An energy efficiency analysis of user-centric cell-free networks

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***Abstract*— This paper analyzes the energy efficiency of a user-centric cell-free network with a single user in uplink in a sixth generation scenario. The power consumption model considers the power consumed at the access points, at the user, and through the fronthaul links. Both capacity and energy efficiency are evaluated for different cluster sizes, and a classical cellular setup is adopted as benchmark. Numerical results show that the cell-free setup with all access points is less energy-efficient than the cellular setup, but delivers larger capacity. Besides, by limiting the cluster size, the cell-free energy efficiency is significantly improved at the cost of some affordable decrease in capacity.**

***Keywords*— Energy Efficiency, Sixth Generation, User-centric cell-free.**

I. Introduction

Cell-free (CF) networks have been considered as a potential new network architecture for upcoming sixth generation (6G) systems [1]. Differently from classical cellular networks which suffer from cell-edge impairments discussed in [2] such as inter-cell interference, in CF networks there are multiple access points (APs) evenly distributed within the network's coverage area [3], which decreases the variability of the signal quality experienced by user equipments (UEs). This can be achieved by carrying out joint and coherent signal processing at central processor units (CPUs) with signaling via fronthaul links.

Current research on CF networks adopts a scalable approach with user-centric (UC) AP clusters [4]. That is, only a subset of APs is assigned to serve a given UE. In this context, APs communicate with less UEs. As a consequence, the complexity of signal processing at APs and CPUs does not increase with the UE load. On the other hand, some decrease in the system capacity is usually observed. Consequently, UC cluster techniques should be carefully adopted.

Energy efficiency (EE) is another important aspect in CF networks [5]. In this context, power consumption models take into account the power consumed at APs, UEs and CPUs. Thus, the CF network size and the way UC clusters are formed have a great impact on the EE performance.

This work thus contributes with an EE analysis of a typical UC-CF network. For simplicity, it focuses on the power consumption of a single UE and its AP cluster, which already significantly contributes to the overall EE. The UE capacity and the EE in the uplink are evaluated for different cluster sizes. The classical cellular massive multiple-input, multiple-output (mMIMO) network is adopted as benchmark. Our findings indicate that CF setup with all APs is less energy efficient than the mMIMO, but it can provide a much larger capacity. Besides, by using smaller clusters, the EE is significantly improved at the cost of a slight decrease in capacity.

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II. System Model

This work considers a UC-CF network with a set $\mathcal{M}$ of M single-antenna APs distributed in a uniform grid within an $L \times L$ coverage area. All APs are controlled by a single CPU performing communication in uplink. There is one single-antenna UE with a total transmit power p allocated in system bandwidth B.

Let $h_m \in \mathbb{R}$ be the channel coefficient between the UE and the m-th AP, comprising large-scale fading:

$$h_m(d_m) = \sqrt{10^{-\frac{30.5+36.7\log_{10}(d_m)+X_s}{10}}}, \tag{1}$$

where $d_m > 1$ m is the distance between the UE and the m-th AP, and $X_s \sim \mathcal{N}(0, \sigma_s)$ is the zero-mean, normally-distributed shadowing fading with standard deviation σ_s.

The adopted UC clustering approach assigns a subset $\mathcal{A}_k \subset \mathcal{M}$ of k APs, with $|\mathcal{A}_k| = k$, that have the highest channel gains $|h_m(d_m)|^2$ to be the UC cluster that serves the UE. That said, let $\gamma_{\text{CF},k}$ be the signal-to-noise-ratio (SNR) experienced by the UE when served by APs in $\mathcal{A}_k$:

$$\gamma_{\text{CF},k} = \frac{p}{\sigma_n^2} \sum_{m\in\mathcal{A}_k} |h_m(d_m)|^2, \tag{2}$$

where σ_n is the noise power. The SNR expression in (2) assumes maximum ratio (MR) combining at the CPU [3].

Furthermore, the user capacity is calculated as [2]:

$$C_{\text{CF},k} = B\,\log_2(1+\gamma_{\text{CF},k})\,. \tag{3}$$

From (3), one can realize that the cluster size k plays an important role in the capacity as it impacts the SNR.

III. Energy efficiency analysis

Let $P(k)$ be the power consumption model when k APs serve the UE, defined as [5]:

$$P(k) = P_0(k) + kP_{\text{fh}} \tag{4}$$

where $P_0(k) = p\nu^{-1} + kP_{\text{ap}}$ stands for the power consumed by the k APs and the UE, ν is the UE power amplifier efficiency, and P_{ap} is the power consumed by AP internal circuitry. At last, P_{fh} is the power consumption due to fronthaul signaling, which depends on the AP-CPU distance.

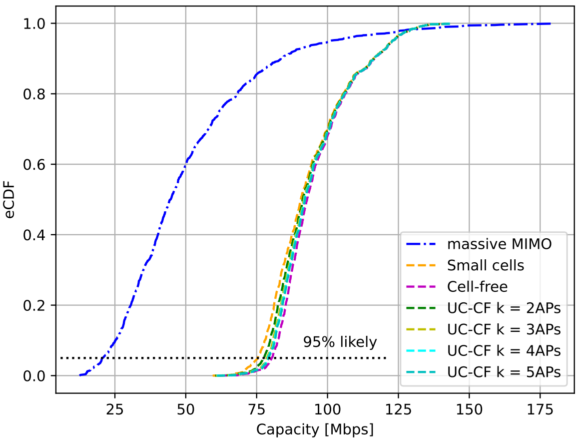

Fig. 1. Capacity of analyzed scenarios.

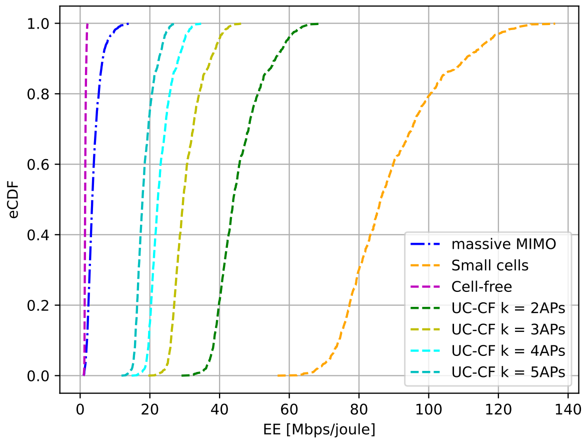

Fig. 2. Energy efficiency in all analyzed scenarios.

Finally, Let $\text{EE}_{\text{CF},k}$ be the EE when the APs in $\mathcal{A}_k$ are assigned to serve the UE, defined as [5]:

$$\text{EE}_{\text{CF},k} = \frac{C_{\text{CF},k}}{P(k)}\,. \tag{5}$$

By definition, the EE in (5) measures how many bits can be transmitted per unit of energy.

IV. Numerical Results

In this work, we computationally simulate a UC-CF network within a coverage area of $400\ \text{m} \times 400\ \text{m}$, with $M = 64$ APs connected to a single CPU. The adopted key performance indicators (KPIs) are the user capacity in (3) and the EE in (5). The UE height is 1.5 m, and the APs height is 11.5 m. The system bandwidth and the noise power σ_n^2 are 10 MHz and -96 dBm, respectively. Furthermore, $k \in \{2, 3, 4, 5\}$, $\nu = 0.4$, $P_{\text{ap}} = 0.2$ W, $P_{\text{fh}} = 0.825$ W and $p = 10$ dBm.

For comparison, two cellular setups are considered, namely small-cell (SC) and mMIMO. The SC setup can be seen as a particular case of the CF network with $k = 1$, i.e., the UE connects only to its best AP. Its KPIs are defined as $C_{\text{SC}} = C_{\text{CF},1}$ and $\text{EE}_{\text{SC}} = \frac{C_{\text{SC}}}{P_0(1)}$. As for mMIMO, there is a single AP centered at the coverage area and equipped with M antenna elements, and its KPIs are C_{MM} as defined in [3] and $\text{EE}_{\text{MM}} = \frac{C_{\text{MM}}}{P_0(M)}$.

In Fig. 1, we have the empirical cumulative distribution function (CDF) of capacity for all studied setups. It is possible to observe that the mMIMO capacity is generally worse than those of CF and SC setups due to the longer expected distances between the UE and the AP. For the SC scenario (i.e., $k = 1$), we can observe a high proximity to the UC-CF scenario for $k = 2$, with a difference of 2.02 Mbps in the 5-th percentile. Yet in the $k = 2$ case, we have a difference of 1.79 Mbps for the $k = 5$ APs scenario of 1.79 Mbps in the same percentile. Still looking at the UC-CF scenario with $k = 5$, we see that it has a difference of 1.13 Mbps to the CF scenario (i.e., $k = M$) still in the 5-th percentile, so the difference in capacity between the CF and SC scenarios is 4.94 Mbps in the 5-th percentile. This small capacity difference is due to the way the SNR of the scenarios is processed, since in the SC scenario, the SNR is calculated from the highest channel coefficient, which will also be counted in the SNR of the CF scenario [3].

In Fig. 2, It is possible to observe significant differences in EE, where the CF setup ($k = M$) has the worst EE profile, closely followed by the mMIMO setup. The UC-CF scenarios have an EE profile inversely proportional to the number of APs associated in the clustering, where the best EE profile is achieved in the $k = 2$ case, which nevertheless has a lower EE than the SC scenario. Due to the lower number of APs operating in the SC and UC-CF scenarios, these represent the lowest power consumption in the network, and are therefore more energy-efficient.

V. Conclusion

This paper analyzed the channel capacity and EE of the SC, mMIMO and CF for different UC cluster sizes, showing that the CF and UC-CF scenarios have good channel capacity, although their EE is lower than that of the SC case. Overall, UC-CF with small cluster size presented an interesting tradeoff between EE and capacity. Regarding perspectives for future work, one can think of performing uplink power control and distributed processing at CF APs for more than one single user.

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