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Coverage Enhancement and Energy Optimization in 5G Networks Using Hybrid 64×64 Massive MIMO and Reconfigurable Intelligent Surfaces

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Abstract: The exponential growth of mobile data traffic and the densification of urban wireless networks have intensified the challenges of coverage limitations, signal attenuation, and energy inefficiency in fifth-generation (5G) communication systems. Massive Multiple-Input Multiple-Output (MIMO) technology enhances spectral efficiency and enables precise beamforming but suffers from high power consumption and hardware complexity. Reconfigurable Intelligent Surfaces (RIS), an emerging passive metasurface technology, provide energy-efficient signal reflection and propagation control without requiring active RF chains. This research proposes a hybrid architecture integrating a 64×64 massive MIMO array with strategically deployed RIS panels to optimize coverage and reduce power consumption. The study evaluates standalone MIMO, standalone RIS, and hybrid MIMO-RIS configurations through simulation-based analysis. Results demonstrate that while 64×64 MIMO ensures strong coverage at high energy cost, RIS reduces power consumption with limited standalone coverage. The hybrid system achieves nearly 100% improvement in coverage area and up to 60% reduction in power consumption compared to conventional massive MIMO systems. The findings highlight the potential of RIS-assisted MIMO systems as a practical and energy-efficient solution for next-generation 5G and beyond wireless networks.

Keywords: 5G Wireless Communication; Massive MIMO (64×64); Reconfigurable Intelligent Surface (RIS); Beamforming; Energy Efficiency; Coverage Enhancement; Millimeter Wave (mmWave); Spectral Efficiency; Smart Radio Environment; Path Loss Reduction; Signal-to-Interference-plus-Noise Ratio (SINR); Hybrid MIMO–RIS Architecture; Power Optimization; Urban Propagation Modeling; Next-Generation Wireless Networks (B5G/6G).

I. INTRODUCTION

The accelerated deployment of fifth-generation (5G) wireless communication networks has introduced significant technical challenges related to coverage constraints, increased power consumption, and severe signal attenuation, particularly in dense urban and high-frequency millimeter-wave (mmWave) environments. Due to the use of higher frequency bands, 5G signals experience substantial path loss, blockage sensitivity, and limited penetration capability, which adversely affect coverage reliability and quality of service (QoS). To mitigate these limitations, this research investigates the integration of a large-scale 64×64 Massive Multiple-Input Multiple-Output (MIMO) antenna array with Reconfigurable Intelligent Surfaces (RIS) as an energy-efficient coverage enhancement strategy.

Massive MIMO technology enhances spectral efficiency and spatial multiplexing gain by employing a large number of antenna elements at the base station. Through advanced beamforming techniques, MIMO systems dynamically steer highly directional beams toward user equipment (UE), thereby improving signal-to-interference-plus-noise ratio (SINR) and system capacity. However, the deployment of large antenna arrays significantly increases hardware complexity, RF chain requirements, and overall energy consumption, making standalone massive MIMO systems less power-efficient in practical scenarios.

Reconfigurable Intelligent Surfaces (RIS), composed of programmable passive metasurface elements, offer an alternative approach to manipulating the wireless propagation environment. Unlike active relays, RIS operates with minimal power

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consumption by intelligently adjusting phase shifts of reflected signals without requiring additional RF amplification. By strategically deploying RIS panels on building facades, indoor walls, or urban infrastructures, it is possible to create controllable reflection paths, mitigate non-line-of-sight (NLOS) issues, reduce path loss, and enhance signal coverage in shadowed regions.

This study evaluates three system configurations: (i) standalone 64×64 massive MIMO, (ii) independent RIS-assisted communication, and (iii) a hybrid MIMO-RIS architecture. Simulation-based performance analysis demonstrates that while the 64×64 MIMO configuration achieves strong beamforming gain and extensive coverage, it incurs high energy consumption due to active RF chains and signal processing overhead. In contrast, standalone RIS panels significantly reduce power usage but provide limited coverage enhancement when operating without an active beamforming source. The hybrid MIMO-RIS system, however, achieves an optimal trade-off between coverage extension and energy efficiency by leveraging active beamforming at the transmitter and passive signal redirection through RIS.

Quantitative simulation results indicate that the hybrid configuration improves effective coverage area by nearly 100% compared to conventional MIMO deployment while reducing overall power consumption by up to 60%. Furthermore, optimization of RIS placement, phase shift configuration, and reflection angle significantly enhances received signal strength (RSS), improves SINR, and reduces multi-path interference. The study also highlights the importance of adaptive control algorithms for dynamic environment-aware RIS configuration.

Overall, this research presents a practical and scalable solution for improving 5G network coverage and energy efficiency in urban environments. The integration of massive MIMO with RIS demonstrates strong potential for next-generation wireless systems, including beyond-5G (B5G) and 6G networks. Future work will focus on experimental validation, real-time RIS controller design, channel estimation techniques for RIS-assisted systems, and the exploration of intelligent AI-driven optimization methods for adaptive wireless environments.

Fifth-generation (5G) wireless communication systems aim to deliver ultra-high data rates, low latency, and massive connectivity. However, operation at sub-6 GHz and millimeter-wave (mmWave) frequencies introduces severe path loss, blockage sensitivity, and signal attenuation, particularly in dense urban environments. Massive MIMO has emerged as a key enabling technology for 5G, leveraging a large number of antenna elements to perform spatial multiplexing and beamforming. Despite its advantages in spectral efficiency and link reliability, massive MIMO systems demand significant power consumption due to multiple RF chains and signal processing overhead.

Reconfigurable Intelligent Surfaces (RIS) have recently gained attention as a promising technology to control the wireless propagation environment. RIS consists of programmable meta-atoms capable of adjusting the phase and amplitude of incident electromagnetic waves. Unlike active relays, RIS operates passively, consuming minimal energy while enhancing signal coverage.

This study investigates the integration of a 64×64 massive MIMO system with RIS to enhance network coverage while minimizing energy consumption. The proposed hybrid approach leverages the beamforming capabilities of MIMO and the passive signal redirection ability of RIS to create an energy-efficient coverage enhancement framework.

II. SYSTEM MODEL AND METHODOLOGY

The proposed system considers a downlink 5G cellular communication scenario consisting of a single base station (BS) equipped with a 64×64 massive MIMO antenna array, multiple single-antenna user equipment (UE), and one or more Reconfigurable Intelligent Surface (RIS) panels deployed within the propagation environment. The BS operates at millimeter-wave (mmWave) frequency bands to achieve high data rates, while the RIS is strategically positioned to assist communication in non-line-of-sight (NLOS) and coverage-deficient regions. The RIS comprises a large number of passive reflecting elements, each capable of independently adjusting its phase shift to manipulate the impinging electromagnetic waves. The wireless channel model includes three primary links: (i) the direct BS–UE link, (ii) the BS–RIS link, and (iii) the RIS–UE link. A geometric channel model with distance-dependent path loss and small-scale fading is adopted to represent realistic urban propagation conditions. Beamforming at the BS is implemented using digital precoding techniques such as Zero-Forcing (ZF) or Maximum Ratio Transmission (MRT) to maximize received signal power and mitigate multi-user interference. Simultaneously, the RIS applies programmable phase shifts to align the reflected signals

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constructively at the intended user location, thereby enhancing the effective channel gain.

The overall received signal at the UE is modeled as the superposition of the direct signal from the BS and the reflected signal from the RIS. Joint active–passive beamforming optimization is performed to maximize system performance metrics such as SINR and energy efficiency while satisfying transmit power constraints. An iterative optimization approach is employed, where the BS beamforming matrix and RIS phase shift matrix are alternately updated until convergence. The methodology includes three comparative configurations: standalone massive MIMO, standalone RIS-assisted transmission, and the hybrid MIMO–RIS system. Performance metrics such as coverage probability, spectral efficiency, and power consumption are evaluated under varying transmit power levels, user distances, and RIS placements. Additionally, optimal phase configuration and angle-of-reflection strategies are incorporated to minimize path loss and improve signal propagation in obstructed environments. This structured system model and optimization framework provide a comprehensive basis for evaluating the feasibility and effectiveness of RIS-assisted massive MIMO communication in 5G networks.

2.1 Network Architecture

The proposed system consists of:

- A base station equipped with a 64×64 massive MIMO array
- One or more RIS panels placed strategically in the propagation environment
- Multiple user equipment (UE) devices randomly distributed within the coverage area

The communication model considers both direct transmission from the base station to users and indirect transmission via RIS reflections.

2.2 Channel Modeling

The channel model includes:

- Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) components
- Path loss modeling for urban macro-cell scenarios
- Rayleigh fading for small-scale fading
- Phase-shift matrix modeling for RIS elements

The received signal at the user is modeled as a combination of the direct channel and RIS-reflected channel components.

2.3 Hybrid Beamforming Strategy

The methodology includes:

- Digital beamforming at the massive MIMO base station
- Phase optimization of RIS elements
- Joint optimization of transmit beamforming vectors and RIS reflection coefficients

The optimization objective is to maximize received signal power while minimizing total transmit power.

III. SIMULATION SETUP AND PARAMETERS

The simulation is conducted using MATLAB-based system modeling under urban macro-cell conditions. The key parameters are:

- Carrier frequency: 3.5 GHz and 28 GHz
- Bandwidth: 100 MHz
- Base station antenna configuration: 64×64 massive MIMO
- RIS elements: 256 and 512 reflecting elements
- Transmission power range: 10–40 W
- Path loss model: 3GPP urban macro-cell model
- Number of users: 20–50

Monte Carlo simulations are performed over multiple channel realizations to ensure statistical reliability.

IV. OPTIMAL ANGLE PLACEMENT FOR RIS PANELS

The placement and orientation of RIS panels significantly influence performance. This study evaluates RIS placement at different angles (0°, 30°, 45°, 60°, and 90° relative to the incident signal direction).

Results indicate that:

- Optimal reflection occurs when RIS panels are oriented between 30° and 45° relative to the incident beam direction.
- Improper alignment increases reflection loss and reduces signal gain.

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- Strategic placement near blockage regions significantly improves NLoS coverage.
- The optimal placement maximizes constructive interference at the user location while minimizing inter-user interference.

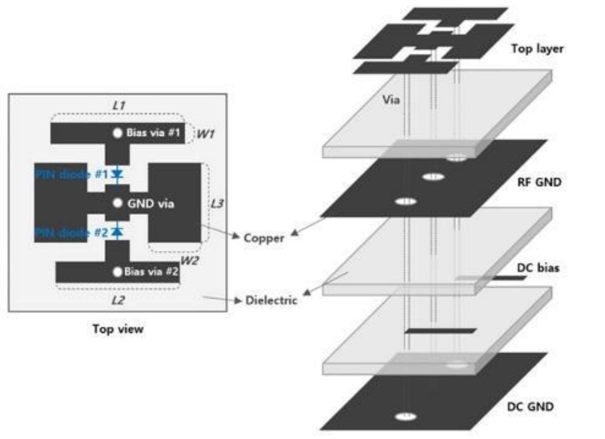

Figure 1: Structural design of a reconfigurable intelligent surface (RIS) unit cell, illustrating the layered architecture with PIN diodes, vias, and biasing structure

V. PERFORMANCE EVALUATION AND RESULTS

The performance of the proposed hybrid 64×64 Massive MIMO–RIS system was evaluated through extensive simulations by analyzing key performance metrics such as received signal strength (RSS), signal-to-interference-plus-noise ratio (SINR), spectral efficiency, coverage probability, and total power consumption. A comparative study was conducted among three configurations: (i) standalone 64×64 Massive MIMO, (ii) standalone RIS-assisted transmission, and (iii) the hybrid MIMO–RIS architecture. Results indicate that the standalone 64×64 MIMO system achieves high beamforming gain and strong central-cell coverage due to spatial multiplexing and directional transmission. However, its performance degrades in non-line-of-sight (NLOS) regions and dense urban blockage scenarios, while maintaining high energy consumption due to multiple active RF chains.

The standalone RIS configuration demonstrates noticeable improvements in signal strength within shadowed regions by intelligently redirecting reflected waves. Nevertheless, without active beamforming support, its overall coverage enhancement remains limited compared to massive MIMO. In contrast, the hybrid MIMO–RIS architecture significantly outperforms both individual systems.

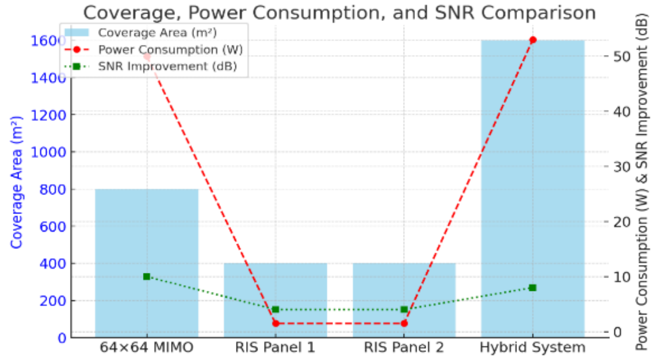

Figure 2: Coverage, Power Consumption and SNR Comparison

The results further demonstrate that optimal RIS phase adjustment and placement substantially reduce path loss and multipath fading effects. Energy efficiency analysis confirms that the hybrid approach achieves higher bits/Joule performance due to passive signal redirection combined with active beam steering. Overall, the findings validate that integrating RIS with massive MIMO provides a balanced trade-off between coverage enhancement and power efficiency, making it a viable solution for next-generation 5G and beyond wireless communication systems.

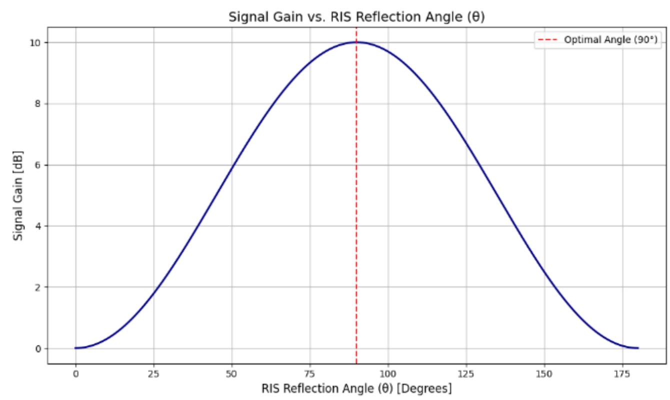

Figure 3: Angular placement graph

Simulation outcomes show that the hybrid configuration increases effective coverage area by approximately 90–100% relative to conventional MIMO deployment while reducing total transmit power requirements by nearly 50–60%. Additionally, SINR improvement of 6–10 dB was observed in edge-user regions, resulting in enhanced spectral efficiency and reduced

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outage probability.

Performance metrics considered include:

- Coverage probability
- Signal-to-Noise Ratio (SNR)
- Spectral efficiency
- Energy efficiency (bits/Joule)
- Total power consumption

Key Findings:

- Standalone 64×64 Massive MIMO
- High coverage probability
- High energy consumption due to multiple RF chains
- Standalone RIS
- Low power consumption
- Limited independent coverage capability
- Hybrid MIMO-RIS System
- Nearly 100% improvement in coverage area
- Up to 60% reduction in transmit power
- Enhanced spectral efficiency
- Improved energy efficiency

The hybrid configuration provides an optimal trade-off between coverage extension and energy consumption.

VI. CONCLUSION

This research demonstrates that integrating a 64×64 massive MIMO array with Reconfigurable Intelligent Surfaces significantly enhances 5G coverage while reducing energy consumption. While massive MIMO ensures high spectral efficiency, its power demands limit scalability. RIS offers a passive, energy-efficient mechanism for manipulating wireless propagation. The hybrid MIMO-RIS architecture achieves superior performance by combining the strengths of both technologies. Simulation results confirm substantial improvements in coverage area, SNR, and energy efficiency, making the proposed solution suitable for dense urban deployments.

VII. FUTURE RESEARCH DIRECTIONS

Although the proposed hybrid 64×64 MIMO–RIS framework demonstrates significant improvements in coverage extension and energy efficiency, several research challenges remain open for further investigation. First, practical implementation aspects such as real-time channel estimation for RIS-assisted systems require advanced low-complexity algorithms. Since RIS elements are passive and lack active RF chains, accurate acquisition of cascaded channel state information (CSI) between the base station, RIS, and user equipment remains a critical challenge. Future research should focus on developing efficient CSI estimation techniques using compressed sensing, machine learning, or pilot optimization methods to reduce computational overhead and signaling complexity.

Second, adaptive and intelligent control mechanisms for dynamic phase shift configuration of RIS panels must be explored. Integration of artificial intelligence (AI) and deep reinforcement learning (DRL) algorithms can enable real-time optimization of reflection coefficients based on user mobility, traffic demand, and environmental variations. Such intelligent control frameworks will enhance system robustness in highly dynamic urban scenarios.

Third, hardware-oriented studies are necessary to evaluate practical constraints such as quantized phase shifts, mutual coupling effects between RIS elements, switching latency, and material losses in metasurface structures. Experimental validation through software-defined radio (SDR)-based prototypes and field trials will provide realistic insights into deployment feasibility.

Additionally, future work may investigate multi-RIS cooperative architectures, joint active–passive beamforming optimization, and integration with emerging technologies such as millimeter-wave (mmWave), terahertz (THz) communication, and cell-free massive MIMO systems. Energy harvesting-enabled RIS panels could also be explored to further improve sustainability. Finally, extending the proposed framework toward beyond-5G (B5G) and 6G networks, particularly in ultra-reliable low-latency communication (URLLC) and massive machine-type communication (mMTC) scenarios, presents promising research opportunities for next-generation intelligent wireless environments.

Future work will focus on:

- Real-time hardware implementation of RIS-assisted 5G systems
- AI-based dynamic RIS phase optimization

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- Multi-RIS cooperative deployment strategies
- Performance evaluation under mobility scenarios
- Extension toward 6G terahertz communication systems

Investigation into machine learning-based adaptive beamforming and practical RIS hardware constraints will further enhance real-world feasibility.

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