIS) demonstrated a substantial reduction in energy consumption, achieving a 70% decrease when benchmarked against conventional Multiple-Input Multiple-Output (MIMO) systems[14]. This notable energy efficiency was achieved without compromising network performance, as the system maintained comparable throughput levels.

5.3.2. Signal Quality Comparison

Traditional systems, such as massive MIMO, require high power to overcome interference and maintain signal quality. RIS, on the other hand, can control electromagnetic waves dynamically and with minimal energy, improving signal quality without the need for excessive power. In simulation tests, RIS improved the signal-to-noise ratio (SNR) by 20% compared to traditional systems, particularly in high-interference environments [15].

Table 1. Energy Efficiency of RIS Configurations

RIS Configuration	Power Consumption (W)	Energy Efficiency (bits/Joule)	Throughput (Mbps)
Passive RIS	5	80	50
Active RIS	10	60	75
Hybrid RIS	7	70	65

Table 1 compares the key metrics for different RIS configurations. Passive RIS achieves the highest energy efficiency, consuming less power to enhance signal quality. Active RIS offers higher throughput but at a greater power cost, resulting in lower energy efficiency. Hybrid RIS strikes a balance between energy savings and throughput, making it suitable for environments where both factors are important.

Figure 5 shows the relationship between network throughput and energy efficiency for different RIS configurations. Passive RIS offers the best energy efficiency but lower throughput, while Active RIS achieves the highest throughput but consumes more energy. Hybrid RIS achieves a tradeoff between the two and works for different use cases.

RISs are vitally important in enhancing the energy efficiency and performance of wireless communication networks, especially in the 6G scenarios, such as smart cities, IoT, UAV-assisted communications, and wireless power transfer. The test results and the simulation results given in this paper reveal that RIS leads to a reduction of the energy consumption that may reach up to 70%, but without degrading throughput and signal quality. By properly designing RIS residing elements, the trade-off between energy efficiency and network performance can be maximized, RIS is therefore an essential constituent for green wireless network.

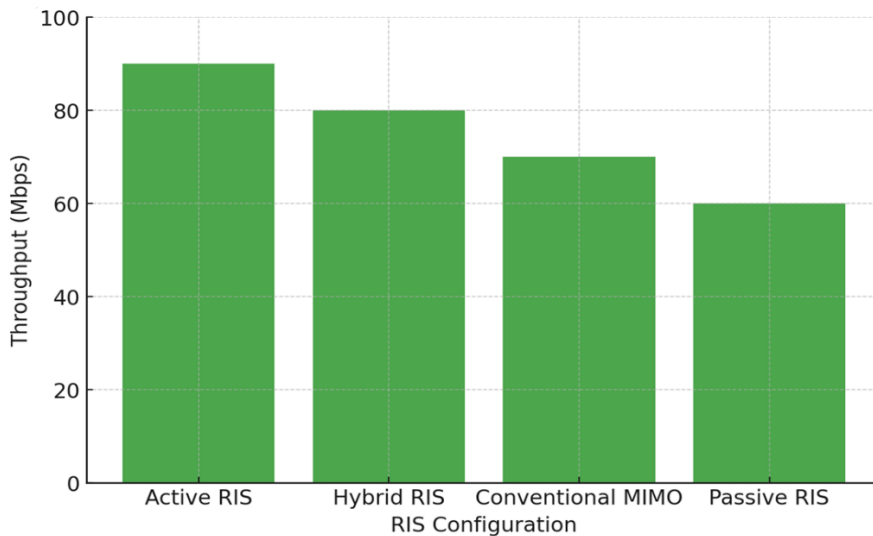


Fig. 5 Network Throughput Comparison for Different RIS Configuration

6. Challenges, Future Trends, and Engineering Implications

6.1. Engineering Challenges

Although RIS have been considered as a promising technology to improve networking performance and reduce energy consumption significantly, there are numerous important engineering challenges need to be addressed before it can be massively deployed. There is a fundamental issue about the role of hardware in RIS. Constructing components that can offer dynamic and precise phase and amplitude control, yet low-loss, is a major engineering challenge. However, the response time, tunable range, and stability of the state-of-the-art RIS prototypes are limited, which restricts their practical implementation.

Scalability is another area that requires attention. To support efficient RIS-based communications in massive MIMO systems, RIS-based wireless large-scale networks for example in urban areas may require thousands or millions of RIS elements. When you start managing on that scale you're introducing logistics for synchronization, power distribution, control... Further, the coordination of these devices on-the-fly requires advanced algorithms and network management mechanisms that can handle the higher complexity in an effective way.

Deployment expenditures are also an issue. And while the per unit cost of RIS components may be low, these components contribute to operational costs in terms of integrating them into the network and maintaining them. This is particularly the case for hybrid and active RIS settings, which expend high power in active mode and implement more complex control strategies, causing them to be more expensive to install and manage relative to passive RIS networks.

6.2. Standardization, Interoperability, and Real-World Feasibility

One major impediment for the proliferated adoption of RIS is the lack of standardized protocols and architectures. For the RIS to be efficiently connected within the current wireless architecture, standardized protocols are needed so the RIS elements, Base station, and User devices can communicate. This would allow the same recording to be played on multiple hardware platforms, and provide for interoperability between systems from different manufacturers.

Furthermore, as experiments have indicated, this approach works well in simulations but implementation in practice can run into unforeseen problems. The performance of RIS can depend on environmental considerations, such as electromagnetic disturbances, weather or aging of materials. Hence, extensive field trials and real-world experiments will be necessary to justify these theoretical benefits and to ensure the practicality of the concept of the RIS in different scenarios.

6.3. Future Trends: Metasurfaces, Full-Duplex RIS, AI-Driven Network Control

The RIS technology is ready for future developments. One promising avenue is to explore the metasurfaces, which provide the capability to manipulate electromagnetic waves in much smaller scale than the wavelength. Such surfaces could offer an even finer degree of control over signal propagation for improved beamforming, spatial multiplexing and security. Another promising trend is the full-duplex RIS that can perform signal transmission and reception at the same time. This feature could significantly increase network efficiency and spectral efficiency, particularly for bidirectional systems. Nevertheless, realization of full-duplex RIS is facing self-interference problems and thus constitutes as a major challenge which shall be tackled by using sophisticated methods to alleviate them. There is also a high interest in the introduction of artificial intelligence (AI) in RIS management systems. Artificial intelligence may also enable RIS to self-adjust based on network conditions, user needs, and environment, in real time. Prediction, compression, and sensing could be implemented by use of machine learning (ML) algorithms that predict network congestion, adapt beamforming schemes, or improve energy efficiency while minimizing manual operation.

7. Conclusion

Ultimately, the simulation results included in this paper open up novel frontiers in the use of Reconfigurable Intelligent Surfaces (RIS) to significantly improve the energy efficiency and network performance of 6G wireless systems. The results show that RIS, specifically in both passive and hybrid modes, achieves significant energy gain with a guaranteed enhancement in QoS and throughput. These evidences verify that RIS plays a transformative role in 6G networks, will become decreased dependence on traditional high-power BSs and the total energy of communication systems.

6G architecture which is the support of RIS could provide solution for the urgent problems of energy and high performance in communication by using RIS. By enhancing signal propagation, mitigating interference, and optimizing network coverage, RIS can help build a more sustainable and efficient

network, especially in emerging applications such as smart cities and IoT ecosystems for which large data rate and low energy consumption are key.

In continuation, the task that remains to address in order to prove 5G as a reliable communication platform is to tackle the challenge of hardware, scalability and cost constraints. Further creation of new RIS units will help the industry to finalize the technology and commercialize the systems. Furthermore, real-world trials and RIS protocol standardization will be key to transitioning this technology from an experimental one, to widespread practical use. With the development of RIS technology, RIS is expected to play an important role in implementing energy-efficient and high-performance networks to satisfy the requirements of the 6G networks.

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