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# Low-Complexity RF Chains Activation Based on Hungarian Algorithm for Uplink Cell-Free Millimetre-Wave Massive MIMO Systems

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***Abstract*—The increasing demand for throughput, ultra-low latency, ultra-high reliability, and ubiquitous coverage have made researchers explore several novel solutions to set the basis for future generations of wireless communications. These demands, however, will consume a significant amount of resources, particularly in the case of cell-free millimetre-wave (mm-Wave) massive multiple input multiple output systems (MIMO), which is the promising approach for future wireless generations. In this paper, we propose a novel and low-complexity matching approach to dynamically activate a set of radio frequency (RF) chains based on the Hungarian algorithm to maximize the total energy efficiency in the uplink of the cell-free mm-Wave massive MIMO systems. Simulation results demonstrate that our proposed scheme achieves up to $13.5\%$, $20\%$ and $58.7\%$ energy efficiency improvement compared to state-of-the-art adaptive RF chains activation (ARFA), random access point activation and fixed activation scheme when all RF chains at each AP are switched on, respectively. In addition, compared to the ARFA scheme, the proposed matching scheme achieves a complexity reduction ratio of up to $189.6\%$.**

***Index Terms*—Cell-free, massive MIMO, RF Chains, Hungarian algorithm, hybrid beamforming.**

## I. INTRODUCTION

Due to the availability of very wide bandwidth, much research has been concentrated on achieving very high data rates by leveraging the mm-Wave range of frequencies. Unfortunately, mm-Wave suffers considerable propagation loss from a communication point of view due to its high frequency. This issue can be handled by effective implementation of mm-Wave massive MIMO systems employing large antenna arrays with beamforming techniques to offset the influence of path loss [1], [2]. However, the use of fully digital beamforming in massive MIMO architecture is thought to have a severe detriment in terms of power consumption and production costs [3]. To counter this, a large antenna array is connected to limited RF chains via high dimensional RF precoders that are implemented by analog phase shifters and low dimensional baseband digital precoders, resulting in hybrid beamforming. Additionally, the cell-free massive MIMO has been proposed to achieve high QoS, in which a large number of access points (APs) are connected to a central processing unit (CPU) and are generally deployed for servicing fewer users with the same resources [3], [4].

The performance of the cell-free mm-Wave massive MIMO systems was studied using a hybrid beamforming technique with limited fronthaul capacity, in which precoders and combiners were created using an eigen beamforming scheme to find a balance between fronthaul and data rate requirements [3]. In the cell-free massive MIMO systems with large number of distributed APs and limited number of RF chains at each AP, power consumption is proportional to both RF chains and APs [4]. It is obvious that turning off some RF chains at each AP will reduce the total power consumption of the cell-free MIMO system. However, the optimal number of active RF chains at each AP must be obtained to reduce the performance loss caused by switching off of some RF chains. When dealing with a huge number of APs, an exhaustive search approach achieves optimal results but with prohibitive computational complexity. Accordingly, the authors in [4] proposed the ARFA scheme with fast search algorithms to obtain the optimal number of active RF chains at each AP based on global channel state information (CSI), where the fully connected hybrid beamformer is individually created at each AP. Additionally, a hybrid beamforming technique with fixed phase shifters based on alternating minimization algorithm for the uplink cell-free massive MIMO system was presented in [5]. While these approaches are less computationally demanding compared to exhaustive search, their complexities significantly increases with the size of the network.

In this paper, to allocate each AP to the optimal set of RF chains, we propose an efficient low-complexity algorithm based on matching theory in order to maximize the total energy efficiency for the cell-free network. The following are the paper's most significant contributions.

- We formulate maximum-weighted assignment optimization problem to assign each AP to its optimal number of active RF chains that can maximize the total energy efficiency of the cell-free massive MIMO network.
- We propose a novel matching method based on the Hungarian algorithm to solve the formulated optimization problem and obtain the maximum total energy efficiency.
- We study the complexity analysis of the proposed scheme compared to the state-of-the-art schemes.

The remainder of this paper is organized as follows. Section II presents the system model, while the problem formulation and the proposed solution are presented in Section III. Section IV provides the complexity analysis of our proposed matching algorithm. Simulation results and discussions are provided in

Section V. We conclude our paper in Section VI.

## II. SYSTEM MODEL

Consider the uplink of cell-free mm-Wave massive MIMO system, where $M$ APs and $K$ single-antenna User Equipment (UEs) are randomly distributed in the coverage area. Also, fronthaul links are used to connect the APs to the CPU, in which each AP is equipped with $N_r$ receive antennas and $N(\leq N_r)$ RF chains as presented in [4]. Furthermore, each AP has a fully connected analog combining architecture and a narrowband-block fading channel model is applied as the propagation environment between $M$ APs and $K$ UEs [1], [2].

The channel between $m_{th}$ AP and $k_{th}$ UE is denoted by $h_{k,m} \in \mathbb{C}^{N_r \times 1}$ and obtained by the geometric Saleh-Valenzuela channel which is the typical channel model in mm-Wave systems. Therefore, $h_{k,m}$ is given as [1], [4], [6], [12]

$$h_{k,m} = \sqrt{\frac{G_a N_r}{\beta_{k,m} \omega_{k,m}}} \sum_{\omega=1}^{\omega_{k,m}} \alpha_{k,m}^{(\omega)} \mathbf{a}_r(\phi_{k,m}^{(\omega)}), \tag{1}$$

where $G_a$ denotes the antenna gain, and $\beta_{k,m}$ represents large scale fading between the $k_{th}$ UE and $m_{th}$ AP. Moreover, the pathloss model is expressed as

$$\beta_{k,m}[dB] = 10\log_{10}(\frac{4\pi d_o}{\lambda})^2 + 10\,\varepsilon \log_{10}(\frac{d_{k,m}}{d_o}) + \chi_{k,m}, \tag{2}$$

where $d_o$ is the reference distance which is equal one, $\lambda$ is the wavelength, $d_{k,m}$ represents the distance between $m_{th}$ AP and $k_{th}$ UE, the average pathloss exponent over the distance is represented by $\varepsilon$, and $\chi_{k,m} \sim \mathcal{N}(0, \varsigma^2)$ gives the shadow fading component with zero mean Gaussian random variable and $\varsigma$ standard deviation. Furthermore, $\omega_{k,m}$ represents the number of the propagation paths; the complex small scale fading gain is denoted by $\alpha_{k,m}^{(\omega)} \sim \mathcal{CN}(0,1)$ for all the APs and UEs in the service area; and $\phi_{k,m}^{(\omega)} \in [0, 2\pi]$ is known as the Azimuth Angle of Arrival (AoA) for each channel path. Each AP is assumed to be equipped with a Uniform Linear Array (ULA) and this structure of the antenna array is utilized to obtain the receive array response vector at $m_{th}$ AP, where $\mathbf{a}_r$ is given by $\mathbf{a}_r(\phi) = \frac{1}{\sqrt{N_r}}[1, e^{j\frac{2\pi}{\lambda} d_s \sin\phi}, ..., e^{j(N_r-1)\frac{2\pi}{\lambda} d_s \sin\phi}]^T$, where $d_s$ denotes the antenna spacing [1]. Finally, let us consider $\mathcal{A}_{k,m} = [\mathbf{a}_r(\phi_{k,m}^{(1)}), ..., \mathbf{a}_r(\phi_{k,m}^{(\omega_{k,m})})] \in \mathbb{C}^{N_r \times \omega_{k,m}}$ and $\Upsilon_{k,m} = [\alpha_{k,m}^{(1)}, ..., \alpha_{k,m}^{(\omega_{k,m})}] \in \mathbb{C}^{\omega_{k,m} \times 1}$. Then, $h_{k,m}$ can be expressed [4] as $h_{k,m} = \sqrt{\frac{G_a N_r}{\beta_{k,m}\omega_{k,m}}} \mathcal{A}_{k,m} \Upsilon_{k,m}$. Thus, $h_{k,m} \sim \mathcal{CN}(0, \sqrt{\frac{G_a N_r}{\beta_{k,m}\omega_{k,m}}} \mathbb{E}\{\mathcal{A}_{k,m}\mathcal{A}_{k,m}^H\})$. In addition, the channel matrix between $K$ UEs and $m_{th}$ AP is $H_m = [h_{1,m}, ..., h_{k,m}] \in \mathbb{C}^{N_r \times K}$ and the composite channels between $K$ UEs and all APs in the coverage area can be expressed as $H = [H_1, ..., H_M]^T \in \mathbb{C}^{MN_r \times K}$.

### A. Uplink Channel Estimation

Let $\tau_p$ represent the uplink training phase duration which is smaller than the duration of the coherence interval $\tau_c$, such that the transmitted pilot by $k_{th}$ UE is given as $\sqrt{\tau_p}\varphi_k \in \mathbb{C}^{\tau_p \times 1}$, where $||\varphi_k||^2 = 1$ and $k = 1, ..., K$. Thus, the received pilots at $m_{th}$ AP from $K$ UEs, is expressed by $Y_m = \sqrt{\tau_p \rho_p} \sum_{k=1}^{K} h_{k,m} \varphi_k^H + Z_m$, where $\rho_p$ denotes the transmit power of each pilot sequence sent by $k_{th}$ UE, and $Z_m \in \mathbb{C}^{N_r \times \tau_p}$ is known as a matrix of independent identically distributed (i.i.d.) received noise samples and each entry is distributed as $\mathcal{CN}(0, \sigma^2)$, in which $\sigma^2$ is the noise power that can be computed as $\sigma^2 = -174\frac{\text{dBm}}{\text{Hz}} + 10\log_{10}(B) + NF$, where $B$ is the system bandwidth, and $NF$ is the noise figure. Based on $Y_m$, the $m_{th}$ AP can estimate $h_{k,m}$. Then, $y_{k,m}$ is the projection of $Y_m$ onto $\varphi_k$, which is expressed as

$$y_{k,m} \triangleq Y_m \varphi_k = \sqrt{\tau_p \rho_p}(h_{k,m} + \sum_{i \neq k}^{K} h_{i,m} \varphi_i^H \varphi_k) + Z_m \varphi_k. \tag{3}$$

Thus, the estimated channel $\hat{h}_{k,m}$ can be obtained by the minimum mean square error (MMSE) of $h_{k,m}$ under the assumption of the knowledge of $\mathbb{E}\{\mathcal{A}_{k,m}\mathcal{A}_{k,m}^H\}$, which is the correlation matrix, at $m_{th}$ AP [7]. Thus, $\hat{h}_{k,m}$ can be determined as [4]

$$\begin{aligned} \hat{h}_{k,m} &= \mathbb{E}\{h_{k,m} y_{k,m}^H\}(\mathbb{E}\{y_{k,m} y_{k,m}^H\})^{-1} y_{k,m} \qquad (4) \\ &= \sqrt{\tau_p \rho_p}(\frac{G_a N_r}{\beta_{k,m}\omega_{k,m}})\mathbb{E}\{A_{k,m}A_{k,m}^H\} \\ &(\tau_p \rho_p \sum_{i=1}^{K} \frac{G_a N_r}{\beta_{i,m}\omega_{i,m}} \mathbb{E}\{A_{i,m}A_{i,m}^H\}|\varphi_i^H \varphi_k|^2 + \sigma^2 I_{N_r})^{-1} y_{k,m}. \end{aligned}$$

Accordingly, the estimated channels between APs and $K$ UEs can be given as $\hat{H}_m = \left[\hat{h}_{1,m}, \hat{h}_{2,m}, ..., \hat{h}_{k,m}\right] \in \mathbb{C}^{N_r \times K}$ and $\hat{H} = \left[\hat{H}_1, \hat{H}_1, ..., \hat{H}_M\right]^T \in \mathbb{C}^{MN_r \times K}$.

### B. Uplink Data Transmission

The symbol sent from the $k_{th}$ UE to all APs is symbolized by $x_k$, such that $\mathbb{E}\{|x_k|^2\} = 1$ and it can be detected by applying hybrid beamforming to the received signal at $m_{th}$ AP. The received signal at $m_{th}$ AP is presented as $r_m = \sqrt{\rho}\sum_{k=1}^{K} W_m^H F_m^H h_{k,m} x_k + W_m^H F_m^H Z_m$, where $\rho$ represents the maximum average transmit power at $k_{th}$ UE. $Z_m$ is $\sim \mathcal{CN}(0, \sigma^2)$ is a vector of the noise with i.i.d. random variables (RVs); while $F_m$; such that $F_m \in \mathbb{C}^{N_r \times N}$ is the analog combining matrix at $m_{th}$ AP in which its $n_{th}$ column is given as $f_{l,n} = [f_{l,n}^{(1)}, ..., f_{l,n}^{(N_r)}]^T$ corresponding to $n_{th}$ RF chain while $i_{th}$ element of $f_{l,n}$ is obtained by $f_{l,n}^{(i)} = \frac{1}{\sqrt{N_r}} e^{j\theta_{l,n}^{(i)}}$. $W_m \in \mathbb{C}^{N \times K}$ denotes the digital combining matrix at $m_{th}$ AP. Then, $r_m$ is sent to the CPU by $m_{th}$ AP via fronthaul link to be detected. In addition, the information is sent between the APs and the CPU via a simple centralized decoding technique. As a result, at the CPU, the final decoded signal is the average of local estimations $\frac{1}{M}\sum_{m=1}^{M} r_m$ [7]. Therefore, the CPU's composite received signal is represented as

$$\begin{bmatrix} r_1 \\ r_2 \\ . \\ . \\ r_M \end{bmatrix} = \sqrt{\rho} \sum_{k=1}^{K} \begin{bmatrix} W_1^H F_1^H h_{k1} \\ W_2^H F_2^H h_{k2} \\ . \\ . \\ W_M^H F_M^H h_{k,m} \end{bmatrix} x_k + \begin{bmatrix} W_1^H F_1^H Z_1 \\ W_1^H F_1^H Z_2 \\ . \\ . \\ W_M^H F_M^H Z_M \end{bmatrix}. \tag{5}$$

The analog and digital combining for all APs in the coverage area of the cell-free mm-Wave massive MIMO network are denoted as $F$ = blkdiag $\{F_1, F_2, ..., F_M\} \in \mathbb{C}^{MN_r \times MN}$ and $W$ = blkdiag $\{W_1, W_2, ..., W_M\} \in \mathbb{C}^{MN \times MK}$, respectively.

### *C. Achievable Rate*

In this work, we assume that all analog and digital combiners for all APs are computed at the CPU based on the estimated channel $\hat{H}$ which is considered as CSI in order to obtain $\{F_1, ..., F_M\}$. Therefore, (5) can be rewritten as

$$r = \sqrt{\rho} W^H F^H \hat{H} x + W^H F^H Z, \tag{6}$$

where $x = [x_1, ..., x_K]^T \in \mathbb{C}^{K \times 1}$. Thus, the total achievable rate is given as [2]

$$R = \upsilon \log_2 \det |I_{M,K} + \rho \delta^{-1} W^H F^H \hat{H} \hat{H}^H F W|, \tag{7}$$

where $\upsilon = \frac{\tau_c - \tau_p}{\tau_c}$, and $\delta = \sigma^2 W^H F^H F W$. This work seeks to propose a novel design of hybrid combining for the uplink cell-free mm-Wave massive MIMO systems based on the matching theory. Then, the first step is to design the analog combining $F$ and the digital combining $W$ can be obtained by using the designed $F$. Therefore, the total achievable rate $R$ for the cell-free massive MIMO network is expressed as [4]

$$R = \sum_{m=1}^{M} R_m, \tag{8}$$

where $R_m = \upsilon \log_2 \det(I_N + \frac{\rho}{\sigma^2} F_m^H \hat{H}_m \mu_{m-1}^{-1} \hat{H}_m{}^H F_m)$ with $\mu_o = I_K$ and $\mu_{m-1} = \mu_{m-2} + \frac{\rho}{\sigma^2} \hat{H}_{m-1}^H F_{m-1} F_{m-1}^H \hat{H}_{m-1}$.

### *D. Power Consumption and Energy Efficiency Models*

The uplink cell-free mm-Wave massive MIMO systems' total power consumption is expressed as [4], [8]

$$P_{\text{Total}} = (\sum_{k=1}^{K} P_{\text{TX}_k} + P_{\text{CP}_k}) + \sum_{m=1}^{M} (P_{\text{fix}_m} + P_{\text{HBF}_m} + P_{\text{FH}_m}), \tag{9}$$

where $P_{\text{TX}_k}$ and $P_{\text{CP}_k}$ represent the transmit power and the amount of power required to operate the circuit components for each UE in the coverage area, respectively. Furthermore, $P_{\text{TX}_k}$ is expressed as [9] $P_{\text{TX}_k} = \rho \sum_{k=1}^{K} \frac{\mathbb{E}\{|x_k|^2\}}{\eta_k}$, where $\eta_k$ denotes the power amplifier efficiency at $k_{th}$ UE. Furthermore, $P_{\text{fix}_m}, P_{\text{HBF}_m}$, and $P_{\text{FH}_m}$ are fixed power consumption, power consumption related to the hybrid beamforming architecture, and the consumed power of the fronthaul link for $m_{th}$ AP, respectively.

Regarding the hybrid beamforming structure, each antenna at $m_{th}$ AP is connected to a low-noise amplifier (LNA) and two mixers while each RF chain requires one analog-to-digital converter (ADC) and $N_r N$ phase shifters (PSs) network. Therefore, $P_{\text{HBF}_m}$ can be expressed as $P_{\text{HBF}_m} = N_r(P_{\text{LNA}} + 2P_{\text{mixer}}) + n_m(N_r P_{\text{PS}} + P_{\text{RF}} + P_{\text{ADC}})$, where $P_{\text{LNA}}, P_{\text{mixer}}, P_{\text{PS}}, P_{\text{RF}}$ and $P_{\text{ADC}}$ present the consumed power by LNA, mixer, PSs, RF chains and ADC, respectively. $n_m$ is the number of selected RF chains at $m_{th}$ AP. Furthermore, the required maximum power for the fronthaul traffic at full capacity $C_{\text{FH}_m}$ is denoted by $P_{\text{FH}_m}$ and expressed as $P_{\text{FH}_m} = \frac{P_{\text{FH}_{max}} R_{\text{FH}_m}}{C_{\text{FH}_m}}$ as mentioned in [8], where $R_{\text{FH}_m}$ gives the actual fronthaul rate between $m_{th}$ AP and the CPU and is expressed as $R_{\text{FH}_m} = \frac{2K(\tau_c - \tau_p)\alpha_m}{T_c}$, where $\alpha_m$ and $T_c$ represent the number of quantization bits at $m_{th}$ AP, and the coherence time (in seconds), respectively.

For simplicity, we assume that all APs have the same value of $P_{\text{FH}_m}, \alpha_m, C_{\text{FH}_m}$ and $P_{\text{fix}_m}$. In addition, all UEs have the value of both $\eta_k$ and $P_{\text{CP}_k}$. Thus, $P_{\text{Total}}$ can be rewritten as

$$P_{\text{Total}} = \frac{K\rho}{\eta} + KP_{\text{CP}} + MP_{\text{fix}} + MP_{\text{FH}} + \sum_{m=1}^{M} P_{\text{HBF}_m}. \tag{10}$$

Energy Efficiency (EE) in $[\frac{\text{bit}}{\text{Joule}}]$ of the cell-free mm-Wave massive MIMO systems can be expressed as

$$\text{EE} = \frac{\sum_{m=1}^{M} BR_m}{P_{\text{Total}}}, \tag{11}$$

where $B$ is the system bandwidth.

## III. PROBLEM FORMULATION AND PROPOSED SOLUTION

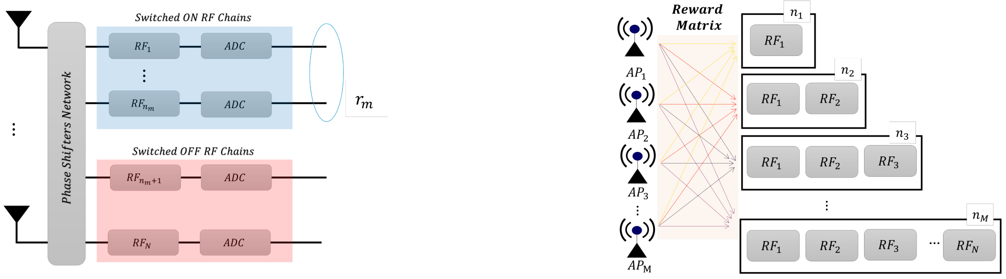
The achievable rates $\{R_1, R_2, ..., R_M\}$ are determined by the analog combiners that correspond to the APs $\{1, ..., M\}$ in the cell-free network. As a result of the APs' random distribution throughout the coverage area, variable pathloss and shadowing effects exist on the communication channels. The analog combiners' contributions to achievable rates at various APs are then varied. Different contributions to $R_m$ can be obtained by combining vectors of $F_m = \{f_{m,1}, ..., f_{m,N}\}$.

When the subset of the analog combining vectors $\{f_{1,1}, ..., f_{M,N}\}$ is omitted from $F$, it is unlikely to cause significant performance loss. As a consequence, the analog combining of each AP in the cell-free massive MIMO network demonstrates the impact of the $N_r N$ PSs possible connections to the RF chains and followed by ADC. Insignificant analog combining vectors can be excluded from signal combining by switching off their RF chains, ADC and PSs, which reduces total power consumption as shown in Figure (1a). This motivates us to propose a novel design of activation RF chains based on matching theory to maximize the energy efficiency of the uplink cell-free mm-Wave massive MIMO systems. Let us consider $n = \{n_1, ..., n_M\}$, in which $n_m$ presents the number of selected RF chains at $m_{th}$ AP and is constrained to $0 \leq n_m \leq N$ as demonstrated in Figure (1b). All RF chains at $m_{th}$ AP are turned off when $n_m = 0$. Therefore, this AP does not consume any power to perform the process of the signal combining.

### *A. Problem Formulation*

It is essential to formulate an assignment problem, which is a fundamental combinatorial optimization problem, in order to determine the optimum assignment of $n_m$ to $m_{th}$ AP, that can maximize the EE of the cell-free mm-Wave massive MIMO network as illustrated in Figure (1b). Thus, the proposed assignment problem is formulated as

$$\begin{aligned} \max_{x_{n_m,m}} \quad & \frac{B \sum_{m=1}^{M} \sum_{n_m=0}^{N-1} R_m^{(n_m)} x_{n_m,m}}{P_{\text{Total}}} \\ \text{s.t.} \quad & x_{n_m,m} \in [0,1], \\ & 0 \leq n_m \leq N, \end{aligned} \tag{12}$$



(a) Hybrid beamforming structure for each AP after utilizing RF chains activation based on Figure (1b).

(b) Bipartite graph construction for RF chains activation scheme for each AP.

Figure 1: The illustration of matching scheme for RF chains activation/deactivation in the uplink cell-free mm-Wave massive MIMO systems.

where $x_{n_m,m}$ shows that each AP is assigned to just one $n_m$ out of $N$. Moreover, $x_{n_m,m}$ equals 1 if $m_{th}$ AP is assigned to $n_m$ RF chains and vice versa. In this work, we formulate a reward matrix to make the assignment between $M$ APs and $n_m$ RF chains as shown in Figure (1b). The reward matrix might be non-square due to $M > N$. Thus, the obtained reward matrix coming with size $M \times N$ where the element in the $i_{th}$ row and $j_{th}$ column represents $\mathrm{EE}_{m,n}$ between $m_{th}$ AP and $n_m$ RF chains. The sum of $\mathrm{EE}_{m,n}$ is the maximum EE of the cell-free network. For simplicity, the reward matrix ($\digamma$) in this work is divided into sub matrices and each one of them, the number of APs equals $N$ RF chains. The total number of sub square matrices is expressed as $C = \frac{M}{N}$, and each sub square matrix is denoted by $M_s^{c_\ell}$, where $\ell = \{1, 2, ..., C\}$. For example, if $M = 16$ APs and $N = 8$ RF chains, $\digamma$ is with size $(16 \times 8)$ and $C = 2$ sub square matrices and each one of them is with size $8 \times 8$, such that $M_s^{c_1}$ and $M_s^{c_2}$ have 8 APs out of $M$ APs. It is noted that $M_s^{c_1} \cap M_s^{c_2} = \varnothing$ and $M_s^{c_1} \cup M_s^{c_2} = \{1, ..., M\}$.

### B. Proposed Solution

$\digamma$ that can be used for matching is obtained by Algorithm 1. The first two steps are used to find the analog combining for each AP. Then, the next two steps give the total achievable rate $R$ and $\mathrm{EE}_m$, respectively. Then, digital combining for $m_{th}$ AP is computed based on $F^\star$. $\digamma$ is obtained and its elements are $EE_m^{n_m}$ between each AP and $n_m$ RF chains. Therefore, $\digamma$ is the input of the proposed Hungarian algorithm as illustrated in Algorithm 2, and $\digamma$ is divided into sub square matrices when $M > N$. Thus, the Hungarian algorithm is applied at each $M_s^{c_\ell} \times N$ matrix to obtain the maximum weighted matching. This algorithm is one of the most well-known and often used combinatorial methods for solving the maximum weighted matching problem in a bipartite network. In Algorithm 2, we provide the details of the proposed fast and efficient implementation of James Munkres' Hungarian algorithm [11].

**Algorithm 1** Hybrid beamforming design [4] to obtain the reward matrix $\digamma$

```
for $m = 1 \rightarrow M$ do
    for $n = 1 \rightarrow N$ do
        - Compute the Singular value decomposition
          (SVD) for $\hat{H}_m \mu_{m-1}^{-1} \hat{H}_m^H$
        - The left singular vector
          $F_m^\star = \{u_{m,1}^\star, u_{m,2}^\star, ..., u_{m,N}^\star\}$.
        - Compute $R_m$ corresponding to $n_m$
          using (8).
    end
    $Q_m = \hat{H}_m^H F_m^\star {F_m^\star}^H \hat{H}_m$
    $\mu_m = \mu_{m-1} + \frac{\rho}{\sigma^2} Q_m$
    Compute digital combining for $m_{th}$ AP as
    $W_m^\star = \frac{F_m^\star \hat{H}_m}{{F_m^\star}^H \hat{H}_m {\hat{H}_m}^H F_m^\star} + \frac{\sigma^2 F_m^\star {F_m^\star}^H}{\rho}$.
    - Compute $P_{\text{Total}}$ and $\mathrm{EE}_m$
      from (10) and (11), respectively.
end
- $\digamma$ with size $M \times N$ is obtained, whose $(m, n_m)$-entries are
$\mathrm{EE}_m^{n_m}$, where $n_m = \{0, 1, 2, ..., N\}$.
```

## IV. COMPLEXITY ANALYSIS

The computational complexities are affected by the number of $N$ RF chains and $M$ APs in the coverage area to obtain the optimal number of the activated RF chains at each AP, which results in obtaining the total EE. Thus, the total computational complexity to obtain the total achievable rate for all APs in the cell-free systems by utilizing FS-ARFA scheme [4] is $(\mathcal{I}_{\mathcal{FS}} + 1)\mathcal{O}(K^3 + 2K^2 N_r + N N_r^2 + N K N_r + 2NK^2 + (N^2+1)K)$ where $\mathcal{I}_{\mathcal{FS}}$ denotes the number of iterations. Regarding our proposed matching scheme, its total computational complexity is $\mathcal{O}(K^3 + 2K^2 N_r + N N_r^2 + N K N_r + 2NK^2 + (N^2 + 1)K + C(M_s^{c_\ell})^3)$. It is obvious that the proposed matching scheme overcomes the FS-ARFA scheme because our proposed scheme does not require large number of iterations to obtain the optimal number of active RF chains at each AP. Another way to analyse the computational complexity of our proposed scheme compared to the FS-ARFA scheme is to count how many number of examined candidates of the total number of active RF chains for all APs in the cell-free network. For example, when $M = 48$, $N = 8$ and $K = 8$, the required number of examined candidates is 105 for the FS-ARFA, whereas our proposed scheme requires only 8 candidates, based on the number of sets of RF chains from 0 to $N$, to perform matching between these sets and APs to obtain the maximum total EE. Thus, the complexity-reduction ratio is 189.6%

**Algorithm 2** The Hungarian algorithm [11] to solve (12).

```
if $M > N$ then
    - $\digamma$ from Algorithm 1 is divided into $\ell$ sub matrices and
      each one of them is with size $M_s^{c_\ell} \times N$.
    - Find $\Delta^+$ which is maximum element in $\digamma$
    - Then, $\bar{\digamma} = \Delta^+ \mathbb{1}_{M_s^{c_\ell} \times N} - \digamma$.
    - Find the lowest element in each row of $\bar{\digamma}$ and
      subtract it from all other elements in the row.
    - In each column, repeat the process of previous step.
    - Cover all zeros with a few horizontal and vertical lines.
    -$\chi$ = the total number of lines.
    if $\chi = M_s^{c_\ell}$ then
        Among the zeros, optimal assignment is achieved.
        Break.
        else
            repeat
                - Let $\bar{\Delta}^*$ is the smallest uncovered element,
                  by a line and subtract it from all
                  uncovered elements, then add it to all elements
                  that are covered twice.
                - Cover all zeros with a few horizontal
                  and vertical lines as possible.
            until $\chi = M_s^{c_\ell}$
        end
        Among the zeros, optimal assignment is achieved.
    end
    - Repeat until $\sum_{\ell=1}^{C} M_s^{c_\ell} = M$,
end
-Then, $\text{EE}^\star = \sum_{\ell=1}^{C} \text{EE}_\ell^\star$.
```

## V. SIMULATION RESULTS AND DISCUSSIONS

This section includes the simulation results that evaluate the performance of our proposed scheme in terms of total power consumption, total EE and total achievable rate. In this paper, we employed Monte Carlo simulation, whereby new APs positions are randomly distributed over a square area of $1000 \times 1000$ m. Furthermore, we assume $f = 28$ GHz, and $B = 500$ MHz [12]. To obtain the path loss coefficients between the APs and the UEs based on (2), we assume $\varepsilon = 4.1$, and $\varsigma = 7.6$. Table I contains the utilized parameters in all simulations in this section.

Table I: Simulation parameters

| Parameter | Value |
|---|---|
| Antenna gain ($G_a$) | 15 dBi [4] |
| $\tau_c$, and $\tau_p$ | 200, and 20 samples |
| Propagation paths $\omega_{k,m}$ | 3 $\forall\ k, m$ [1], [2] |
| Pilot sequence transmit power ($\rho_p$) | 100 mW |
| $T_c$ and $\alpha_m$ | 2 ms, 2 bits [8] |
| Noise Figure ($NF$) | 9 dB |
| Amplifier efficiency $\eta$ | 0.3 [8] |
| Fronthaul capacity $C_{FH}$ | 500 Mbps |
| Fronthaul maximum power $P_{\text{FH}}$ | 50 W [4] |
| Power components | $P_{\text{LNA}} = 20$ mW, $P_{\text{ADC}} = 200$ mW, $P_{\text{RF}} = 40$ mW, $P_{\text{PS}} = 30$ mW, $P_{\text{mixer}} = 0.3$ mW, $P_{\text{CP}} = 1$ W, $P_{\text{fix}} = 0.825$ W, $\rho = 23$ dBm. |

Figure 2 shows that the total achievable rate versus different numbers of APs in the coverage area for $N = K = 8$, and $N_r = 64$. It can be seen that our proposed matching scheme outperforms the fixed activation scheme when $N = n_m = 4$ for all AP and the random AP activation scheme when all RF chains are turned on at each AP. This is reasonable because a fixed activation scheme with 50% active RF chains for each AP is unable to achieve maximum achievable rate, whereas our proposed matching scheme can exploit the advantages of matching theory to assign each AP to a set of RF chains, restricted to $0 \leq n_m \leq N$ RF chains, in order to maximize the achievable rate. Regarding the random AP activation scheme, we choose $\bar{n} = 4$ which is the average number of active RF chains for all APs, and the number of selected APs is equal $\frac{M*\bar{n}}{N}$ in order to make a fair comparison as mentioned in [4]. The random AP activation technique is outperformed by our proposed scheme because it turns off the APs without considering the impact on system performance in terms of the overall achievable rate. Furthermore, when all RF chains are turned on, FS-ARFA achieves 10.8% close to the fixed activation scheme, whereas our proposed scheme performs within 12.9% of the fixed activation scheme. The FS-ARFA system, on the other hand, has a very high computational complexity to obtain optimal results, whereas our suggested scheme has the lowest computational complexity, as explained earlier.

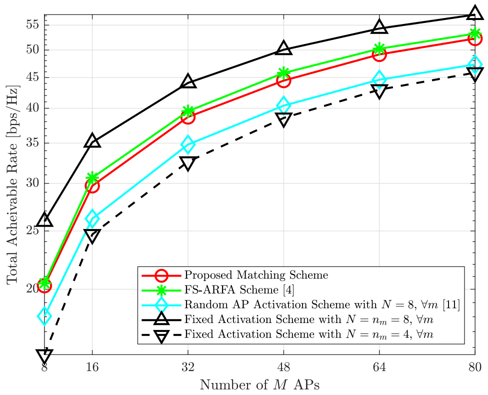


Figure 2: The total achievable rate versus $M$ APs, in which the proposed matching scheme is compared to ARFA schemes in [4], random APs activation scheme [10] when each AP has $N = 8$ RF chains, and fixed RF chain activation schemes when $K = 8$, $N_r = 64$, and $N = 8$.

Figure 3 shows the total power consumption against increasing number of APs for $N = K = 8$ and $N_r = 64$. It is evident that our proposed scheme based on the Hungarian algorithm consumes less power when $M = 80$ compared to the fixed activation schemes both with $N = 8$ or $N = n_m = 4$, FS-ARFA scheme and random AP activation by 71.80%, 16.74%, 13.87% and 10.45%, respectively. Furthermore, the obtained results revealed that our proposed matching scheme can achieve lower power consumption and computational complexity compared to the state-of-the-art schemes without a significant performance loss in terms of the total achievable rate.

Figure 4 shows the total EE performance against increasing number of APs for $N = K = 8$ and $N_r = 64$. It is observed

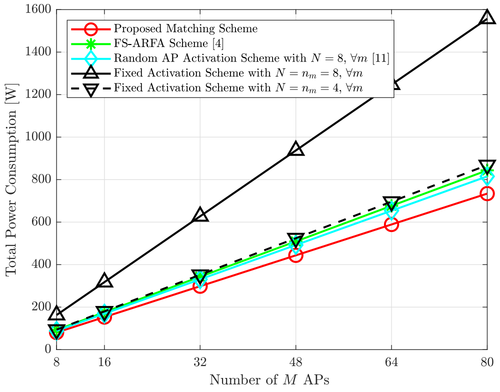


Figure 3: The power consumption versus $M$ APs with same simulation parameters as well as same comparable schemes as mentioned in Figure 2.

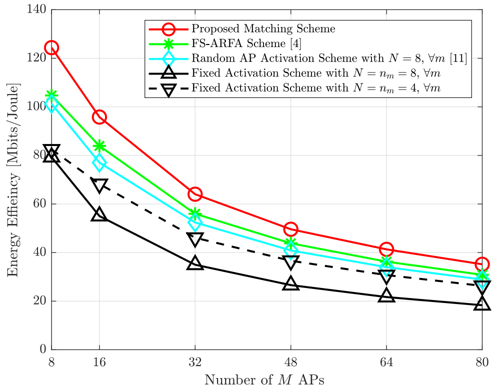


Figure 4: The energy efficiency versus $M$ APs with same simulation parameters as well as same comparable schemes as mentioned in Figure 2.

that the total energy efficiency for all schemes decrease when $M$ increases, which is obvious because the additional APs come with resultant increase in power consumption as seen in Figure 3. Our proposed matching technique outperforms existing schemes by matching each AP to the appropriate active RF chains to maximize energy efficiency. Our proposed scheme can attain 13.5%, 20%, 32.56% and 58.7% EE improvement compared to FS-ARFA, random AP activation scheme, fixed activation with partially RF chains activated ($N = n_m = 4$), and with fully RF chains activation scheme, respectively.

## VI. CONCLUSION

In this paper, we proposed a low complexity matching scheme for RF chains activation for uplink CF mm-Wave massive MIMO systems. We considered a semi-centralized hybrid beamforming scheme in which all analog and digital combiners for all APs are executed at the CPU based on the received CSI from all APs. Then, we formulated an assignment problem to match APs and the activated RF chains to maximize the total EE. Also, we utilized the Hungarian algorithm to solve the formulated problem to achieve the optimal analog combiner based on matching the sets of RF chains to APs to maximize the total achievable. We also investigated the power consumption of our proposed scheme and compared the findings to state-of-the-art methods of RF chain activation. Our proposed matching technique has a significantly lower computational complexity, yielding a higher total EE.

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## REFERENCES

[1] A. Alkhateeb, O. El Ayach, G. Leus and R. W. Heath, ”Channel Estimation and Hybrid Precoding for Millimeter Wave Cellular Systems,” in *IEEE Journal of Selected Topics in Signal Processing*, vol. 8, no. 5, pp. 831-846, Oct. 2014, doi: 10.1109/JSTSP.2014.2334278.

[2] O. E. Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi and R. W. Heath, ”Spatially Sparse Precoding in Millimeter Wave MIMO Systems,” in *IEEE Transactions on Wireless Communications*, vol. 13, no. 3, pp. 1499-1513, March 2014, doi: 10.1109/TWC.2014.011714.130846.

[3] G. Femenias and F. Riera-Palou, ”Cell-Free Millimeter-Wave Massive MIMO Systems With Limited Fronthaul Capacity,” in *IEEE Access*, vol. 7, pp. 44596-44612, 2019, doi: 10.1109/ACCESS.2019.2908688.

[4] N. T. Nguyen, K. Lee and H. Dai, ”Hybrid Beamforming and Adaptive RF Chain Activation for Uplink Cell-Free Millimeter-Wave Massive MIMO Systems,” *in IEEE Transactions on Vehicular Technology*, doi: 10.1109/TVT.2022.3176389.

[5] A. Ayidh, Y. Sambo, S. Ansari and M. A. Imran, ”Hybrid Beamforming with Fixed Phase Shifters for Uplink Cell-Free Millimetre-Wave Massive MIMO Systems,” *2021 Joint European Conference on Networks and Communications 6G Summit (EuCNC/6G Summit)*, 2021, pp. 19-24, doi: 10.1109/EuCNC/6GSummit51104.2021.9482579.

[6] S. Han, C. I, Z. Xu and C. Rowell, ”Large-scale antenna systems with hybrid analog and digital beamforming for millimeter wave 5G,” in *IEEE Communications Magazine*, vol. 53, no. 1, pp. 186-194, January 2015, doi: 10.1109/MCOM.2015.7010533.

[7] E. Björnson and L. Sanguinetti, ”Making Cell-Free Massive MIMO Competitive With MMSE Processing and Centralized Implementation,” in *IEEE Transactions on Wireless Communications*, vol. 19, no. 1, pp. 77-90, Jan. 2020, doi: 10.1109/TWC.2019.2941478.

[8] M. Bashar, K. Cumanan, A. G. Burr, H. Q. Ngo, E. G. Larsson and P. Xiao, ”Energy Efficiency of the Cell-Free Massive MIMO Uplink With Optimal Uniform Quantization,” in *IEEE Transactions on Green Communications and Networking*, vol. 3, no. 4, pp. 971-987, Dec. 2019, doi: 10.1109/TGCN.2019.2932071.

[9] E. Björnson, L. Sanguinetti, J. Hoydis and M. Debbah, ”Optimal Design of Energy-Efficient Multi-User MIMO Systems: Is Massive MIMO the Answer?,” in *IEEE Transactions on Wireless Communications*, vol. 14, no. 6, pp. 3059-3075, June 2015, doi: 10.1109/TWC.2015.2400437.

[10] G. Femenias, N. Lassoued and F. Riera-Palou, ”Access Point Switch ON/OFF Strategies for Green Cell-Free Massive MIMO Networking,” *in IEEE Access*, vol. 8, pp. 21788-21803, 2020, doi: 10.1109/ACCESS.2020.2969815.

[11] J. Munkres, “Algorithms for the assignment and transportation problems,” *Journal of the society for industrial and applied mathematics*, vol. 5, no. 1, pp. 32–38, 1957.

[12] C. D’Andrea, G. Interdonato and S. Buzzi, ”User-centric Handover in mmWave Cell-Free Massive MIMO with User Mobility,” *2021 29th European Signal Processing Conference (EUSIPCO)*, 2021, pp. 1-5, doi: 10.23919/EUSIPCO54536.2021.9616361.