Performance Analysis of RSMA-Based MU-MISO LEO Satellite Downlink System with Imperfect CSI

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***Abstract*—This paper studies rate-splitting multiple access (RSMA) for a multi-user multiple-input single-output downlink channel comprising an M-antenna transmitter and K single-antenna user equipments in low Earth orbit (LEO) satellite systems under imperfect channel state information. We model the proposed system and conduct a comparative analysis of RSMA and spatial division multiple access (SDMA) in terms of sum spectral efficiency (sum-SE) and sum energy efficiency (sum-EE) with respect to transmit power. Simulation results demonstrate that RSMA outperforms SDMA in sum-SE and sum-EE.**

***Index Terms*—Rate-splitting multiple access, low Earth orbit satellite, imperfect channel state information.**

I. INTRODUCTION

To enable global coverage in 6G, non-terrestrial networks particularly low Earth orbit (LEO) satellites offering low latency and high data rates have attracted considerable interest. Multi-user multiple-input single-output (MU-MISO) is one of the essential techniques for supporting high-mobility users in LEO systems by enhancing link reliability and capacity under rapid channel variations and severe path loss. However, accurate channel state information (CSI) remains a key challenge due to satellite mobility, fading, and large path loss [1].

Rate-splitting multiple access (RSMA) has been proposed as a promising solution to address these issues, offering greater flexibility in interference management and power allocation by splitting common and private streams [1].

In this paper, we apply the RSMA approach to a LEO satellite-based MU-MISO downlink (DL) system and evaluate its performance in a satellite channel environment, incorporating key features such as shadowed Rician fading, free space path loss, and imperfect CSIT [2], [3]. We conduct a comparative analysis of RSMA and conventional spatial division multiple access (SDMA) with respect to sum spectral efficiency (Sum-SE) and sum energy efficiency (Sum-EE), under varying transmit power levels.

II. SYSTEM MODEL

We consider a RSMA-based MU-MISO DL scenario between a LEO satellite and ground UEs. The satellite serves as a base station and is equipped with M transmit antennas, while each of the K UEs is equipped with a single receive antenna, thereby forming a MU-MISO system [1]–[3]. This overall channel can also be represented as a multiple-input multiple-output channel. During the coherence time T, pilot signals are transmitted for τ_p symbols with power p_p, and data transmission occurs over the remaining duration [1].

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The wireless channel between the satellite and UEs is modeled as a Rician fading channel with shadow fading components. The channel $\mathbf{H} \in \mathbb{C}^{M\times K}$ is expressed as follows:

$$\mathbf{H} = \sqrt{\frac{\kappa\bar{\chi}}{\kappa+1}}\mathbf{R}^{\frac{1}{2}}\bar{\mathbf{H}} + \sqrt{\frac{\chi_w}{\kappa+1}}\mathbf{R}^{\frac{1}{2}}\mathbf{H}_w, \tag{1}$$

where $\left[\bar{\mathbf{H}}\right]_{mk} = e^{-j(m-1)\varphi_k}$ and $\mathbf{H}_w$ denote the deterministic and random components, respectively. $\ln(\bar{\chi}) \sim \mathcal{N}(0, \bar{\sigma}^2)$ and $\ln(\chi_w) \sim \mathcal{N}(0, \sigma_w^2)$ represent the shadow fading component. φ_k is the phase shift introduced by the angle of arrival, the channel is modeled as block fading and remains constant within each coherence interval. $\mathbf{R} = \frac{1}{2\Delta_k}\int_{\theta_k-\Delta_k}^{\theta_k+\Delta_k} e^{-\frac{2\pi}{\lambda}\psi(\alpha)(\mathbf{r}_i-\mathbf{r}_j)}\mathrm{d}\alpha$, where $\mathbf{R} \in \mathbb{C}^{M\times M}$ denotes the spatial correlation matrix obtained from the local scattering model [1]–[3]. θ_k and Δ_k represent the azimuth angle and the angular spread, respectively. The vector $\boldsymbol{\psi}$ corresponds to the wave vector of a planar wave impinging with angle α, λ is the wavelength, and $\mathbf{r}_i$ denotes the position vector of the i-th antenna element [1]. Minimum mean squared error channel estimation is employed as the channel estimation, and the real channel $\mathbf{H}$ is given as follows:

$$\mathbf{H} = \hat{\mathbf{H}} + \tilde{\mathbf{H}}, \tag{2}$$

where $\hat{\mathbf{H}} = \left[\hat{\mathbf{h}}_1, \cdots, \hat{\mathbf{h}}_K\right]$ and $\tilde{\mathbf{H}} = \left[\tilde{\mathbf{h}}_1, \cdots, \tilde{\mathbf{h}}_K\right]$ denotes the MMSE channel estimate obtained from pilot signals and the residual error, respectively. And each channel component for user k, follows a complex Gaussian distribution, i.e., $\hat{\mathbf{h}}_k \sim \mathcal{CN}(\mathbb{E}[\hat{\mathbf{h}}_k], \hat{\beta}\mathbf{I}_M), \tilde{\mathbf{h}}_k \sim \mathcal{CN}(0, \tilde{\beta}\mathbf{I}_M)$. In this system, orthogonal pilot sequences of length τ_p are employed, and the condition $\tau_p \geq K$ is required. Furthermore, $\hat{\beta} = \frac{p_p\tau_p\beta^2}{(\kappa+1)(p_p\tau_p\beta+\sigma_n^2)}$ and $\tilde{\beta} = \frac{\beta}{\kappa+1} - \hat{\beta}$ denote the estimated and error channel gains, respectively. κ denotes K-factor component. The pilot length τ_p and a pilot power p_p represent the sounding duration and strength, jointly determining the estimation accuracy.

In the RSMA transmission framework, user messages are split into a common message and individual private messages, and the overall transmit signal is expressed as follows [1]:

$$\mathbf{x} = \sqrt{P_c}\mathbf{w}_c s_c + \sum_{k=1}^{K}\sqrt{P_{p,k}}\mathbf{w}_{p,k}s_{p,k}, \tag{3}$$

where $P, P_c = (1-t)P$, and $\sum_k P_{p,k} = P - P_c$ represent the total, common, and sum of private transmit powers, respectively. And $t \in (0,1]$ denotes the power splitting ratio for the private stream and is obtained using an exhaustive search method with a step size of 0.05. s_c and $s_{p,k}$ represent the common and private messages, each assumed to have zero mean and unit variance. And

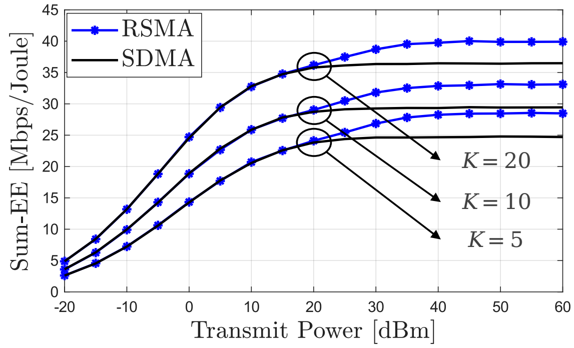

Fig. 1. Sum-SE vs Transmit power (M = 100, 5,000 realizations)

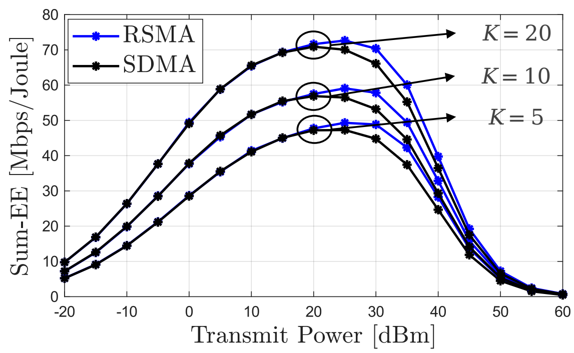

Fig. 2. Sum-EE vs Transmit power (M = 100, 5,000 realizations)

$\mathbf{w}_c$ and $\mathbf{w}_{p,k}$ denote the precoding vectors, which are designed based on matched beamforming (MBF) and regularized zero-forcing (RZF), respectively. The precoding vector is obtained as follows [1]:

$$\mathbf{W}_p = \frac{K}{\text{Tr}(\hat{\mathbf{H}}^H \mathbf{N}^H \mathbf{N}\hat{\mathbf{H}})} \mathbf{N}\hat{\mathbf{H}},\ \mathbf{N} = (\hat{\mathbf{H}}\hat{\mathbf{H}}^H + M\epsilon \mathbf{I}_M)^{-1}, \quad (4)$$

$$\mathbf{w}_c = \sum_k a_k \hat{\mathbf{h}}_k, \quad (5)$$

where $\mathbf{W}_p = [\mathbf{w}_{p,1}, \cdots, \mathbf{w}_{p,K}]$ and $\epsilon = \frac{K}{MP}$ and $a_k = \frac{1}{\sqrt{MK}}$ denote normalization factors [1].

At the receiver side, k-th UE receive the signal y_k, and first decode the common messages s_c, and then remove it from received signal via successive interference cancellation before decoding their private messages $s_{p,k}$. The received signal is expressed as follows:

$$y_k = \sqrt{P_c}\mathbf{h}_k^H \mathbf{w}_c s_c + \sum_{j=k}^{K} \sqrt{P_{p,j}}\mathbf{h}_k^H \mathbf{w}_{p,j} s_{p,j} + n_k. \quad (6)$$

After removing the decoded common message, each user decodes private messages. The common stream rate and private stream rate of the k-th UE, as well as the total system sum rate R, are given as follows [1]:

$$R_{c,k} = \log_2\left(1 + \frac{P_c \left|\mathbf{h}_k^H \mathbf{w}_c\right|^2}{\sum_{j=1}^{K} P_{p,j}\left|\mathbf{h}_k^H \mathbf{w}_{p,j}\right|^2 + \sigma_n^2}\right), \quad (7)$$

$$R_{p,k} = \log_2\left(1 + \frac{P_{p,k} \left|\mathbf{h}_k^H \mathbf{w}_{p,k}\right|^2}{\sum_{j\neq k} P_{p,j}\left|\mathbf{h}_k^H \mathbf{w}_{p,j}\right|^2 + \sigma_n^2}\right), \quad (8)$$

$$R = \left(\frac{T - \tau_p}{T}\right)\left[\min_k \{R_{c,k}\} + \sum_{k=1}^{K} R_{p,k}\right], \quad (9)$$

where $n_k \sim \mathcal{CN}(0, \sigma_n^2)$ denotes additive white Gaussian noise.

Energy efficiency represents the data rate that the system can achieve per unit of energy consumption, and is defined as follows:

$$EE = \frac{BW \times R}{P + P_{circuit}}, \quad (10)$$

where $P_{circuit}$ denotes the fixed circuit power consumption of RF chains, independent of the transmit power [4].

III. Simulation Result

This section presents the performance evaluation of the proposed RSMA-based LEO satellite system through simulation results averaged over realizations. Simulations are conducted with $M = 100$ transmit antennas and $K = 5, 10, 20$ UEs. The coherence time $T = 200$ is used, with pilot length $\tau_p = 20$ and pilot power $p_p = 25$ [dBm]. A Rician fading channel with K-factor $\kappa = 10$ [dB], operating at $f_c = 2.4$ [GHz] with $BW = 20$ [MHz]. The satellite altitude is 500 km with a 30-degree elevation angle. Shadowing components are set to $\bar{\sigma}$=4 [dB] and σ_w=6 [dB]. Noise power is calculated based on the thermal noise formula, and the circuit power $P_{circuit} = 10$ [W]. The spatial correlation matrix is generated based on the model in [1].

Fig. 1 presents the sum-SE comparison between RSMA and SDMA for $K = 5, 10, 20$ UE as the transmit power. RSMA shows comparable performance to SDMA in the low-power regime, where inter-user interference is limited. However, beyond 20 dBm, RSMA begins to outperform SDMA, achieving up to 20% higher sum-SE. This improvement stems from the use of the common stream in RSMA, which effectively mitigates interference among users, especially in high-SNR scenarios where private stream performance saturates.

Fig. 2 illustrates the sum-EE variation over transmit power for the same $K = 5, 10, 20$ values. While SDMA reaches its peak sum-EE at 20 dBm, RSMA demonstrates a delayed but higher peak in the 25–30 dBm range. Notably, RSMA maintains equal or higher sum-EE across the transmit power. The observed behavior indicates that RSMA not only improves spectral efficiency but also provides better energy utilization, especially in interference-limited and high-power conditions.

IV. Conclusion

This paper analyzed the performance of RSMA-based MU-MISO LEO satellite DL systems in terms of sum SE and EE. Simulation results show that RSMA outperforms conventional SDMA, particularly in the high-SNR regime, by better managing inter-user interference through its common message structure. These results confirm the potential of RSMA for future satellite-based MU-MISO systems requiring high performances.

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