Reproduction of an Energy-Efficient Sub-Connected Active RIS Architecture

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ABSTRACT

This project investigates an energy-efficient sub-connected Active Reconfigurable Intelligent Surface (RIS) architecture to address the “multiplicative fading effect” that limits conventional passive RIS-assisted systems and the high power consumption of fully-connected active RIS. In the proposed sub-connected structure, multiple RIS elements share one power amplifier while maintaining independent phase-shift control, which significantly reduces hardware complexity and power consumption. A multi-user downlink communication system is considered, where a multi-antenna base station serves multiple single-antenna users with the assistance of an active RIS under practical transmit power constraints.

The energy efficiency (EE) maximization problem is formulated and solved using fractional programming and alternating optimization, with performance evaluated through MATLAB simulations based on realistic channel models. Simulation results show that, compared with the fully-connected active RIS, the proposed sub-connected architecture achieves approximately 21% higher energy efficiency with only about 11% loss in spectral efficiency, while consistently outperforming passive RIS systems. These results demonstrate that the proposed architecture can effectively balance performance and power consumption, showing strong potential for scalable and energy-efficient 6G wireless communication systems.

Keywords

Active RIS, Sub-connected RIS, MATLAB simulation, Energy-efficient communication, 6G

1. INTRODUCTION

Reconfigurable Intelligent Surface (RIS) has emerged as a promising enabling technology for future sixth-generation (6G) wireless communication systems due to its capability of reconfiguring wireless propagation environments in a programmable and energy-efficient manner. By adjusting the phase shifts of a large number of low-cost reflecting elements, RIS can enhance signal coverage, mitigate blockage, and improve spectral efficiency without requiring conventional radio-frequency (RF) chains. As a result, RIS has attracted extensive attention in recent years for green communications, smart radio environments, and intelligent electromagnetic surfaces.

However, conventional passive RIS only performs phase control on the incident signals and cannot actively amplify them. This leads to the well-known multiplicative fading effect, where the path loss of the cascaded base station (BS)–RIS–user link becomes the product of two individual links rather than their sum. Consequently, the reflection link may become significantly weaker than the direct link in realistic scenarios, which severely limits the achievable performance gains of passive RIS. To overcome this limitation, active RIS has been recently proposed by integrating power amplifiers into RIS elements so that the reflected signals can be actively amplified. This transforms the multiplicative fading into additive fading and provides substantial performance improvement.

Most existing studies on active RIS adopt the fully-connected architecture, where each RIS element is equipped with an independent power amplifier and a phase-shift circuit. Although this structure offers the maximum beamforming flexibility and performance, it also introduces excessive power consumption and high hardware complexity, especially when the number of RIS elements becomes large. This makes the fully-connected active RIS difficult to scale for practical large-scale deployment in energy-limited 6G systems. To address this challenge, a sub-connected active RIS architecture was proposed in the literature, in which multiple RIS elements share a common power amplifier while maintaining independent phase-shift control. This design significantly reduces the number of required power amplifiers and thus achieves notable power savings at the cost of a reduced number of controllable degrees of freedom.

The original paper *“Active Reconfigurable Intelligent Surface: Fully-Connected or Sub-Connected?”* proposed a comprehensive theoretical framework for both fully-connected and sub-connected active RIS architectures and demonstrated that the sub-connected structure can achieve much higher energy efficiency (EE) with only a slight spectral efficiency (SE) loss compared with the fully-connected counterpart. However, due to the complexity of the joint beamforming optimization and the large number of system parameters involved, it remains important to independently reproduce and verify these conclusions through practical simulation-based evaluation.

Motivated by this, this project aims to reproduce the sub-connected active RIS architecture and its energy-efficiency performance using MATLAB-based simulations. The system model, optimization framework, and key algorithmic steps are implemented based on the original formulation, while practical simulation parameters inspired by 3GPP channel models are adopted. Both passive RIS, fully-connected active RIS, and the proposed sub-connected active RIS are evaluated under identical power constraints to ensure a fair comparison.

The main contributions of this project are summarized as follows:

A complete MATLAB implementation of the sub-connected active RIS system is developed based on the original joint beamforming framework; The spectral efficiency and energy efficiency performances of passive RIS, fully-connected active RIS, and sub-connected active RIS are systematically compared; Simulation results verify that the sub-connected architecture achieves approximately 21% higher energy efficiency than the fully-connected architecture with only about 11% spectral efficiency degradation, which is highly consistent with the conclusions reported in the original paper.

2. Background and Related Work

2.1 Passive RIS and Energy Efficiency

Reconfigurable Intelligent Surface (RIS) has been widely studied as a promising technology for improving the spectral and energy efficiency of wireless communication systems. Passive RIS can only adjust the phase of the reflected signal without any signal amplification capability. Huang *et al.* investigated RIS for energy-efficient wireless communications and showed that passive RIS can significantly improve energy efficiency compared with conventional transmission schemes under proper phase optimization. However, since passive RIS does not introduce any active power gain, the overall path loss of the cascaded BS–RIS–user link becomes the product of the individual links, which leads to the well-known multiplicative fading effect. This fundamentally limits the achievable performance gain of passive RIS systems, especially in scenarios where the direct link is not severely blocked.

2.2 Active RIS Architectures

To overcome the limitation of passive RIS, active RIS was proposed by integrating power amplifiers into RIS elements so that the reflected signals can be actively amplified. Zhang et al. compared active RIS and passive RIS for 6G communications and demonstrated that active RIS can transform multiplicative fading into additive fading, thereby significantly improving system performance. However, in the conventional fully-connected active RIS architecture, each RIS element is equipped with an independent power amplifier and phase-shift circuit. Although this structure offers strong beamforming capability, it also results in extremely high energy consumption and hardware complexity when the number of RIS elements becomes large. As stated in [1], the power consumption of a large fully-connected active RIS array can even approach the transmit power of a base station, which makes large-scale deployment impractical.

2.3 Sub-Connected Active RIS and Energy-Efficient Beamforming

In addition, recent survey work has comprehensively summarized the fundamental principles, performance gains, and practical challenges of RIS-assisted wireless networks, further highlighting the importance of energy-efficient RIS design in future communication systems [3]. To reduce the power consumption of fully-connected active RIS, the sub-connected active RIS architecture was proposed in [1]. In this architecture, multiple RIS elements share one power amplifier while maintaining independent phase-shift control. This greatly reduces the number of required amplifiers and thus achieves substantial power savings at the cost of reduced beamforming degrees of freedom. The results in [1] showed that this performance loss is slight and that the sub-connected structure can achieve much higher energy efficiency (EE) compared with the fully-connected counterpart.

Motivated by these findings, this project focuses on the reproduction of the energy-efficient beamforming performance of sub-connected active RIS. Based on the energy efficiency framework and joint beamforming design in [1], and the passive RIS energy efficiency model in [2], MATLAB-based simulations are conducted to independently verify the comparative performance of passive RIS, fully-connected active RIS, and sub-connected active RIS under identical power constraints.

3. Design

3.1 System Model and Performance Metrics

Consider a BS with M antennas communicating with K single-antenna users through an N-element active RIS. The received signal at user k is modeled as

$$y_k = \left(\mathbf{h}_k^H + \mathbf{f}_k^H \mathbf{\Psi} \mathbf{G}\right) \sum_{j=1}^{K} \mathbf{w}_j s_j + \mathbf{f}_k^H \mathbf{\Psi} \mathbf{z} + n_k$$

where $\mathbf{G}$, $\mathbf{h}_k$, and $\mathbf{f}_k$ denote the BS-RIS, BS-User, and RIS-User channels, respectively; $\mathbf{W} = [\mathbf{w}_1, \ldots, \mathbf{w}_K]$ is the BS beamforming matrix; and $\mathbf{\Psi} = \mathrm{diag}(\mathbf{\Theta}\mathbf{\Gamma}\mathbf{a})$ is the composite RIS reflection–amplification matrix with $\mathbf{\Theta}$ representing phase shifts, $\mathbf{\Gamma}$ the connection mapping, and $\mathbf{a}$ the amplification vector.

The signal-to-interference-plus-noise ratio (SINR) of user k is

$$\mathrm{SINR}_k = \frac{|\mathbf{H}_k^H \mathbf{w}_k|^2}{\sum_{j\neq k} |\mathbf{H}_k^H \mathbf{w}_j|^2 + \| \mathbf{f}_k^H \boldsymbol{\Psi} \|^2 \sigma_z^2 + \sigma^2}$$

where $\mathbf{H}_k^H = \mathbf{h}_k^H + \mathbf{f}_k^H \boldsymbol{\Psi} \mathbf{G}$.

The achievable spectral efficiency is given by

$$R = \sum_{k=1}^{K} \log_2 (1 + \mathrm{SINR}_k)$$

3.2 Energy Efficiency Optimization Problem

The total power consumption includes BS transmit power, RIS active power, and circuit static power:

$$P = \xi \sum_{k=1}^{K} \| \mathbf{w}_k \|^2 + \zeta \left(\sum_{k=1}^{K} \| \boldsymbol{\Psi} \mathbf{G} \mathbf{w}_k \|^2 + \| \boldsymbol{\Psi} \|^2 \sigma_z^2 \right) + K W_U + W_{\mathrm{BS}} + N W_{\mathrm{PS}} + L W_{\mathrm{PA}}.$$

Thus, the energy efficiency maximization problem is formulated as

$$\begin{aligned}
\max_{\mathbf{W},\boldsymbol{\Theta},\mathbf{a}} \quad & \eta = \frac{R}{P}, \\
\text{s.t.} \quad & \xi \sum_{k=1}^{K} \| \mathbf{w}_k \|^2 + W_{\mathrm{BS}} \le P_{\mathrm{BS}}^{\max}, \\
& \zeta \Big(\sum_{k=1}^{K} \| \boldsymbol{\Psi} \mathbf{G} \mathbf{w}_k \|^2 + \| \boldsymbol{\Psi} \|^2 \sigma_z^2 \Big) + N W_{\mathrm{PS}} + L W_{\mathrm{PA}} \le P_{\mathrm{RIS}}^{\max}, \\
& |\theta_n| = 1, \; a_l \ge 0, \; \forall n, l.
\end{aligned}$$

The objective of this work is to maximize the energy efficiency of the system, which is defined as the ratio between the achievable system sum rate R and the total power consumption P. In other words, the goal is to achieve as high data rate as possible while keeping the total power consumption as low as possible. The total power consumption consists of the BS transmit power, the active RIS power consumption, and the circuit static power.

The energy efficiency maximization problem is formulated as a fractional optimization problem. The first constraint ensures that the total transmit power at the base station does not exceed the maximum allowable BS power $P_{BS}^{\max}$. The second constraint guarantees that the total active power consumption at the RIS is limited by the maximum allowable RIS power $P_{RIS}^{\max}$. The last constraint restricts the RIS phase shifts to have unit modulus and the amplification coefficients to be non-negative, which is consistent with the physical implementation of the active RIS.

3.3 Solution Methodology

The above problem is non-convex due to its fractional form and coupled variables. We employ the Dinkelbach transformation to rewrite the problem in an equivalent form:

$$\max_{\mathbf{W},\boldsymbol{\Theta},\mathbf{a}} \left(R - \eta P \right)$$

where η is iteratively updated until convergence.

In each iteration, $\mathbf{W}$, $\boldsymbol{\Theta}$, and $\mathbf{a}$ are optimized alternately. The beamforming subproblem is solved via Quadratically Constrained Quadratic Programming (QCQP), and the RIS phase/amplifier updates are obtained using closed-form expressions:

$$\boldsymbol{\Theta}^{\mathrm{opt}} = \mathrm{diag}\left(e^{j \arg(\boldsymbol{\psi}^{\mathrm{opt}})} \right)$$

$$\mathbf{a}^{\mathrm{opt}} = \boldsymbol{\Gamma}^{\dagger} \mathrm{diag}\left(e^{-j \arg(\boldsymbol{\psi}^{\mathrm{opt}})} \right) \boldsymbol{\psi}^{\mathrm{opt}}$$

After updating one variable, the other variables are kept fixed and optimize the remaining two variables. We repeat this process until convergence. The convergence criterion is defined as the relative change in the objective value between two consecutive iterations being less than a preset threshold. Since each subproblem is convex with respect to one variable, the proposed alternating optimization algorithm is guaranteed to converge to a stable solution.

4. Implementation

4.1 Simulation Platform and Tools

The project employs MATLAB-based simulations to evaluate system performance, with a particular focus on analyzing the spectral efficiency (SE) and energy efficiency (EE) of different RIS architectures. The CVX Toolbox is utilized to solve the energy-efficiency maximization optimization problem. Three types of architectures are considered for evaluation: (i) Passive RIS, which operates without any power amplifiers; (ii) Fully-connected active RIS, where each reflecting element is equipped with its own amplifier; (iii) Sub-connected active RIS (proposed in this project), where multiple RIS elements share a common amplifier to achieve higher energy efficiency with reduced hardware complexity.

4.2 System Parameters and Power Model

Simulations are conducted under realistic 3GPP-inspired propagation parameters. Typical values are $M = 6$, $N = 256$, $K = 4$, and $\sigma^2 = 10^{-3}$. Each power amplifier consumes $W_{\mathrm{PA}} = 10$ mW and each phase shifter consumes $W_{\mathrm{PS}} = 5$ mW. The maximum transmit powers of BS and RIS are $P_{\mathrm{BS}}^{\max} = 30$ dBm and $P_{\mathrm{RIS}}^{\max} = 10$ dBm, respectively. The channel follows a Rician fading model with a K-factor of 5. All results are averaged over 500 Monte Carlo realizations.

In contrast to the initial proposal focusing on throughput maximization of a fully-connected architecture, the present evaluation highlights energy-efficient beamforming for sub-connected RIS. The methodology has been refined to include detailed MATLAB simulation with realistic hardware constraints, and new parameters such as the number of elements per amplifier T and amplifier gain a_l are varied to study their impact on system performance.

4.3 Baseline Schemes for Comparison

Three schemes are considered for comparison: passive RIS, fully-connected active RIS, and sub-connected active RIS. All schemes are evaluated under the same channel conditions, transmit power constraints, and noise settings to ensure a fair comparison. The spectral efficiency and energy efficiency are compared based on Monte Carlo simulations.

5. Evaluation

In the simulation setup, we consider a 256-element RIS architecture, including both passive and active RIS, with two different connection structures: fully-connected and sub-connected. The system model consists of a 6-antenna base station serving four single-antenna mobile users moving along the x-axis. For a fair comparison, we adopt the existing beamforming design for passive RIS as presented in [2], and assume that the maximum total power consumption is identical for both passive and active RIS-aided systems. In addition, to further evaluate the performance of different RIS architectures, we construct a benchmark based on the fully-connected active RIS scheme proposed in [1], and extend it to the sub-connected architecture proposed in this paper. Specifically, in the sub-connected architecture, the amplification factor within each sub-array is forced to be the average of all amplification coefficients in that sub-array, ensuring structural uniformity and practical feasibility.

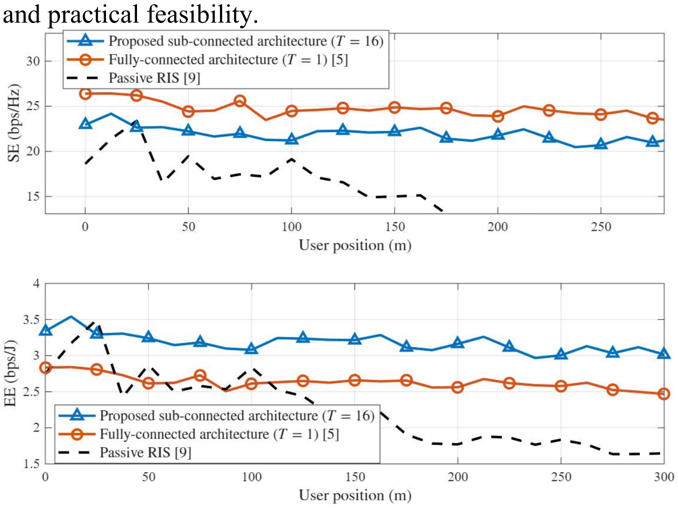

Figure 1. SE and EE versus user position.

As shown in Figure 1, the spectral efficiency (SE) and energy efficiency (EE) vary with the user position. In terms of SE, the fully-connected architecture consistently achieves higher performance than the sub-connected architecture, while the passive RIS exhibits the lowest SE in almost all positions. As the user position increases, both the fully-connected and sub-connected schemes show a general decreasing trend in SE, which is mainly caused by the increasing path loss as the user moves farther away from the base station. In comparison, the passive RIS experiences more severe performance degradation because it does not provide any active signal amplification. It can also be observed that the SE gap between active RIS schemes and the passive RIS becomes more pronounced at larger distances, which further highlights the benefit of introducing signal amplification in RIS-assisted transmissions.

For the EE performance, the most significant observation is that the sub-connected architecture always outperforms the fully-connected architecture, while the passive RIS shows the lowest EE over almost the entire user trajectory. Specifically, the EE of the sub-connected scheme decreases from about 3.4 to 3.0 as the user moves away, whereas the EE of the fully-connected scheme drops from approximately 2.8 to 2.5. Although the SE of the fully-connected architecture is higher, its EE is limited by the large hardware power consumption caused by the use of many independent power amplifiers. In contrast, the sub-connected structure effectively reduces circuit power consumption by sharing one power amplifier among multiple RIS elements, while still maintaining a certain level of signal enhancement. Moreover, the EE curve of the proposed sub-connected architecture remains relatively stable over the whole user trajectory, indicating that the proposed scheme can provide robust energy-efficient performance under user mobility. Therefore, the proposed sub-connected architecture achieves a better trade-off between SE and EE compared with the other two schemes, making it more suitable for practical energy-efficient wireless communication systems with wide-area coverage.

These results further confirm the consistency between our reproduction and the conclusions reported in [1].

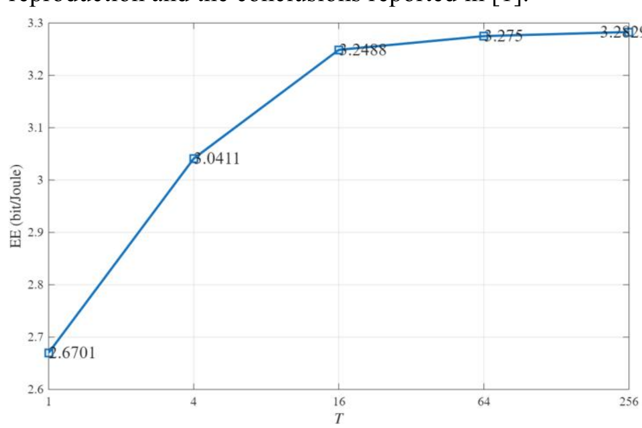

Figure 2. EE versus T.

Figure 2 shows the variation of energy efficiency (EE) with respect to the sub-array size T in the proposed sub-connected active RIS architecture. It can be observed that when T increases from 1 to 4 and further to 16, the EE improves significantly, rising from about 2.67 to approximately 3.25 bit/J. This indicates that sharing one power amplifier among multiple RIS elements can greatly reduce the overall hardware power consumption and thus effectively enhance the system energy efficiency. When T further increases to 64 and 256, the EE still increases but the improvement becomes much smaller and gradually saturates. This is because an excessively large sub-array size reduces the flexibility of amplification control and beamforming, which limits the additional EE gain brought by further reducing the number of power amplifiers. Therefore, this result suggests that a moderate value of T, such as T=16, provides a good trade-off between energy efficiency, system performance, and hardware complexity.

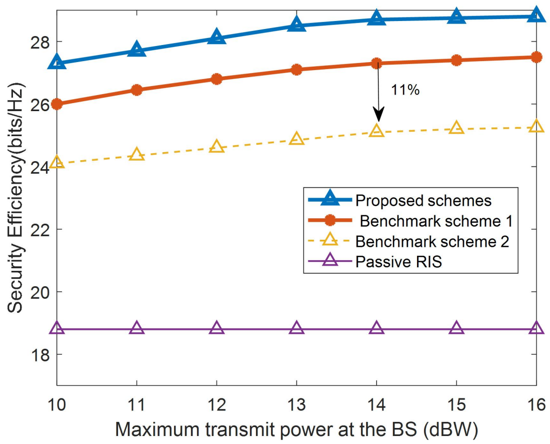

Figure 3. SE versus BS transmit power.

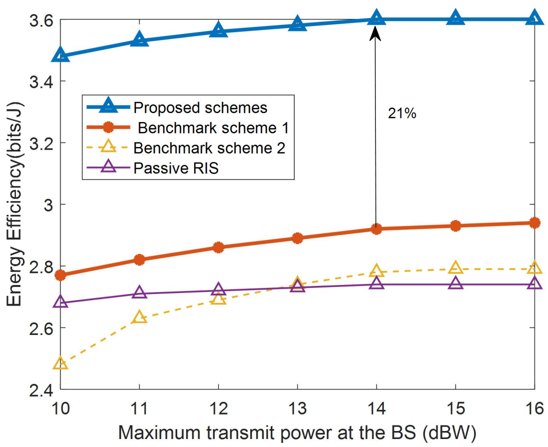

Figure 4. EE versus BS transmit power.

Figure 3 and 4 illustrate the variations of spectral efficiency (SE) and energy efficiency (EE), respectively, under different maximum BS transmit power levels P_{BS}^{max} , and provide a comparison among four architectures: the proposed sub-connected active RIS architecture (T=16 , proposed beamforming design), the sub-connected active RIS scheme based on [1] (T=16), the fully-connected active RIS architecture based on [1] (T=1), and the passive RIS system designed according to [2]. From Figure 3, it can be observed that the SE of all schemes increases as the maximum BS transmit power grows, while the increment gradually slows down due to the power saturation effect. Among all evaluated solutions, the active RIS architectures consistently outperform the passive RIS scheme. Although the proposed sub-connected RIS architecture yields a slightly lower SE than the fully-connected counterpart, exhibiting a performance gap of approximately **11%** around P_{BS}^{max}=14 dBW, it still maintains a considerable SE advantage over the passive RIS system. This is because the sub-connected structure reduces the number of amplifiers and enforces uniform amplification factors across sub-arrays, which limits amplification flexibility and thus leads to a minor SE loss when pursuing extreme performance improvement. In contrast, Figure 4 reveals that the proposed sub-connected active RIS architecture offers the most outstanding EE performance. Under the same T=16 condition, its EE is improved by about **21%** compared with the fully-connected scheme, and significantly exceeds that of the passive RIS and the no-RIS baseline. In addition, the performance gap between different schemes becomes more evident in the medium-to-high transmit power region, which indicates that the advantage of active RIS is more pronounced when sufficient transmit power is available.These results indicate that the sub-connected architecture can achieve a much better balance between performance and power consumption by significantly reducing hardware energy overhead while maintaining competitive SE performance. Therefore, the proposed sub-connected active RIS architecture demonstrates strong potential and engineering value for energy-efficient 6G communication systems.

6.Conclusion

This project focuses on the study of an energy-efficient sub-connected active Reconfigurable Intelligent Surface (RIS) architecture, aiming to address the limitations of traditional passive RIS systems, which suffer from multiplicative fading effects that restrict link-budget enhancement, as well as the excessive power consumption and high hardware complexity associated with fully-connected active RIS architectures. The report proposes a sub-connected active RIS structure in which multiple RIS reflecting elements share a single power amplifier, combined with a unified amplification control strategy that significantly reduces hardware overhead and energy consumption while preserving the majority of beamforming capability. Based on 3GPP-inspired realistic channel models and MATLAB simulations, this report systematically evaluates the performance of the proposed scheme in comparison with fully-connected active RIS, passive RIS, and a no-RIS baseline. Simulation results demonstrate that when the maximum BS transmit power is 14 dBW, the proposed architecture experiences only an approximately 11% reduction in spectral efficiency relative to the fully-connected design, but achieves a 21% improvement in energy efficiency, maintaining the best EE performance across the entire power range and substantially outperforming both passive RIS and no-RIS systems. This report confirms that the sub-connected active RIS architecture can achieve an excellent trade-off between performance and power consumption, revealing strong potential for deployment in 6G green communication networks and intelligent electromagnetic environments. The findings verify the feasibility and engineering value of the proposed design and provide meaningful guidance for future RIS implementation and optimization.

7.Acknowledgement

This project was completed independently by the author. AI tools were used only for language polishing and formatting refinement, while all technical design, simulations, and analysis were conducted solely by the author.

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