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J. Electrical Systems 21-2 (2025): 182-194

Regular paper

Improving 5G Performance with Rate Splitting Multiple Access

Journal of Electrical Systems

Rate-splitting multiple access has emerged as a promising framework for enhancing 5G communication systems and beyond. RSMA addresses key 5G challenges, including diverse quality of service requirements and the demand for massive connectivity. By enabling a flexible transition between treating interference as noise and fully decoding interference, RSMA offers a more general and adaptable transmission framework compared to non-orthogonal multiple access and space-division multiple access. Specifically, RSMA partially decodes interference while treating the remaining portion as noise. This approach not only simplifies transceiver design but also improves system robustness against variations in channel state information at the transmitter quality, ultimately leading to enhanced overall system performance. This paper demonstrates RSMA's ability to satisfy the stringent demands of 5G communication systems under varying parameters, such as CSIT quality and signal-to-noise ratio, across diverse deployment scenarios. Furthermore, we showcase RSMA's advantages over NOMA and SDMA. Through a comprehensive analysis of transmission frameworks and detailed examination of simulation results, this study highlights RSMA's significant potential to fulfill the requirements of 5G networks and beyond.

Keywords:RSMA, NOMA, SDMA, CSIT, SNR, rate region.

1. Introduction

Multiple access refers to the ability for multiple users to access the same communication channel simultaneously. Multiple access is a key component of cellular communication systems [1].The early cellular networks implemented orthogonal multiple access techniques (OMA) such as Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), or Code Division Multiple Access (CDMA) [2]. In TDMA, information's for each user are sent in interference-free time slots, making precise synchronization necessary, which can be challenging, especially in the uplink. In FDMA implementations, such as OFDMA, information for each user is allocated to a subset of orthogonal subcarriers. However, with theadvancement of cellular network technologies, these orthogonal techniques can no longer meet the high requirements of future radio access systems [2].

For 5G, several multiple access schemes are under investigation to select the most optimal technique. Each of these schemes has its advantages and disadvantages, so it is unlikely that a single technique can meet all requirements. The goal is to adopt the most optimal techniques to ensure the efficiency and performance of the 5G system [1].

The first access techniques to generate significant interest in the context of 5G were Non-Orthogonal Multiple Access (NOMA), and Space Division Multiple Access (SDMA).

However, 5G goes even further by introducing a new approach called Rate-Splitting Multiple Access (RSMA). This approach divides a message into two parts (common and private) and transmits them in a non-orthogonal manner. By combining linear precoding (LP) and successive interference cancellation (SIC).

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To assess the effectiveness of an access technique and understand its impact on the performance of a 5G system, it is essential to consider certain key system parameters and measure its performance. We study in this paper the performances of RSMA and compare it with the performances of NOMA and SDMA

In this work, we focus on identifying the limitations of NOMA and SDMA and the ability to overcome these limitations by RSMA. Throw a study and a simulation of the three access techniques in 5G systems.

The rest of this paper is organized as follows. In Section 2, we described the system model and defined the parameters and metrics to measure the performances of access techniques. The transmission framework differences between NOMA, SDMA and RSMA are explained in Section 3. Numerical results are illustrated in Section 4. Section 5 concludes the paper.

2. The literature review

Rate-splitting multiple access is a multiple access technique for future wireless networks, offering substantial performance gains over established methods like spatial division multiple access and non-orthogonal multiple access, especially in tackling the diverse quality-of-service demands and massive connectivity requirements of 5G and beyond [4][5].

RSMA's core principle involves splitting user messages into common and private components. The common parts are encoded into a shared stream accessible by all users, while private parts are encoded into individual streams intended for specific users. This method allows for adaptable interference management, striking a balance between treating interference as noise and complete decoding [4].

RSMA excels in various scenarios, including those with imperfect channel state information at the transmitter [4]. Its flexibility in adapting to different channel conditions and efficient interference management makes RSMA a compelling choice for upcoming wireless communication systems. Ongoing research delves into advanced precoding designs [5] and explores applications in aerial networks [6].

3. System model

We Consider the same system as in [7], where a base station (BS) equipped with 4 transmit antennas serves K single-antenna users. The users are indexed by the set $\mathcal{K} = \{1, \ldots., K\}$. Let $\boldsymbol{x} \in \mathbb{C}^{N_t \times 1}$ denotes the signal vector transmitted in a given channel use. It is subject to the power constraint $E\{\|\boldsymbol{x}\|^2\} \leq P_t$.$E\{*\}$ is the expectation function and P_t is the total power. The signal received at user-k is:

$$y_k = h_k^H \boldsymbol{x} + n_k \; \forall k \in \mathcal{K} (1)$$

Where $h_k \in \mathbb{C}^{N_t \times 1}$ is the channel between the BS and user-k, n_k is the additive white Gaussian noise (AWGN) at the receiver. We assume the noise variances are equal to one for all users. The transmit SNR is equal to the total power consumption P_t.

We assume CSI of users is perfectly known at the BS in the following model. The imperfect CSIT scenario will be discussed in the proposed algorithm and the numerical results. Channel state information at the receivers (CSIR) is assumed to be perfect.This technique is based on the key parameters given in the following subsections. The model for three users is given by figure 1. In section 4 the algorithm will explain all symbols used in it.

3.1. The Accuracy of Channel State Information (CSI)

Channel State Information (CSI) is a key concept in wireless communications, representing the known properties of a radio link's channel. It characterizes how signals behave as they travel from a transmitter to a receiver, considering factors like signal attenuation, scattering and fading. CSI is crucial for assessing the quality of a radio link [9][10].

In practical terms, CSI influences the configuration of the physical layer in communication systems. It determines modulation schemes and impacts resource allocation and interference management. Precise CSI is essential for efficient communication [11].

It is evident that obtaining CSI takes a considerable amount of time. Therefore, acquiring CSI cannot meet the CSI refreshment requirement at the pace demanded by a 5G wireless communication system [10][12]. This is why adopting multiple access techniques that depends less on the quality of CSI in 5G communication systems proves advantageous.

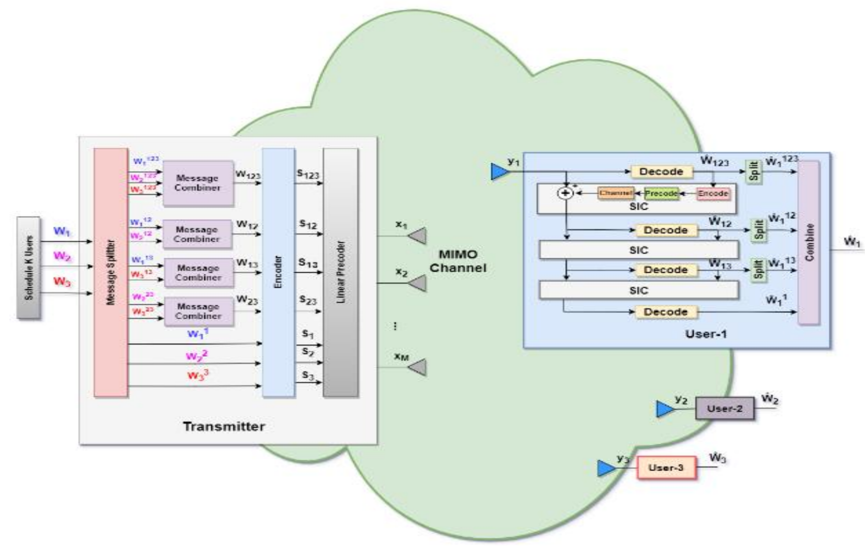

Figure 1. Three-User Transmission Model Using Rate-Splitting (RS) [4]

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3.2. Signal-to-noise ratio

SNR (Signal-to-Noise Ratio), often written as S/N, is the ratio of the received signal power to the noise floor. The SNR is an indicator used to assess the quality of the received signal. Its value is expressed in decibels (dB) and can be calculated using the following formula [11][15][16]:

$$SNR(dB) = 10log_{10}\left(\frac{P_{received\_signal}}{P_{Noise}}\right) \qquad (2)$$

The positive SNR means that the signal power is greater than the noise power, i.e. the receiver will be able to demodulate the signal. The negative SNR means that the signal power is less than the noise power [11][17].

3.3. Performance metrics

There are several performance metrics such as Sum-DoF (Degree of Freedom) or Max-Min Fairness (MMF) to evaluate the performances, but in this work the metric used is the rate region (RG). WeConsider a Massive MIMO system where a base station (BS) equipped with M antennas serves two users [12][18]. The achievable data rates for users 1 and 2 can be expressed in:

$$R_1 = log_2\left(1 + \frac{\propto_1\mu_1}{\mu_{1,1}\eta_1 + \mu_{1,2}\eta_2 + 1}\right) \qquad (3)$$

$$R_2 = log_2\left(1 + \frac{\propto_2\mu_2}{\mu_{2,1}\eta_1 + \mu_{2,2}\eta_2 + 1}\right) \qquad (4)$$

Where:

$-\ \eta_k$ is the power control coefficient and $\propto_k \geq 0$ is the effective channel gain for user-k, where k = 1, 2. The noise power is normalized to 1.

- $\mu_{1,1} \geq 0$ *and* $\mu_{2,2} \geq 0$ are self-interference coefficients caused by imperfect CSIT.
- $\mu_{1,2} \geq 0$ *and* $\mu_{2,1} \geq 0$ are inter-user interference coefficients. It should be noted that η_1 and η_2 are design variables.

In DL (DownLink) the power constraint at the BS is:
$0 \leq \eta_1 + \eta_2 \leq 1$. In UL (UpLink), the power constraints for both users are: $0 \leq \eta_1 \leq 1$ and $0 \leq \eta_2 \leq 1$ [12].

The rate region is described by finding the maximum possible data rates achievable when each user is subject to a maximum transmit power constraint [13].

4. SDMA, NOMA and RSMA techniques

In this approach, different power levels are assigned to users based on their distance from the Base Station (BS). Users farther away receive higher power, while those closer to the BS receive lower power [2][14][19].

4.1. Non-Orthogonal Multiple Access (NOMA)

This method employs unique spreading sequences specific to each user to enable superposition [4][15][20].NOMA relies on the concept of SC-SIC: which is superposition coding at the transmitter, consists of a linear combination of the user signals multiplied by their respective coefficients to generate a composite signal received by all the users [4]. Then comes successive interference cancellation at the receiver in which each user first decodes the strongest signal first. It then subtracts the decoded signal from the received signal. The SIC receiver repeats this iterative subtraction operation until it obtains its own signal [2][15].

In Multi-antenna Systems: the two main strategies in multi-antenna NOMA are the SC–SIC and SC–SIC per group. SC–SIC can be treated as a special case of SC–SIC per group where there is only one group of users [3][16][21].

The SC-SIC per group strategy involves grouping the K users into G groups. Within each group, users are served using SC-SIC to improve interference management [3][22].

4.2. Space-Division Multiple Access (SDMA)

In today's wireless networks, access points are often equipped with more than one antenna. This spatial dimension paves the way for another well-known type of multiple access, namely SDMA. SDMA superposes users on the same time-frequency resource and separates them by making appropriate use of spatial dimensions [3][23].The most commonly used precoding technique for multi-antenna broadcast systems, such as MIMO and MISO BC, is Multi-User Linear Precoding (MU-LP). This technique is based on creating separate beams, with each beam receiving a fraction of the total transmission power. It allows for user superposition in the power domain, much like NOMA. However, unlike NOMA, SDMA uses the beamforming technique at the transmitter to separate users, rather than using the SIC technique at the receivers [3].

4.3. Rate Splitting Multiple Accessalgorithm

The concept of RSMA is not particularly new. Its roots date back to the early works on the two-user interference channel (IC) by Carleial in [7], as well as the work done by Han and Kobayashi in [8].Those authors developed transmission strategies based on RS to achieve new rate regions. In the Han-Kobayashi scheme, which achieves the best-known inner bound to date, each source divides its message into a “private” part and a “common” part (sometimes referred to as a “public” part). The two parts are encoded using superposition coding and simultaneously transmitted. In addition to decoding its own message consisting of two parts, each receiver also decodes part of the interference, specifically the other receiver’s common part [7].

Rate-Splitting Multiple Access (RSMA) is a multiple access scheme based on the concept of Rate-Splitting (RS) and linear precoding for multi-antenna multi-user communications. it splits user messages into common and private parts, and encodes the common parts into one or several common streams while encoding the private parts into separate streams. The streams are precoded using the available (perfect or imperfect) Channel State Information at the Transmitter (CSIT), superposed and transmitted via the Multi-Input Multi-Output (MIMO) or Multi-Input Single-Output (MISO) channel. All the receivers then decode the common stream(s), perform Successive Interference Cancellation (SIC) and then decode their respective private streams. Each receiver reconstructs its original message from the part of its message embedded in the common stream(s) and its intended private stream [9].

Various RSMA schemes exist, such as 1-layer RS, 2-layer hierarchical RS (HRS), generalized RS, RS and common message decoding (RS-CMD) [10]. Each one of these strategies have its advantages in terms of complexity, and quality of service. The algorithm of this technique is given in this eight steps :

1. Message Splitting: Each user's message is split into a common (s_k^c) and private (s_k^p) part:

$$s_k = s_k^c + s_k^p, \quad \forall k \in \mathcal{K}(1)$$

2. Superposition Coding: The base station applies precoding and transmits the combined signal:

$$x = \sum_{k\in\mathcal{K}} w_k^c s_k^c + \sum_{k\in\mathcal{K}} w_k^p s_k^p \quad (2)$$

where w_k^c and w_k^p are precoding vectors for common and private messages.

3. Signal Reception: Each user receives the signal:

$$y_i = h_i x + n_i, \quad \forall i \in \mathcal{K} \quad (3)$$

where h_i is the channel coefficient, and $n_i \sim \mathcal{CN}(0, \sigma^2)$ is noise.

4. SINR Calculation:

Common Message:

$$\gamma_i^c = \frac{|h_i w_c|^2}{\sum_{j\in\mathcal{K}} |h_i w_j^p|^2 + \sigma^2} \quad (4)$$

Private Message:

$$\gamma_i^p = \frac{|h_i w_i^p|^2}{\sum_{j\neq i} |h_i w_j^p|^2 + \sigma^2} \quad (5)$$

5. Rate Calculation:

Common Message Rate:

$$R^c = \min_{i\in\mathcal{K}} \log_2(1 + \gamma_i^c) \quad (6)$$

Private Message Rate:

$$R_i^p = \log_2\left(1 + \gamma_i^p\right) \quad (7)$$

Total User Rate:

$$R_i = R^c + R_i^p, \quad \forall i \in \mathcal{K} \quad (8)$$

6. Power Allocation Optimization:

$$\max_{w_c, w_p} \sum_{i\in\mathcal{K}} R_i, \quad \text{s.t.} \sum_{i\in\mathcal{K}} ||w_i^c||^2 + ||w_i^p||^2 \leq P_{\max} \quad (9)$$

7. Successive Interference Cancellation (SIC):

Users first decode the common message while ensuring:

$$R^c \leq R_i^c, \quad \forall i \in \mathcal{K} \quad (10)$$

After decoding, the common message is removed from the received signal, and users then decode their private message.

8. Message Reconstruction: Each user recovers its original message:

$$\hat{s}_k = \hat{s}_k^c + \hat{s}_k^p \quad (11)$$

This algorithm allows for an efficient use of resources, improves spectral efficiency and enhances the overall performance of wireless networks.

5. Numerical Results and discussions

In this section, we evaluate the performance of RSMA by illustrating the achievable rate region of different strategies.
In all the following results:

- SC-SIC refers to NOMA.
- MU-LP refers to SDMA.
- RS refers to RSMA.

A. Achievable rate region:

When K =2, the rate region of all strategies can be explicitly compared in a two-dimensional figure. As mentioned earlier, the rate region is the set of all achievable points. Its boundary is calculated by varying the weights assigned to users [3][11]. In this work, the weight of user-1 is fixed to $\mu_1 = 1$.
The weight of user-2 is varied as $\mu_2 = 10^{[-3,-1,-0.95,\cdots,0.95,1,3]}$
The user channels are realized as follows:

$$h_1 = [1,1,1,1]^H, h_2 = \gamma \times [1, e^{j\theta}, e^{j2\theta}, e^{j3\theta}]^H (18)$$

In the channel realizations above, the parameters, γ and θ are control variables. The additional path loss experienced by the channel strength of user-2 is controlled by γ. When γ = 1 the channel strength of user-1 is equal to that of user-2. All the following results are achieved for γ = 1. The parameter θ is used to adjust the angle formed between the channels used by the two users.

- **Underloaded two-user deployment with perfect CSIT:**

In the perfect CSIT (Channel State Information at the Transmitter) scenario, the capacity region is achieved by Dirty Paper Coding (DPC). Therefore, to evaluate the performance of different techniques, we compare the achievable throughput region with the DPC region [14][15]. The DPC region is generated using the algorithm described in subsection 4.3 [16][17][18].

In the following we study the Effect of Signal-to-Noise Ratio (SNR) on the achievable rate region for various strategies in a underloaded 2-users deployment and perfect CSIT.

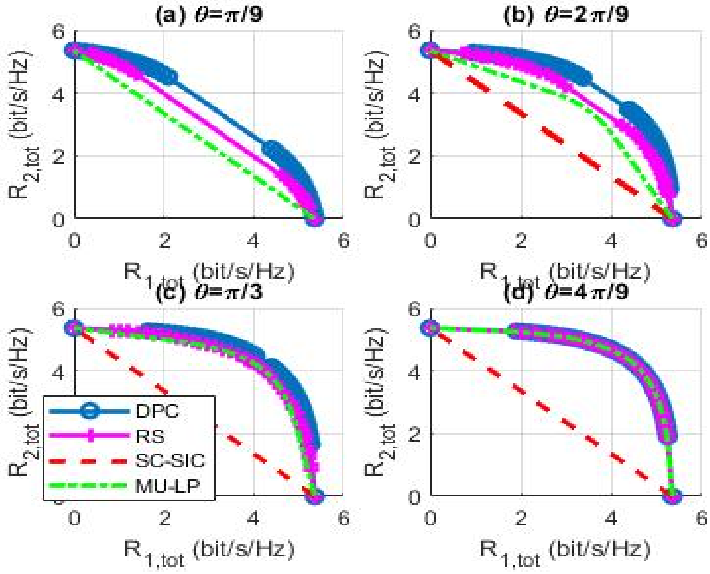

Figure 2. Achievable rate region comparison with under-loaded two-user deployment with perfect CSIT, SNR=10 dB.

In all subfigures from figure 2 and 3, the rate region achieved by RS is equal to or larger than that of SC–SIC and MU–LP.We observe that the decrease in SNR leads to a narrowing of the capacity region as well as the achievable rate regions for all three strategies. This decrease is primarily due to an increase in noise power.

The SC-SIC strategy exhibits a constant region that is the smallest among the visualized regions, indicating its limitations in terms of achievable rates. Conversely, the RS and MU-LP regions improve as the value of θ increases. Among the two, the RS region consistently remains the widest, thus demonstrating its superiority over the other strategies.

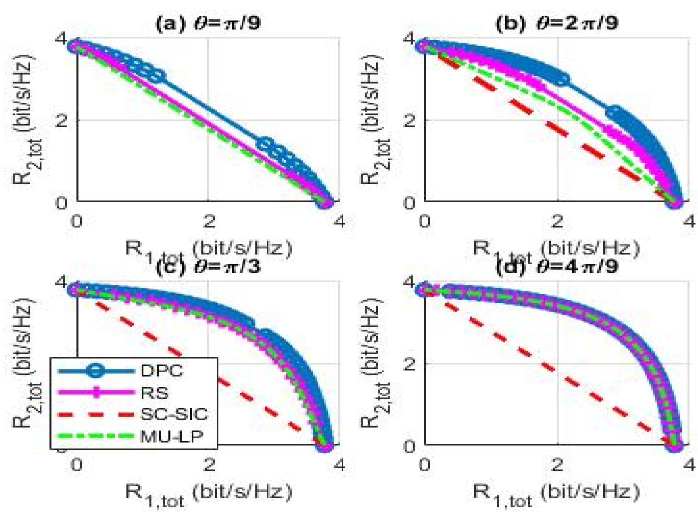

Figure 3. Achievable rate region comparison with under-loaded two-user deployment with perfect CSIT, SNR=5 dB.

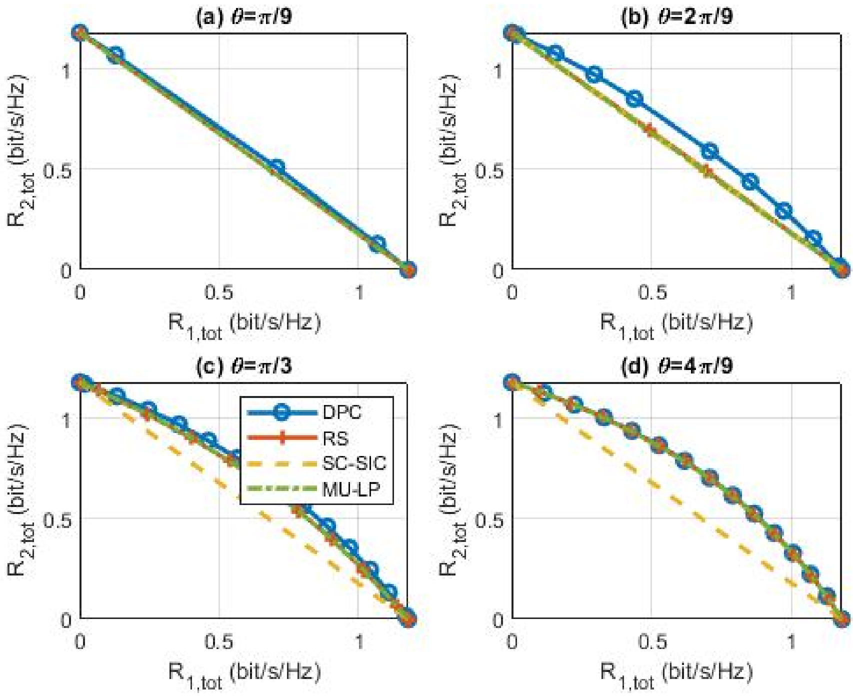

Figure 4. Achievable rate region comparison with under-loaded two-user deployment with perfect CSIT, SNR= -5 dB.

Under the low signal-to-noise ratio conditions depicted in Figure 4 at -5 dB SNR, all the multiple access strategies exhibit significant degradation in their respective achievable rate regions. This suggests that the desired signal is overwhelmed by the noise, severely limiting the attainable rate regions for all the strategies. However, the Rate-Splitting Multiple Access approach demonstrates relatively better performance compared to the Successive Interference Cancellation-based Non-Orthogonal Multiple Access strategy, and its performance is similar to that of Multi-User Linear Precoding. Nonetheless, the achievable rate regions for all the studied multiple access techniques are notably reduced under these low SNR conditions.

- **Underloaded two-user deployment with imperfect CSIT:**

In the scenario of imperfect CSIT, we assume that both users have perfect channel estimation, while the instantaneous channel estimation at the base station is imperfect [15][19][20].

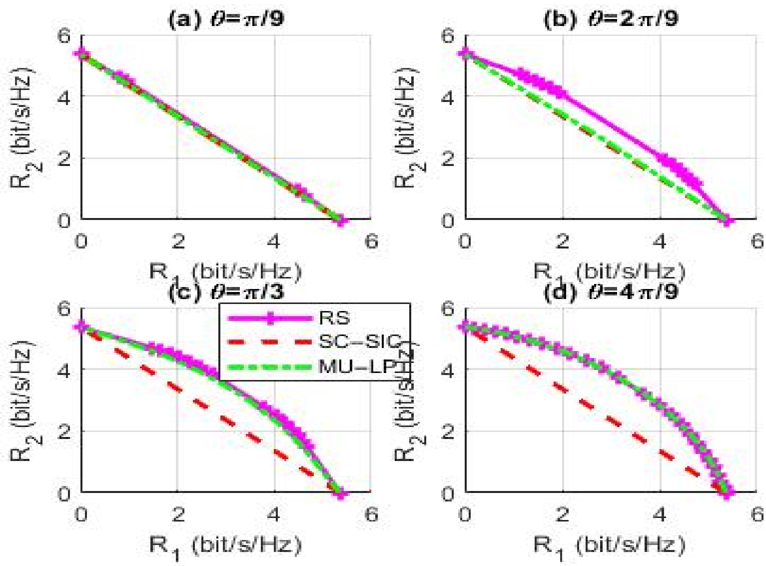

Figure 5. Achievable rate region comparison with under-loaded two-user deployment with imperfect CSIT, SNR=10 dB.

We observe in figures 5,6 and 7 that the decrease in SNR results in a reduction of the achievable rate region, as well as the capacity region, just like in the case of perfect CSIT.

Although the decrease in SNR results in a reduction of the achievable rate region and capacity region, as observed in Figures 4, 5, and 6, this trend may not always hold true in the case of imperfect CSIT. The performance of different multiple access strategies can vary significantly under imperfect CSIT conditions. In certain scenarios, the Rate-Splitting Multiple Access technique may demonstrate improved robustness and outperform other strategies, such as NOMA and SDMA, even in the presence of low SNR.

We can also see that the RS strategy has the most extensive region. The region of MU-LP approaches that of RS when the channels of the two users tend towards orthogonality. On the other hand, the SC-SIC technique reaches its when the channels are aligned.

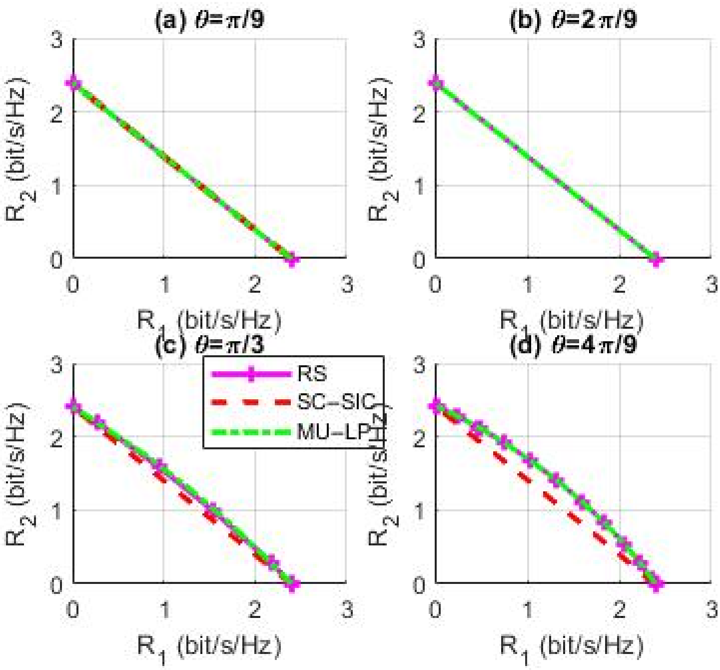

Figure 6. Achievable rate region comparison with under-loaded two-user deployment with imperfect CSIT, SNR= 5dB.

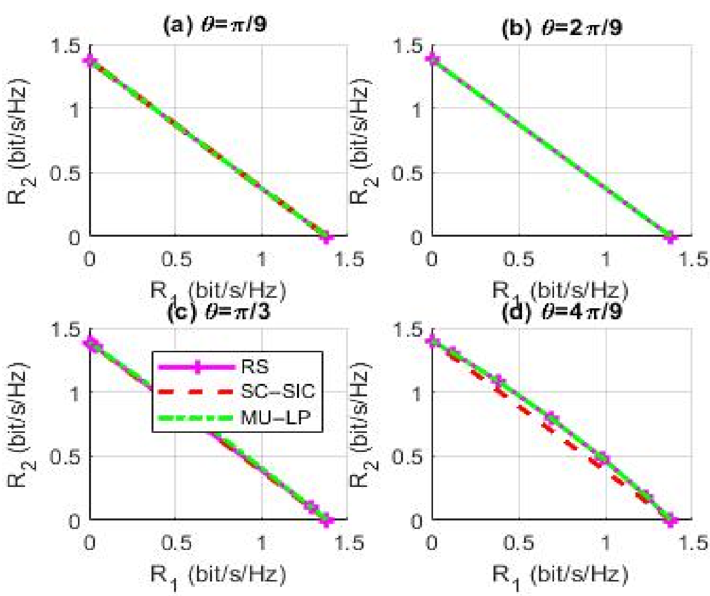

Figure 7. Achievable rate region comparison with under-loaded two-user deployment with imperfect CSIT, SNR= -5dB.

Is noticed that the gap region between RS and MU-LP, as seen in Figure 4 with imperfect CSIT, is wider than the one seen in Figure 1 with perfect CSIT. Therefore, RS is the most effective technique in the scenario of imperfect CSIT, which is closer to reality.

This observation is attributed to the introduction of residual interference. The elimination of interference using MU-LP is disrupted, leading to residual interference at the receiver. This compromises the achievable throughput.Contrary to the above, the gap region between RS and SC-SIC is smaller in imperfect CSIT than in perfect CSIT.RS is more robust than MU-LP in imperfect CSIT due to its flexibility in adjusting the amount of interference decoded by users based on channel conditions and CSIT inaccuracies.

5. Conclusion

Finding an effective access technique that can enhance the performance and meet the massive demands placed on 5G communication systems has been an active area of research in recent years. RSMA technique, with its generality and flexibility, has emerged as a promising solution that can address these challenges.We have examined and compared the performance of RSMA, NOMA and SDMA in this study.
Moreover, the RSMA approach exhibits enhanced resilience, retaining its effectiveness even in the presence of imperfect CSIT. This attribute positions RSMA as a promising candidate for practical scenarios where accurate channel state information may not be readily available.

The Rate-Splitting Multiple Access technique has emerged as one of the most promising approaches, demonstrating greater robustness and resilience to the quality of Channel State Information at the Transmitter. This attribute enables RSMA to optimize and maximize the key performance measures of 5G and future communication systems while efficiently utilizing their resources. Simulation results confirm that the RSMA technique is a generalization of Non-Orthogonal Multiple Access and Spatial Division Multiple Access techniques, highlighting its versatility and flexibility in effective interference management, which is crucial for improving the overall system performance. The Rate-Splitting Multiple Access technique shows promise for application in future 6G communication networks.

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