

Impact of Low-Resolution ADCs on SIM-Aided Cell-Free Massive MIMO Under Fronthaul Constraints

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Abstract—Cell-free massive multiple-input multiple-output (CF-mMIMO) removes conventional cell boundaries by coordinating distributed APs through a central processing unit (CPU), providing the uniform coverage required by sixth-generation (6G) networks. Its deployment, however, is hindered by the hardware cost of one radio-frequency (RF) chain per antenna, high power consumption, and limited fronthaul capacity. To address these, we propose a downlink CF-mMIMO architecture that combines stacked intelligent metasurface (SIM)-based hybrid beamforming with low-resolution analog-to-digital converters (ADCs) at the user equipment (UE). Under the limited fronthaul, the wave-domain SIM can achieve a sum rate close to that of conventional digital beamforming with significantly fewer RF chains, while the low-resolution ADCs reduce UE power consumption. We jointly optimize the digital and wave-domain beamformers to maximize the achievable sum rate and evaluate the resulting energy efficiency. Numerical results show that the energy efficiency peaks at a moderate ADC resolution, confirming that a coarse ADC is the energy-efficient choice, and that the number of SIM layers trades energy efficiency against sum rate, with fewer layers favoring efficiency and more layers favoring rate.

Index Terms—Cell-free massive MIMO, stacked intelligent metasurface, hybrid beamforming, low-resolution ADC, sum-rate optimization, energy efficiency.

I. INTRODUCTION

Cell-free massive multiple-input multiple-output (CF-mMIMO), a key candidate technology for sixth-generation (6G) networks, distributes many access points (APs) over a wide area under the control of a central processing unit (CPU) [1], [2]. By removing conventional cell boundaries, it delivers seamless and uniform service. Such coverage, however, demands many APs and large per-AP arrays, which inevitably raise implementation cost and power consumption and create a fronthaul bottleneck. To curb the implementation cost, the

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stacked intelligent metasurface (SIM) has been introduced to reduce the number of RF chains.

SIM [3]–[5] comprises multiple programmable metasurface layers that beamform in the electromagnetic wave domain and is known to approach fully-digital performance with significantly fewer RF chains. Combined with digital processing, such hybrid beamforming balances cost and performance. In parallel, low-resolution ADCs [6]–[8] are widely adopted for hardware efficiency. Since ADC power grows exponentially with the resolution bits b [6], coarse quantization saves power at the cost of a rate loss due to quantization noise (QN).

Prior works applied either low-resolution ADCs [6], [8] or SIM [5], [9] to CF-mMIMO separately. In this paper, we combine fronthaul-constrained SIM-based hybrid beamforming with UE-side low-resolution ADCs in the downlink and analyze its sum-rate and energy-efficiency performance, showing that a coarse ADC is energy-efficient while the SIM depth trades energy efficiency against sum rate.

II. SYSTEM MODEL

We consider a downlink CF-mMIMO system comprising A APs, indexed by $\mathcal{A} = \{1, \dots, A\}$, and K single-antenna UEs, indexed by $\mathcal{K} = \{1, \dots, K\}$. Each AP has N antennas (one RF chain each) and a SIM of L layers, each with M meta-atoms, placed between the antennas and the air interface. The CPU connects to each AP via a fronthaul link of capacity C_F [bps/Hz], and each UE uses a low-resolution ADC. We process signals per AP, i.e., in N dimensions, rather than stacking all APs into one long vector.

The CPU jointly precodes each UE symbol $s_k \sim \mathcal{CN}(0, 1)$ across the APs, so AP a transmits

$$\mathbf{x}_a = \sum_{k \in \mathcal{K}} \mathbf{p}_{k,a} s_k \in \mathbb{C}^N, \quad (1)$$

where $\mathbf{p}_{k,a} \in \mathbb{C}^N$ is the beamformer for UE k at AP a . For the finite-capacity fronthaul, the CPU quantizes $\mathbf{x}_a$ with a Gaussian test channel model that represents the quantization error as additive Gaussian noise [5], [7], producing the compressed signal

$$\hat{\mathbf{x}}_a = \mathbf{x}_a + \mathbf{q}_a, \quad \mathbf{q}_a \sim \mathcal{CN}(\mathbf{0}, \mathbf{\Omega}_a). \quad (2)$$

Reliable decompression and the per-AP power budget $\mathcal{P}_A$ require

$$\log_2 \det \left(\sum_k \mathbf{p}_{k,a} \mathbf{p}_{k,a}^H + \boldsymbol{\Omega}_a \right) - \log_2 \det(\boldsymbol{\Omega}_a) \leq C_F, \quad (3)$$

$$\sum_k \|\mathbf{p}_{k,a}\|^2 + \text{tr}(\boldsymbol{\Omega}_a) \leq \mathcal{P}_A. \quad (4)$$

The decompressed signal propagates through the SIM, yielding the radiated signal $\tilde{\mathbf{x}}_a = \mathbf{G}_a \hat{\mathbf{x}}_a \in \mathbb{C}^M$ with

$$\mathbf{G}_a = \boldsymbol{\Phi}_{a,L} \mathbf{W}_{a,L} \cdots \boldsymbol{\Phi}_{a,2} \mathbf{W}_{a,2} \boldsymbol{\Phi}_{a,1} \mathbf{T}_a \in \mathbb{C}^{M \times N}, \quad (5)$$

where $\boldsymbol{\Phi}_{a,l} = \text{diag}(e^{j\theta_{a,l,1}}, \dots, e^{j\theta_{a,l,M}})$ holds the layer- l phase shifts $\theta_{a,l,m} \in [0, 2\pi)$, which are the optimization variables. The fixed antenna-to-layer matrix $\mathbf{T}_a$ and inter-layer matrices $\mathbf{W}_{a,l}$ ($l = 2, \dots, L$) follow the Rayleigh-Sommerfeld diffraction model, whose entries are given by [3]

$$[\mathbf{W}_{a,l}]_{m,m'} = \frac{S \cos \chi_{m,m'}}{r_{m,m'}} \left(\frac{1}{2\pi r_{m,m'}} - \frac{j}{\lambda} \right) e^{j2\pi r_{m,m'}/\lambda} \quad (6)$$

where S is the meta-atom area, $r_{m,m'}$ is the distance from the m' -th meta-atom on layer $l-1$ to the m -th meta-atom on layer l , $\chi_{m,m'}$ is the angle the propagation direction makes with the normal direction of the $(l-1)$ -th metasurface layer of AP a , and λ is the wavelength. The entries of $\mathbf{T}_a$ are obtained analogously.

Let $\mathbf{h}_{k,a} \in \mathbb{C}^M$ be the channel from AP a 's SIM output to UE k , modeled as correlated Rayleigh fading $\mathbf{h}_{k,a} \sim \mathcal{CN}(\mathbf{0}, \beta_{k,a} \mathbf{R})$, where $\beta_{k,a}$ is the large-scale fading coefficient and $\mathbf{R}$ is the meta-atom spatial correlation matrix with $[\mathbf{R}]_{n,n'} = \text{sinc}(2d_{n,n'}/\lambda)$ for inter-atom spacing $d_{n,n'}$. Defining the effective channel $\tilde{\mathbf{h}}_{k,a}^H = \mathbf{h}_{k,a}^H \mathbf{G}_a$, the aggregate gain $d_{k,j} \triangleq \sum_{a \in \mathcal{A}} \tilde{\mathbf{h}}_{k,a}^H \mathbf{p}_{j,a}$, and the fronthaul-noise power $\nu_k \triangleq \sum_{a \in \mathcal{A}} \mathbf{h}_{k,a}^H \boldsymbol{\Omega}_a \mathbf{h}_{k,a}$, the UE receives

$$y_k = d_{k,k} s_k + \sum_{j \neq k} d_{k,j} s_j + \sum_{a \in \mathcal{A}} \tilde{\mathbf{h}}_{k,a}^H \mathbf{q}_a + n_k, \quad (7)$$

where $n_k \sim \mathcal{CN}(0, \sigma_n^2)$ is the additive white Gaussian noise (AWGN) at UE k . The UE then quantizes y_k with a low-resolution ADC. By the additive quantization noise model (AQNM) [8],

$$\tilde{y}_k = \alpha y_k + n_{q,k}, \quad (8)$$

where $\alpha = 1 - \zeta$ is the quantization gain, with the distortion factor ζ depending on the resolution b ($\zeta \approx \frac{\pi\sqrt{3}}{2} 2^{-2b}$ for $b > 5$), and $n_{q,k} \sim \mathcal{CN}(0, r_{q,k})$ is the quantization noise (QN), uncorrelated with y_k and of variance $r_{q,k} = \alpha(1-\alpha)\mathbb{E}\{|y_k|^2\}$ with $\mathbb{E}\{|y_k|^2\} = \sum_j |d_{k,j}|^2 + \nu_k + \sigma_n^2$.

Substituting $r_{q,k}$ into the post-quantization SINR obtained from (8) and simplifying, the SINR of UE k is

$$\text{SINR}_k = \frac{\alpha |d_{k,k}|^2}{\sum_{j \neq k} |d_{k,j}|^2 + (1-\alpha)|d_{k,k}|^2 + \nu_k + \sigma_n^2}, \quad (9)$$

and $R_k = \log_2(1 + \text{SINR}_k)$. Since the term $(1-\alpha)|d_{k,k}|^2$ in the denominator grows in proportion to the desired signal

power $|d_{k,k}|^2$, the SINR saturates at $\alpha/(1-\alpha)$, the fundamental rate limit set by the UE's coarse quantization.

Finally, to evaluate the energy efficiency (EE), defined as

$$\text{EE} = \frac{B \sum_{k \in \mathcal{K}} R_k}{P_{\text{tot}}} \quad [\text{bits/Joule}] \quad (10)$$

with system bandwidth B , we adopt the cell-free power model of [8], [10] augmented with the SIM power, so that the total power consumption is

$$P_{\text{tot}} = A \left(\frac{\mathcal{P}_A}{\eta} + NP_{\text{RF}} + P_0 + BC_F P_{\text{bt}} + P_{\text{con}} + LMP_{\text{atom}} \right) + K(P_{\text{rx}} + P_{\text{ADC}}), \quad (11)$$

where the per-AP cost combines the transmit power $\mathcal{P}_A$ over efficiency η , the RF-chain power NP_{RF} , the fronthaul power $P_0 + BC_F P_{\text{bt}}$ (a fixed per-link term P_0 and a traffic term $BC_F P_{\text{bt}}$ proportional to the fronthaul rate BC_F), the fixed SIM-controller power P_{con} , and the SIM power LMP_{atom} [11], while the per-UE cost combines the receive-chain power $P_{\text{rx}} = P_{\text{LNA}} + P_{\text{mix}} + P_{\text{IFA}} + P_{\text{filt}} + P_{\text{syn}} + cP_{\text{AGC}}$ ($c = 0$ for $b = 1$, otherwise $c = 1$) and the ADC power. The ADC power follows [8]

$$P_{\text{ADC}} = \frac{3V_{dd}^2 L_{\min}(2B + f_{\text{corr}})}{10^{-0.1525b+4.838}}, \quad (12)$$

which increases with the resolution b . Here, V_{dd} , $L_{\min}$, and f_{corr} denote the supply voltage, the minimum channel length, and the corner frequency, respectively.

III. SIM HYBRID BEAMFORMING OPTIMIZATION

We maximize the sum rate over the digital beamformers $\{\mathbf{p}_{k,a}\}$, the fronthaul covariances $\{\boldsymbol{\Omega}_a\}$, and the SIM phases $\{\theta_{a,l,m}\}$. The optimization problem is formulated as

$$\max_{\{\mathbf{p}_{k,a}\}, \{\boldsymbol{\Omega}_a\}, \boldsymbol{\theta}} \sum_{k \in \mathcal{K}} R_k \quad (13a)$$

$$\text{s.t.} \quad \log_2 \det \left(\sum_k \mathbf{p}_{k,a} \mathbf{p}_{k,a}^H + \boldsymbol{\Omega}_a \right) - \log_2 \det(\boldsymbol{\Omega}_a) \leq C_F, \quad \forall a, \quad (13b)$$

$$\sum_k \|\mathbf{p}_{k,a}\|^2 + \text{tr}(\boldsymbol{\Omega}_a) \leq \mathcal{P}_A, \quad \forall a, \quad (13c)$$

$$\boldsymbol{\Omega}_a \succeq \mathbf{0}, \quad \theta_{a,l,m} \in [0, 2\pi), \quad \forall a. \quad (13d)$$

Problem (13) is non-convex, since the objective is a sum of log-ratios, the variables $\{\mathbf{p}_{k,a}\}$, $\{\boldsymbol{\Omega}_a\}$, and $\boldsymbol{\theta}$ are mutually coupled, and the fronthaul constraint is a difference of two log det terms. The only addition over the downlink problem of [5] is the UE-side quantization noise, whose terms $(1-\alpha)|d_{k,k}|^2$ and ν_k are quadratic in $\{\mathbf{p}_{k,a}\}$ and linear in $\{\boldsymbol{\Omega}_a\}$ and thus fit the same fractional-programming (FP) form without altering its structure. We therefore adopt the alternating-optimization (AO) algorithm of [5], updating the digital block $\{\mathbf{p}_{k,a}, \boldsymbol{\Omega}_a\}$ and the wave-domain block $\boldsymbol{\theta}$ in turn while the other is held fixed.

For fixed θ , the effective channels $\tilde{\mathbf{h}}_{k,a}$ are constant. By the matrix Lagrangian-duality (FP) bound of [12], each rate $R_k = \log_2(1 + \text{SINR}_k)$ is replaced by the concave surrogate

$$\tilde{R}_k = \log_2(1 + \tau_k) - \frac{\tau_k}{\ln 2} + \frac{1 + \tau_k}{\ln 2} \left(2\sqrt{\alpha} \text{Re}\{\omega_k^* d_{k,k}\} - |\omega_k|^2 e_k \right), \quad (14)$$

where $e_k = \sum_j |d_{k,j}|^2 + \nu_k + \sigma_n^2$, which lower-bounds R_k with equality at the closed-form auxiliary values $\tau_k = \text{SINR}_k$ and $\omega_k = \sqrt{\alpha} d_{k,k}/e_k$. Since $d_{k,j}$ is linear in $\{\mathbf{p}_{k,a}\}$, the objective $\sum_k \tilde{R}_k$ is concave in $\{\mathbf{p}_{k,a}\}$ for fixed $\{\tau_k, \omega_k\}$. The fronthaul constraint (3) remains non-convex because its first log det term is concave, so we replace that term by its first-order Taylor upper bound through Fenchel's inequality [5] and obtain a convex restriction. The resulting convex problem in $\{\mathbf{p}_{k,a}, \Omega_a\}$ is solved by a standard solver such as CVX, in alternation with the closed-form auxiliary updates until this block converges.

For fixed $\{\mathbf{p}_{k,a}, \Omega_a\}$, the phases enter only through the unit-modulus terms $e^{j\theta_{a,l,m}}$, so the θ -subproblem is unconstrained and is updated by gradient ascent (GA) as

$$\theta^{(t+1)} = \theta^{(t)} + \mu \nabla_{\theta} \sum_k R_k(\theta^{(t)}), \quad (15)$$

where t is the iteration index, the gradient $\nabla_{\theta} \sum_k R_k$ is obtained by the chain rule through the phase-shift matrices $\Phi_{a,l}(\theta)$ embedded in $\mathbf{G}_a$, and the step size μ is set by backtracking line search.

The two blocks are updated alternately until the sum rate converges. Since each update is non-decreasing and the objective is bounded above by the power and fronthaul constraints, the AO algorithm converges to a stationary point of (13).

IV. SIMULATION RESULTS

We consider $A = 10$ APs and $K = 20$ single-antenna UEs dropped uniformly at random over a $500 \times 500 \text{ m}^2$ area [7], where each AP has $N = 2$ RF chains and a SIM whose L layers each comprise $M = 16$ meta-atoms in a 4×4 array. Unless stated otherwise, the per-AP power budget is $\mathcal{P}_A = 15 \text{ dBm}$, the fronthaul capacity is $C_F = 5 \text{ bps/Hz}$, the bandwidth is $B = 15.36 \text{ MHz}$, and the noise power is $\sigma_n^2 = -95.14 \text{ dBm}$. The large-scale fading coefficient $\beta_{k,a}$ follows the 3GPP 38.901 urban-microcell street-canyon model given by [7], [13]

$$\beta_{k,a} [\text{dB}] = - (32.4 + 20 \log_{10}(f_c) + 31.9 \log_{10}(d) - \mathcal{N}(0, 8.2^2)) \quad (16)$$

at a carrier frequency $f_c = 8 \text{ GHz}$ and with log-normal shadowing, where d is AP-UE distance. The AQNM coefficient follows the standard values [8], giving $\alpha = 0.637, 0.882, 0.991$ for $b = 1, 2, 4$ bits ($\alpha = 1$ for the ideal case $b = \infty$).

For the power model (11)–(12), we set the PA efficiency $\eta = 0.4$, the per-RF-chain power $P_{\text{RF}} = 0.2 \text{ W}$, and the fronthaul powers $P_0 = 0.825 \text{ W}$ and $P_{\text{bt}} = 0.25 \text{ W/Gbps}$ [10], while

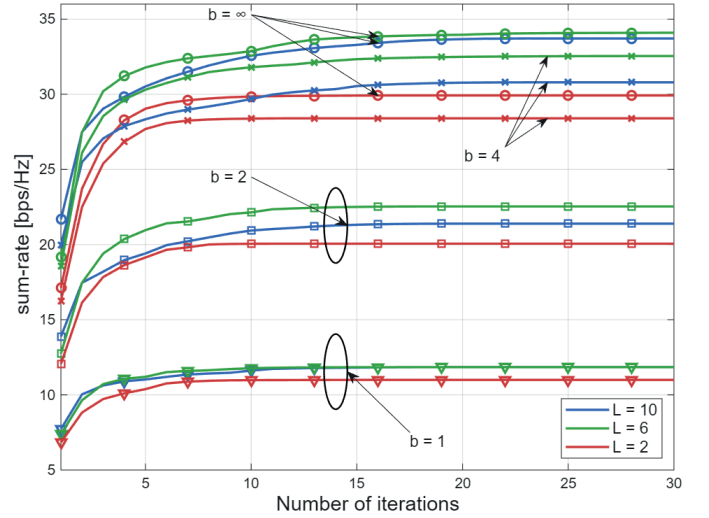


Fig. 1. Sum rate versus the number of AO iterations ($A = 10$, $K = 20$, $\mathcal{P}_A = 15 \text{ dBm}$, $C_F = 5 \text{ bps/Hz}$).

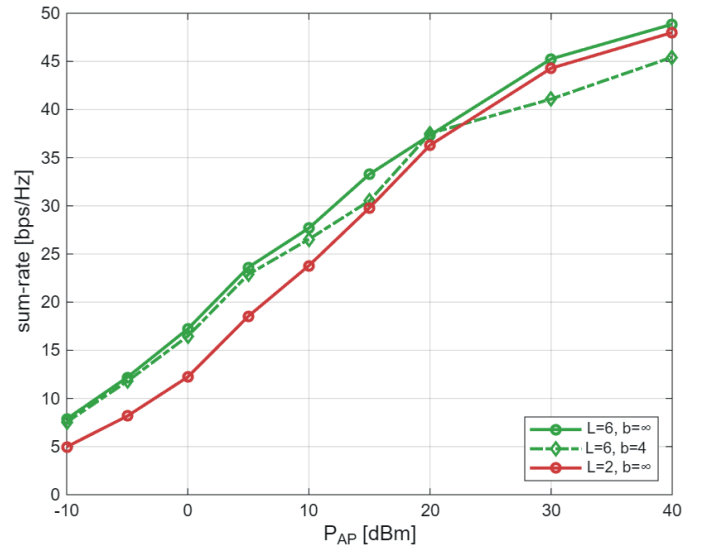


Fig. 2. Sum rate versus the per-AP power $\mathcal{P}_A$ for low- and ideal-resolution SIMs with different numbers of layers.

the SIM uses a controller power $P_{\text{con}} = 316 \text{ mW}$ and a per-meta-atom power $P_{\text{atom}} = 10 \text{ mW}$ [11]. On the UE side, the receive-chain power is $P_{\text{rx}} = 105.8 \text{ mW}$ (the LNA, mixer, IFA, filter, and synthesizer combined) plus $P_{\text{AGC}} = 2.5 \text{ mW}$ for $b > 1$, and the ADC uses $V_{dd} = 3 \text{ V}$, $L_{\text{min}} = 0.5 \mu\text{m}$, and $f_{\text{corr}} = 1 \text{ MHz}$ [8]. The EE is computed from (10)–(12).

Fig. 1 shows the sum rate versus the number of AO iterations for $L \in \{2, 6, 10\}$ and $b \in \{1, 2, 4, \infty\}$. Every configuration increases monotonically and converges within about 15 iterations, corroborating the convergence analysis in Sec. III. A larger number of layers yields a higher sum rate, showing that the SIM achieves a high sum rate with only a few RF chains. Notably, even a 4-bit ADC ($b = 4$) already achieves a sum rate close to that of the ideal unquantized ($b = \infty$) ADC, recovering most of the achievable rate.

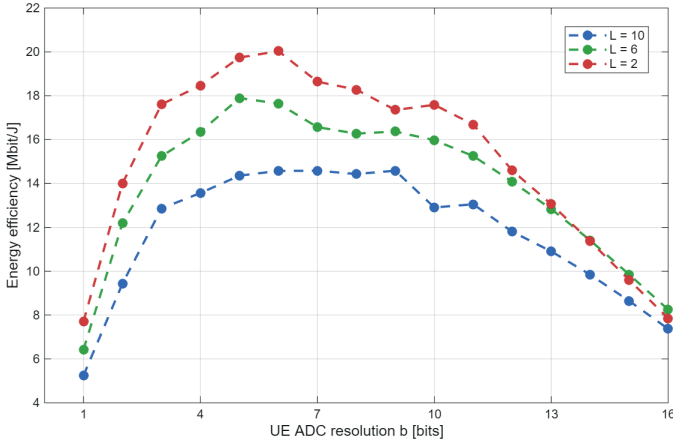


Fig. 3. Energy efficiency versus the UE ADC resolution b ($P_A = 15$ dBm, $C_F = 5$ bps/Hz).

Fig. 2 plots the sum rate against the per-AP power P_A . The sum rate increases with both the transmit power and the number of layers, and over the low-to-moderate power range the 4-bit curves stay close to the ideal-ADC ones, indicating a small rate loss from the low-resolution ADCs. At high power, however, the 4-bit curves saturate at the SINR ceiling $\alpha/(1-\alpha)$, because raising the transmit power scales up $(1-\alpha)|d_{k,k}|^2$ in step with the desired signal $|d_{k,k}|^2$, whereas the ideal-ADC curves keep growing.

Fig. 3 shows the EE against the ADC resolution b . For every layer count the EE peaks at a moderate resolution ($b = 5, b = 6$) and decreases as b grows, because the ADC power rises exponentially with b . hence a coarse ADC, rather than a high-resolution one, is the energy-efficient choice. Across layers, $L = 2$ achieves the highest EE, followed by $L = 6$ and then $L = 10$, since the SIM power scales with the number of layers. A deeper SIM thus trades energy efficiency for the higher sum rate it delivers, so the number of layers should balance sum rate against power consumption.

V. CONCLUSION

In this paper, we proposed a downlink SIM-based CF-mMIMO architecture with UE-side low-resolution ADCs and applied the AO framework of [5] to jointly optimize the digital and wave-domain beamformers under a finite-capacity fronthaul. Numerical results showed that the proposed algorithm converges within about 15 iterations, that the SIM achieves a high sum rate with few RF chains, and that even a 4-bit ADC achieves a sum rate close to that of the ideal unquantized ADC. Moreover, the energy efficiency peaks at a moderate ADC resolution ($b \approx 5-6$), so a coarse UE ADC is the energy-efficient choice, while the number of SIM layers governs a trade-off between energy efficiency (favoring fewer layers) and sum rate (favoring more layers).

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