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Research on Channel Modeling and Performance Optimization of RIS-assisted Massive MIMO Systems

Xiaoding Zhou[1,a,*]

[1]*International School Beijing University of Posts and Telecommunications, Beijing, 100080, China*
a. 170665060@bupt.edu.cn
**corresponding author*

Abstract: With the rapid development of wireless communication technologies, Massive MIMO (Multiple Input Multiple Output) technology has attracted considerable attention because of its potential to enhance system capacity and spectrum efficiency. However, challenges such as signal coverage in non-line-of-sight (NLOS) scenarios and high-frequency channel fading limit its application in complex environments. This study focuses on integrating Reconfigurable Intelligent Surface (RIS) technology with Massive MIMO systems to enhance performance in such scenarios. The research constructs a channel model for a RIS-assisted Massive MIMO system and investigates the impact of RIS element configuration on system capacity and energy efficiency. Numerical simulations are conducted to evaluate the effectiveness of RIS in improving overall system performance. Convex optimization and deep learning algorithms are utilized to optimize RIS reflection matrices, adjusting the phase and amplitude of reflection elements to maximize channel gain. The results demonstrate that RIS significantly enhances system capacity, spectrum efficiency, and energy savings in both line-of-sight (LOS) and NLOS environments, providing practical insights for the deployment of RIS in future 6G networks.

Keywords: Massive, MIMO RIS, channel model, simulations

1. Introduction

With the rapid development of wireless communication technology, Massive MIMO (Multiple Input Multiple Output) technology has become a key research area due to its potential to significantly enhance system capacity and spectrum efficiency[1,2]. By increasing the number of antennas at base stations and user devices, Massive MIMO supports simultaneous communication for a large number of users. However, current research mainly focuses on ideal environments and has not addressed challenges such as signal coverage in non-line-of-sight (NLOS) scenarios[2,3]. While high-frequency bands like millimeter-wave and terahertz offer larger bandwidths, they also introduce issues like channel fading and propagation loss, limiting the practical application of Massive MIMO in complex environments[3]. Furthermore, the large quantity of antennas in such systems can lower the accuracy of channel estimation[4].

To address these challenges, this paper focuses on introducing Reconfigurable Intelligent Surface (RIS) technology to optimize Massive MIMO performance in complex scenarios. This paper aims to establish a channel model for a Massive MIMO system integrated with RIS, verify the effectiveness of RIS in improving system performance through numerical simulations, analyze the impact of RIS

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element configuration on system capacity and energy efficiency, and explore how to utilize RIS to optimize the performance of Massive MIMO systems.

By enhancing performance in complex environments, RIS technology is expected to provide new solutions for future 6G networks, offering theoretical guidance for RIS deployment and practical insights for addressing challenges in high-frequency communication.

2. RIS-assisted Massive MIMO System Channel Model

2.1. RIS-Integrated Massive MIMO System:

In existing research, the integration of RIS (Reconfigurable Intelligent Surface) technology and Massive MIMO offers a novel solution to enhancing communication performance in complex environments [5]. By incorporating RIS into Massive MIMO systems, the system can effectively improve channel capacity and energy efficiency in non-line-of-sight (NLOS) transmission scenarios[6,7].

2.1.1. Channel Modeling

By introducing RIS reflective elements into traditional Massive MIMO channel models, the signal propagation paths can be reconstructed. RIS-assisted channels can create multipath environments, improving signal reception quality. However, due to the high-dimensional phase control mechanism of RIS, channel modeling becomes more complex, particularly in multi-user and multi-antenna scenarios. Efficiently estimating RIS-assisted channels remains a challenge.

2.1.2. System Performance Optimization

Most current research focuses on how RIS's beamforming capabilities can enhance system performance. Some studies put forward deep - learning - based optimization algorithms to dynamically adjust the phase control of RIS, maximizing the system capacity or energy efficiency.

2.2. System Model Construction:

2.2.1. Channel Transmission Mechanism Between Base Station, RIS, and Users

In an RIS-assisted Massive MIMO system, the signal can reach users via two paths: directly from the base station to the user (direct link), or via RIS reflection (indirect link[8]. Without RIS, the direct link between the base station and the user can be described using traditional Rayleigh fading or Rician fading models[9]. The Rayleigh model is suitable for non-line-of-sight (NLOS) environments, while the Rician model is suitable for line-of-sight (LOS) environments, where both direct and scattered signals jointly determine communication quality.

2.2.2. Reflection Channel Model Between Base Station, RIS, and User

When RIS is introduced, the signal undergoes an additional reflection process between the base station and the user. The signal first propagates from the base station to the RIS, and then the RIS adjusts the signal's phase and amplitude through its array of reflection elements before reflecting the signal to the user[8,10]. The reflection matrix of RIS controls the phase adjustment for each reflection element, specifically denoted as $\Theta=\mathrm{diag}(e^{j\theta 1},e^{j\theta 2},\ldots,e^{j\theta N})$, where θ_i represents the phase of the i-th reflection element.

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2.3. Derivation of the Overall Channel Model

2.3.1. Total Channel Model

Based on the constructed channels, the system's total channel can be regarded as the sum of the direct and indirect links, expressed as follows.

$$\mathrm{H_{total}} = \mathrm{H_{BU}} + \mathrm{H_{BR}}\Theta\mathrm{H_{RU}} \quad (1)$$

- $\mathrm{H_{total}}$ represents the total channel matrix between the base station (B) and the user (U),
- $\mathrm{H_{BU}}$ represents the direct channel matrix between the base station (B) and the user (U),
- $\mathrm{H_{BR}}$ represents the channel matrix between the base station (B) and RIS (R),
- $\mathrm{H_{RU}}$ represents the channel matrix between RIS (R) and the user (U),
- Θ represents the RIS reflection coefficient matrix, containing the phase and amplitude control information for each RIS element. The diagonal elements of this matrix denote the reflection properties of each RIS element.

This model integrates the two signal propagation paths. By adjusting the phase shift in Θ, RIS optimizes the transmission path and signal quality, thus enhancing system performance indicators such as channel capacity and signal strength[6,7].

2.3.2. Model Analysis

The performance of the RIS-assisted channel model varies in different communication scenarios. In line-of-sight transmission, RIS can effectively enhance the direct signal by optimizing the signal phase. In non-line-of-sight scenarios, RIS can compensate for signal fading by constructing reflection paths. Further analysis shows that the number of RIS elements, antenna quantity, and their distribution directly affect channel gain, signal fading, and transmission delay[11]. For instance, increasing the number of RIS elements can improve channel gain, but it also increases system complexity. Adding more antennas helps alleviate multipath effects, thereby enhancing communication reliability.

2.3.3. RIS Reflection Matrix Optimization

(1) Optimization Objectives:

To maximize system capacity and transmission gain, the RIS reflection matrix Θ must be optimized. Specifically, this involves controlling the phase of each reflection element to achieve favorable signal superposition at the receiver, thereby enhancing communication quality. The optimization goals are typically to maximize channel capacity, minimize transmission errors, or improve energy efficiency[12].

(2) Optimization Methods:

Convex Optimization: A convex optimization model for system capacity or energy efficiency can be constructed to solve for the optimal reflection matrix configuration. Convex optimization methods can effectively find the global optimum solution when system parameters are known.

Greedy Algorithm: In high-dimensional, multi-variable systems, greedy algorithms can iteratively optimize the phase of each reflection element, gradually approaching the optimal solution. While this method may not guarantee a global optimum, it has the advantage of lower computational complexity.

Deep Learning: Neural networks can be trained to learn the optimal phase configuration under complex channel conditions, enabling real-time optimization of the RIS reflection matrix. This method is especially suitable for large-scale antenna and multi-user scenarios, significantly reducing computational overhead while ensuring performance.

3. System Performance Analysis and Optimization

3.1. System Capacity Analysis

3.1.1. Derivation of the System Capacity Formula

According to Shannon's capacity theorem, the channel capacity CCC of the system can be expressed as follows.

$$C=B\log_2\left(1+\frac{P}{N_0}\|H_{total}\|^2\right) \tag{2}$$

B is the system bandwidth, P is the transmit power, N_0 is the noise power, H_{total} is the total channel gain matrix.

After introducing RIS, the total channel gain includes contributions from both the direct path and the indirect path through RIS[4,8].

3.1.2. Relationship Between Capacity and System Parameters

By deriving the relationship between channel capacity and the number of antennas, users, and RIS elements, we can observe the following.

Number of Antennas: Increasing the number of base station antennas can enhance system capacity through more precise beamforming, especially in multi-user scenarios.

Number of Users: As the number of users increases, competition for system resources intensifies, slowing the growth rate of system capacity. However, the introduction of RIS can mitigate this effect by creating more efficient reflection paths to increase capacity.

Number of RIS Elements: Increasing the number of RIS reflection elements significantly boosts channel gain. The more RIS elements there are, the more precisely the signal phase can be controlled, resulting in an increase in channel capacity.

Through the synergy of antennas and RIS, the system can more effectively enhance channel capacity in large-scale antenna arrays, maximizing spectrum efficiency[7,9].

3.2. Energy Efficiency Optimization

3.2.1. Passive Reflection Characteristics of RIS

The passive reflection characteristics of RIS mean that it does not require active signal transmission, greatly reducing power consumption[8,11]. Unlike traditional relay devices, RIS enhances signal transmission paths by adjusting signal reflection phases, thereby reducing the need for high transmission power. This makes RIS particularly suitable for energy-constrained communication scenarios[7].

3.2.2. Energy Efficiency Analysis and Optimization:

Energy efficiency (EE) is typically defined as the ratio of system capacity to power consumption:

$$EE=\frac{C}{P_{total}} \tag{3}$$

With the introduction of RIS, the base station's transmission power can be significantly reduced while maintaining high channel capacity, resulting in an overall improvement in energy efficiency[13,14].

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3.3. Channel Estimation and Feedback Mechanism Design

3.3.1. Low-Complexity Channel Estimation Algorithms

In RIS - assisted Massive MIMO systems, channel estimation becomes considerably more complex, and traditional channel estimation methods are less applicable in such systems. Therefore, designing low-complexity channel estimation algorithms becomes particularly important.

One common low-complexity channel estimation method is based on compressed sensing algorithms. These algorithms exploit channel sparsity, significantly reducing the training overhead and feedback required for channel estimation[14]. Additionally, deep learning-based channel estimation methods have also gained attention. Deep neural networks can be trained to learn channel features and achieve rapid channel estimation.

3.3.2. Feedback Mechanism Design

The design of the channel feedback mechanism between RIS and Massive MIMO is key to system optimization[7]. In the system, the base station needs to dynamically adjust the RIS reflection matrix Θ based on channel state information (CSI) to achieve optimal channel configuration. However, the introduction of RIS increases both the dimensions and the frequency of CSI feedback. To address this, a partial feedback mechanism can be adopted, where only the most impactful channel information is fed back, reducing overhead.

4. Simulation and Result Analysis

4.1. Simulation Scenario Setup

4.1.1. Direct Link between Base Station and User

Without RIS, the signal is transmitted directly from the base station to the user through a multiple-input multiple-output system. In this case, the channel model adopts the typical Rayleigh fading channel to represent the transmission characteristics of wireless signals in a non - line - of - sight (NLOS) environment, where signals experience multiple reflections and scatterings.

4.1.2. Reflection Link among Base Station, RIS, and User

When RIS is introduced, the RIS surface consists of numerous controllable reflection elements that can adjust each element's phase to redirect the signal, thereby optimizing the propagation path. In complex environments, RIS enhances signal quality in NLOS conditions by increasing channel capacity and reducing the negative impact of multipath effects on communication quality.

4.1.3. Energy Efficiency (EE) Optimization for Massive MIMO System with RIS

Energy efficiency, defined as the ratio of channel capacity to transmission power, is a critical performance metric in energy-constrained communication environments. By optimizing the phase configuration of RIS, the system can maximize channel capacity at lower transmission power levels, thereby significantly enhancing energy efficiency.

4.2. Performance Metrics

4.2.1. Channel Capacity

Channel capacity is the core metric for measuring system performance. The simulation will compare the difference in channel capacity with and without RIS under various configurations (varying numbers of users, antennas, and RIS elements), demonstrating the capacity gain brought by RIS through optimizing channel conditions.

4.2.2. Spectrum Efficiency

The simulation will analyze the improvement in spectrum efficiency in RIS-assisted systems at different frequencies, particularly in millimeter-wave communications. Due to severe signal attenuation in the millimeter-wave band, RIS can significantly enhance signal transmission, improving spectrum utilization.

4.2.3. Coverage Area

In NLOS conditions, RIS intelligently controls signal reflections to extend the signal propagation range. The simulation will evaluate how RIS improves signal coverage in various scenarios, particularly in large-scale networks.

4.2.4. Energy Efficiency Analysis

Energy efficiency is a key metric in future green communications. The simulation will compare the energy efficiency of systems under different transmission power conditions, verifying RIS's advantage in reducing transmission power requirements and improving energy efficiency, showcasing RIS-assisted systems' energy-saving effects.

4.3. Verification of Optimization Algorithm Effectiveness

4.3.1. Effectiveness of Optimizing the Reflection Matrix

The simulation will verify the performance improvements bring about by optimizing the RIS reflection matrix. Using convex optimization or deep learning algorithms to optimize the phase and amplitude of the reflection elements, the simulation will demonstrate the impact of these methods on enhancing channel gain, system capacity, and spectrum efficiency. It will focus on evaluating the actual performance differences between various optimization algorithms, proving their applicability and advantages in complex scenarios.

4.3.2. Simulation Analysis

Channel Gain:

Channel Gain Comparison: Calculate and visualize the channel gain with and without RIS, using charts to display the variations in signal strength under different antenna configurations.

Channel Capacity Comparison: Using Shannon's capacity theorem, compute the system's channel capacity in both cases, with and without RIS. According to figure 1 and 2, RIS has a good effect on improving the performance of communication systems.

Plotting: The code visualizes the channel gain matrices with and without RIS for comparison. The color intensity represents the gain, and it provides a clear visual comparison of the channel's behavior in both cases.

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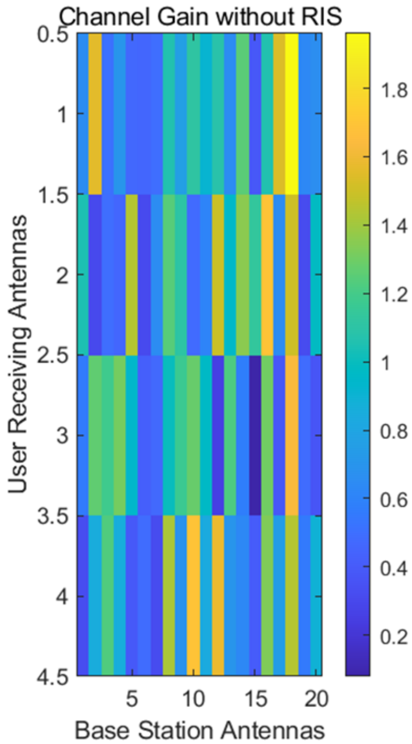

Figure 1: Channel Gain Without RIS

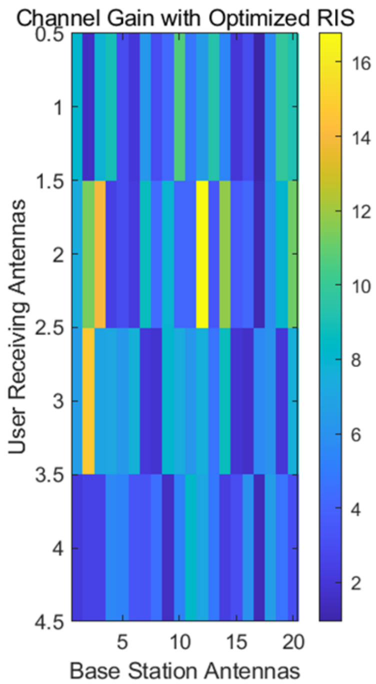

Figure 2: Channel Gain With Optimized RIS

System Energy Efficiency Optimization:

Energy Efficiency Curve: The simulation produces an energy efficiency curve that demonstrates system energy efficiency (defined as channel capacity per unit of power) across different transmission

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power levels. By optimizing the RIS phase configuration, the system achieves maximum channel capacity at lower transmission power, resulting in a significant enhancement in energy efficiency.

Optimal Energy Efficiency Point: The code outputs the transmission power level at which the system's energy efficiency reaches its maximum. This result provides a valuable reference for selecting optimal power levels during system design.

In this simulation, RIS elements optimize the transmission path by reflecting signals, thereby effectively enhancing the direct channel between the base station and the user. The simulation employs a random search optimization method to find the optimal RIS phase configuration that maximizes channel capacity at a given power level.

5. Conclusion

This paper delves into the integration of Reconfigurable Intelligent Surface (RIS) technology and Massive MIMO systems, with an emphasis on optimizing system performance in complex communication environments. Moreover, this paper puts forward several key innovations. This paper presents several key innovations. First, an optimized channel model incorporating RIS is proposed to address the issue of channel instability in traditional MIMO systems under complex environmental conditions. Second, a low-complexity channel estimation and feedback mechanism is introduced, specifically tailored for RIS-assisted environments, which reduces the overhead associated with channel estimation.

While the combination of RIS and Massive MIMO presents promising advancements in improving system capacity, spectrum efficiency, and energy efficiency, several technical challenges remain for future research and development.

One major challenge is efficient channel estimation. Given the passive nature of RIS and the high dimensionality of the system, accurately estimating the channel becomes significantly more complex. Future research must prioritize the design of low-complexity, high-precision channel estimation algorithms that maintain communication performance while minimizing computational load. This challenge becomes particularly pronounced in large-scale antenna systems, where dynamic environments require novel methods to handle rapid channel variations.

Another challenge lies in real-time signal control in dynamic environments. Wireless communication systems of the future will operate in more complex and constantly changing conditions. When integrating RIS with Massive MIMO, real-time control of signal reflections is necessary for optimal performance. Current RIS control methods, which are often based on static configurations, struggle to adapt to these real-time changes. Therefore, developing fast-response algorithms for dynamic adjustments in mobile communication environments will be a key area of future research.

In conclusion, RIS technology holds great potential for enhancing the performance of future wireless communication systems, particularly when combined with Massive MIMO. However, challenges related to channel estimation, dynamic control, and integration with machine learning must be addressed for the full potential of RIS to be realized. The findings and models presented in this paper provide a foundation for addressing these challenges and advancing the application of RIS in future communication networks.

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