Maximizing Energy Efficiency in LEO Satellite Communications via SIM-Enabled Holographic MIMO

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Abstract

This paper investigates energy efficiency (EE) maximization in a downlink low Earth orbit (LEO) satellite communication (SATCOM) system enabled by stacked intelligent metasurfaces (SIM) and enhanced with rate-splitting multiple access (RSMA). A SIM is deployed at the multi-antenna transmitter to facilitate holographic MIMO (HMIMO) beamforming while reducing radio frequency (RF) chain complexity. The system model captures the spatial correlation among densely packed meta-atoms and employs a ray-tracing-based approach for channel characterization. Given the challenges in acquiring instantaneous channel state information (CSI) in dynamic LEO environments, ergodic rate bounds are adopted to reformulate the EE objective. The resulting non-convex optimization problem, arising from the fractional EE metric and the coupling of beamforming and SIM parameters, decomposed into two subproblems via a block coordinate descent (BCD) framework and each successively convexified using quadratic transform (QT) and successive convex approximation (SCA).Simulation results confirm that combining SIM with RSMA yields substantial EE gains over both SIM-free configurations and systems employing conventional space division multiple access (SDMA).

I. Introduction.

The increasing demand for ubiquitous connectivity has positioned low Earth orbit (LEO) satellite communication (SATCOM) systems as a promising extension to terrestrial wireless networks, offering high data rates and wide-area coverage. However, LEO SATCOM faces critical challenges such as severe path loss and rapid channel variation due to high mobility. While massive multiple input multiple output (MIMO) has been investigated to enhance spectral efficiency, its reliance on numerous active radio frequency (RF) chains results in substantial hardware complexity, power consumption and cost. Holographic MIMO (HMIMO) has emerged as a potential alternative by employing a spatially continuous aperture to achieve finer beamforming and spatial resolution, though its implementation using conventional RF-chain architectures is often infeasible due to excessive energy and hardware demands. To overcome this, intelligent surface-based solutions such as stacked intelligent metasurfaces (SIM), comprising multilayer low-cost subwavelength meta-atoms, have been proposed to realize HMIMO more efficiently. Acting as external components, SIM enhances beamforming without requiring additional RF chains, thereby improving system-level energy efficiency (EE) while maintaining performance. In this work we integrate SIM into satellite systems and adopt rate-splitting multiple access (RSMA) to jointly address interference management and EE. Specifically, we formulate and solve an EE maximization problem by leveraging the slowly varying statistical and geometrical properties of satellite-to-user channels in LEO environments.

II. System Model

We consider a downlink LEO SATCOM system assisted by SIM, where SIM is deployed at the multi-antenna transmitter alongside a RSMA scheme. The transmitter is equipped with a uniform planar array (UPA) comprising $M = M_x \times M_y$ antennas, and RSMA is employed as an effective strategy for mitigating inter-user interference (IUI) arising from non-orthogonal user channels in LEO downlink scenarios. The SIM structure is responsible for performing wave-domain beamforming for K communication users and consists of L metasurface layers, each containing N meta-atoms. Let $\mathcal{L} = \{1, \cdots, L\}$, $\mathcal{N} = \{1, \cdots, N\}$, and $\mathcal{K} = \{1, \cdots, K\}$ represent the sets of metasurface layers, meta-atoms per layer, and users, respectively. Furthermore, the transmission matrix from the $(l-1)$-th to the l-th metasurface layer, denoted by $\mathbf{W}_l \in \mathbb{C}^{N\times N}$, $\forall l \neq 1, l \in \mathcal{L}$, is modeled based on the Rayleigh–Sommerfeld diffraction theory [1]. The diagonal matrix representing the phase shifts of the l-th metasurface layer can be expressed as:

$$\mathbf{\Phi} = \mathrm{diag}\left(e^{j\phi_1^l}, \cdots, e^{j\phi_N^l}\right) \in \mathbb{C}^{N\times N}, \quad (1)$$

where $e^{j\phi_n^l}$, $\forall l \in \mathcal{L}$, and $\forall n \in \mathcal{N}$, represents the electromagnetic (EM) response of the n-th meta-atom on the l-th metasurface layer, with $\phi_n^l \in [0, 2\pi)$ denoting its associated phase shift. Accordingly, the overall end-to-end transmission matrix of the SIM, denoted by $\mathbf{P} \in \mathbb{C}^{N\times M}$, is formulated as:

$$\mathbf{P} = \mathbf{\Phi}_L \mathbf{W}_l \cdots \mathbf{\Phi}_2 \mathbf{W}_2 \mathbf{\Phi}_1 \mathbf{W}_1. \quad (2)$$

The transmitted signal $\mathbf{x}(t) \in \mathbb{C}^{M\times 1}$ at the t-th time-index is given by:

$$\mathbf{x}(t) = \mathbf{f}_c s_c(t) + \textstyle\sum_{k=1}^{K} \mathbf{f}_k s_k(t), \quad (3)$$

where $s_c(t)$ denotes the common stream, and $s_1(t), \cdots, s_K(t)$ represent the private streams at time index t, as defined by the RSMA scheme implemented at the transmitter. Correspondingly, $\mathbf{f}_c$ and $\mathbf{f}_1, \cdots, \mathbf{f}_K$ are the transmit beamforming vectors associated with the common and private streams, respectively. To model the satellite channel, a widely adopted ray-tracing-based approach is utilized. The channel vector from the SIM to the k-th user, denoted by $\mathbf{h}_k \in \mathbb{C}^{N\times 1}$, is modeled using a widely adopted ray-tracing technique that accounts for the spatial correlation among the tightly packed meta-atoms in the output metasurface layer of the SIM and is formulated as:

$$\mathbf{h}_k(t) = g_k(t) \mathbf{a}_k \mathbf{R}^{\frac{1}{2}}, \quad (4)$$

where $\mathbf{a}_k \in \mathbb{C}^{N\times 1}$ denotes the array response vector of the k-th user, and g_k is modeled as a Rician-distributed random variable following an independent and identically distributed (i.i.d.) complex Gaussian distribution with a specified Rician K-factor. The average channel power is given by $\mathbb{E}[|g_k(t)|^2] = A_k$. The matrix $\mathbf{R} \in \mathbb{C}^{N\times N}$ represents the spatial correlation at the SIM and is defined as $[\mathbf{R}]_{n,\tilde{n}} = \mathrm{sinc}(2r_{n,\tilde{n}}/\lambda)$, where, $r_{n,\tilde{n}}$ $\forall n, \tilde{n} \in \mathcal{N}$, denotes the spacing between the n-th and $\tilde{n}$-th meta-atoms on the output layer of the SIM. Accordingly, the received signal $y_k(t) \epsilon \mathbb{C}$ at the k-th user and time index t is expressed as:

$$y_k(t) = \mathbf{h}_k^H(\mathrm{t})(\mathbf{P}\mathbf{f}_c s_c(t) + \mathbf{P}\sum_{k=1}^{K}\mathbf{f}_k s_k(t)) + n_k(t), \quad (5)$$

where $n_k \sim \mathcal{CN}(0, \sigma_k^2)$ is the i.i.d. additive white Gaussian noise at the k-th user.

III. Problem Formulation

This work focuses on maximizing the EE of the proposed system by jointly optimizing the variables $\mathbf{f}_c, \mathbf{f}_1, \cdots, \mathbf{f}_k, c_1, \cdots, c_K$ and $\mathbf{\Phi}_1, \cdots, \mathbf{\Phi}_L$ EE is defined as the ratio of the sum rate to the total power consumption. Given the difficulty in acquiring instantaneous channel state information (CSI) in LEO SATCOM systems, we adopt the ergodic rate as a performance metric. However, since directly handling the exact ergodic rate is analytically intractable, we employ upper bounds for the common and private ergodic rates, denoted by $\bar{R}_{c,k}$ and $\bar{R}_{p,k}$, respectively, which are defined as follows:

$$\bar{R}_{c,k} = \log_2\left(1 + \frac{A_k\left|\mathbf{a}_k^H\mathbf{R}^{1/2}\mathbf{P}\mathbf{f}_c\right|^2}{\sigma_k^2 + \sum_{i=1}^{K} A_k\left|\mathbf{a}_k^H\mathbf{R}^{1/2}\mathbf{P}\mathbf{f}_i\right|^2}\right), k\epsilon\mathcal{K}, \quad (6)$$

$$\bar{R}_{p,k} = \log_2\left(1 + \frac{A_k\left|\mathbf{a}_k^H\mathbf{R}^{1/2}\mathbf{P}\mathbf{f}_k\right|^2}{\sigma_k^2 + \sum_{i=1, i\neq k}^{K} A_k\left|\mathbf{a}_k^H\mathbf{R}^{1/2}\mathbf{P}\mathbf{f}_i\right|^2}\right), k\epsilon\mathcal{K}. \quad (7)$$

On the other hand, the total power consumption is given by

$$P = P_0 + \frac{1}{\varepsilon}\left(\|\mathbf{f}_c\|_2^2 + \sum_{k=1}^{K}\|\mathbf{f}_k\|_2^2\right), \quad (8)$$

where $\varepsilon \, \epsilon \, (0, 1]$, and P_0 denotes the sum of the power consumed by the circuitries in the RF chain. Thus, the EE can be defined as follows:

$$EE = \frac{\sum_{k=1}^{K}(c_k + \bar{R}_{p,k})}{P}, \quad (9)$$

where c_k denotes the portion of the common rate allocated to the k-th user. To ensure successful decoding of the common stream and fulfillment of user-specific rate requirements, the constraints $\bar{R}_{p,k} + c_k \geq R_{\min}$, where $R_{\min}$ denotes the minimum required rate for each user k, and $\sum_{k=1}^{K} c_k \leq \min_{k\epsilon\mathcal{K}} \bar{R}_{c,k}$ must be satisfied. Accordingly, the EE maximization problem is formulated subject to: (i) non-negativity of the common rate allocation, $c_k \geq 0$; (ii) the combined common and private rate constraint, $\bar{R}_{p,k} + c_k \geq R_{\min}$; (iii) the rate splitting constraint $\sum_{k=1}^{K} c_k \leq \min_{k\epsilon\mathcal{K}} \bar{R}_{c,k}$; (iv) the total transmit power constraint, $\|\mathbf{f}_c\|_2^2 + \sum_{k=1}^{K}\|\mathbf{f}_k\|_2^2 \leq P_{\max}$, where $P_{\max}$ denotes the maximum power budget at the transmitter.

IV. Proposed Algorithm for EE Maximization

Due to the fractional structure of the objective function and the coupling among the optimization variables, the optimization problem is inherently non-convex. To tackle this challenge, we adopt the block coordinate descent (BCD) method. Specifically, by fixing $\mathbf{\Phi}_1, \cdots, \mathbf{\Phi}_L$, the EE maximization problem is reformulated into a convex problem via the quadratic transform (QT) technique [2], facilitated by introduction of appropriate slack variables. Subsequently, by fixing the variables $\mathbf{f}_c, \mathbf{f}_1, \cdots, \mathbf{f}_k, c_1, \cdots, c_K$, we employ the successive convex approximation (SCA) approach to further transform the resulting subproblem into a convex subproblem is then efficiently solved using the CVX optimization toolbox [3].

V. Simulation Results

The performance of the proposed SIM-assisted RSMA framework is evaluated in a downlink LEO SATCOM system using a UPA-equipped satellite and stacked intelligent metasurfaces. Four configurations are compared in terms of EE under various minimum rate requirements, with simulation parameters detailed in Table 1. Figure 1 demonstrates that the use of SIM and RSMA significantly improvs EE.

Table 1: Simulation Parameters

Parameter	Value	Parameter	Value
M	16	$P_{\max}$(dBm)	45
L	3	N	64
K	3	$R_{\min,k}$(bps/Hz)	$\{0.15, 0.2, \cdots, 0.45\}$

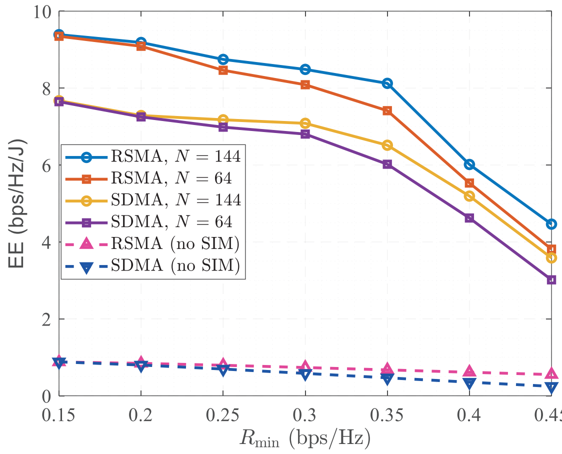

Figure 1: The average EE versus the minimum required rate for RSMA and SDMA multiple access schemes, with and without SIM.

VI. Conclusion

This paper focuses on maximizing EE in a downlink SIM-aided LEO satellite communication system using RSMA at a multi-antenna transmitter. Due to the non-convex nature of the problem, a BCD approach is used, where the problem is split into subproblems. Each subproblem is converted into a convex form using QT and SCA.

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References

[1] S. Lin, *et. al.*, “Stacked intelligent metasurface enabled LEO satellite communications relying on statistical CSI,” *IEEE Wireless Commun. Lett.*, vol. 13, no. 5, pp. 1295–1299, 2024..

[2] K. Shen and W. Yu, “Fractional programming for communication systems part II: Uplink scheduling via matching,” *IEEE Trans. Signal Process.*, vol. 66, no. 10, pp. 2631–2644, 2018.

[3] Z. Liu, *et. al.*, "Rate-splitting multiple access for quantized ISAC LEO satellite systems: A max-min fair energy-efficient beam design," *IEEE Trans. Wireless Commun.*, vol. 23, no. 10, pp. 15394-15408, Oct. 2024.