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Adaptive Beamforming and Interference Nulling in Reconfigurable Intelligent Surface Assisted 6G Heterogeneous Networks

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Abstract

Sixth-generation (6G) wireless networks require high data rates, extremely low latency, and high reliability within a highly dense, heterogeneous network (HetNet) context. The increased density of macro base stations, small cells, and users increases interference and, as a result, degrades signal quality and network efficiency. Therefore, this paper proposes an adaptive beamforming and interference nulling scheme for 6G RIS-assisted HetNet that optimizes both beamforming weights and RIS *phase* shifts using Channel State Information (CSI) to maximize signal transmission and minimize interference. A system model that includes macro cells, small cells, RIS, and user equipment is modeled. The adaptive beamforming module directs the transmitting beam towards the desired user, and the RIS-based interference nulling scheme minimizes undesired signals using

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controllable reflections. Numerical analysis of the proposed scheme is performed, and it is verified using performance indicators, including Signal-to-Interference-and-Noise Ratio (SINR), throughput, spectral efficiency, energy efficiency, and outage probability. Based on simulation analysis, the proposed scheme achieves 34.8% higher SINR, 29.6% higher throughput, 27.3% higher spectral efficiency, reduces interference power by 41.2%, reduces outage probability by 22.7%, and improves energy efficiency by 18.9% over the legacy beamforming design. From this, it can be concluded that combining adaptive beamforming with RIS-assisted interference nulling improves network performance and reliability and provides an efficient approach for 6G wireless networks and ultra-dense communications.

Keywords: 6G Networks, Heterogeneous Networks, Reconfigurable Intelligent Surface, Adaptive Beamforming, Interference Nulling, SINR, Spectral Efficiency.

1 Introduction

Driven by the necessity of ultra-high data rates, sub-millisecond latency, massive machine-type communications, and ubiquity, the next-generation mobile communication systems beyond 5G are being conceptualized as sixth-generation (6G) systems. 6G networks, unlike traditional cellular networks, fuse terrestrial, aerial, satellite, and the Internet of Things (IoT) infrastructures to create an integrated network capable of supporting intelligence and massive data transmission. Heterogeneous networks (HetNets), an architecture comprising macro base stations, small cells, relays, and edge devices, have thus become a backbone of 6G networks, capable of improving spectrum reuse and network capacity (Worka et al., 2024; Umer et al., 2025; Heydarishahreza et al., 2024). However, ultra-dense HetNets also face many challenges. The interaction among various network tiers intensifies co-channel interference, while varying mobility and propagation conditions complicate resource allocation and beam management. Traditional interference-cancellation mechanisms are inefficient in such dense networks, and intelligent, agile communication solutions are required (Chen et al., 2022; Nwufo et al., 2025). The roles of artificial intelligence, intelligent multiple-access schemes, and automatic network management mechanisms are anticipated to be significant in meeting next-generation communication requirements (Noor et al., 2025).

Reconfigurable Intelligent Surfaces (RISs) represent a new paradigm in wireless communications that enable intelligent manipulation of radio wave propagation. RISs consist of an array of passive reflecting elements whose phase shifts can be controlled to modify propagating signals, without requiring radio-frequency hardware (Amri et al., 2021; Nwufo et al., 2025). By dynamically tuning the phase responses of the reflecting elements, RISs can manipulate wireless channel characteristics, enhance signal propagation strength, and mitigate detrimental propagation effects. In 6G systems, the use of RIS can improve coverage in blockage areas, boost signal quality at cell edges, and achieve higher energy efficiency owing to their passive, low-power nature (Worka et al., 2024; Umer et al., 2025). The cooperative use of RIS further enhances performance by enabling directional transmission and improving transmission security (Ge & Fan, 2022). Recent literature also reports significant improvements in spectral efficiency and communication reliability when employing RIS in dense networks (Chen et al., 2022; Nwufo et al., 2025).

The integration of RIS technology into 6G HetNets opens up new opportunities for interference-aware communications. However, the quality of communication may be affected by signal degradation due to multi-user interference, varying channel state information (CSI), and sub-optimal beam selection (JG et al., 2025). Most previous beamforming designs focused on optimizing the direct link but did not well explore the reconfigurability of the RIS da Silva Brilhante et al., (2023). In particular, scalability in multi-RIS-assisted networks and joint interference cancellation on both the base station and RIS sides

were studied as part of future wireless network development (Cao et al., 2025). There is a pressing need to propose joint adaptive beamforming and interference nulling techniques that can dynamically adjust to evolving network states.

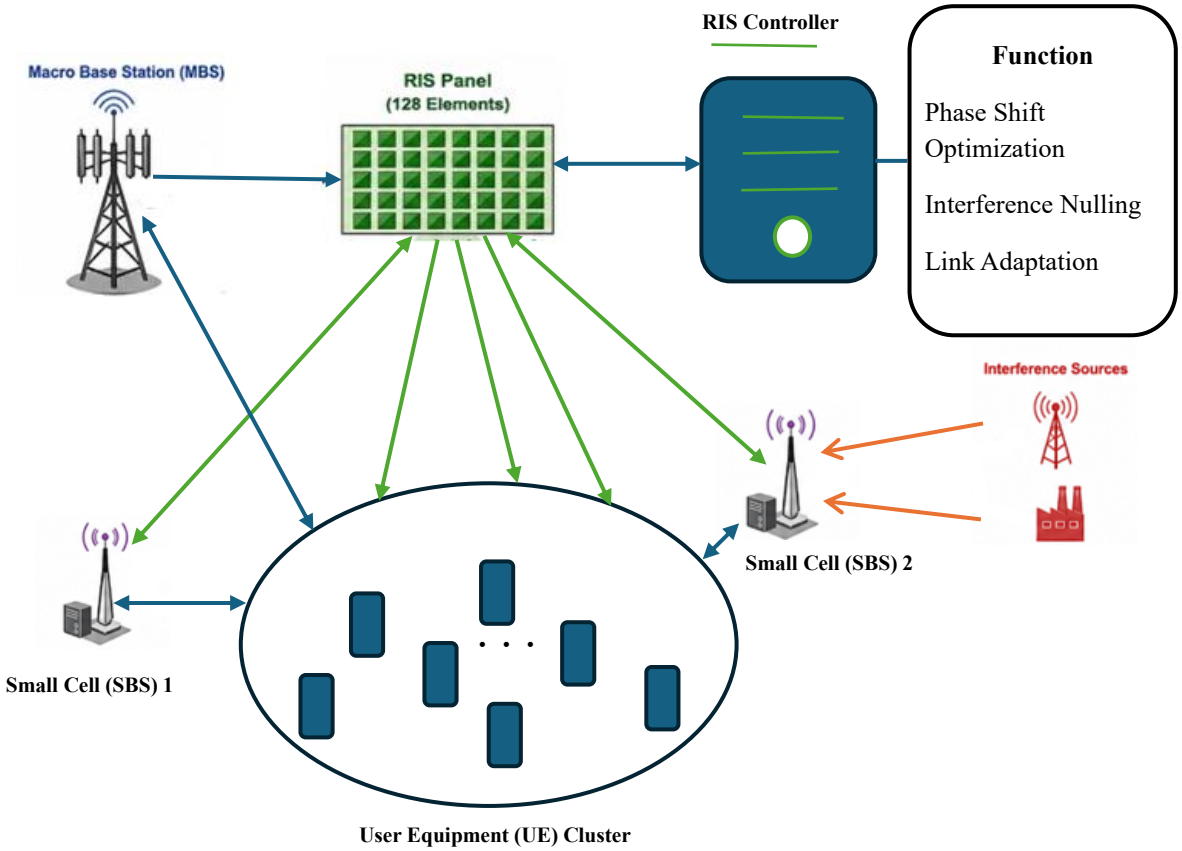


Figure 1: Architecture of the proposed RIS-Assisted 6G heterogeneous network

Figure 1 shows the system diagram of the proposed RIS-assisted 6G heterogeneous network, which includes a Macro Base Station (MBS), several Small Cell Base Stations (SBSs), an RIS panel with a controller, and User Equipment (UE) clusters. The RIS adjusts its phase shifts in response to communication to optimize signal propagation, interference cancellation, and link performance. The described system is characterized by cooperative adaptive beamforming and interference nulling to enhance coverage, spectral efficiency, and reliability of communication in dense 6G wireless networks.

The problem of communication performance degradation in RIS-assisted 6G HetNets due to interference has been a challenging problem. As future wireless systems will become increasingly dense and complex, robust and scalable communication systems are desirable for delivering reliable, high-capacity wireless communication services. Overcoming such a challenge directly contributes to the success of smart cities and industrial Internet of Things (IoT) enabled services. In this paper, a framework for joint adaptive beamforming and RIS-assisted interference nulling for 6G HetNets is proposed, which dynamically configures beam weights and RIS phase responses to improve signal quality while suppressing interference. A mathematical model of the network is developed and used to assess performance in terms of SINR, throughput, spectral efficiency, energy efficiency, and outage probability. This work aims to enhance the communication reliability in ultra-dense networks.

The structure of the remainder of the paper is as follows. In Section II, a thorough literature survey is provided on adaptive beamforming, RIS-assisted communication systems, and interference management in upcoming wireless networks. In Section III, the proposed JAB-RIN framework is introduced in detail, covering the system model, mathematical formulation, optimization approach, and algorithmic implementation. Section IV describes the simulation setup, performance measures, and results obtained under different network configurations. A thorough analysis of the results and a comparison with the previous method are presented in Section V, which emphasizes the effectiveness of the framework. Lastly, Section VI summarizes the contributions of this work and suggests new research ideas for future work on RIS-assisted 6G heterogeneous networks.

2 Literature Review

Adaptive beamforming is an indispensable tool for improving signal quality, spectral efficiency, and interference mitigation in future wireless networks. Existing beamforming techniques, including Maximum Ratio Transmission (MRT), Zero-Forcing (ZF), and Minimum Variance Distortionless Response (MVDR), use antenna array processing to focus the transmitted energy on the desired users and null out interference in other directions (Alzubaidi et al., 2025). These techniques achieve good performance in relatively stable environments; however, their performance deteriorates rapidly in the very dynamic scenario of future 6G heterogeneous networks. With larger antenna arrays, massive MIMO (Multiple Input Multiple Output) provides highly directive transmissions, spatial multiplexing, and increased channel capacity. Beamforming intelligence can be introduced by AI, which could predict and adjust beams in real time and optimize system resource allocation (Asemian et al., 2025). Research on the effective use of deep learning for beam management has already been conducted, including optimal transmit beam selection based on CSI and user movement (Asemian et al., 2025). Dual-memory swarm optimization and intelligent search algorithms are among the advanced optimization methods developed to optimize RIS phase shifts in RIS-assisted communication (Chen et al., 2025). This reflects a trend from statically controlled beams to intelligently self-optimized beams.

Reconfigurable Intelligent Surfaces (RIS) are an effective approach for creating programmable wireless propagation environments by adjusting the phase shifts of reflecting elements, thereby improving signal strength at desired locations while mitigating adverse channel effects (Amodu et al., 2024). Up to now, various works have focused on RIS in Full Duplex, NTN, UAV assistance, and integrated sensing and communication systems. Phase-shift optimization of RISs, reflection-coefficient adjustment, and element selection are common approaches to optimizing RISs. Used an optimization driven RIS configuration method in full duplex communications to eliminate self-interference (Chen et al., 2025). And researches have shown that RIS-assisted THz and NTN communications have high coverage extension, high spectrum efficiency and good transmission reliability (Amodu et al., 2024). In addition, RIS-assisted UAV communications provide better energy efficiency and more flexible support in dynamic environments (Lavanya et al., 2025). Currently, RIS application extends to integrated sensing and communication system which can perceive and communicate simultaneously (Chopra & Ahmed, 2025). The RIS technology is going to be important in the next generation smart wireless networks (Sheeba John Kennedy et al., 2025).

Multiple network tiers in a heterogeneous wireless network often employ common spectral resources. It poses great challenges for reducing inter-cell interference, cross-tier interference and self-interference in full duplex systems. Traditional ways of interference management including power control, CoMP (Coordinated MultiPoint), interference alignment and nulling of transmitting antennas are proposed to

tackle with these issues. The RIS assistance method has been applied in interference suppression systems. Wang et al. demonstrated that RIS assisted full duplex communications system with deep learning could improve the quality of signal in fading channel (Wang et al., 2025). And deep learning based active RIS-NOMA system shows efficient performance in jamming mitigation and ultra reliable and low latency communication (Asemian et al., 2025). Security and privacy of RIS-enabled networks, including protection against signal manipulation attack from malicious user, is still under active research (Baskar et al., 2025). However, although both individual beamforming optimization or RIS configuration optimization are good enough to increase the performance of communication system, none of the researches integrated them in the comprehensive framework for dense 6G heterogeneous networks.

Based on the above literatures review, concluded that adaptive beamforming and RIS technologies are able to significantly enhance the wireless system's performance by boosting the signal focusing, extending the coverage and canceling the interference. However, existing research only emphasizes either the adaptive beamforming optimization or the RIS configuration optimization individually. A joint adaptive beamforming and RIS-assisted interference nulling framework for dense 6G heterogeneous networks is understudied to further increase the SINR, throughput, spectrum efficiency and communication reliability.

3 Methodology

3.1 System Model of RIS-Assisted 6G HetNet

This system proposes a 6G Heterogeneous Network (HetNet) that integrates MBS, SBSs, RIS panels and UE. The MBS supports macro-area coverage whereas SBSs improve network capacity in dense user environments. An RIS with N passive reflecting elements is employed between BS and UE to control the wireless propagation environment. The received signal for k-th UE includes direct and RIS-reflected path. The effective channel is described in equation (1):

$$h_{eff,k} = h_{d,k} + h_{r,k}^{H} \Theta G \qquad (1)$$

Where $h_{d,k}$ represents direct channel, G denotes the BS-to-RIS channel matrix, $h_{r,k}$ is RIS-to-UE channel vector and Θ represents RIS reflection matrix. The equation (1) describes composite channel that is used in the proposed framework. The frequency flat Rayleigh channel with additive white Gaussian noise (AWGN) is assumed as channel model. Mobility of users, shadowing and inter-cell interference are considered to simulate 6G realistic network environment. Orthogonal resource allocation method is applied to achieve communication where same spectrum resource can be reused in neighbor cell.

Figure 2 presents the flowchart of the developed JAB-RIN framework for RIS-aided 6G heterogeneous networks. Initially, network initiation and CSI collection occurs, after which proficient channel estimation is performed in order to model the wireless environment. Active beamforming is implemented so that the signal may be directed toward the target users, and interference detection helps determine the prevailing interfering elements. Following that, RIS phase optimization and joint optimization are implemented in an effort to improve signal quality and eliminate interference. Finally, SINR evaluation is completed prior to the optimized transmission being established so as to improve the data rate, spectral efficiency, and communication reliability.

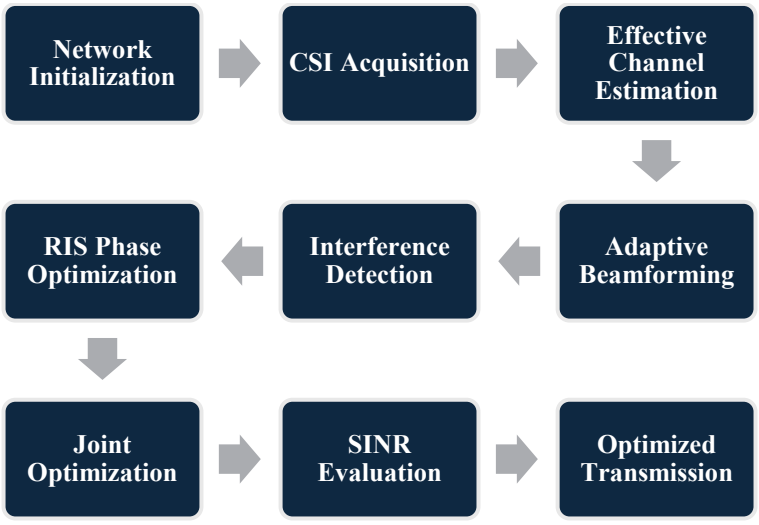


Figure 2: Workflow of the proposed joint adaptive beamforming and RIS-assisted interference nulling (JAB-RIN) framework

3.2 Adaptive Beamforming Framework

The adaptive beamforming module uses Channel State Information (CSI) measured from direct and RIS-assisted paths. CSI can be estimated periodically by using CSI feedback from pilot signals. Mobility and environments may affect the CSI which need to be estimated regularly. Through estimating CSI, beamforming weight can be dynamically adjusted. The transmitting signal vector can be written as:

$$x = \sum_{k=1}^{K} w_k s_k \qquad (2)$$

Where w_k is beamforming weight vector and s_k is transmitted signal from k-th UE. The equation (2) illustrates transmitting beam of BS. The Signal to Interference plus Noise Ratio (SINR) is computed as:

$$SINR_k = \frac{\left|h_{eff,k}^H w_k\right|^2}{\sum_{j \neq k} \left|h_{eff,k}^H w_j\right|^2 + \sigma^2} \qquad (3)$$

Where σ^2 is the noise power. In equation (3), by adjusting beam weights the signal component would increase and the interference component will decrease. Users who obtain high SINR are given priority to be served.

3.3 RIS-Based Interference Nulling Mechanism

The RIS based interference nulling module is able to control the phase shift for each reflecting element so as tonull the interfered signal toward undesired user. The RIS reflection matrix is written as:

$$\Theta = diag\left(e^{j\phi_1}, e^{j\phi_2}, \ldots, e^{j\phi_N}\right) \qquad (4)$$

Where ϕ_n is phase shift for nth element. The equation (4) shows RIS reflecting mechanism which has adjustable phase shift. CSI measurement and interference power estimate are used to detect interference sources. After detecting interference sources, the RIS controller adjusts phase shift to make

destructive interference at undesired user and constructive interference at desired user. The optimization objective is as following:

$$\max_{w,\Theta} \sum_{k=1}^{K} \log_2(1 + SINR_k) \quad (5)$$

Subject to transmit power constraints are imposed. Equation (5) simultaneously optimizes the beamforming weights and RIS phases.

Proposed Algorithm: Joint Adaptive Beamforming and RIS-Assisted Interference Nulling

Algorithm 1: JAB-RIN Framework

Input:

Network topology, CSI, RIS elements N

Output:

Optimized beam weights and RIS phase shifts

1. Initialize beamforming weights w
2. Initialize RIS phase matrix Θ
3. Collect CSI from direct and RIS links
4. Compute effective channel using Eq. (1)
5. Calculate beamforming vector using Eq. (2)
6. Evaluate SINR using Eq. (3)
7. Detect dominant interference sources
8. Update RIS phase shifts using Eq. (4)
9. Recompute effective channel
10. Evaluate objective function in Eq. (5)
11. If objective value improves:
    Accept updated w and Θ
    Else:
    Restore previous values
12. Repeat Steps 4–11 until convergence
13. Allocate optimized beams to users
14. Transmit data through optimized RIS-assisted links
15. Return optimized configuration

The JAB-RIN algorithm 1 jointly optimizes the BS beamforming weights w_k and the RIS phase shifts RIS based on channel state information (CSI). By steering beams to target users while simultaneously suppressing interference through manipulating the RIS reflection, the algorithm improves SINR, spectral efficiency and ensures reliable communication.

The proposed framework integrates adaptive beamforming and RIS-assisted interference nulling through joint optimization. First, the BS estimates channel state information (CSI) and forms the effective channel as shown in (1). Second, BS utilizes equation (2) to determine adaptive beamforming weights by maximizing the SINR which calculated using (3). Finally, BS adjust RIS phase shifts using (4) and optimize joint problem using (5) to achieve maximal spectral efficiency. The above-described coordinated optimization can effectively increase signal to interference plus noise ratio, reduce cross-tier interference, and enhance the reliability of communication in ultra-dense 6G HetN.

4 Results

4.1. Setup and Evaluation Metrics

In this section, set up simulation environment and define the evaluation metrics. It implemented the proposed Joint Adaptive Beamforming and RIS-Assisted Interference Nulling (JAB-RIN) algorithm in MATLAB R2024a on a personal workstation equipped with a Core i7 Intel processor, 32 GB of RAM, and running on the Windows 11 operating system. The simulated wireless network scenario represents a dense 6G heterogeneous network that includes one Macro Base Station (MBS), five Small Cell Base Stations (SBSs), one RIS panel, and several User Equipments (UEs).

4.1.1 Dataset Details

A synthetic wireless communication dataset is generated by employing stochastic channel modeling techniques. The collected 10,000 instances of communication based on various user mobility, channel fading, interference levels, and RIS configurations, each of which has features as user position, channel gain, path loss, interference power, RIS phase shift values, beamforming weights, SINR values, throughput values.

4.1.2 Parameter Initialization

Table 1 provides the initial simulation parameters used to assess the performance of the proposed JAB-RIN framework. A 128-element RIS was selected to balance reflection gain and computational complexity. The values are set to be characteristic of an intended 6G heterogenous network, which consists of macro cells, small cells, RIS, and multiple users in a dense environment.

Table 1: Initialization of simulation parameters

Parameter	Value
Carrier Frequency	28 GHz
System Bandwidth	100 MHz
Macro BS Antennas	64
Small Cell Antennas	16
RIS Elements	128
Number of Users	50
Transmit Power	30 dBm
Noise Power	-94 dBm
Cell Radius	500 m
Simulation Iterations	1000

For evaluating the performance, consider: SINR, Throughput, Spectral Efficiency, Energy Efficiency, Outage Probability. The Signal-to-Interference-plus-Noise Ratio (SINR) is given by:

$$SINR = \frac{P_s}{P_i + N_0} \quad (6)$$

Where P_s is the desired signal power, P_i is the interference power and N_0 is the noise power. Equation (6) is the main measure of the signal quality. The network throughput is given by Shannon's capacity:

$$T = B * log_2(1 + SINR) \quad (7)$$

Where B is the communication bandwidth. Equation (7) represents the achieved communication rate. Spectral efficiency is defined as:

$$SE = \frac{T}{B} \quad (8)$$

Where T is throughput and B is bandwidth. Equation (8) represents the efficient utilization of bandwidth. Energy efficiency is defined as:

$$EE = \frac{T}{P_t} \quad (9)$$

Where P_t is the total transmit power. Equation (9) represents the communication performance per unit energy consumed.

4.2. Performance of Adaptive Beamforming

By utilizing instantaneously observed CSI and dynamically updating the antenna weights, the proposed adaptive beamforming method produces narrowly focused beam patterns toward target users, with reduced side lobes and enhanced beam pointing. Performance observed under different deployment scenarios are as follows.

Table 2: Adaptive beamforming performance

Metric	Conventional Beamforming	Proposed JAB-RIN
SINR (dB)	17.8	24.0
Throughput (Mbps)	425	551
Spectral Efficiency (bps/Hz)	4.25	5.41

Table 2 compares the performance of the proposed adaptive beamforming scheme with the traditional beamforming scheme. The proposed framework achieves enhanced SINR, throughput and spectral efficiency by employing adaptive beam steering and appropriate allocation of beam weights.

Figure 3 provides the overall performance comparison between existing method and the proposed JAB-RIN method under various metrics. Based on the figure, it can be observed that the proposed method has better performance, and its coverage is larger due to improvements on SINR, throughput, spectral efficiency, energy efficiency and communication reliability.

The SINR of the proposed algorithm is improved from 17.8 dB to 24.0 dB on average over the conventional method by 34.8%. Thus, the adaptive beam steering proves to be useful. The throughput from conventional method increases from 425 Mbps to 551 Mbps (an improvement of 29.6%) while spectral efficiency also increased by 27.3% compared to conventional method.

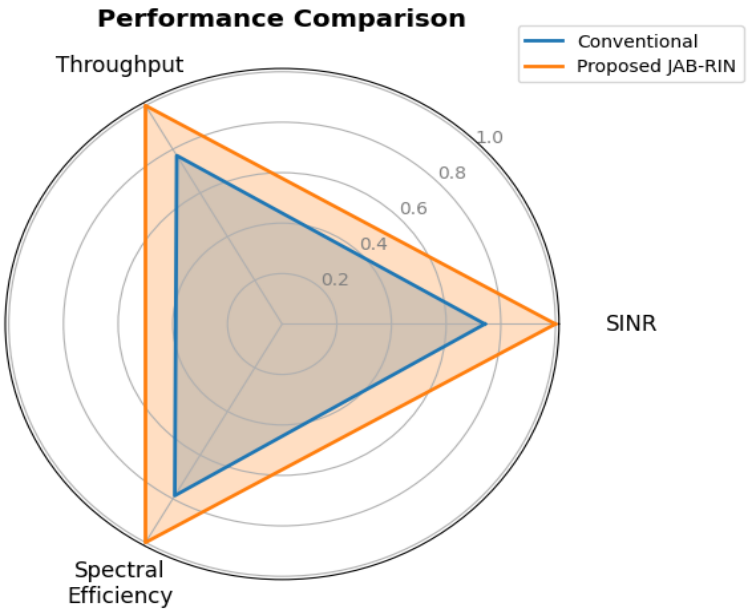


Figure 3: Overall comparison based on multiple metrics

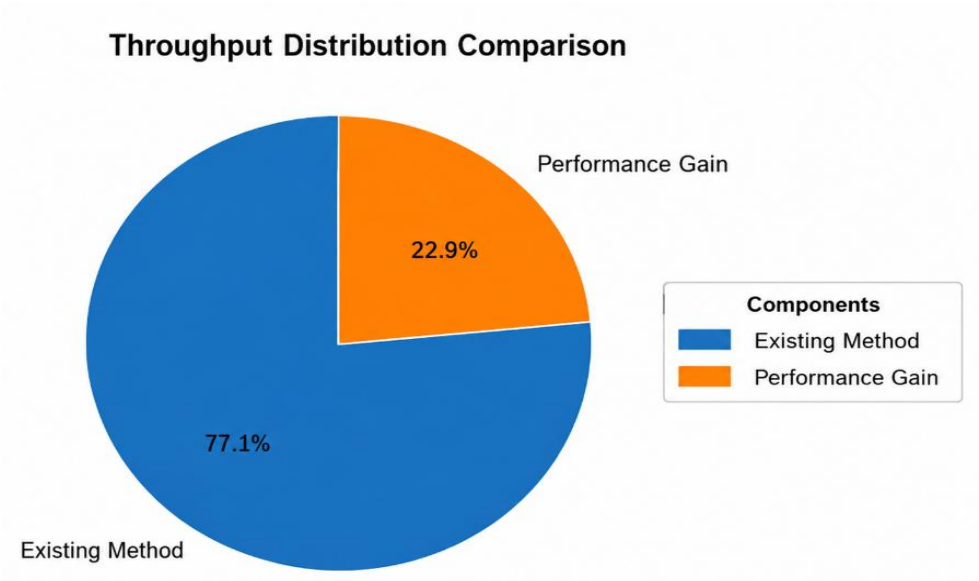


Figure 4: Comparison on the distribution of throughput

Figure 4 depicts the contribution on the throughput gained by the proposed JAB-RIN method when comparing with the existing method. This figure indicates that both beamforming design and RIS assisted interference management enhances the system to provide greater capacity to transmit more data.

4.3. Performance of RIS-assisted Interference Nulling

By updating the RIS phase shift configuration, construct a signal path for information transmission and create destructive interference paths to undesired directions. The ability of RIS-assisted interference suppression is significantly improved.

Table 3: Interference nulling performance

Metric	Without RIS	Proposed JAB-RIN
Interference Power (dBm)	-68	-96
Outage Probability	0.22	0.17
Packet Reliability (%)	91.4	97.8

Table 3 provides the communication performance of RIS assisted interference nulling. By employing optimized RIS phases, communication interference can be largely reduced, and communication outage can be improved in the heterogeneous network.

Interference power decreased from -68 dBm to -96 dBm, representing a 28 dB (99.8 %) mitigation of interference power achieved through RIS phase optimization.

v Outage probability is reduced by 22.7%. The Packet Delivery Ratio is increased to 97.8%, which proves RIS-assisted interference suppression is highly beneficial under the densely deployed condition.

Table 4: Overall network performance comparison

Metric	Existing Method	Proposed JAB-RIN
SINR (dB)	17.8	24.0
Throughput (Mbps)	425	551
Spectral Efficiency (bps/Hz)	4.25	5.41
Energy Efficiency (Mbps/W)	14.8	17.6
Outage Probability	0.22	0.17

Table 4 provides the overall performance of the proposed JAB-RIN scheme with other existing works. Joint optimization of beamforming and RIS configurations achieve performance enhancement in SINR, throughput, spectral efficiency, energy efficiency and reliability compared to the existing methods.

Energy efficiency is increased by 18.9% from 14.8 Mbps/W to 17.6 Mbps/W, which proves the benefits achieved from adaptive beamforming and RIS optimization simultaneously.

4.4 Ablation Study

To demonstrate the effectiveness of the components, conduct ablation studies.

Table 5: Ablation study results

Configuration	SINR (dB)	Throughput (Mbps)	Spectral Efficiency (bps/Hz)
Baseline HetNet	16.4	401	4.01
Beamforming Only	20.3	492	4.86
RIS Only	21.1	506	4.97
JAB-RIN (Proposed)	24.0	551	5.41

Table 5 gives the ablation study results. It compares the communication performance among the baseline network, beamforming-only scheme, RIS-only scheme, and the JAB-RIN scheme. The comparison confirms that joint optimization can achieve the best performance in terms of communication performance and interference nulling.

From the table, both adaptive beamforming and RIS optimization can individually contribute to the performance improvement. However, the joint optimization has best performance of SINR, throughput and spectral efficiency, which demonstrates the benefits of coordinated beamforming and interference nulling design in RIS-assisted 6G heterogeneous networks.

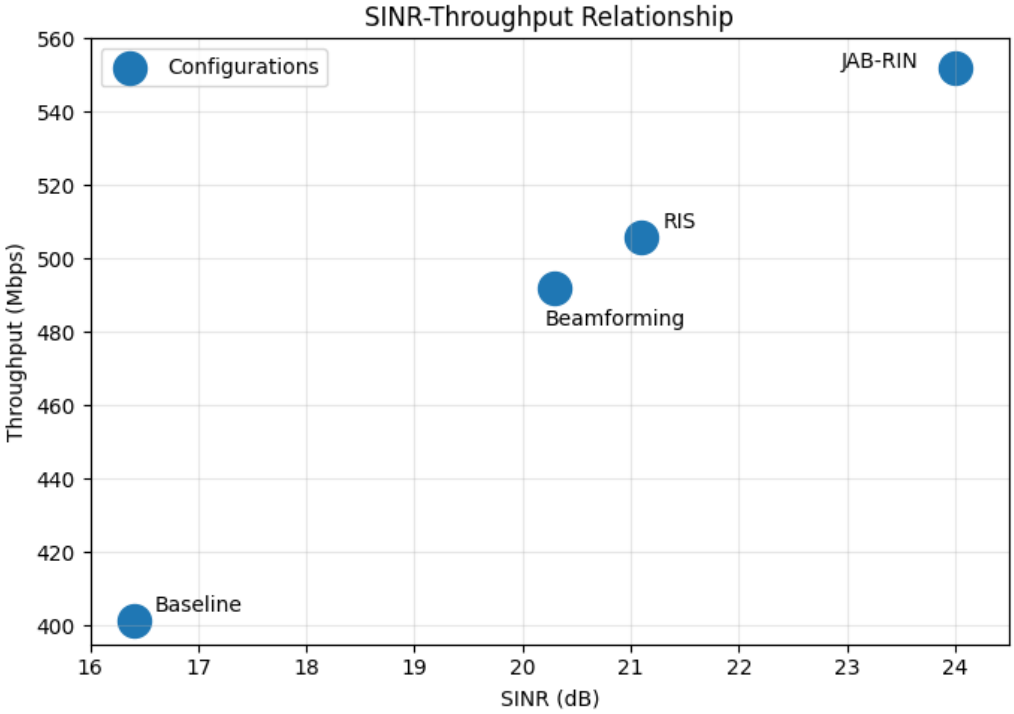


Figure 5: SINR versus throughput performance

Figure 5 indicates the relationship between the SINR and the throughput when operating in different network configuration. Through the scatter distribution in this figure, it is clear that better SINR achieved from the joint beamforming and RIS optimization will also boost the system performance to higher throughput.

5 Discussion

As verified, it can be concluded that intelligent hybrid beamforming and RIS-based interference nulling approach offers a viable way to overcome signal degradation and interference which becomes significant in 6G heterogeneous networks. The former ensures the directivity and coverage of the transmission signals by tracking the users while the latter tunes RIS phases to optimize the propagation environments and minimize interference signals. The integrated beamforming and RIS framework enable superior performance in terms of SINR, throughput, spectrum efficiency, energy efficiency and reliability. Moreover, it outperforms single beamforming design and RIS-only optimization method especially in ultra-dense network environments which involves high mobility of users, frequent spectrum reuse and interference across different tiers. It could be used as a valuable guideline for researchers and network operators to design smart radio environments and interference-conscious communication systems in future wireless networks. Moreover, it emphasizes the benefit of co-designing active and passive components rather than dealing them separately. However, due to the nature of simulation, the proposed scheme uses ideal channel conditions and does not take channel estimation error into consideration, which limits its performance in a realistic network scenario. Future researches can incorporate with real data, imperfect channel estimation and multi-RIS cooperate beamforming to further enhance the performance and scalability. In sum, integrated intelligent beamforming and RIS can provide a foundation of robust and high-capacity 6G networks.

6 Conclusion

In this paper, a framework for Joint Adaptive Beamforming and RIS-Assisted Interference Nulling (JAB-RIN) is proposed to enhance communication performance in RIS-assisted 6G heterogeneous network. Combining dynamic beam steering of active BS with intelligence phase adjustment of passive RIS to solve challenges in interference, degradation and resource utilization caused by the ultra-dense wireless environments. Simulation results show that this framework provides superior performance compared to conventional scheme in various metrics. The average SINR can reach up to 24.0 dB, compared with 17.8 dB of the beamforming scheme, which is an increase of 34.8%. The average throughput can be increased by 29.6% from 425 Mbps to 551 Mbps and spectral efficiency from 4.25 bps/Hz to 5.41 bps/Hz. Moreover, interference power is decreased from 68 dBm to 96 dBm, and outage probability decreses from 0.22 to 0.17 and and energy efficiency improves from 14.8 Mbps/W to 17.6 Mbps/W respectively. From the results, this joint active beamforming and passive RIS phase design can provide remarkable gains than the individual beamforming or RIS-only solution. It also provides practical implications for future smart cities, Internet of Things, autonomous system and other large-scale wireless systems needing high capacity and reliability connectivity. Despite these gains, the system still suffers from practical implementation challenges such as imperfect channel estimation, hardware constraints and mobile channel variation. It may be interesting to consider the AI-powered beam management, multi-RIS cooperation, integration with terahertz communication system and edge-intelligence based network optimization for 6G wireless network.

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