INTERNATIONAL JOURNAL OF Telecommunications
AIR DEFENSE COLLEGE

The Cell-Free Networks Enhancement by Relays Implementation

Mohamed Shalaby[1,*], Mohamed Shahein[2], Mona Shokair[3] & A. M. Benaya[4]

Citation:
Shalaby, M.; Shahein, M.; Shokair, M.; Benaya , A.M.
Inter. Jour. of Telecommunications, ***IJT'2023****, Vol. 03, Issue 01, pp. 1-13, 2023.*
Editor-in-Chief: Youssef Fayed.
Received: 23/02/2023.
Accepted: date 28/03/2023.
Published: date 01/04/2023.

[1] 6th of October Technological University; mhmd_shlpy@yahoo.com.
[2] Communication Department, Faculty of Electronic Engineering, mosakr20202@gmail.com.
[3] Communication Department, Faculty of Electronic Engineering, mona.sabry@el-eng.menofia.com.
[4] Communication Department, Faculty of Electronic Engineering, ahmeddiab@el-eng.menofia.edu.

Abstract: Data rates that users can sustain in both uplink and downlink can be increased because of multiple input multiple output (MIMO) technology. MIMO is therefore a new technology for 5G networks and beyond. Because of the large number of existing antennas, users are empowered by large data rates inside massive MIMO (mMIMO). A modified form of mMIMO known as cell-free mMIMO distributes the current antennas through the cell. In addition, a central controller that can integrate signals from many access points APs using a cooperation mechanism takes the position of the base station. By applying the maximal ratio combining (MRC), the cell-Free networks were analyzed and simulated. The implemented APs cooperated at four different levels. This manuscript is concerned with relay implementation inside cell-Free networks. The required analysis is carried out as well as simulation which is carried out with Matlab program. It can be observed that the proposed system performance is very good when the MRC is used.

Keywords: Cell-Free networks, Relays, Maximal Ratio Combining, Spectral efficiency, and Energy efficiency.

1. Introduction

There are many tools that can be used in 5G networks and beyond. These tools include beam shaping, tiny cells, massive MIMO, multiple input multiple output (MIMO), and many others. Cellular systems may be able to utilize the same resources frequently due to the small size of the cells. The system has a high capacity as a result of resource reuse. Additionally, it may enable short-range communication between user equipment and a base station. Additionally, the use of small size cells is a potent instrument for developing green communication systems and high spectral efficiency SE [1-4].

The application of MIMO techniques can enhance beamforming, spatial multiplexing, and diversity in a communication system. Since more antennas are employed at the transmitter and receiver, mMIMO systems are able to achieve greater gains in beamforming and other areas than MIMO systems. Because of large number of antennas, the mMIMO has satisfying performance. Two antennas only can be implemented at user equipment however, the large number of antennas at mMIMO systems [5-8]. MIMO as well as mMIMO can provide high uplink and downlink capacity. The system has various flaws, including poor interior service coverage, shadowed users, dead zone users, cell edge users, and many more. Users, who are located in these locations, could not function well at all.

A modified version of mMIMO known as "Cell-Free mMIMO" replaces the many antennas installed at base stations with several APs. The simulation models and mathematical analysis for a cell-free network was the subject of numerous investigations [9]. The four levels of AP collaboration were taken into account. In Matlab, there are also a tonne of simulation models accessible. The research in cell-Free networks is various.

The Cell-Free network was theoretically examined in order to improve system performance when employing low resolution analog to digital (A/D) converters [10]. Authors made the assumption that there were several UEs as well as APs. They derived formulas for the relationship between quantization noise and spectral efficiency SE. They raised the SE of a Cell-Free mMIMO system. Others have made an effort to improve the performance of the uplink system by using conjugate beamforming (CB) and zero-forcing (ZF) [11]. For the ZF receiver, the authors also provided an accurate approximation rate. APs with numerous antennas, estimation inaccuracy, pilot contamination, and power management techniques were also taken into consideration.

Line of vision Cell-Free mMIMO and tiny cells are both governed by line of sight (LOS) propagation. NLOS propagation, however, may be influenced by fading effects, mobility, and other variables. The same system was evaluated by the authors of [12] on the presumption of correlated fading channels. To reduce the overall system's total power consumption, they also made an effort to reduce the amount of downlink power used by each antenna. Since green communication is necessary for 5G networks and beyond, a green cell-Free network is designed for an internet of thing (IOT) application [13].

Non-orthogonal multiple access (NOMA) can increase the SE in cellular systems. In a cellular system, NOMA describes how users are allocated resources. The power sector could be able to reuse resources more. Combination between NOMA and cell-Free networks exists in [14]. OMA and NOMA are compared when they are applied inside cell-Free networks. The performance metrics for a cell-free mMIMO are; SE and energy efficiency (EE). As a result, these indications need to be improved upon and modified. In [15], a brand-new and comprehensive SE and EE optimization problem was introduced. They used approaches for AP selection and power control in their analysis. It was an excellent and powerful method for improving Cell-Free mMIMO performance. [16] expanded on the work of [10] for integration a mixed analog to digital (ADC) receiver able to operate in cell-Free networks under Rician fading channels. NOMA challenge still exists. In [17], authors applied NOMA in cell-Free networks to improve SE as well as EE. Inside cell-Free networks, optical back hauls were examined [18].

Green communication systems may provide extremely high EE levels. A low-power, cell-free mMIMO network was developed by the authors of [19]. For their analysis, they only used downlink operation. When a Cell-Free mMIMO system with several pairs of single antenna users used a two-way half-duplex decode and forward (DF) relaying system, the SE was then maximized in [20]. Both the geographical variation and coverage have increased. Others recommended adapting between cells to attain the best throughput [21]. The channel aging effects in cell-Free networks was a challenge [22].

In [23], authors analyzed the cell-Free networks and they simulated it. They assumed four cooperation levels. During the simulation, various numbers of APs and various numbers of antennas for each AP were utilized. In addition, the combined SEs and the SE of different users were simulated after usage of interference cancellation procedures. Additionally, a closed form formula was employed to mathematically analyses how well a Cell-Free network performed in terms of SE as well as EE-based bit error rate in the work previously mentioned bit error rate (BER).

Relays are low-powered base stations that can only cover small areas. They might be viewed as APs. Relays help communication systems use less electricity, making them more ecologically friendly. They can be utilized in cooperative communication when LOS communication is not available. Additionally, they can help cellular systems adequately cover users who are indoors, in the shade, or who frequently find themselves in dead zones. In this manuscript Cell-Free mMIMO system, relays are used to allow each AP to provide users a low-power information signal. Because the receiver may combine the signals it gets from original transmitters and relays, the obtained signal to noise ration SNR is improved.

In general, the cooperative communication can raise the performance of communication systems. In [24-25], authors studied the interference impact on cooperative systems based on intelligent reflecting surfaces. They tried to improve the channel characteristics by applying space time block codes (STBC). The applied interference models were clarified in [26]. SE will be enhanced. In other words, low-power transmission from the original emitter can be achieved by combining the original transmitter signals and their relayed copies. This combination results in a green communication system. In brief, authors enhanced the cell-Free performance by relays depending on MRC.

The format of our paper is as follows: A mathematical model of cell-Free network, including relays, is provided in Section 2. Following a simulation of the system, performance comparisons as well as conclusions are given in Section 3 and Section 4, respectively.

2. Relay Based Cell-Free mMIMO System

Look at a cell-Free mMIMO network that uses L-distributed APs. Figure 1 displays the architecture of a cell-Free network. Each AP has N antennas. The APs are connected via a centralized controller called a "cloud-edge processor". These APs can support K users. Assume that $h_{k,l}$ describes the channel between the l AP and the k user. It is believed that the channel vector coefficients have a Rayleigh distribution.

The uplink operation only is considered. Data segments can be sent to the APs by both UEs and relays. Before being delivered to an AP, the UE signal may first be received by a relay. There are actually numerous relaying tactics. However, our manuscript applies decode and forward category.

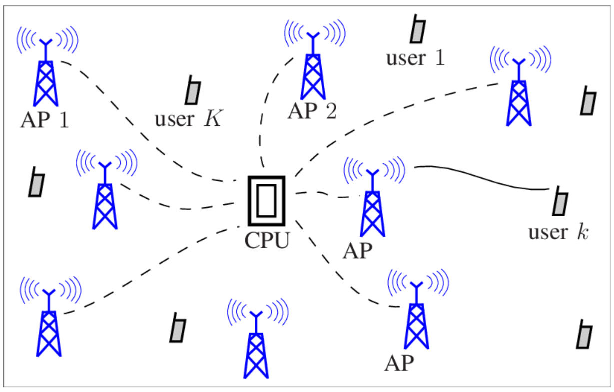


Figure 1: The architecture of a Cell-Free network [9].

2.1. Pilot Transmission

Assume that, pilot signals are mutually orthogonal, such as 1, 2, 3,..., p. For channel estimate during the data transmission phase, these pilots are used. The overall length of the pilots, which are solely utilized for control activities, shouldn't be more than 20% of the total time.

There are three groups of pilots accessible in all, and they are;

- The pilots used for estimating UEs to relays' channel are combined into Group 1.
- Group 2 consists of the sum of the pilots used to calculate relays to APs channels.
- Group 3 is the total pilots for channels between UEs and APs.

The total pilot length is τ_p. Three equal segments make up the entire pilot's length. The length of each component is $\tau_p/3$. The number of users may exceed the number of pilots because there aren't as many pilots as there are users. A pilot can be used by a large number of people, which can contaminate the pilot. The pilots in the proposed work are split into three groups. Increased pilot contamination comes from this division [23]. The received pilot at a relay from when the UEs send their pilots can be represented as;

$$\boldsymbol{Z}_{lSR} = \sum_{i=1}^{k} \sqrt{p_i}\, \boldsymbol{\beta}_{SRil} \emptyset_{t_i}^{T} + \boldsymbol{N}_{LSR} \qquad 0 \le t \le \frac{\mathcal{T}_p}{3} \tag{1}$$

Where Z_{LSR} refers to the received pilot signal at a relay coming from UE. K is the number of existing users. p_i is transmitted power, β_{SRiL} is the channel parameter, Φ_{ti} is the pilot signal at the transmitter, and N_{LSR} is the noise signal.

Mathematically expressed, the pilots, used to estimate the channel between a relay and an AP, are as follows:

$$\boldsymbol{Z}_{lRD} = \sum_{i=1}^{k} \sqrt{p_i}\, \boldsymbol{\beta}_{RDil} \emptyset_{t_i}^{T} + \boldsymbol{N}_{LRD} \qquad \frac{\mathcal{T}_p}{3} + 1 \le t \le \frac{2\mathcal{T}_p}{3} \tag{2}$$

Where Z_{LRD} refers to the received pilot signal at a destination AP coming from relay. K is the number of existing users. β_{RDiL} is the channel parameter between relay and destination, Φ_{ti} is the pilot signal at the relay, and N_{LRD} is the noise signal in the channel between the relay and destination.

Mathematically, the pilots that are used to estimate the channel between a UE and an AP are stated as;

$$\boldsymbol{Z}_{lSD} = \sum_{i=1}^{k} \sqrt{p_i}\, \boldsymbol{\beta}_{SDil} \emptyset_{t_i}^{T} + \boldsymbol{N}_{LSD} \qquad \frac{2\mathcal{T}_p}{3} + 1 \le t \le \mathcal{T}_p \tag{3}$$

where $\mathbf{p}_i$ is the transmit power of i[th] user, $\boldsymbol{\beta}_{SR}$ between a UE and a Relay, is the channel vector, $\boldsymbol{\beta}_{RD}$ is the channel vector between a Relay and an AP, $\boldsymbol{\beta}_{SD}$ is the channel vector between a UE and an AP. The parameter of $\mathbf{N}_{LSR}$, $\mathbf{N}_{LRD}$, and $\mathbf{N}_{LSD}$ is the signal noise. The relay and each AP should compare the received pilot signals with a locally produced version of the pilot signal to estimate the channel characteristics.

The channel parameters that exist between each UE and a relay should be ascertained by correlating the received UE pilot signal with its duplicate. The following are some mathematical ways to express this correlation;

$$Z_{t_k l} = \sum_{i=1}^{k} \frac{\sqrt{p_i}}{\sqrt{\frac{\mathcal{T}_p}{3}}} \boldsymbol{\beta}_{SRil}\, \emptyset_{t_i}^{T}\, \emptyset_{t_k}^{*} + \frac{1}{\sqrt{\frac{\mathcal{T}_p}{3}}} \boldsymbol{N}_{LSR} \emptyset_{t_k}^{*} = \sum_{i \in P_k} \sqrt{\frac{p_i \mathcal{T}_p}{3}}\ \boldsymbol{\beta}_{SRil} + \boldsymbol{n}_{t_k l} \tag{4}$$

Where τ_p refers to total pilot signal length and $\frac{\mathcal{T}_p}{3}$ is for this trial transmission's allotted period. The channel parameter is estimated using the minimum mean square error (MMSE) between a UE and a relay, $\hat{\beta}_{SRkl}$, can be given by;

$$\hat{\beta}_{SRkl} = \sqrt{\frac{p_k\mathcal{T}_p}{3}}\boldsymbol{R}_{kl}\,\Psi_{t_kl}^{-1}\,z_{t_kl} \tag{5}$$

where;

$$\Psi_{t_kl} \; = \; \mathbb{E}\left\{\boldsymbol{z}_{t_kl}\,\boldsymbol{z}_{t_kl}^{H}\right\} = \textstyle\sum_{i\in P_k}\frac{\mathcal{T}_p}{3}\;p_i\boldsymbol{R}_{il} \;+\boldsymbol{I}_N \tag{6}$$

Eq. 6 gives an expression for the correlation matrix of the received signal at relays.

At an AP, relays transmit the first pilot signal that is ever received. You can use this figure to determine the wireless channel between an AP and a relay. The received pilot is compared to a replica that was created nearby. The following mathematical expression of this association is possible:

$$Z_{t_kl} = \sum_{i=1}^{k}\frac{\sqrt{p_i}}{\sqrt{\frac{\mathcal{T}_p}{3}}}\boldsymbol{\beta}_{RDil}\,\emptyset_{t_i}^{T}\;\emptyset_{t_k}^{*} + \frac{1}{\sqrt{\frac{\mathcal{T}_p}{3}}}\,\boldsymbol{N}_{LRD}\emptyset_{t_k}^{*} = \sum_{i\in P_k}\sqrt{\frac{p_i\mathcal{T}_p}{3}}\;\boldsymbol{\beta}_{RDil} + \boldsymbol{n}_{t_kl} \tag{7}$$

where $\frac{\mathcal{T}_p}{3}$ is duration of the pilot transmission window. By estimating the channel parameter between a relay and the MMSE and an AP, $\hat{\beta}_{RDkl}$, can be given by;

$$\hat{\beta}_{RDkl} = \sqrt{\frac{p_k\mathcal{T}_p}{3}}\boldsymbol{R}_{kl}\,\Psi_{t_kl}^{-1}\,z_{t_kl} \tag{8}$$

Where;

$$\Psi_{t_kl} \; = \; \mathbb{E}\left\{\boldsymbol{z}_{t_kl}\,\boldsymbol{z}_{t_kl}^{H}\right\} = \textstyle\sum_{i\in P_k}\frac{\mathcal{T}_p}{3}\;p_i\boldsymbol{R}_{il} \;+\boldsymbol{I}_N \tag{9}$$

Eq. 9 presents an expression for the initial pilot signal's correlation matrix at an AP.

At an AP, UEs transmit the second pilot signal that is received. To determine the wireless channel between a UE and an AP, this map might be used. The received pilot is compared to a replica that was created nearby. The following mathematical expression of this association is possible:

$$Z_{t_kl} = \sum_{i=1}^{k}\frac{\sqrt{p_i}}{\sqrt{\frac{\mathcal{T}_p}{3}}}\boldsymbol{\beta}_{SDil}\,\emptyset_{t_i}^{T}\;\emptyset_{t_k}^{*} + \frac{1}{\sqrt{\frac{\mathcal{T}_p}{3}}}\,\boldsymbol{N}_{LSD}\emptyset_{t_k}^{*} = \sum_{i\in P_k}\sqrt{\frac{p_i\mathcal{T}_p}{3}}\;\boldsymbol{\beta}_{SDil} + \boldsymbol{n}_{t_kl} \tag{10}$$

where $\frac{\mathcal{T}_p}{3}$ is duration of the pilot transmission By estimating the channel parameter with the MMSE between a UE and an AP, $\hat{\beta}_{SDkl}$, can be given by;

$$\hat{\beta}_{SDkl} = \sqrt{\frac{p_k\mathcal{T}_p}{3}}\boldsymbol{R}_{kl}\,\Psi_{t_kl}^{-1}\,z_{t_kl} \tag{11}$$

where;

$$\Psi_{t_k l} = \mathbb{E}\left\{\boldsymbol{z}_{t_k l}\, \boldsymbol{z}_{t_k l}^H\right\} = \sum_{i\in P_k} \frac{\mathcal{T}_p}{3}\, p_i \boldsymbol{R}_{il} + \boldsymbol{I}_N \quad (12)$$

Eq. 12 presents an expression for the second pilot signal's correlation matrix at an AP.

2.2. Data Transmission

Mathematically, the received signal at an AP can come from each UE as well as relays as follows;

$$y = \sum_{i=1}^{k} \boldsymbol{\beta}_{SDil}\, s_i + \sum_{i=1}^{k} \boldsymbol{\beta}_{RDil}\, s_R + n \quad (13)$$

where received signal is given by y, S_R and S_i refer to relay signal as well as source one, and n is channel noise. while UE is the transmitted signal from a UE. n is the channel noise, and $\boldsymbol{\beta}_{RD}$ is the channel vector between a relay and an AP, $\boldsymbol{\beta}_{SD}$ is the route loss and shadowing that may be present in the channel vector from a UE to an AP.

2.2.1 Cooperation among the APs

The fundamental idea is predicated on the notion of a cell-Free network, based on relays. Distributed APs completely cover the coverage area, allowing user equipment to get services from both the nearest AP and the closest relay. The received SNR can be increased by combining the AP signal with the relay signal. Additionally, it can make the system more energy-efficient. There are four levels that can be used to coordinate the various APs and relays. These levels are listed below;

- **Fully Centralized APs "Level 4"**

Both APs and relays are able to provide users with downlink service under this cooperative mechanism. In the uplink, APs pick up signals coming from both relays as well as UEs. Each AP improves the signal that is received. Actually, each AP has the ability to send data and pilots to a central controller for processing. In comparison to an AP, the centralized controller has greater processing power. The mentioned formula in Eq. 13 can be used to express the received waveform.

The following relationships can be used to compute the signal to interference plus noise ratio (SINR), SE & EE;

$$SINR_k^{(4)} = \frac{p_k\left|V_k^H\, \hat{\beta}_{SDK}\right|^2 + p_k\left|V_k^H\, \hat{\beta}_{RD}\right|^2}{\sum_{i=1, i\neq k}^{k} p_i\left|V_k^H\, \beta_{SDi}\right|^2 + V_k^H\left(\sum_{i=1}^{k} p_i\, \boldsymbol{C}_i + \boldsymbol{\sigma^2 I_{LN}}\right) V_k} \quad (14)$$

The *SINR* refers to the signal to noise plus interference ratio. From the previous equation, it can be calculated as the summation of the signal coming from the source as well as the signal coming from the relays divided by the summation of interference and noise.

$$SE_K^{(4)} = \frac{1}{2}\left(1 - \frac{\mathcal{T}_p}{\mathcal{T}_c}\right) \mathbb{E}\left\{ log_2\left(1 + \beta_{SD}\, SINR^{(4)} + \min\left(\beta_{SR}`\beta_{RD}\right) \times SINR^{(4)}\right) \right\} \quad (15)$$

The *SE* refers to the spectral efficiency. Where (…) refers to the time period devoted to the data transmission. Moreover, β_{SD} refers to the channel parameter between the source and destination and β_{SR} refers to the channel parameter between the source and relay wheras β_{RD} refers to the channel parameter between the relay and destination.

The EE can be evaluated by;

$$EE = BW \frac{SE}{P_c + P_T} \tag{16}$$

P_C stands for power used in circuits, BW for bandwidth, and P_T for transmitted power.

- **Level 3**

When cooperation is at this level, APs can receive from relays and UEs. Each AP has a pilot detection capability for channel estimation. Then, a centralized controller receives the estimated channel characteristics related to the received data signals. The SINR, SE can be written as;

$$SINR_k^{(3)} = \frac{p_k\left|a_k^H \mathbb{E}\{g_{kk}\}\right|^2 \Big| s + p_k\left|a_k^H \mathbb{E}\{g_{kk}\}\right|^2 \Big| R}{\sum_{i=1}^{k} p_i\, \mathbb{E}\left\{\left|a_k^H g_{ki}\right|^2\right\} \Big| S+R-p_k\left|a_k^H \mathbb{E}\{g_{kk}\}\right|^2 \Big| S+R+\sigma^2 a_k^H \mathrm{D}_k a_k} \tag{17}$$

$$SE_K^{(3)} = \frac{1}{2}\left(1 - \frac{\mathcal{T}_p}{\mathcal{T}_c}\right) log_2\left(1 + \boldsymbol{\beta}_{SD} SINR_k^{(3)} + \min(\boldsymbol{\beta}_{SR}, \boldsymbol{\beta}_{RD})\right) SINR_k^{(3)}) \tag{18}$$

- **Level 2**

When cooperation is at this level, APs can receive from relays and UEs. The controller can detect the average of channel estimates as well as data. The SE and SINR are as follow;

$$SE_K^{(2)} = \frac{1}{2}\left(1 - \frac{\mathcal{T}_p}{\mathcal{T}_c}\right) log_2(1 + \boldsymbol{\beta}_{SD} SINR_k^{(2)} + \min(\boldsymbol{\beta}_{SR}, \boldsymbol{\beta}_{RD})\, SINR_k^{(2)}) \tag{19}$$

$$SINR_k^{(2)} = \frac{p_k\left|\sum_{i=1}^{k} \mathbb{E}\{V_{kl}^H \boldsymbol{\beta}_{SDl}\}\right|^2 + p_k\left|\sum_{i=1}^{k} \mathbb{E}\{V_{kl}^H \boldsymbol{\beta}_{RDl}\}\right|^2}{\sum_{i=1}^{k} p_i\, \mathbb{E}\left\{\left|\sum_{l=1}^{L} V_{kl}^H \boldsymbol{\beta}_{SDil}\right|^2\right\} \Big| S+R-p_k\left|\sum_{l=1}^{k} \mathbb{E}\{V_{kl}^H \boldsymbol{\beta}_{SDkl}\}\right|^2 \Big| S+R+\sigma^2 \sum_{l=1}^{k} \mathbb{E}\{\|V_{kl}\|^2\}} \tag{20}$$

- **Fully Distributed Level 1**

When cooperation is at this level, APs can receive from relays and UEs. The central controller is for cooperaytion among APs which are able to detect pilots as well as data. The SE and SINR can be given by;

$$SE_K^{(1)} = \frac{1}{2}\left(1 - \frac{\mathcal{T}_p}{\mathcal{T}_c}\right) \max_{l \in \{1,\ldots,L\}} \mathbb{E}\left\{log_2(1 + \boldsymbol{\beta}_{SD} SINR_k^{(1)} + \min(\boldsymbol{\beta}_{SR}, \boldsymbol{\beta}_{RD})\, SINR_k^{(1)})\right\} \tag{21}$$

$$SINR_{kl}^{(1)} = \frac{p_k\left|V_{kl}^H \widehat{\boldsymbol{\beta}}_{SDKl}\right|^2 + p_k\left|V_{kl}^H \widehat{\boldsymbol{\beta}}_{RDKl}\right|^2}{\sum_{i=1, i\neq k}^{k} p_i\left|V_{kl}^H \boldsymbol{\beta}_{SDil}\right|^2 + V_{kl}^H\left(\sum_{i=1}^{k} p_i\, \boldsymbol{C}_{il} + \boldsymbol{\sigma}^2 \boldsymbol{I}_N\right) V_{kl}} \tag{22}$$

3. Results Discussion

This section simulates Cell-Free networks, which is built on relays. Table 1 summarises the simulation parameters. The cell has a 20 m diameter. Additionally, the relays are strewn about the coverage area at random. On the other hand, the ideal location for a relay deployment is halfway between a transmitter and a receiver. According to 3GPP standard [23], the channel propagation and fading models are used. Eqs. 23 and 24 contain the path loss models. In the aforementioned work [23], these models are utilized.

$$\beta_{kl}[dB] = -30.5 - 36.7\, log_{10}\left(\frac{d_{kl}}{1m}\right) + F_{kl} \tag{23}$$

$$\mathbb{E}\left\{F_{kl}\, F_{ij}\right\} = \begin{cases} 4^2 2^{-\delta_{ki}/9m} & l = j \\ 0 & l \neq j \end{cases} \quad (24)$$

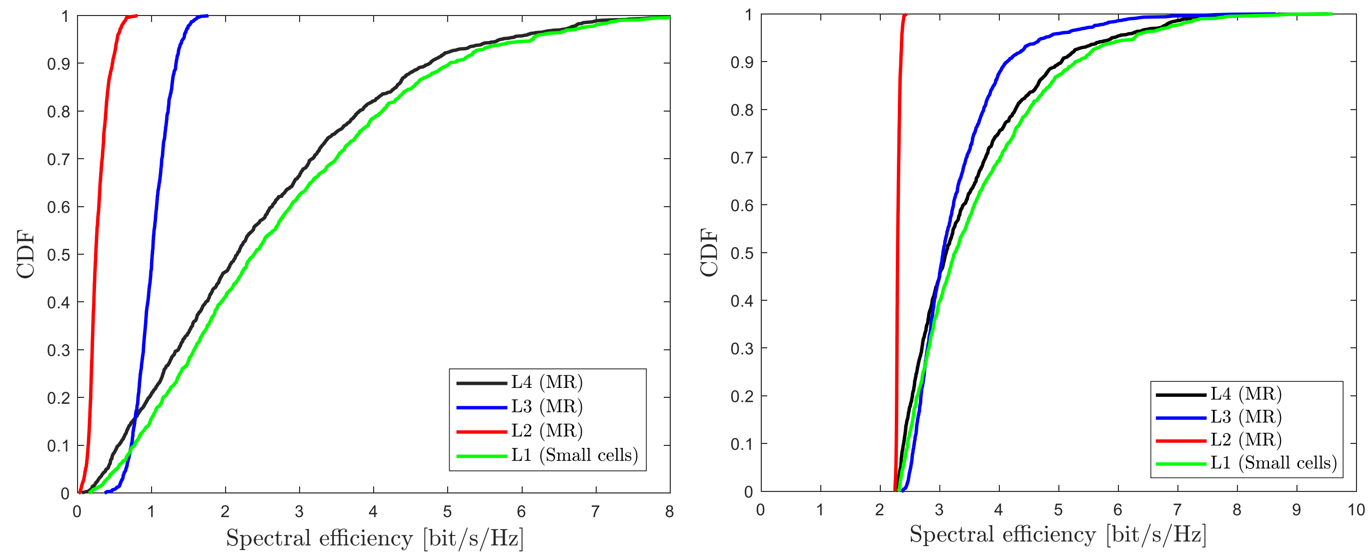
Figure 2 (a) displays the SE performance of a cell-Free mMIMO system before the relay deployment. On the other side, the relay deployment impact is investigated in Figure 2 (b). The two figures are displayed assuming that the MRC is applied. In conclusions, a cell-Free mMIMO network's SE performance can be improved by relay deployment. When there are relays, the four levels of cooperation can function more effectively.

Figure 3 (a) displays the EE performance of a cell-Free mMIMO system before the relay deployment. On the other hand, the relay deployment impact is investigated in Figure 3 (b). The two figures are displayed assuming that the MRC is applied. In conclusions, a cell-Free mMIMO network's EE performance can be improved by relay deployment. When there are relays, the four levels of cooperation can function more effectively.

Figures (2 & 3) show that, particularly for low level users, the relay existence can improve SE as well as EE of Cell-Free networks. Users at cell edges, shadowy users, and others could be considered low level users. Some users might perform with zero SE and EE without relays. The relay existence allows all users to perform well.

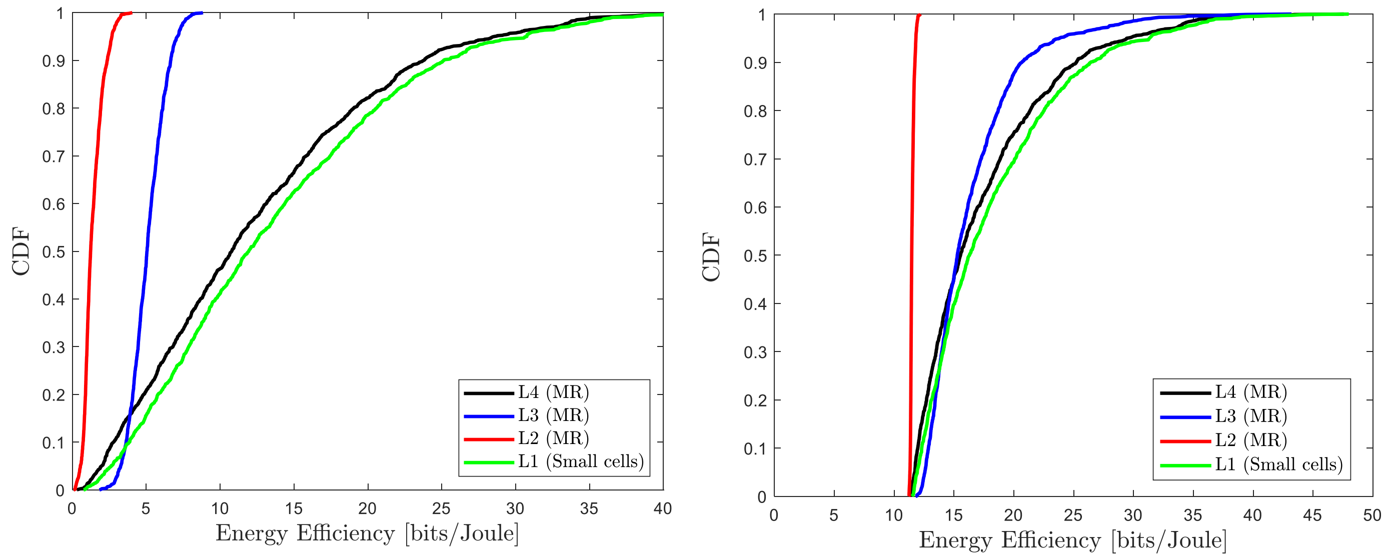
Table 1. The simulation Parameters.

Parameter		**Value**
Base stations' Number		4
Antenna count for each base station		100
Area		1km ×1 km
Fading		Rayleigh Fading
Shadowing	Standard Deviation	4 dB
	Correlation Distance among	0.5 m
	Decorrelation distance	9 m
Noise Figure		9 dB
Bandwidth		20 MHz
Spacing between Antennas		0.5λ
Uplink power		20 dBm
UEs' Number		40
P_T		100 mWatt
P_C		0.1 Watt



(a) Without relays "related work" (b) With relays "proposed work"

Figure 2: The SE performance of the proposed system.



(a) Without relays "related work" (b) With relays "proposed work"

Figure 3: The EE performance of the proposed system.

4. Conclusions

This manuscript handled the implementation of the relays inside a cell-Free mMIMO system in order to increase the SE as well as EE performance. The cell-Free mMIMO system, based on relays, was mathematically analyzed and simulated. The simulation was carried out and the simulation results were given. From the simulation results, it can be observed that the relays' deployment can greatly increase the cell-Free mMIMO system performance. The future work of the issue can extend to include the implantation of modern digital signal processing (DSP) algorithms especially in the cooperation among the APs. It is predicted that these algorithms can increase the SE as well as EE performance.

Declarations

Upon reasonable request, the contributing author will make the datasets created and/or analyzed during the current work available.

This project is being funded by the college of electronic engineering at Menoufia University in Menouf, Egypt.

This work does not clash with any other published works.

Any reasonable request will get you access to the Matlab code.

References

1. D. Muirhead, M. A. Imran and K. Arshad, "A Survey of the Challenges, Opportunities and Use of Multiple Antennas in Current and Future 5G Small Cell Base Stations," in IEEE Access, vol. 4, pp. 2952-2964, 2016, doi: 10.1109/ACCESS.2016.2569483.
2. Y. Yang, B. Bai and W. Chen, "Spectrum Reuse Ratio in 5G Cellular Networks: A Matrix Graph Approach," in IEEE Transactions on Mobile Computing, vol. 16, no. 12, pp. 3541-3553, 1 Dec. 2017, doi: 10.1109/TMC.2017.2696005.
3. A. Taufique, M. Jaber, A. Imran, Z. Dawy and E. Yacoub, "Planning Wireless Cellular Networks of Future: Outlook, Challenges and Opportunities," in IEEE Access, vol. 5, pp. 4821-4845, 2017, doi: 10.1109/ACCESS.2017.2680318.
4. F. Song et al., "Probabilistic Caching for Small-Cell Networks With Terrestrial and Aerial Users," in IEEE Transactions on Vehicular Technology, vol. 68, no. 9, pp. 9162-9177, Sept. 2019, doi: 10.1109/TVT.2019.2929839.
5. Y. Xin, D. Wang, J. Li, H. Zhu, J. Wang and X. You, "Area Spectral Efficiency and Area Energy Efficiency of Massive MIMO Cellular Systems," in IEEE Transactions on Vehicular Technology, vol. 65, no. 5, pp. 3243-3254, May 2016, doi: 10.1109/TVT.2015.2436896.
6. Shojaeifard, K. Wong, M. Di Renzo, G. Zheng, K. A. Hamdi and J. Tang, "Massive MIMO-Enabled Full-Duplex Cellular Networks," in IEEE Transactions on Communications, vol. 65, no. 11, pp. 4734-4750, Nov. 2017, doi: 10.1109/TCOMM.2017.2731768.
7. Y. Han, B. D. Rao and J. Lee, "Massive Uncoordinated Access With Massive MIMO: A Dictionary Learning Approach," in IEEE Transactions on Wireless Communications, vol. 19, no. 2, pp. 1320-1332, Feb. 2020, doi: 10.1109/TWC.2019.2952843.
8. L. You et al., "Pilot Reuse for Vehicle-to-Vehicle Underlay Massive MIMO Transmission," in IEEE Transactions on Vehicular Technology, vol. 69, no. 5, pp. 5693-5697, May 2020, doi: 10.1109/TVT.2020.2982013.
9. 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.
10. Y. Zhang, M. Zhou, X. Qiao, H. Cao and L. Yang, "On the Performance of Cell-Free Massive MIMO With Low-Resolution ADCs," in *IEEE Access*, vol. 7, pp. 117968-117977, 2019, doi: 10.1109/ACCESS.2019.2937094.
11. Y. Zhang, H. Cao, M. Zhou and L. Yang, "Cell-free massive MIMO: Zero forcing and conjugate beamforming receivers," in Journal of Communications and Networks, vol. 21, no. 6, pp. 529-538, Dec. 2019, doi: 10.1109/JCN.2019.000053.
12. J. Qiu, K. Xu, X. Xia, Z. Shen and W. Xie, "Downlink Power Optimization for Cell-Free Massive MIMO Over Spatially Correlated Rayleigh Fading Channels," in IEEE Access, vol. 8, pp. 56214-56227, 2020, doi: 10.1109/ACCESS.2020.2981967.
13. S. Chen, J. Zhang, Y. Jin and B. Ai, "Wireless powered IoE for 6G: Massive access meets scalable cell-free massive MIMO," in China Communications, vol. 17, no. 12, pp. 92-109, Dec. 2020, doi: 10.23919/JCC.2020.12.007.

14. Y. Zhang, H. Cao, M. Zhou and L. Yang, "Non-orthogonal multiple access in cell-free massive MIMO networks," in *China* Communications, vol. 17, no. 8, pp. 81-94, Aug. 2020, doi: 10.23919/JCC.2020.08.007.
15. H. V. Nguyen *et al*., "On the Spectral and Energy Efficiencies of Full-Duplex Cell-Free Massive MIMO," in IEEE Journal on Selected Areas in Communications, vol. 38, no. 8, pp. 1698-1718, Aug. 2020, doi: 10.1109/JSAC.2020.3000810.
16. Y. Zhang, M. Zhou, H. Cao, L. Yang and H. Zhu, "On the Performance of Cell-Free Massive MIMO With Mixed-ADC Under Rician Fading Channels," in IEEE Communications Letters, vol. 24, no. 1, pp. 43-47, Jan. 2020, doi: 10.1109/LCOMM.2019.2947462.
17. O. Maraqa, A. S. Rajasekaran, S. Al-Ahmadi, H. Yanikomeroglu and S. M. Sait, "A Survey of Rate-Optimal Power Domain NOMA With Enabling Technologies of Future Wireless Networks," in IEEE Communications Surveys & Tutorials, vol. 22, no. 4, pp. 2192-2235, Fourthquarter 2020, doi: 10.1109/COMST.2020.3013514.
18. L. Yu, J. Wu, A. Zhou, E. G. Larsson and P. Fan, "Massively Distributed Antenna Systems With Nonideal Optical Fiber Fronthauls: A Promising Technology for 6G Wireless Communication Systems," in *IEEE Vehicular Technology Magazine*, vol. 15, no. 4, pp. 43-51, Dec. 2020, doi: 10.1109/MVT.2020.3018100.
19. A. Papazafeiropoulos, H. Q. Ngo, P. Kourtessis, S. Chatzinotas and J. M. Senior, "Towards Optimal Energy Efficiency in Cell-Free Massive MIMO Systems," in IEEE Transactions on Green Communications and Networking, vol. 5, no. 2, pp. 816-831, June 2021, doi: 10.1109/TGCN.2021.3059206.
20. A. K. Papazafeiropoulos, P. Kourtessis, S. Chatzinotas and J. M. Senior, "Multipair Two-Way DF Relaying With Cell-Free Massive MIMO," in IEEE Open Journal of the Communications Society, vol. 2, pp. 423-438, 2021, doi: 10.1109/OJCOMS.2021.3060661.
21. S. Elhoushy and W. Hamouda, "Towards High Data Rates in Dynamic Environments Using Hybrid Cell-Free Massive MIMO/Small-Cell System," in IEEE Wireless Communications Letters, vol. 10, no. 2, pp. 201-205, Feb. 2021, doi: 10.1109/LWC.2020.3021026.
22. R. Chopra, C. R. Murthy and A. K. Papazafeiropoulos, "Uplink Performance Analysis of Cell-Free mMIMO Systems Under Channel Aging," in IEEE Communications Letters, vol. 25, no. 7, pp. 2206-2210, July 2021, doi: 10.1109/LCOMM.2021.3073778.
23. M. Shalaby, H. M. Hussein, and M. Shokair, "The cell-free mMIMO networks: mathematical analysis and performance evaluation," Telecommunication Systems, Springer, 77, 625–641 (2021). Available on this link: https://doi.org/10.1007/s11235-021-00776-z.
24. M. Shalaby, D. Helmy, Mina Wagih, and M. Shokair, "Study of EMI Effects in IRS Aided Communication in Alamouti Coded 5G Networks" International Journal of Telecommunication (Journal of Air Defense College), ISI indexed Journal (IF=0.8), December 2022.
25. M. Shalaby, D. Helmy, Mina Wagih, and M. Shokair, "Intelligent Reflecting Surfaces: Performance Simulation in Millimeter Wave Channels" International Journal of Telecommunication (Journal of Air Defense College), ISI indexed Journal (IF=0.8), February 2023.
26. M. Shalaby, W. Saad, M. Shokair, and N. Messiha, "Evaluation of Electromagnetic Interference in Wireless Broadband Systems," Wireless Personal Communication **96**, 2223–2237 (2017). https://doi.org/10.1007/s11277-017-4294-0.