Mathematical Analysis and Performance Evaluation of the Cell-Free mMIMO Networks Based on Cognitive Relays

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Abstract

The cell-Free massive multiple input multiple output “mMIMO” networks can provide a satisfied performance for the fifth generation “5G” systems and beyond even there are shadowed users or indoor ones. The performance of the cell-Free mMIMO systems was mathematically analyzed and simulated in a lot of previous works. However, this work aims to provide a complete mathematical model and simulation for a cell-Free mMIMO system that applies relays which operate with the cognitive radio theory. The proposed work can provide novel contributions on two axes. Firstly, the relays can improve the coverage performance of a cell-Free mMIMO network especially at shadowed users, indoor users, and the cell-edge ones. Secondly, the cognitive radio can mitigate the interference in a cell-Free mMIMO network. The interference mitigation results in performance enhancement. Therefore, the cell-Free mMIMO network, based on cognitive relays, is studied. The proposed system is mathematically analyzed and simulated. The spectral efficiency “SE” and signal to interference plus noise ratio “SINR” is deduced. They are given in a closed form formula. It can be concluded that the cognitive relays can improve; SINR, SE, and Energy Efficiency “EE” of a cell-Free mMIMO system.

Keywords  mMIMO · Cell-free networks · Cell-free mMIMO · MRC · Relays · Cognitive radio · SE · EE

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1 Introduction

The small size cells can play an important role in achievement of a high data rate in 5G networks and beyond. In addition to small size cells, there are a lot of tools that can enhance the performance. These tools include; mMIMO, beamformers, and much more. When the mobile cells have a small size, they can efficiently devote their resources to a limited number of users. In addition, the SINR, SE, and EE of the cellular system can be further enhanced when small size cells are applied [1–4]. During application of MIMO and mMIMO technologies, a lot of antennas at, a transmitter and at a receiver are implemented. This implementation let the cellular system have more; diversity gain, beam-forming gain, or spatial multiplexing gain [5–8]. The mMIMO is an improved version of the MIMO technology wherein a massive number of antennas are implemented at each transmitter and at each receiver. Therefore, the mMIMO is a key motivation toward the 6G networks. In mMIMO systems, there are at least 64 antennas at each communication terminal. The large number of implemented antennas can further improve the cellular system performance.

The mMIMO systems have a lot of advantages. However, they have a lot of challenges. These challenges include; limited service for indoor users as well as the blocked users which are under shadowing effects. In fact, the modern generation mobile systems should provide a ubiquitous coverage for users anywhere. In order to provide full coverage for users, the mMIMO technology is improved to the cell-Free technology. The centralized number of antennas, in mMIMO, is replaced by a distributed number of antennas APs that are connected to a central controller over fronthaul links. The cell-Free concept is shown in Fig. 1 [9–11].

There are a lot of previous works that handled the cell-Free mMIMO networks through mathematical models and simulations. In Ref. [9], the cooperation among the APs could provide reliable data transmission. The authors assumed four level of cooperation among the APs. There were other works in Ref. [10]. This work handled the mathematical model for a cell-Free mMIMO system that applied low resolution analog to digital converters. Thanks to the existing converters, the SE was greatly improved. Other work exhibited the zero-forcing in addition to conjugate beam forming in order to provide improvement in the uplink performance [11].

The line of sight “LOS” operation should exist in the cell-Free operation. However, many works adopted the fading conditions as well as Doppler spread. Correlated fading condition was assumed in the cell-Free mMIMO systems in Ref. [12]. The authors analyzed the cell-Free mMIMO system under the previously mentioned conditions.

Fig. 1 The cell-Free mMIMO network [9]
They aimed to reduce the power consumption in these systems by reducing power consumed in each antenna. As an extension of green cell-Free mMIMO system, a scalable and energy efficient internet of things “IOT” system, with massive connectivity, was designed in Ref. [13].

The non-orthogonal multiple access “NOMA” can play an important role in 5G and 6G networks. Really, it is a powerful tool toward having a resource efficient cellular system. The NOMA was applied in cell-Free technology in Ref. [14]. The SE was greatly improved. The NOMA effect studied in the previously mentioned work. The authors held comparisons between OMA and NOMA effect in the cell-Free mMIMO networks. In addition, the authors tried to drive a novel closed form SE formula that consider pilot contamination and other effects. A comprehensive SE optimization algorithm was applied in cell-Free mMIMO in Ref. [15]. This optimization was based on power control combined with AP selection. The work in Ref. [10] was developed in Ref. [16]. The authors of Ref. [16] introduced a mixed analog to digital converter “ADC” receiver architecture for a cell-Free mMIMO system operated under Rician fading conditions. The mixed ADC architecture permits some of receiver’s antennas to be implemented with economical low resolution ADCs while the rests are equipped with high priced perfect ADCs.

Ref. [17] presented a NOMA based cell-Free mMIMO system. This system had a high spectral efficiency. It is known that when the SE increases, the EE increases. Optical back-hauling techniques were applied in distributed antenna system [18]. Other authors concentrated on EE improvement in cell-Free networks, as example, Ref. [19] wherein a downlink green communication operation was achieved. Other works depended on implementation of half duplex relays in order to provide a high SE cell-Free mMIMO system [20]. There were other trials as selection operation between small cells and cell-Free in Ref. [21] in order to provide the optimal performance. Other trials depended on channel aging cell-Free mMIMO system [22].

The authors of Ref. [23] gave a mathematical model for a cell-Free mMIMO system. This system depended on four level of cooperation. The system was simulated for a different number of APs and different number of antennas per each AP. The interference cancellation mechanism could improve the system performance. The SE and EE, based on BER, were given in a closed form formula.

Other work in Ref. [24] studied how the random access problem can be addressed in a cell-Free mMIMO system especially when the pilot collisions happen. The cell-Free mMIMO served well in vehicle communication in Ref. [25]. The fore-mentioned system was studied assuming there are multi-antenna access points “APs” serve single-antenna unmanned aerial vehicles “UAVs” and ground users “GUEs”. The authors derived a closed-form downlink spectral efficiency “SE” expression by using practical models for the channel mixture, and by considering channel estimation errors. The authors of Ref. [26] searched for solution to apply the optimal beam-forming mechanisms in a cell-Free mMIMO system. They try to reduce the overhead and signaling between the APs and the central controller.

The relays can be implemented in cellular systems in order to improve the coverage especially at cell edges and dead zones. In addition, they can reduce the consumption power in a cellular system. The relay based communication systems are called cooperative communication systems. During the cooperation process, the receiver can combine the received signal from the original transmitter as well as the incoming version from relays. This combination results in improvement of the SINR. One of the motivations of our proposed work is applying relays in cell-Free mMIMO system [27–30].
The second motivation of our work is to apply the cognitive radio theory inside the cell-Free mMIMO systems. The cognitive radio is applied between the relays and the cell-Free APs for purpose of interference mitigation. The cognitive radio technology let two categories of users operate at the same time without considerable interference. There are primary users who have the priority to operate at resources any time. On the other side, the secondary users can operate only at the vacant resources from the primary users [31–34]. In fact, the application of cognitive relays in a cellular system let the system have low interference levels and high EE values. The low interference level can improve the signal to interference plus noise ratio SINR. In addition, the high EE levels let the cellular system to be a green one.

Our paper is organized as follows: Sect. 2 provides the mathematical analysis of the cell-Free mMIMO network that is based on cognitive relays. Subsequently, the system is simulated and performance comparisons are held in Sect. 3. Finally, conclusions are given in Sect. 4.

2  Cognitive Relay Based Cell-Free mMIMO

Assume there is a cell-Free mMIMO communication system wherein L number of APs exists. Moreover, there are N antennas for each AP. The existing APs can represent one base station. For more clarifications, there is a connection between the APs to a central controller over front-haul links. Let the channel between l AP and the k user is given by $h_{k,l}$. The channel vectors are assumed to have a Rayleigh distribution in order to consider the worst case of channel coefficients. Inside the considered cell-Free mMIMO system, there is a layer of randomly distributed relays which can offer the cooperative communication services.

The cell-Free mMIMO operation is considered with the cooperative relays that can operate by the cognitive radio theory. The cell-Free mMIMO cells are primary cells and their users are primary users whereas the relays and their users can be considered as secondary users. The studied case is at the uplink operation, in such a way that, the AP can receive from the user equipment as well as cognitive relays. Assuming that decode and forward relays are implemented, cognitive relays can receive the UE signal and then, forward it to an AP.

2.1 Proposed Cognitive Relay Based Cell-Free mMIMO Network

The cognitive radio theory is assumed, between the cell-Free mMIMO system and the relays, in order to reduce and mitigate the interference among them. The cell-Free users are primary users and then they have the priority to access resources anytime. The relay users are secondary users who can only access the vacant spectrum in order to have no interference with the primary users. The cognitive radio algorithm can be explained as follow:

- The relays should operate at vacant spectrum only that the APs do not operate on.
- By applying a cooperative sensing mechanism, the users can detect the spectrum holes that the APs do not operate on.
- The spectrum server “spectrum broker” can collect the vacant spectrum from the sensing information of all users. Then, these resources will be applied to relays.
- The relays can operate at the vacant resources only.
• The relays can operate by full duplex time division manner; in such a way that, both UE and relay can send to an AP in subsequent time slots. In other words, the AP can receive a UE data in a time slot and then it can receive its relayed version “from a relay” at the subsequent time slot.

• By application of cognitive radio concept between relays and APs, the SINR of a user can be reduced to be SNR only.

2.2 Pilot Transmission

Let $\varphi_1, \varphi_2, \varphi_3, \ldots, \varphi_{\tau_p}$ represent the mutually orthogonal pilots which can be applied for channel estimation. These pilots are used for control purposes only. Therefore, the total pilot length should not exceed 20% of the total frame time in order not to waste the resources. These pilots can be divided into three groups which are;

The total available pilots can be divided into three group and they are;

• Group 1 is a summation of pilots that are applied to estimate the channel between UEs and cognitive relays.
• Group 2 is a summation of pilots that are applied to estimate the channel between cognitive relays and APs.
• Group 3 is a summation of pilots that are applied to estimate the channel between UEs and APs.

The total frame time is divided into; pilot time period as well as data time periods. In other words, $\tau_c = \tau_d + \tau_p$ where $\tau_c$ refers to the total frame time, $\tau_d$ refers to the time devoted to data transmission, and $\tau_p$ refers to the time devoted to pilots. Then, the total pilot time is divided into three equally group. Each group can be applied for specific channel estimation. For more clarification, $\tau_p$ is divided into three groups each with length $\tau_p / 3$. When the number of users is more than the number of existing pilots, a lot of users can operate at one pilot which results in the so called pilot contamination [23]. When the UEs transmit their pilots, the received pilot at a relay can be expressed as;

$$Z_{lSR} = \sum_{i=1}^{k} \sqrt{p_i} \beta_{SRi} \theta_{l_i}^T + N_{LSR} \quad 0 \leq t \leq \frac{T_p}{3}$$  \hspace{1cm} (1)

The channel, between a relay and an AP, can be estimated over its group of pilots. This process can be mathematically modeled as follow;

$$Z_{lRD} = \sum_{i=1}^{k} \sqrt{p_i} \beta_{RDi} \theta_{l_i}^T + N_{LRD} \quad \frac{T_p}{3} + 1 \leq t \leq \frac{2T_p}{3}$$ \hspace{1cm} (2)

By the same way, the pilots applied for estimating the channel, between a UE and an AP, can be given by the following formula;

$$Z_{lSD} = \sum_{i=1}^{k} \sqrt{p_i} \beta_{SDi} \theta_{l_i}^T + N_{LSD} \quad \frac{2T_p}{3} + 1 \leq t \leq T_p$$  \hspace{1cm} (3)

where $p_i$ is the transmit power of ith user, $\beta_{SR}$ is the channel vector between a UE and a Relay, $\beta_{RD}$ is the channel vector between a Relay and an AP, and $\beta_{SD}$ is the channel vector between a UE and an AP. The parameter of $N_{LSR}, N_{LRD},$ and $N_{LSD}$ is the noise signals. To
estimate the channel parameters, the Relay and each AP should correlate the received pilot signals with a locally generated version of the pilot signal in order to determine the channel parameters.

The received signal, pilot, at a relay will be correlated with a known replica and this correlation can be mathematically modeled as in the following equation;

\[
Z_{t_k} = \sum_{i=1}^{k} \frac{p_{t_i}}{T_{p_i}} \beta_{SRil}^* \tilde{\theta}_{t_k}^* + \frac{1}{\sqrt{T_{p_i}}^*} N_{LSRil}^* = \sum_{i \in P_k} \frac{p_{t_i}T_{p_i}}{3} \beta_{SRil} + n_{t_k}
\]  

(4)

where \(T_{p_i}\) is the time allowed for this pilot transmission. There are a lot of combining schemes which are MMSE and MRC. However, the proposed work handles the MRC combining scheme only. The channel parameter, \(\hat{\beta}_{SRil}\), can be given by;

\[
\hat{\beta}_{SRil} = \sqrt{\frac{p_{t_i}T_{p_i}}{3}} R_{il} \Psi^{-1} t_{i,l} \]

(5)

where:

\[
\Psi_{t_{i,l}} = \mathbb{E}\left\{ z_{i,l} z_{i,l}^H \right\} = \sum_{i \in P_k} \frac{T_{p_i}}{3} p_i R_{il} + I_N
\]

(6)

By the same way, there is a correlation at the AP for the received signal incoming from relays. This correlation can be mathematically modeled as follow;

\[
Z_{t_k} = \sum_{i=1}^{k} \frac{p_{t_i}}{T_{p_i}} \beta_{RDil}^* \tilde{\theta}_{t_k}^* + \frac{1}{\sqrt{T_{p_i}}^*} N_{LRDil}^* = \sum_{i \in P_k} \frac{p_{t_i}T_{p_i}}{3} \beta_{RDil} + n_{t_k}
\]  

(7)

where \(T_{p_i}\) is the time allowed for pilot transmission. When the MMSE is applied, the channel coefficients \(\hat{\beta}_{RDil}\) can be given by;

\[
\hat{\beta}_{RDil} = \sqrt{\frac{p_{t_i}T_{p_i}}{3}} R_{il} \Psi^{-1} t_{i,l} \]

(8)

where:

\[
\Psi_{t_{i,l}} = \mathbb{E}\left\{ z_{i,l} z_{i,l}^H \right\} = \sum_{i \in P_k} \frac{T_{p_i}}{3} p_i R_{il} + I_N
\]

(9)

There is another correlation at each AP. This correlation is for estimating the channel coefficients which are between APs and UEs. The fore-mentioned correlation process can be given as;

\[
Z_{t_k} = \sum_{i=1}^{k} \frac{p_{t_i}}{T_{p_i}} \beta_{SDil}^* \tilde{\theta}_{t_k}^* + \frac{1}{\sqrt{T_{p_i}}^*} N_{LSDil}^* = \sum_{i \in P_k} \frac{p_{t_i}T_{p_i}}{3} \beta_{SDil} + n_{t_k}
\]

(10)
where \( \frac{T_p}{3} \) is the time allowed for pilot transmission. After application of the MMSE estimator, the channel vectors \( \hat{\beta}_{SDkl} \) can be expressed as:

\[
\hat{\beta}_{SDkl} = \sqrt{\frac{p_k T_p}{3} R_{kl} \Psi_{t,l}^{-1} z_{t,l}}
\]

where:

\[
\Psi_{t,l} = \mathbb{E}\left\{ z_{l,t} z_{l,t}^H \right\} = \sum_{i \in P_k} \frac{T_p}{3} p_i R_{il} + I_N
\]

### 2.3 Data Transmission

Our work concentrates on the uplink transmission process. The received signal at each AP is the summation of the UE signal as well as the cognitive relay signal. It can be mathematically represented as follow:

\[
y = \sum_{i=1}^{k} \beta_{SDil}s_i + \sum_{i=1}^{k} \beta_{RDiil}s_R + n
\]

where \( y \) is the received signal, \( s_i \) is the transmitted signal from UE, while \( s_R \) is the transmitted signal from relay, \( n \) is the channel noise, and \( \beta_{RD} \) is the channel vector between a cognitive relay and an AP, \( \beta_{SD} \) is the channel vector between a UE and an AP that can include the path loss and shadowing.

#### 2.3.1 Cooperation among the APs

The existing APs can represent a base station. In other words, the APs should cooperate among them in order to provide a good service for users as they can be considered as one base station. The existing APs can cooperate according to one of the following cooperation mechanisms as in Ref. [9]; Fully centralized “Level 4”, level 3, level 2, and fully distributed “level 1”. They will be clarified in the following subsections.

- **Fully Centralized APs “Level 4”**

  During this cooperation type, the received data and pilots are processed at the central controller which connects the APs together. The received signal, \( Y \), can be expressed as a function of the transmitted signal, \( S_i \) and \( S_R \) as follow:

\[
y = \sum_{i=1}^{k} \beta_{SDiil}s_i + \sum_{i=1}^{k} \beta_{RDiil}s_R + n
\]

where \( n \) is the noise signal and \( \beta_{RD} \) is the channel vector between a cognitive relay and an AP, and \( \beta_{SD} \) is the channel vector between a UE and an AP that can include the path
loss and shadowing. The signal to interference and noise ratio, $SINR$, and the spectral efficiency, $SE$, and can be calculated by the following relations:

$$SINR_k^{(4)} = \frac{p_k \left| V_k^H \hat{\beta}_{SDK} \right|^2 + p_k \left| V_k^H \hat{\beta}_{RDK} \right|^2}{V_k^H \sigma^2 I_{LN} V_k}$$  \hspace{1cm} (15)

$$SE_k^{(4)} = \frac{1}{2} \left( 1 - \frac{T_p}{T_c} \right) \log_2 \left( 1 + \beta_{SD} SINR_k^{(4)} + \min (\beta_{SR}, \beta_{RD}) \times SINR_k^{(4)} \right)$$  \hspace{1cm} (16)

With the help of Ref. [23], the energy efficiency, $EE$, can be expressed as;

$$EE = BW \frac{SE}{P_c + P_T}$$  \hspace{1cm} (17)

where $BW$ is the bandwidth, $P_c$ is the power consumed in the circuits, and $P_T$ is the transmitted power. The transmission power, during the uplink is the mobile equipment power. The $EE$ can be calculated per unity $BW$ value.

- **Level 3**

In this cooperation level, the AP can carry out the pilot detection and then the channel estimation is carried out at each AP. The central controller can receive the channel estimates and then it can carry out the data detection processes. The signal to interference plus noise ratio, $SINR$, and the $SE$ can be expressed as;

$$SINR_k^{(3)} = \frac{p_k \left| a_k^H \mathbb{E} \{g_{kk} \} \right|^2 |s + p_k \left| a_k^H \mathbb{E} \{g_{kk} \} \right|^2 |R}{\sigma^2 d_k^2 D_k a_k}$$  \hspace{1cm} (18)

$$SE_k^{(3)} = \frac{1}{2} \left( 1 - \frac{T_p}{T_c} \right) \log_2 \left( 1 + \beta_{SD} SINR_k^{(3)} + \min (\beta_{SR}, \beta_{RD}) \right) SINR_k^{(3)}$$  \hspace{1cm} (19)

- **Level 2**

The central controller can detect the received data signal based on the average of the channel estimates comes from the APs. The complexity, at the central controller, is reduced in comparable with the previous mechanisms. The spectral efficiency, $SE$, and the signal to interference plus noise ratio, $SINR$, can be calculated by the following relations;

$$SE_k^{(2)} = \frac{1}{2} \left( 1 - \frac{T_p}{T_c} \right) \log_2 \left( 1 + \beta_{SD} SINR_k^{(2)} + \min (\beta_{SR}, \beta_{RD}) \right) SINR_k^{(2)}$$  \hspace{1cm} (20)

$$SINR_k^{(2)} = \frac{p_k \left| \sum_{i=1}^{k} \mathbb{E} \{V_{ki}^H \hat{\beta}_{SDI} \} \right|^2 + p_k \left| \sum_{i=1}^{k} \mathbb{E} \{V_{ki}^H \hat{\beta}_{RDI} \} \right|^2}{\sigma^2 \sum_{i=1}^{k} \mathbb{E} \{V_{ki}^2 \}}$$  \hspace{1cm} (21)
The energy efficiency, $EE$, can be calculated by applying a unity $BW$ value in Eq. 17.

- **Fully Distributed “Level 1”**

The APs can detect both pilots and data signals. The processing functions are carried out at each AP. However, the central controller can carry out the cooperation among the APs as they represent a base station. The spectral efficiency, $SE$, and the signal to interference plus noise ratio, $SINR$, can be calculated by the following relations;

$$SE_{k}^{(1)} = \frac{1}{2} \left( 1 - \frac{T_p}{T_c} \right) \max_{l \in \{1, \ldots, L\}} \left\{ \log_2(1 + \beta_{SD}SINR_{k}^{(1)} + \min(\beta_{SR}, \beta_{RD})SINR_{k}^{(1)}) \right\}$$  \hspace{1cm} (22)

$$SINR_{k}^{(1)} = \frac{p_k |V_{kl}^H \hat{H}_{SDKl}|^2 + p_k |V_{kl}^H \hat{H}_{RDkl}|^2}{V_{kl}^H \sigma^2 I_N V_{kl}}$$  \hspace{1cm} (23)

The $EE$ can be calculated as in Eq. 17.

### 3 Simulation Results

The cell-Free mMIMO communication system is simulated in Matlab program when the cognitive relays are implemented. In the proposed work, the simulation parameters are chosen in order to be compatible with the previously mentioned work in order to have fair comparisons and in order to clarify the effect of the proposed ideas. Table 1 summarizes the simulation parameters. The shadowing models are chosen as in previous work [23]. These shadowing

| Table 1 | The simulation parameters |
|----------|--------------------------|
| Parameter | Value |
| Number of cellular base stations | 4 |
| Number of antennas per each base station | 100 |
| Area | 1 × 1 km |
| Fading | Rayleigh Fading |
| **Shadowing** | |
| Standard Deviation | 4 dB |
| Correlation Distance among UEs | 0.5 m |
| Decorrelation distance | 9 m |
| Noise Figure | 9 dB |
| Bandwidth | 20 MHz |
| Antenna Spacing | 0.5 |
| UE Transmission power | 20 dBm |
| Number of UEs | 40 |
| PT | 100 mWatt |
| PC | 0.1 Watt |
models can be considered as the best models for shadowing representation in a cell-Free mMIMO system. The shadowing models can be represented as follow;

$$\beta_{kl}[dB] = -30.5 - 36.7 \log_{10} \left( \frac{d_{kl}}{1m} \right) + F_{kl} \tag{24}$$

$$\mathbb{E}\{F_{kl}F_{ij}\} = \begin{cases} 42^{2-\delta_{ij}/9m} & l = j \\ 0 & l \neq j \end{cases} \tag{25}$$

Figure 2 and Fig. 3 can show the improvement in the SE and EE respectively for a cell-Free mMIMO system with and without application of cognitive relays. It can be observed that the application of cognitive relays can greatly increase the SE and EE of a cell-Free mMIMO system.
4 Conclusions

The cell-Free mMIMO system performance was enhanced by applying cognitive relays. The relays can enhance the cellular system performance. Moreover, the cognitive radio theory was applied between the cell-Free system and the relays in order to mitigate the interference. Application of cognitive relays, inside a cell-Free mMIMO system, can increase the signal to interference plus noise ratio as well as spectral efficiency. This work can be improved by applying intelligent reflecting surfaces and cognitive intelligent reflecting surfaces. In addition, the SINR and SE can be increased when advanced signal processing schemes are applied.

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Code Availability  The Matlab code is available on reasonable request.

Data Availability  The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest  There is no conflict between this work and other published work.

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