Recent Advancements in Rate-Splitting Multiple Access with a Focus on Antenna Technologies: A Survey

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***Abstract*—Rate-Splitting Multiple Access (RSMA) has emerged as a promising and versatile multiple access scheme, particularly in multi-antenna systems, where it effectively manages multi-user interference. The performance of RSMA is intrinsically linked to the underlying antenna technology. This survey provides a comprehensive overview of how RSMA is integrated with cutting-edge antenna paradigms, including movable antennas (MAs), active intelligent reflecting surfaces (IRS), and extremely large-scale antenna arrays (ELAAs). We explore the challenges and performance gains achieved through the co-design of RSMA and these advanced antenna systems. The analysis also covers RSMA's application in novel antenna-driven paradigms like joint radar and communications (JRC) and cognitive radio (CR) networks. The collective findings demonstrate that RSMA's robustness to imperfect channel state information and its ability to unify interference management strategies position it as a powerful enabler for future wireless networks, especially when co-optimized with advanced antenna technologies.**

***Index Terms*—RSMA, RIS, ISAC, 6G, Interference Management.**

I. Introduction

Modern wireless networks face the fundamental challenge of efficiently managing multi-user interference (MUI) as the number of connected devices and data traffic grow exponentially. Multi-antenna systems, a cornerstone of modern wireless communications, are critical for mitigating this interference and boosting system capacity. However, traditional multi-antenna access schemes, such as Space Division Multiple Access (SDMA), are highly susceptible to performance degradation when Channel State Information at the Transmitter (CSIT) is imperfect [1]. Rate-Splitting Multiple Access (RSMA) presents a powerful solution by leveraging the multi-antenna broadcast channel to manage interference more robustly [2]. At its core, RSMA operates by splitting user messages into common and private streams, which are then linearly precoded and transmitted from a multi-antenna array. At the receiver, each user employs successive interference cancellation (SIC) to remove the common stream before decoding their private message. This hybrid approach, which partially decodes interference and partially treats it as noise, allows RSMA to generalize and outperform both SDMA and Non-Orthogonal Multiple Access (NOMA) in a wide range of scenarios, particularly those with multi-antenna systems and imperfect CSIT [1], [2]. To highlight the key distinctions and benefits of RSMA, a detailed comparison is provided in Table. I, outlining its core principles, robustness, and application scenarios. This comparative analysis demonstrates why RSMA is considered a more versatile and robust solution for future wireless systems. This survey synthesizes recent research to highlight the expanding role of RSMA in concert with advanced antenna technologies. We first review the fundamental interplay between RSMA and multi-antenna systems and then delve into specific integrations with modern antenna paradigms.

II. Fundamentals of RSMA In Multi-Antenna Systems

Multi-antenna systems, a foundational technology for RSMA, are central to the scheme's ability to manage interference. In a multi-user, multi-antenna downlink system, the transmitter utilizes a linear precoder to spatially filter the common and private data streams. This precoding step is where the intelligence of the multi-antenna array is applied. The common stream is precoded such that it can be decoded by all users, acting as a form of partial interference management. The private streams are then encoded with a precoder based on the available CSIT, intended for individual users.

The multi-antenna setup is critical because it allows for flexible beamforming, which is a key component of the precoding process. By shaping the transmitted signal's energy, the system can direct power to desired users and manage interference to others. This capability, combined with RSMA's message-splitting and decoding strategy, makes the system particularly robust to challenges like imperfect CSIT, channel aging, and user mobility [1], [3] . The antenna array's configuration—from its size to the physical placement of its elements—directly impacts the precoding gain and the overall system performance. The number of antennas determines the number of available spatial degrees of freedom, which can be leveraged by RSMA to serve a larger number of users simultaneously while maintaining high data rates and reliability. This is particularly important for scenarios such as Ultra-Reliable Low-Latency Communication (URLLC), where strict Quality-of-Service (QoS) requirements must be met, even in challenging channel conditions [4]

TABLE I: Comparison of RSMA with other Multi-User Multiple Access Schemes

Feature	RSMA	SDMA	NOMA
Core Principle	Splits user messages into common and private streams, partially decoding interference and treating the rest as noise.	Fully cancels interference at the transmitter by using dedicated spatial beams for each user.	Partially cancels interference at the receiver using successive interference cancellation (SIC) based on power levels.
Robustness to Imperfect CSIT	Highly robust. The common stream manages a portion of the interference, making the system resilient to channel inaccuracies.	Very sensitive. Performance degrades significantly with even minor CSIT imperfections.	Sensitive. Relies on accurate channel knowledge for effective SIC at the receiver.
Complexity	Moderate to high. Requires precoding for both common and private streams and SIC at the receiver.	Moderate. Requires sophisticated precoding to completely null out interference.	High. Requires complex SIC at the receiver, which can be challenging to implement accurately.
Applications	Diverse, including systems with imperfect CSIT, JRC, and high-load scenarios. A versatile and general scheme.	Best for low-load systems with perfect or near-perfect CSIT. Less suitable for dynamic environments.	Suited for scenarios with a wide range of channel gains between users.

III. RSMA Intergration with Advanced Antenna Technologies

The flexibility of RSMA allows for its seamless integration with emerging antenna hardware, unlocking significant performance gains in diverse wireless environments. This synergy is a key driver in pushing beyond the limitations of traditional antenna arrays. By co-designing RSMA with advanced hardware, such as movable antennas and intelligent reflecting surfaces, systems can achieve unprecedented levels of control over the wireless channel, leading to enhanced spectral and energy efficiency. The robust nature of RSMA's interference management strategies complements these new antenna paradigms, making the combined systems more resilient to real-world challenges like channel imperfections and complex propagation environments. The following subsections detail how RSMA is being leveraged with specific cutting-edge antenna technologies.

A. Movable Antennas (MAs) in RSMA Systems

Traditionally, enhancing a system's spectral efficiency requires a larger number of fixed antennas, which is both costly and physically demanding. A promising alternative is the use of movable antennas (MAs). In an MA-assisted RSMA scheme for Ultra-Reliable Low-Latency Communication (URLLC) services, a small number of MAs can be optimally positioned to achieve flexible beamforming and higher spatial multiplexing gains. The physical location of the antennas becomes an additional degree of freedom for optimization. The problem of jointly optimizing the beamforming and antenna positions is formulated as a sum rate maximization problem, subject to URLLC requirements. This high-dimensional, non-convex problem is solved using an alternating optimization (AO) algorithm, which includes a novel particle swarm optimization method for efficiently finding the best antenna positions [4].

B. Active Intelligent Reflecting Surfaces (IRS) with RSMA

Intelligent Reflecting Surfaces (IRS) are passive surfaces that can manipulate incident radio waves. However, the double-fading effect in their cascaded link can limit performance. Active IRS, which can amplify and reflect signals, mitigates this issue but can also introduce amplified interference. To manage this, an active IRS-aided RSMA scheme has been proposed for millimeter-wave hybrid antenna arrays. The system uses a two-layer RS strategy with SIC to effectively cancel this amplified interference. This approach enables the system to utilize the full potential of active IRS without being limited by co-channel interference. The central challenge is to maximize the max-min fairness (MMF) by jointly optimizing the digital precoder, the RS vector, and the reflecting vector of the active IRS, which is solved using an iterative optimization algorithm [5].

C. Extremely Large-Scale Antenna Arrays (ELAAs) and Imperfect CSIT

Extremely Large-Scale Antenna Arrays (ELAAs) offer unprecedented spatial resolution but are highly sensitive to channel imperfections. Achieving perfect CSIT is particularly challenging in ELAA systems due to user mobility and feedback delays, which leads to severe multi-user interference. RSMA is a perfect fit for this environment because it is designed to relax this sensitivity to imperfect CSIT while still taking advantage of the high spatial resolution offered by the ELAAs. To address the challenge of managing interference with partial CSIT, a federated learning (FL)-assisted predictive beamforming framework has been proposed for ELAA systems with RSMA. This framework uses an FL-based training approach to calculate the optimal beamformers, effectively combining the robust interference management of RSMA with the benefits of a massive antenna array [3].

IV. RSMA In Advanced Antenna-Driven System Paradigms

Beyond traditional communications, RSMA's multi-antenna capabilities are being leveraged in integrated systems that rely heavily on antenna design and control. This paradigm shift, from single-purpose to multi-functional systems, highlights the flexibility of RSMA as a foundational technology. The ability to manage a diverse set of communication and sensing functions simultaneously is a key feature of next-generation wireless networks. By co-designing RSMA with advanced antenna architectures, researchers can create unified systems

TABLE II: Integration of RSMA with Advanced Antenna Technologies

Antenna Technology	**Key Characteristics**	**Integration with RSMA**	**Benefits**	**Challenges**
Movable Antennas (MAs)	Small number of antennas with flexible physical positions.	Jointly optimized with beamforming, treating antenna position as an extra degree of freedom.	Flexible beamforming and high spatial multiplexing with fewer antennas, reducing hardware costs.	Complex, high-dimensional non-convex optimization problem for joint position and beamforming.
Active Intelligent Reflecting Surfaces (IRS)	Actively amplify and reflect signals to overcome the double-fading effect of passive IRS.	A two-layer RS strategy cancels the amplified interference.	Overcomes signal loss and enables maximum-min fairness.	Requires complex, iterative optimization of precoders and reflecting vectors.
Extremely Large-Scale Antenna Arrays (ELAAs)	Arrays with a massive number of antennas, offering high spatial resolution.	Manages multi-user interference with imperfect Channel State Information at the Transmitter (CSIT).	Robust to imperfect CSIT, utilizing high spatial resolution to manage interference.	Beamforming design is complex and often addressed with machine learning like Federated Learning (FL).
Joint Radar and Communications (JRC) Systems	A single multi-antenna system for both radar sensing and communications.	A unified strategy for interference management, jointly designing precoders for communication and radar streams.	A single system can perform both communication and sensing tasks simultaneously.	Requires co-optimization to meet the distinct requirements of both communication and radar.
Multi-Antenna Multi-Carrier Cognitive Radio (CR) Systems	Operates in a congested wireless environment, sharing spectrum.	Enables simultaneous communication with secondary users and jamming of adversarial users.	Limits interference to primary users while intelligently jamming others.	Managing interference to avoid disrupting primary users while targeting adversaries is challenging.

that are more efficient and adaptable to complex environments. The following subsections detail two such application spaces: joint radar and communications, and cognitive radio.

A. Joint Radar and Communications (JRC) with Multi-Antenna Systems

The dual-functional radar-communication (DFRC) paradigm aims to achieve Integrated Sensing and Communication (ISAC) by enabling a single multi-antenna system to both communicate with users and sense the environment. RSMA is shown to be a unified and powerful strategy for managing interference in such systems. The multi-antenna base station can use RSMA to simultaneously communicate with downlink users while transmitting a radar sequence to probe angles of interest. This is achieved by jointly designing the message splits and precoders for both the communication streams and the radar sequence, showcasing how RSMA can be tailored to meet the dual requirements of a complex antenna system [6].

B. Communications and Jamming in Cognitive Radio Systems

In congested wireless environments, Cognitive Radio (CR) systems must manage interference with other systems. RSMA has been applied in multi-antenna, multi-carrier CR systems for joint communications and jamming. The proposed scheme leverages the multi-antenna array to simultaneously communicate with Secondary Users (SUs) and jam Adversarial Users (AUs) to disrupt their communications, all while limiting interference to Primary Users (PUs). The intelligent use of the antenna array, combined with the message-splitting capability of RSMA, makes this a powerful tool for sophisticated interference management and electronic warfare applications [7].

To summarize the key findings on the integration of RSMA with various antenna technologies, Table. II provides an overview of the characteristics, benefits, and challenges of each approach. The table highlights how RSMA's robust interference management is tailored to different antenna paradigms, enabling significant performance improvements in diverse communication scenarios.

V. Future Direction

The convergence of Deep Reinforcement Learning (DRL), Federated Learning (FL), and Rate-Splitting Multiple Access (RSMA) offers a compelling frontier for optimizing next-generation wireless networks. Drawing inspiration from the methodologies presented in the provided research, future work can focus on developing intelligent, adaptive, and privacy-conscious antenna control mechanisms for RSMA systems. The primary goal is to dynamically manage complex interference environments and efficiently allocate resources in a distributed manner.

A. DRL for Dynamic RSMA Beamforming and Resource Allocation

A significant opportunity lies in extending DRL-based optimization sum rate maximization for RIS-assisted ISAC-UAV network. One of the papers successfully applied a Deep Deterministic Policy Gradient (DDPG) algorithm to jointly optimize the beamforming matrix and RIS phase shift [8]. A logical next step is to formulate a similar DRL-based approach for RSMA systems. This presents a more complex optimization challenge, as it involves not only power allocation but also the strategic splitting of power between common and private data streams, in addition to the design of sophisticated antenna precoding vectors. The continuous and high-dimensional nature of these variables—such as beamforming angles and power-splitting ratios—makes them well-suited for algorithms like DDPG, which excel in continuous action spaces. A DRL agent could be trained to dynamically adjust RSMA precoders and power levels in real-time to maximize the network's sum-rate or energy efficiency under varying channel conditions and quality-of-service (QoS) constraints [8], [9].

B. Multi-Agent DRL for Cooperative and Autonomous RSMA Networks

The concept of multi-agent systems, as explored in the context of UAV surveillance and smart ocean IoT networks, can be adapted for decentralized RSMA network management. Instead of a single, centralized agent, base stations or even user equipment (UE) in a multi-cell RSMA network could be modeled as cooperative agents [10], [11]. Using a Multi-Agent DRL (MADRL) framework, such as the Multi-Agent DDPG (MADDPG) or CommNet, these agents could learn to autonomously coordinate their antenna beamforming to mitigate inter-cell interference. For instance, UAV-mounted base stations could use MADRL to dynamically optimize their trajectories and antenna orientations, ensuring reliable coverage and high throughput for ground users while minimizing overlap and energy consumption. This approach decentralizes decision-making, making the network more resilient and scalable, particularly in environments with high uncertainty and without a central controller for all agents [10], [11].

VI. Conclusion

This survey highlights that antenna technologies are not merely passive components but are integral to the success and functionality of RSMA. RSMA's robust interference management capabilities are uniquely suited to be co-designed with a variety of advanced antenna technologies, including movable antennas, active intelligent reflecting surfaces, and extremely large-scale antenna arrays. This synergy allows systems to overcome fundamental challenges such as imperfect CSIT, the cost of large arrays, and complex hardware limitations. Furthermore, the combination of RSMA and multi-antenna systems has opened up new application spaces in joint radar and communications and cognitive radio networks.

Future research should continue to explore the intricate relationship between RSMA and antenna technology. Deeper investigations are needed into the joint optimization of RSMA with other emerging hardware, such as reconfigurable intelligent surfaces and advanced massive MIMO systems, to fully realize the potential of these combined

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