

SIM-Aided Cell-Free Massive MIMO Systems With Rate-Splitting Multiple Access

Jonathan Obeng Agyapong^{*§}, Woode Theodore^{*}, Yangho Park[‡], Anokye Lois Oforiwa[‡],
Prince Anokye[†], Kyoung-Jae Lee[‡]

^{*}Dept. of Electronic Engineering, Hanbat National University, Daejeon, South Korea

[†]Dept. of Mathematics and Electrical Engineering, IMT-Atlantique, Brest, France

[§]Dept. of Electrical and Electronic Engineering, Ho Technical University, Ho, Ghana

[‡]School of Electrical and Electronics Engineering, Chung-Ang University, Seoul, South Korea
jobengagyapong@edu.hanbat.ac.kr, woodetheodore@edu.hanbat.ac.kr, yanghopark@cau.ac.kr,
loanokye@cau.ac.kr, princemanokye@yahoo.com, kyoungjae@cau.ac.kr

Abstract—This paper investigates stacked intelligent metasurfaces (SIM) for cell-free (CF) massive multiple-input multiple-output (mMIMO) systems to alleviate the power consumption and hardware cost associated with large number of radio frequency (RF) chains. To enhance the sum rate, rate-splitting multiple access (RSMA) is integrated into the CF-SIM architecture. An alternating optimization framework is then employed to jointly optimize the power allocation between common and private messages and the antenna selection for common message transmission. Numerical results demonstrate that the proposed RSMA-enabled CF-SIM scheme achieves superior sum rate performance, providing significant gains over the conventional CF-SIM system. Moreover, the performance gain further increases with the number of SIM meta-atoms.

Index Terms—Cell-free mMIMO, stacked intelligent metasurfaces, rate-splitting multiple access, sum rate.

I. INTRODUCTION

The increasing demand for high spectral efficiency and seamless connectivity in next-generation wireless networks has driven significant interest in Cell-Free (CF) massive multiple-input multiple-output (mMIMO) systems. CF mMIMO deploys a large number of geographically distributed access points (APs) to serve multiple users over the same time-frequency resources. Owing to the macro-diversity gain and favorable propagation characteristics, CF mMIMO significantly improves user fairness and mitigates interference [1]. However, the dense deployment of APs, each equipped with large-scale antenna arrays and dedicated radio frequency (RF) chains, introduces substantial hardware costs and energy consumption that scale prohibitively with the number of antennas [2]. Conventional CF mMIMO systems relying on fully digital beamforming architectures are therefore practically challenging for large-scale deployments.

This work was supported in part by the National Research Foundation of Korea (NRF) Grants funded by Korean Government through Ministry of Science and ICT (MSIT) under Grant RS-2024-00346319; in part by the Institute for Information & Communications Technology Planning & Evaluation (IITP) through MSIT, Korean Government, through the Information Technology Research Center (ITRC) Support Program under Grant IITP-2026-RS-2024-00437886; and under Grant IITP-2026-RS-2026-25518980 (Radio propagation prediction technologies for next-generation high-speed communications). (Corresponding author: Kyoung-Jae Lee)

To address these limitations, the stacked intelligent metasurface (SIM) has recently emerged as a transformative hardware paradigm for next-generation APs [3], [4]. A SIM device consists of a stacked array of metasurfaces, each composed of low-cost meta-atoms capable of dynamically manipulating the phase shift of incoming electromagnetic (EM) waves. By jointly optimizing the transmission coefficients of all meta-atoms via a smart controller such as a field-programmable gate array (FPGA), SIM-equipped APs can execute signal processing directly in the EM wave domain to suppress interference [5]. Consequently, SIM-assisted architectures require only low-resolution analog-to-digital converters (ADCs) and digital-to-analog converters (DACs), significantly reducing both hardware complexity and energy consumption compared to conventional fully digital systems [5].

Rate-splitting multiple access (RSMA) has recently garnered considerable attention as a powerful and flexible interference management framework for multi-user systems. By utilizing rate-splitting (RS), each user's message is split into a common part, decoded by all users, and a private part, decoded by the intended user only. Therefore, RSMA partially decodes interference and partially treats it as noise [2]. RSMA thus serves as a robust complement to SIM, handling the residual interference that wave-domain processing alone cannot eliminate and unlocking the full performance potential of CF mMIMO systems.

Recent works have studied SIM-assisted CF mMIMO systems. The authors of [6] jointly optimized AP power allocation and SIM wave-domain beamforming to maximize the downlink sum rate, while [7] extended this to a fronthaul-constrained setting using hybrid digital and wave-domain beamforming. On the other hand, [8] incorporated RSMA into a SIM-aided single base station system, demonstrating its effectiveness in managing interference with wave-domain processing. Despite the potential of RSMA in SIM-assisted systems, its integration into CF mMIMO architectures remains unexplored. This paper addresses this gap by integrating RSMA into a SIM-assisted CF mMIMO system to maximize the downlink sum rate. The main contributions of this paper are summarized as follows:

- We propose a downlink RS-CF-SIM framework that integrates RSMA into a SIM-assisted CF mMIMO system to enhance the sum rate performance with reduced RF chain complexity.
- An alternating optimization (AO) framework is developed to jointly optimize the power-splitting factor and common-message antenna selection, where golden-section search (GSS) is used for power allocation and exhaustive search for antenna selection to maximize the sum rate.
- Numerical results validate that the proposed RS-CF-SIM scheme achieves superior sum rate performance compared to the conventional CF-SIM baseline, with further gains observed as the number of meta-atoms increases.

II. SYSTEM MODEL

Consider a downlink CF mMIMO system, where M multi-antenna SIM-integrated APs serve K single-antenna users. Each AP deploys N antennas and connects to a central processing unit via limitless capacity and error-free fronthaul links. The SIM of each AP consists of L stacked metasurfaces, each consisting of S meta-atoms. Let $\mathcal{M} = \{1, 2, \dots, M\}$, $\mathcal{N} = \{1, 2, \dots, N\}$, $\mathcal{L} = \{1, 2, \dots, L\}$, $\mathcal{S} = \{1, 2, \dots, S\}$, $\mathcal{K} = \{1, 2, \dots, K\}$ represent the set of APs, AP antennas, metasurfaces, meta-atoms for each metasurface layer, and users, respectively. The phase shift of the s -th meta-atom corresponding to the m -th AP is given by $e^{j\theta_{m,l}^s}$, $\forall m \in \mathcal{M}$, $\forall l \in \mathcal{L}$, $\forall s \in \mathcal{S}$, where $\theta_{m,l}^s \in [0, 2\pi)$. For $\theta_{m,l}^s$, the interval $\in [0, 2\pi)$ is quantized into discrete set of values $\alpha = [0, \zeta_\theta, 2\zeta_\theta, \dots, (2^b - 1)\zeta_\theta]$ of 2^b levels where b and $\zeta_\theta = \frac{2\pi}{2^b}$ represent the number of control bits and bit resolution, respectively. The phase shift diagonal matrix for the l -th metasurface of the m -th AP SIM is represented as

$$\boldsymbol{\theta}_{m,l} = \text{diag}(e^{j\theta_{m,l}^1}, \dots, e^{j\theta_{m,l}^S}). \quad (1)$$

We denote the transmission matrix from the l -th to the $(l-1)$ -th metasurface by $\mathbf{W}_{m,l} \in \mathbb{C}^{S \times S}$ and let $\mathbf{V}_m \in \mathbb{C}^{S \times N}$ be the transmission matrix from the N antennas to the input metasurface of the m -th AP SIM. The wave domain beamforming matrix at the m -th AP based on SIM is written as

$$\mathbf{G}_m = \boldsymbol{\theta}_{m,L} \mathbf{W}_{m,L} \boldsymbol{\theta}_{m,L-1} \cdots \boldsymbol{\theta}_{m,2} \mathbf{W}_{m,2} \boldsymbol{\theta}_{m,1} \in \mathbb{C}^{S \times S}. \quad (2)$$

Additionally, the (s, s') -th entry $w_{m,l}^{s,s'}$ of $\mathbf{W}_{m,l}$ according to the Rayleigh-Sommerfeld's diffraction theory is given by [9]

$$w_{m,l}^{s,s'} = \frac{A_s \cos \phi_{m,l}^{s,s'}}{d_{m,l}^{s,s'}} \left(\frac{1}{2\pi d_{m,l}^{s,s'}} - j \frac{1}{\lambda} \right) e^{-\frac{j2\pi d_{m,l}^{s,s'}}{\lambda}}, \quad (3)$$

where $A_s = \lambda^2/4$ is the area associated with each meta-atom, $\phi_{m,l}^{s,s'}$ is the angle between the propagation direction and the normal direction of the $(l-1)$ -th metasurface layer of the m -th AP, and the wavelength is represented as λ . $d_{m,l}^{s,n}$ is the transmission distance. The (s, n) -th entry $v_{m,l}^{s,n}$ of $\mathbf{V}_m$ can be obtained using (3) by substituting $\phi_{m,l}^{s,s'}$ with $\phi_{m,l}^{s,n}$

and $d_{m,l}^{s,s'}$ with $d_{m,l}^{s,n}$, respectively [3]. We consider a quasi-static channel between the last metasurface layer of AP- m and UE- k $\mathbf{h}_{m,k} \in \mathbb{C}^{S \times 1}$ modelled as correlated Rayleigh-fading where $\mathbf{h}_{m,k} \sim \mathcal{CN}(0, \beta_{mk} \mathbf{R}_m)$. β_{mk} denotes the distance-dependent pathloss (PL) between the m -th AP and the k -th UE and $\mathbf{R}_m \in \mathbb{C}^{S \times S}$ defines the covariance matrix between the corresponding meta-atoms. Assuming an isotropic scattering environment with uniformly distributed multi-path components, the (s, s') -th element of $\mathbf{R}_m$ is given by [10]

$$\mathbf{R}_m = \text{sinc} \left(\frac{2d_{m,l}^{s,s'}}{\lambda} \right). \quad (4)$$

The distance-dependent PL is expressed by

$$\beta_{mk} = F_s (d_{mk}/d_o)^{-\mu}, d_{mk} > d_o, \quad (5)$$

where F_s is the PL to a reference distance of $d_o = 1$ m, d_{mk} is the distance between m -th AP SIM and k -th UE.

III. DOWNLINK DATA TRANSMISSION

The APs split each users message into common and private parts. All the common messages are combined into a single common message s_c . We set $N = K + 1$, such that each of K antennas transmits a private message intended for a distinct user, whereas the remaining antenna is used to transmit the common message to all users. The received signal at the k -th user is expressed as

$$y_k = \sum_{m \in \mathcal{M}} p_{c,m}^{1/2} \mathbf{h}_{mk}^H \mathbf{G}_m \mathbf{v}_{c,m} s_c + \sum_{m \in \mathcal{M}} \sum_{i=1}^K \mathbf{h}_{mk}^H \mathbf{G}_m \mathbf{v}_{p,m}^i p_{mi}^{1/2} s_i + v_k, \quad (6)$$

where s_i is the private data symbol and $v_k \sim \mathcal{CN}(0, \sigma_k^2)$ is the additive white Gaussian noise at the k -th user. Let $n_c \in \mathcal{N}$ denote the antenna selected for common message transmission and $n_i \in \mathcal{N} \setminus \{n_c\}$ denote the antenna selected for the i -th private message. $\mathbf{v}_{c,m} = [\mathbf{V}_m]_{(:,n_c)} \in \mathbb{C}^{S \times 1}$, and $\mathbf{v}_{p,m}^i = [\mathbf{V}_m]_{(:,n_i)} \in \mathbb{C}^{S \times 1}$ refer to the common and private transmission vectors, respectively. $p_{c,m}$ and p_{mi} denote the common and private power allocation at the m -th AP, respectively, such that $p_{c,m} = tP_d$ and $p_{mi} = (1-t)P_d/K$, where t is the power-splitting factor and P_d is the power available at the AP. We define $\mathbf{p}_i = [\sqrt{p_{1i}}, \dots, \sqrt{p_{Mi}}]^T \in \mathbb{C}^{M \times 1}$, $\mathbf{p}_c = [\sqrt{p_{c,1}}, \dots, \sqrt{p_{c,M}}]^T \in \mathbb{C}^{M \times 1}$. The SINR for decoding the common message at the k -th user is given by

$$\gamma_{c,k} = \frac{|\mathbf{h}_k^H \bar{\mathbf{G}} \bar{\mathbf{V}}_c \mathbf{p}_c|^2}{\sum_{i=1}^K |\mathbf{h}_k^H \bar{\mathbf{G}} \bar{\mathbf{V}}_p^i \mathbf{p}_i|^2 + \sigma_k^2}. \quad (7)$$

After successfully applying successive interference cancellation to remove the common stream, the SINR for decoding the private message at the k -th user is given by

$$\gamma_{p,k} = \frac{|\mathbf{h}_k^H \bar{\mathbf{G}} \bar{\mathbf{V}}_p^k \mathbf{p}_k|^2}{\sum_{i=1, i \neq k}^K |\mathbf{h}_k^H \bar{\mathbf{G}} \bar{\mathbf{V}}_p^i \mathbf{p}_i|^2 + \sigma_k^2}, \quad (8)$$

where $\mathbf{h}_k \in \mathbb{C}^{MS \times 1}$, $\bar{\mathbf{G}} = \text{blkdiag}(\{\mathbf{G}_m\}_{m \in \mathcal{M}}) \in \mathbb{C}^{MS \times MS}$, $\bar{\mathbf{V}}_c = \text{blkdiag}(\{\mathbf{v}_{c,m}\}_{m \in \mathcal{M}}) \in \mathbb{C}^{MS \times M}$, $\bar{\mathbf{V}}_p^i = \text{blkdiag}(\{\mathbf{v}_{p,m}^i\}_{m \in \mathcal{M}}) \in \mathbb{C}^{MS \times M}$. The achievable rates of the common and private streams at the k -th user are respectively expressed as

$$\mathcal{R}_{c,k} = \log_2(1 + \gamma_{c,k}), \quad (9)$$

$$\mathcal{R}_{p,k} = \log_2(1 + \gamma_{p,k}). \quad (10)$$

To guarantee the successful decoding of the common stream by all users, we set $\mathcal{R}_c = \min_{k \in \mathcal{K}} \mathcal{R}_{c,k}$. Thus, the sum rate of the SIM-RS-CF mMIMO is given by

$$\mathcal{R} = \mathcal{R}_c + \sum_{k=1}^K \mathcal{R}_{p,k}. \quad (11)$$

A. Maximization of Sum rate

In this section, the power-splitting factor and the common message transmit antenna selection are jointly optimized to maximize the sum rate. The optimization problem is formulated as

$$\begin{aligned} & \underset{\{t, n_c\}}{\text{maximize}} \quad \mathcal{R}_c + \sum_{k=1}^K \mathcal{R}_{p,k} \\ & \text{subject to} \quad p_{c,m} + \sum_{i=1}^K p_{mi} \leq P_d, \quad \forall m \in \mathcal{M}, \\ & \quad 0 \leq t \leq 1, \\ & \quad n_c \in \{1, \dots, N\}, \end{aligned} \quad (12)$$

where the first constraint is the total per-AP power constraint, the second constraint controls the power-splitting factor and the last constraint restricts the common transmission antenna to the discrete set of antenna indices corresponding to the columns of $\mathbf{V}_m$. The problem in (12) is decomposed into two subproblems and solved using AO. For each fixed common-message transmit antenna ($n_c \in 1, \dots, N$), the optimal power-splitting factor is determined via GSS over $t \in [0, 1]$. GSS is known to efficiently narrow the search interval with minimal iterations, ensuring fast convergence to the optimal solution [11]. Subsequently, the corresponding optimal sum rate is evaluated for all feasible antenna indices, and the antenna yielding the highest sum rate is selected via exhaustive search. This approach jointly optimizes the power-splitting factor and common-message transmit antenna to maximize the sum rate. The detailed procedure is summarized in Algorithm 1.

IV. SIMULATION RESULTS

This section presents simulation results to evaluate the performance of the proposed system. We consider a $100 \text{ m} \times 100 \text{ m}$ area where $K = 4$ users and $M = 3$ SIM-equipped APs are randomly deployed. Each AP is equipped with $N = K + 1$ antennas and an identical SIM architecture comprising S meta-atoms per layer across $L = 3$ metasurface layers, with total thickness $T_{\text{SIM}} = 5\lambda$ and inter-layer spacing $d_{\text{layer}} = T_{\text{SIM}}/L$. Also, we have $\cos\phi_{m,l}^{s,s'} = d_{\text{layer}}/d_{m,l}^{s,s'}$. The carrier frequency is set to 28 GHz, with path loss exponent

Algorithm 1 AO-Based Joint Power Splitting and Antenna Selection

- 1: Initialize candidate antenna set $\mathcal{N} = \{1, \dots, N\}$, tolerance ϵ
 - 2: Set golden ratio $\phi = (\sqrt{5} - 1)/2$
 - 3: $\mathcal{R}^* = 0$
 - 4: **for** each $n_c \in \mathcal{N}$ **do**
 - 5: Set $t_{\min} = 0$, $t_{\max} = 1$
 - 6: **while** $|t_{\max} - t_{\min}| > \epsilon$ **do**
 - 7: $t_1 = t_{\max} - \phi(t_{\max} - t_{\min})$
 - 8: $t_2 = t_{\min} + \phi(t_{\max} - t_{\min})$
 - 9: **if** $\mathcal{R}(t_1, n_c) > \mathcal{R}(t_2, n_c)$ **then**
 - 10: $t_{\max} = t_2$
 - 11: **else**
 - 12: $t_{\min} = t_1$
 - 13: **end if**
 - 14: **end while**
 - 15: $t^*(n_c) = \frac{t_{\min} + t_{\max}}{2}$
 - 16: Compute $\mathcal{R}^*(n_c) = \mathcal{R}(t^*(n_c), n_c)$
 - 17: **if** $\mathcal{R}^*(n_c) > \mathcal{R}^*$ **then**
 - 18: $\mathcal{R}^* = \mathcal{R}^*(n_c)$
 - 19: $n_c^* = n_c$
 - 20: $t^* = t^*(n_c)$
 - 21: **end if**
 - 22: **end for**
 - 23: **Output:** Optimal antenna n_c^* , optimal power-splitting factor t^* , and maximum sum rate $\mathcal{R}^*$.
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$\mu = 3.5$, reference pathloss $F_s = -30$ dB, noise power $\sigma_k^2 = -92$ dBm, $\forall k \in \mathcal{K}$, and transmit power $P_d = 15$ dBm, $\forall m \in \mathcal{M}$. Random phase shifts are assigned to the meta-atoms. This work proposes an RS-CF mMIMO SIM system, where an AO is utilized to jointly optimize the common-private power-splitting and the antenna selection for common message transmission. The proposed scheme, denoted as RS-CF SIM-opt, is benchmarked against RS-CF SIM with power-splitting optimization only and the conventional CF SIM scheme without rate-splitting. In the RS-CF SIM scheme, the common-message transmit antenna is fixed to the N -th antenna, such that $\mathbf{v}_{c,m} = [\mathbf{V}_m]_{(:,N)} \in \mathbb{C}^{S \times 1}$, while the i -th private message is transmitted through the i -th antenna, i.e., $\mathbf{v}_{p,m}^i = [\mathbf{V}_m]_{(:,i)} \in \mathbb{C}^{S \times 1}$.

Fig. 1 shows the sum rate versus transmit power P_d . The sum rate increases with P_d for all schemes. The RSMA schemes consistently outperform CF-SIM, with the performance gap widening at high P_d due to the ability of RSMA to mitigate increasing multi-user interference through flexible power allocation. In addition, the sum rate increases with the number of meta-atoms due to the increased spatial degrees of freedom. Notably, the proposed RS-CF SIM-opt achieves significant gains over the benchmark schemes. At $P_d = 15$ dBm, and $S = 49$, RS-CF SIM achieves 8.00% performance gain over CF-SIM, which increases to 32.65% with RS-CF SIM-opt. Furthermore, the CF-SIM performance saturates beyond $P_d = 15$ dBm, whereas the RSMA schemes continue to

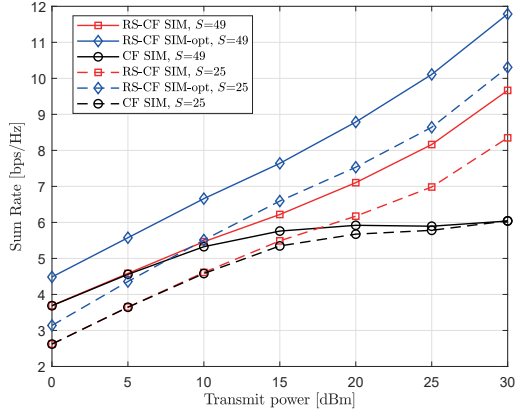


Fig. 1. Sum rate versus transmit power.

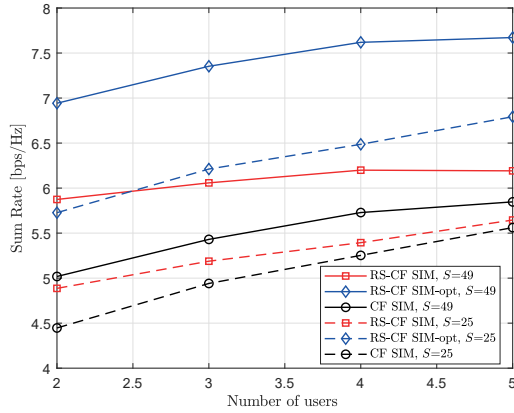


Fig. 2. Sum rate versus the number of users.

improve, highlighting the effectiveness of RSMA in exploiting the high transmit power potential of SIM-assisted CF mMIMO systems.

Fig. 2 illustrates the sum rate versus the number of users K . The sum rate increases with K across all configurations. The RSMA strategies consistently outperform CF-SIM, highlighting the ability of RSMA to mitigate interference. The performance gap of the RS-CF-SIM approach decreases with the number of users because the common message rate is constrained by the weakest user's decoding capability. However, RS-CF SIM-opt exploits the optimal common message transmit antenna selection to enhance the performance gap even with increasing K . Specifically, for $S = 25$, RS-CF SIM-opt increases the gain over CF-SIM for $K = 2$ – 5 from approximately 9.89–1.51% with RS-CF SIM to 28.80–22.15%. Furthermore, increasing the number of meta-atoms enhances the gain of the RSMA frameworks.

V. CONCLUSION

This paper proposes an RSMA-enabled SIM-assisted CF mMIMO framework that employs GSS-based power splitting and exhaustive-search-based common-message transmit antenna selection for sum rate maximization. Numerical results confirm that the RSMA schemes consistently outperform the

conventional CF-SIM system. The proposed RS-CF SIM-opt achieves the highest sum rate performance among all considered schemes, delivering substantial gains over the conventional CF-SIM system. Moreover, these gains become more pronounced as the number of meta-atoms increases. We finally note that extending SIM-assisted CF massive MIMO to incorporate RSMA with joint SIM phase-shift and power optimization is a promising direction for future research.

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