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Performance Analysis and Simulation of Millimeter Wave Cell-Free mMIMO Networks

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Abstract

5G networks and beyond can provide high data rate for the served users. Small cells, massive multiple input multiple outputs (mMIMO) as well as working in millimeter wave bands are emerging tools toward empowering 5G and beyond networks. The cellular mMIMO networks can provide high data rate for users, however their performance is not satisfied for the cell-edge users and shadowed users. Fortunately, the cell-Free mMIMO network can provide a satisfied performance for all users even if they are in shadowed areas or at cell edges. The distributed access points (APs) through the coverage area can allow users to get benefit of the best serving AP. Furthermore, the users can have services anywhere due to the existence of one AP at least. The cell-Free mMIMO networks can provide a high throughput when they are operated in the millimeter wave bands due to the high available bandwidth. The operation in millimeter wave bands can let the 5G networks and beyond have a high data rate. Therefore, this paper gives a great attention to the millimeter wave bands. In this paper, the performance of the cell-Free mMIMO network, operating in the millimeter wave bands, is mathematically evaluated and simulated. The performance can include the spectral efficiency (SE), bit error rate (BER), and energy efficiency (EE). It is observed that the centralized cooperation among the APs, level 4, can provide a high SE and EE even if the maximal ratio combining (MRC) is applied. Moreover, the cell-Free four cooperation levels can perform better than cellular mMIMO when the millimeter wave non-line-of-sight (NLOS) models are applied.

Key Words: Small cells, mMIMO, Cell-Free networks, Millimeter Wave, MMSE, MRC, SE, EE, BER.

1. Introduction

One of the motivations from a mobile generation to the higher ones is the large increase in the supported data rate. In order to achieve higher data rates, some tools may be applied. The reduction of the mobile cell size can allow more frequency reuse that result in a high system capacity. Furthermore, the near base station from its associated users can allow power efficient cellular system as the transmission and reception can be carried out over low path loss distances. In addition, when the base station cover limited number of users, it can provide high throughput for these users as the resources are devoted to a limited number of users. By this way, a high system capacity and link capacity can be achieved. In conclusion, the small cell size let the mobile cellular system have a large SE and EE [1-4].

The MIMO deployment may also increase EE and SE of a cellular system. The MIMO advantages are; spatial diversity, beamforming, or spatial multiplexing. The MIMO array can enable the cellular system to have high performance. The cellular MIMO can get benefit of the several deployed antennas at the transmitter and receiver. The mMIMO can provide a high performance due to the large number of deployed antennas. The mMIMO can be deployed at the base station however, there are a limited number of antennas at the mobile station. Each base station can carry 64 antennas. The great advantage of MIMO and mMIMO is the cellular system performance enhancement without deploying new base stations. However, each base station is improved and be qualified to carry and operate with a large number of antennas [5-8].

The signal processing techniques can be applied in mMIMO systems in order to reduce the interference and improve the network performance. The signal processing, especially error suppression techniques, can improve the mMIMO network performance without base stations cooperation [9-10]. In general, the mMIMO network can provide high SE in downlink and uplink. However, the dead zone users can have a low performance. The dead zones refer to the areas under shadowing and the areas at cell-edges. The cell-Free concept is an acceptable solution for the users that are shadowed or at the cell-edges. The cell-Free mMIMO network can provide a satisfied performance for users anywhere inside the coverage area [11-12]. The similarity between the mMIMO and the cell-Free mMIMO is that both of them can apply and get benefits of the large number of deployed antennas. However, the cell-Free mMIMO depends on having a massive number of antennas; each antenna is carried over one AP. In other words, the cell-Free mMIMO can provide a massive number of antennas but in a distributed manner throughout the coverage area. This distribution can help each user, anywhere, to be associated to a good serving AP. Then, the cell-Free mMIMO can solve the problem of shadowed zones and the cell-edge users [11-13]. The concept of the cell-Free mMIMO is clarified in Figure 1.

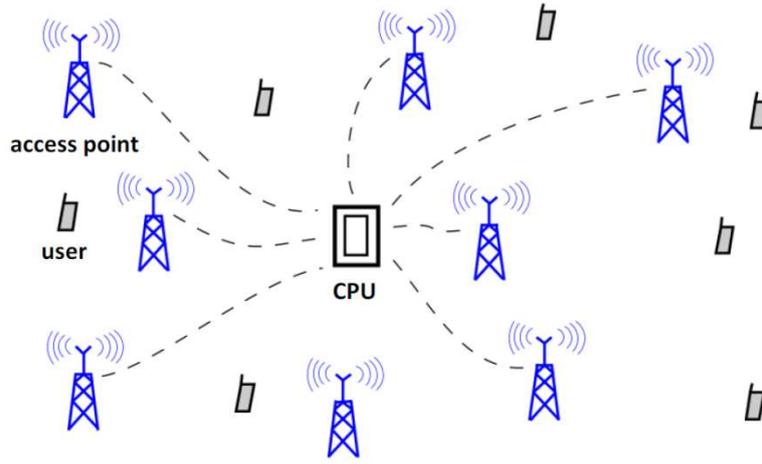


Figure 1 : The cell-Free mMIMO network concept [13-14].

The cell-Free mMIMO architecture depends on randomly distributed APs through the cell, in such a way that, the user can have a good service from a lot of APs whatever the location of this user. For more clarification, the mMIMO depends on deployment of a lot of antennas at each base station. These antennas are built on one base station. On the other hand, the cell-Free mMIMO depends on replacement of the large size base station with a centralized controller that can control a lot of randomly distributed small APs. The randomly distributed APs can provide a wide coverage for users even they are shadowed or cell-edges ones. Moreover, the large size - high consumed power base stations are replaced by small size - power efficient APs “relays” which are randomly distributed inside each cell in order to provide a good coverage for users anywhere.

In [13], the authors carried out a mathematical analysis for the cell-Free mMIMO system assuming four levels of cooperation among the APs. Moreover, they tried to find out the most competitive cell-Free mMIMO model to the cellular mMIMO one. Their analysis depended on simple signal processing techniques such as MMSE and MRC. They concluded that Level 4 of the cell-Free mMIMO can have a better performance than the cellular MIMO when the MMSE is applied. Moreover, they clarified that the path loss propagation model can affect the performance of the cell-Free mMIMO network. Authors of [13] have studied only the performance of the system in terms of SE. Ref. [14] handled a study comparison between the mMIMO and the cell-Free mMIMO at different four levels of cooperation. The SE was calculated depending on BER in a closed form formula. In addition, the effect of BER was simulated. Furthermore, the cognitive radio concept was applied, among the cell-Free users, in order to improve the performance. The previous studies [13-14] studied the mMIMO and the cell-Free mMIMO at radio frequency bands. However, the 5G networks and beyond are operating at the millimeter wave frequency bands. These bands can provide high bandwidth, little noise, high security, and much more. Due to the fore-mentioned advantages of the millimeter waves, it is interesting to study the mMIMO and cell-Free mMIMO at these bands. This study is carried out in this paper. The cell-Free mMIMO operating in the millimeter wave bands is simulated applying four levels of cooperation among the APs. Our work is still based on simple processing techniques such as; MMSE and MRC.

2. Related Work

In order to improve the performance of a cellular system, a lot of neighboring base stations can cooperate with each other. This cooperation results in a good coverage and service for users. This cooperation can waste the bandwidth due to the required overhead signaling among the base stations. The MIMO technique can replace the cooperation mechanism by deploying a lot of antennas at each base station. The mMIMO, wherein a large number of antennas are deployed at each base station, can largely increase the supported SE for users. In order to improve the performance of the cellular mMIMO especially at shadowed areas and at cell-edges, the cell-Free mMIMO can be deployed. Authors in [11], [12] have studied a performance comparison between the cell-Free mMIMO network and the Cellular mMIMO network. They showed a good performance for the cell-Free networks, however a complicated signal processing techniques were applied. The cell-Free mMIMO was mathematically analyzed and simulated in Ref. [13]. The authors proposed four cooperation levels among the APs depending on simple processing techniques. These techniques include; MMSE and MRC. These techniques can reduce the overhead signaling among the APs. In addition, these techniques can reduce the complexity of the cell-Free network as they are simple algorithms. The authors in [13] tried to find out the best comparable cell-Free mMIMO to the cellular mMIMO. Their performance metric is limited to SE only. The cell-Free mMIMO study was extended in [14]. In Ref. [14], the performance comparisons among the mMIMO and cell-Free mMIMO were carried out. The performance was formulated as a function of bit error rate “BER”. In addition, the BER effect was simulated. The study included four different cooperation mechanisms among the APs. Finally, the authors of Ref. [14] suggested the cognitive radio concept as an interference mitigation tool among cell-Free users during the uplink transmission. The cognitive radio was efficient tool to mitigate the mutual interference among the users. Unfortunately, the previous cell-Free studies were carried out at radio frequency bands

however, the cell-Free concept can be applied in 5G networks and beyond which are operating in millimeter wave frequency bands. Therefore, the study of mMIMO and cell-Free mMIMO, at millimeter wave bands, has a great attention and this study will not be clarified up till now. In this paper, the study of mMIMO and cell-Free mMIMO, which are operating at millimeter wave frequency bands, is carried out in this paper.

The main contribution of our paper can be stated as follows;

- The performance of the cell-Free mMIMO and the cellular mMIMO are mathematically analyzed and simulated by applying the millimeter wave propagation models. The motivations to the operation in the millimeter wave bands are; high available bandwidth, high security, easy and simple antenna design, and much more. They are the bands that already applied in the 5G networks and beyond.
- The performance of the cell-Free mMIMO system, operating in the millimeter wave band, is not limited to SE only. Our performance metrics can include; SE based BER as well as the EE.
- The SE, EE, and BER performance of the cell-Free mMIMO operating in the millimeter wave bands is compared to the cellular mMIMO system. There is a trial to find out the most competitive cooperation mechanism of the cell-Free mMIMO to the cellular mMIMO one when both of them operate in the millimeter wave frequency bands.
- The SE based BER and EE performance of the cell-Free mMIMO and the cellular mMIMO is studied for LOS operation and NLOS operation when the millimeter wave bands are applied.

Our paper is organized as follows; Section 3 provides the mathematical analysis of the cell-Free network operating in the millimeter wave band. In section 4, the cooperation mechanisms, among the APs in the millimeter wave cell-Free mMIMO network, will be explained. The millimeter wave channel models are explained in Section 5. Subsequently, the simulation comparisons between the millimeter wave cell-Free networks and the millimeter wave cellular mMIMO are held in Section 6. Finally, conclusions about the paper are given in Section 7.

3. Cell-Free mMIMO Mathematical Model

Consider a cell-Free network model that has L distributed APs. Each AP has N antennas. The APs are connected over a centralized controller “cloud-edge processor”. These APs can serve K users. Assume that $h_{k,l}$ describes the channel between the l^{th} AP and the k^{th} user. The uplink transmission process can be divided into; pilot transmission and data transmission.

3.1. Pilot Transmission

Assume there are mutually orthogonal pilots that can be expressed as; $\phi_1, \phi_2, \phi_3, \dots, \phi_{\tau_p}$. Each pilot symbol has length τ_p . The pilots, that should be orthogonal, can be used for channel estimation and other control processes. These pilots may be less than the user's number that can result in pilot contamination. The reason for this contamination is that there are a lot of users operate on the same pilot. Assume that the UEs transmit their pilots; the pilots that are received can be expressed as;

$$(1) Z = \sum_{i=1}^k \sqrt{p_i} \mathbf{h}_{il} \phi_{t_i}^T + \mathbf{N}_l$$

where p_i is the transmit power of i^{th} user, h_i is the channel vector between i^{th} user and l^{th} AP, and N_l is the noise signal. To estimate the channel parameters, each AP should correlate the received pilot signal with a locally generated version of the pilot signal. The result of this correlation can be as follows;

$$(2) Z_{t_{kl}} = \sum_{i=1}^k \frac{\sqrt{p_i}}{\sqrt{\mathcal{T}_p}} \mathbf{h}_{il} \phi_{t_i}^T \phi_{t_k}^* + \frac{1}{\sqrt{\mathcal{T}_p}} \mathbf{N}_l \phi_{t_k}^* = \sum_{i \in P_k} \sqrt{p_i \mathcal{T}_p} \mathbf{h}_{il} + \mathbf{n}_{t_{kl}}$$

where τ_p is the time allowed for pilot transmission. By using the MMSE, the channel parameter, $h_{k,l}$, can be given by;

$$(3) \hat{h}_{kl} = \sqrt{p_k \mathcal{T}_p} \mathbf{R}_{kl} \Psi_{t_{kl}}^{-1} z_{t_{kl}}$$

where;

$$(4) \Psi_{t_{kl}} = \mathbb{E} \{ \mathbf{z}_{t_{kl}} \mathbf{z}_{t_{kl}}^H \} = \sum_{i \in P_k} \mathcal{T}_p p_i \mathbf{R}_{il} + \mathbf{I}_N$$

Eq. 4 gives an expression for the correlation matrix of the received signal.

3.2. Data Transmission

During the uplink data transmission, the received complex base band signal can be mathematically modeled as;

$$(5) y = \sum_{i=1}^k h_{il} s_i + n$$

where y is the received signal, s_i is the transmitted signal from i^{th} user, n is the channel noise, and h_{il} is the channel parameter that can include the path loss and shadowing.

4. Cooperation among the APs

The cell-Free mMIMO system can deploy free distributed APs through the coverage area. By this way, the AP can be considered as a near relay that can provide good service coverage for near users. For more clarifications, the base station in cellular mMIMO can be replaced by randomly distributed APs in such a way that there is at least one access point available for service anywhere. The APs are connected over backhaul to a cloud-edge processor whose function is the applications of processing techniques on the received data from APs. The cooperation and processing can be carried by applying one of the four following techniques;

- **Fully Centralized APs “Level 4”**

The cloud edge processor can process all data and pilots from the APs. The AP can act as a relay that forward pilots and data directly to the central controller. Although the processing techniques are very simple, the centralized controller can apply more processing functions than an AP. The received signal is related to the transmitted one by the following relation;

The received signal, y_l , can be expressed as a function of the transmitted signal, s_i , as follow;

$$(6) y_l = \sum_{i=1}^k h_{il} s_i + n_l$$

where n_l is the noise signal. The SE can be calculated as follow;

$$(7) SE_K^{(4)} = (1 - \frac{\tau_p}{\tau_c}) \mathbb{E} \left\{ \log_2 (1 + \alpha \times SINR_k^{(4)}) \right\}$$

Where τ_p is the pilot length, τ_c is the block length (pilot and data). $SINR$ represents the signal to interference and noise ratio. α is a parameter depends on the BER as follow;

$$\alpha = -1.5 / \ln(5BER) \quad (8)$$

where BER is the bit error rate. With the help of [14][15], the energy efficiency, EE , can be expressed as;

$$EE = BW \frac{SE}{P_c + P_T} \quad (9)$$

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 level, the APs can detect pilots in order to partially estimate the channel parameters. On the other hand, the cloud edge processor can apply the channel estimates in order to detect the data signals. In this cooperation level, the SE can be calculated as follow;

$$(10) SE_K^{(3)} = (1 - \frac{\tau_p}{\tau_c}) \log_2 (1 + \alpha \times SINR_k^{(3)})$$

The only difference in SE calculations, from the previous cooperation level, is the $SINR$ value.

- **Level 2**

The APs can also detect and perform channel estimates and then the centralized controller can apply the averages of the channel estimates to detect the data correctly. The SE and EE can be calculated as in Eq. 7 and Eq. 9.

- **Fully Distributed “Level 1”**

The APs can detect both of pilots and data signals. The processing functions, related to detection, are applied on each AP. The centralized controller can receive the detected data and perform cooperation among them to provide the best performance. The spectral efficiency, SE , and the signal to interference plus noise ratio, $SINR$, can be calculated by the following relations;

$$SE_K^{(1)} = \left(1 - \frac{T_p}{T_c}\right) \max_{l \in \{1, \dots, L\}} \mathbb{E} \left\{ \log_2(1 + SINR_{kl}^{(1)}) \right\} \quad (11)$$

$$(12) SINR_{kl}^{(1)} = \frac{p_k |V_{kl}^H \hat{h}_{kl}|^2}{\sum_{i=1, i \neq k}^k p_i |V_{kl}^H \hat{h}_{il}|^2 + V_{kl}^H \left(\sum_{i=1}^k p_i C_{il} + \sigma^2 I_N \right) V_{kl}}$$

The EE can be calculated as in Eq. 9.

5. Millimeter Wave Channel Models

The millimeter wave frequency bands are still under research and development. The motivations to operation at millimeter wave bands are; high bandwidth, little noise, high security, and much more. These bands are applied in 5G networks and beyond due to the great advantages offered by them. Ref. [17] provided measurement model for the millimeter wave bands especially 60 GHz at outdoor operation for a cellular system. One of the millimeter wave disadvantages is the short range communication which let it be not suitable for backhalls applications. There should be multi-hop communication in order to provide a good range for millimeter waves. In Ref. [18], the authors tried to apply the millimeter wave as a backhaul for forest communication application. They provided statistical channel models for millimeter waves especially for 5G networks. The authors of Ref. [19] provided indoor small-scale spatiotemporal propagation characteristics across multiple 5G millimeter wave candidate bands. By the same way, Ref. [20] studied the 60 GHz band. The propagation characteristics of mmWave signal in the indoor radio channels were discussed based on the method of shooting and bouncing ray tracing/image (SBR/IM). Omnidirectional path loss models, received power and root-mean-square (RMS) delay spreads statistics were analyzed in terms of line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios. In Ref. [21], the characteristics of spatial channel modeling was simulated for 73 GHz mmWave bands using NYUSIM. Spatial consistency channel models for moving users and channel models for static users without spatial consistency consideration had been compared in terms of different channel parameters for both LOS and non-LOS (NLOS) environment. The authors of Ref. [22] presented an empirically based analysis of propagation characteristics in two vegetated suburban areas with different types and fractions of vegetation cover in 5G millimeter-wave “mmWave” bands.

In this paper, the millimeter wave channel models, which are in Ref. [16], was applied in the mMIMO and the cell-Free mMIMO networks in order to estimate the performance of the two strategies at millimeter wave frequency bands. The models, provided by Theodore Rappaport [16], are the easiest way to validate the performance of mMIMO and the cell-Free mMIMO architecture. The millimeter wave path loss models, PL , in decibels, can be expressed as follow;

$$PL = \alpha + 10\beta \times \text{Log}_{10}(d) + \zeta \quad (13)$$

The values of α , β , and ζ are included in Table 1.

Table 1. The values of the path loss parameters of the millimeter wave channels [16].

	Frequency				
	28 GHz		73 GHz		
	LOS	NLOS	LOS	NLOS (First Model)	NLOS (Second Model)
α	61.4	72	69.8	86.6	82.7
β	2	2.92	2	2.45	2.69
$\zeta \sim \mathcal{N}(\mathbf{0}, \sigma^2)$	$\sigma = 5.8$ dB	$\sigma = 8.7$ dB	$\sigma = 5.8$ dB	$\sigma = 8$ dB	$\sigma = 7.7$ dB

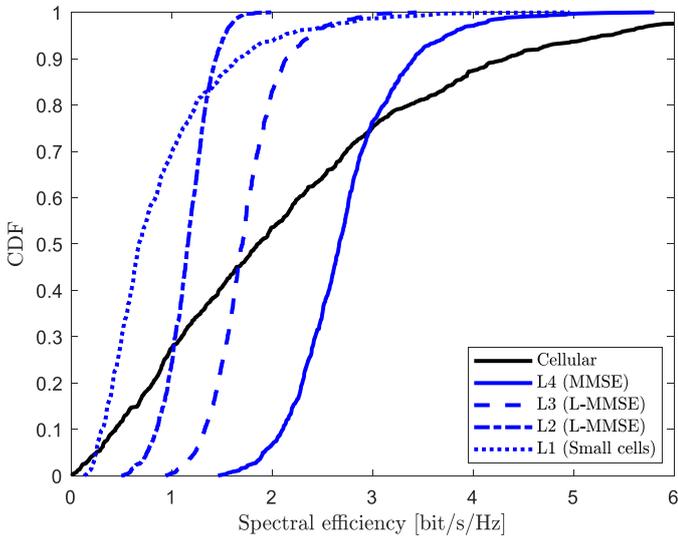
6. Simulation Results

The cell-Free mMIMO system and the cellular mMIMO are simulated when the millimeter wave channel models are applied. The simulation parameters are in Table 2. Figure 2 and Figure 3 show SE and EE of the cell-Free mMIMO system and the cellular mMIMO when the LOS - 28 GHz model is applied assuming that the BER is 10^{-3} and 10^{-8} respectively. The performance can be shown as a CDF value. The CDF is the Cumulative Distribution Function for a specified distribution. It can be given for a real valued random variable, X , by;

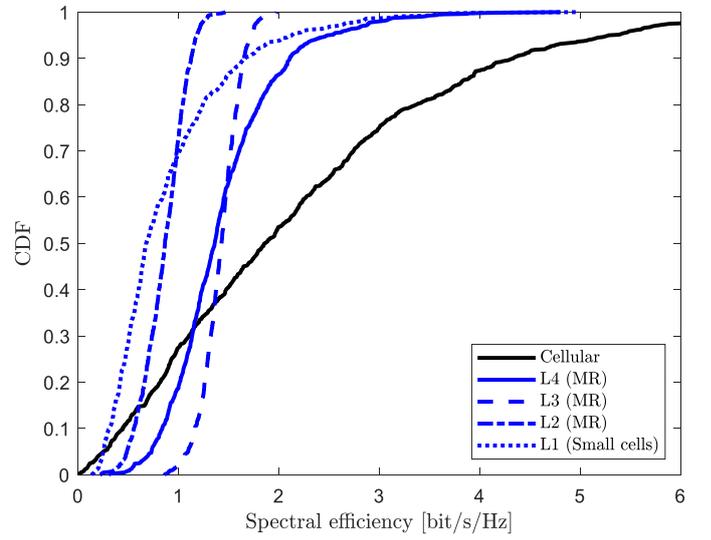
It can be defined as the probability of a random value, X , takes on a value less than or equal to A [23]. As a result, the CDF is the probability of a user's SE and EE becomes below a certain value.

Table 2. The simulation parameters.

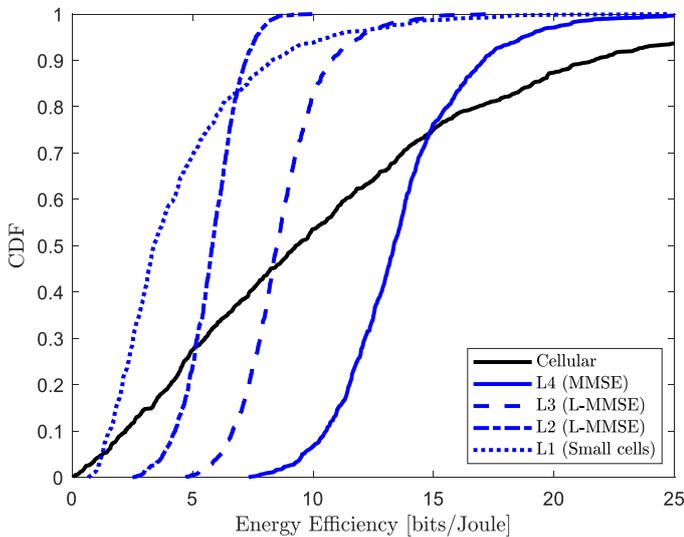
Parameter	Value
Number of cellular base stations	4
Number of antennas per each base station	100
Number of APs	400
Number of antennas per AP	1
Area	1×1 km
Noise Figure	9 dB
Bandwidth	200 MHz
Antenna Spacing	0.5
UE Transmission power	20 dBm
Number of UEs	40
P_T	100 mWatt
P_C	0.1 Watt



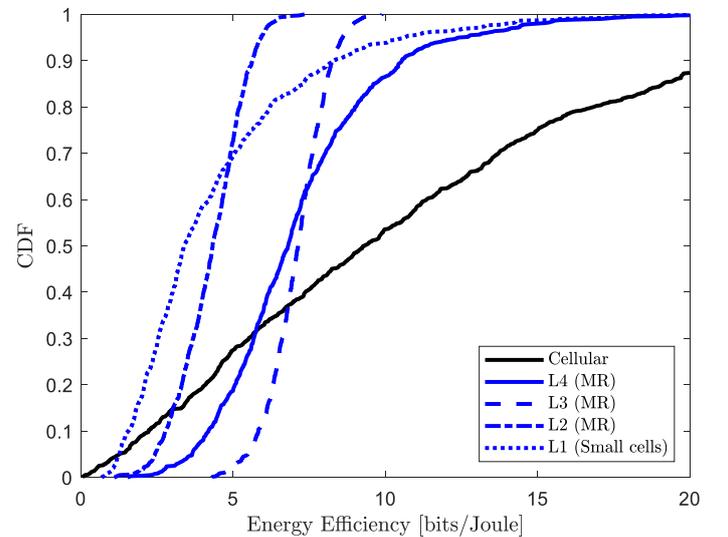
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(b)



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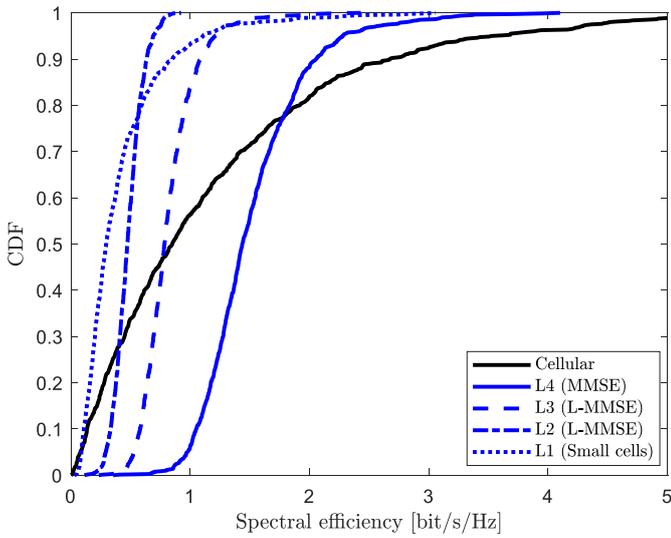


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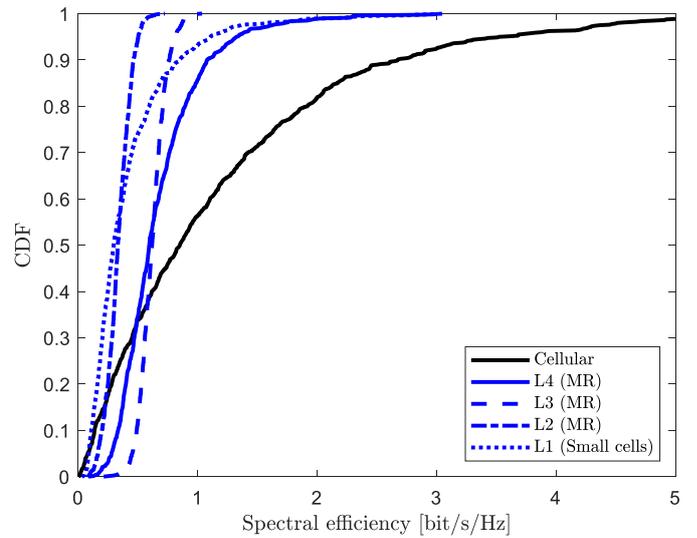
Figure 2 (a, b, c, d) : The SE and EE of cellular mMIMO and cell-Free mMIMO for 28 GHz-LOS model when the BER=10⁻³

From Figure 2 and Figure 3 it can be observed that the low BER value can provide a reliable communication system, however it can reduce both the SE and the EE of the system. Moreover, the Level 4 “Fully Centralized” can provide better SE and EE than the cellular mMIMO network especially for the shadowed users and cell-edge users when the MMSE is applied. Furthermore, the MRC can let the cell-Free mMIMO have a non-satisfied performance. Then, it is not recommended to operate the cell-Free mMIMO at the millimeter wave by the MRC especially at 28 GHz band even there are good LOS operation between the APs and UEs.

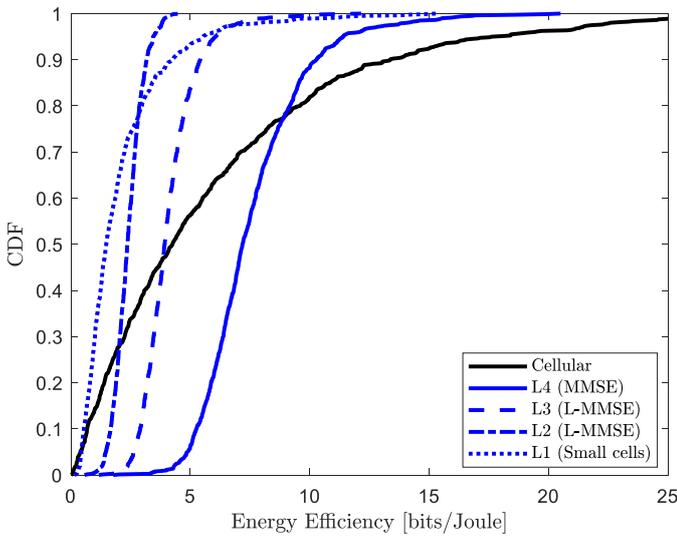
Figure 4 and Figure 5 show SE and EE of cell-Free mMIMO system and cellular mMIMO when the NLOS-28 GHz model is applied assuming that the BER is 10^{-3} and 10^{-8} respectively. From Figure 4 and Figure 5 it can be observed that the low BER value can provide a reliable communication system, however it can reduce both the SE and the EE of the system. In addition, the cell-Free mMIMO has better SE and EE performance “at all cooperation levels” than the cellular mMIMO. However, in general both the cellular mMIMO and the cell-Free mMIMO can have a low SE and EE performance for MMSE and MRC when the 28 GHz NLOS model is applied. It can be concluded that the NLOS operation let the cellular system have a non-satisfied SE and EE performances. However, the cell-Free mMIMO can be a good trial to improve the SE and EE performance of the cellular system. This improvement is due to the existence of one AP, at least, at each location inside the coverage area.



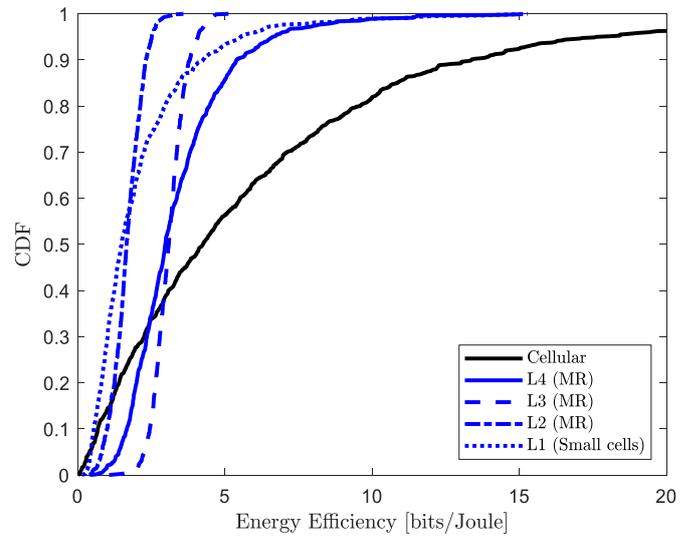
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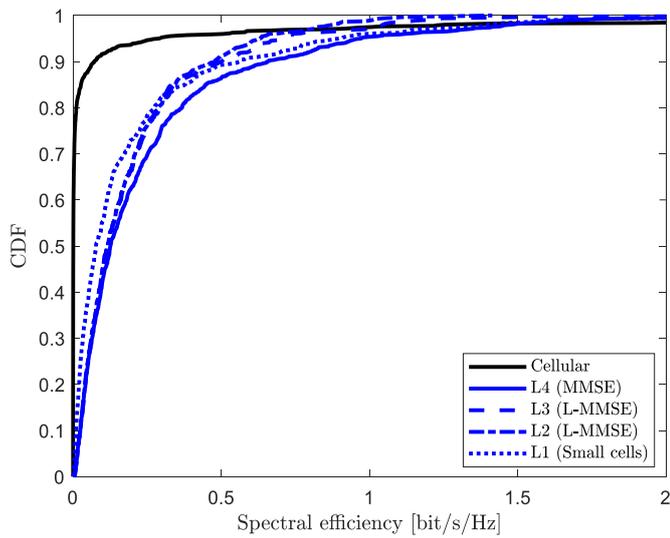


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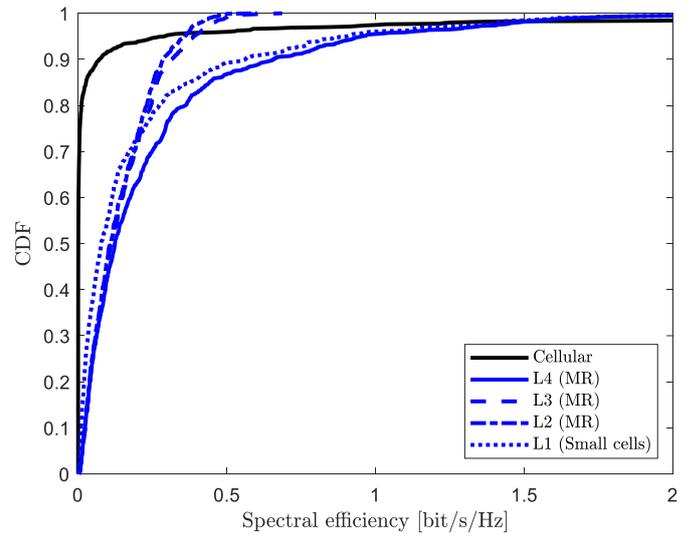


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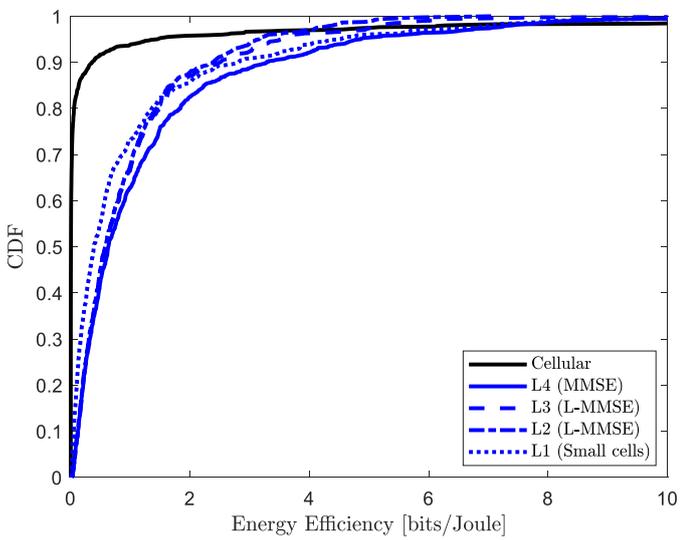
Figure 3 (a, b, c, d) : The SE and EE of cellular mMIMO and cell-Free mMIMO for 28 GHz-LOS model when the BER= 10^{-8}



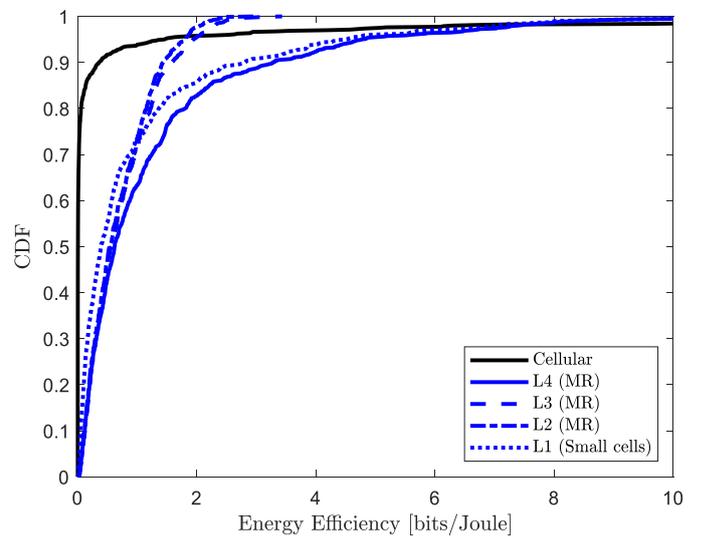
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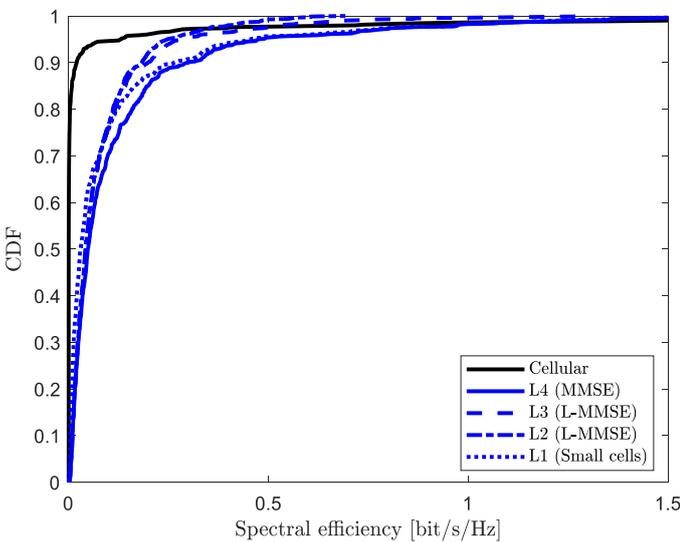


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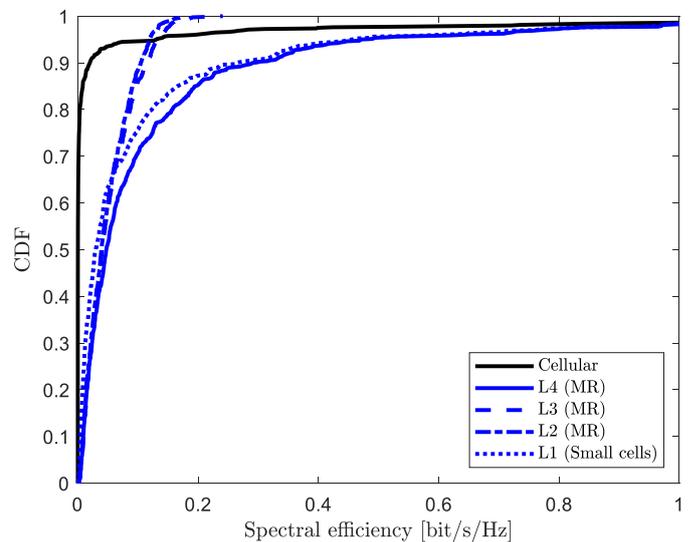


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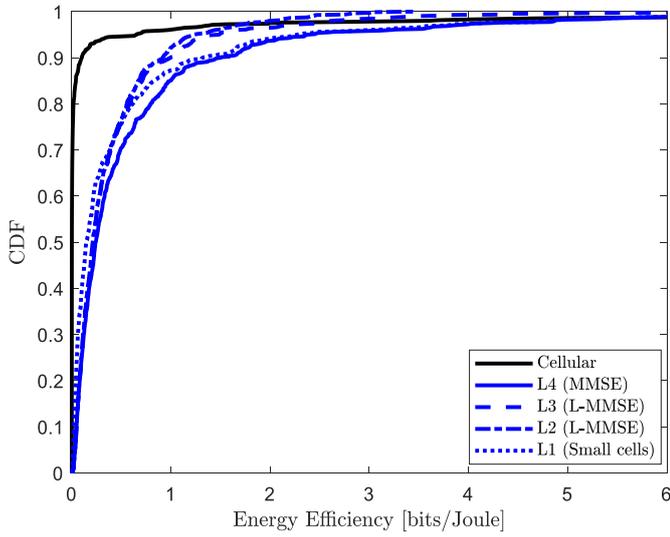
Figure 4 (a, b, c, d) : The SE and EE of cellular mMIMO and cell-Free mMIMO for 28 GHz-NLOS model when the BER= 10^{-3}



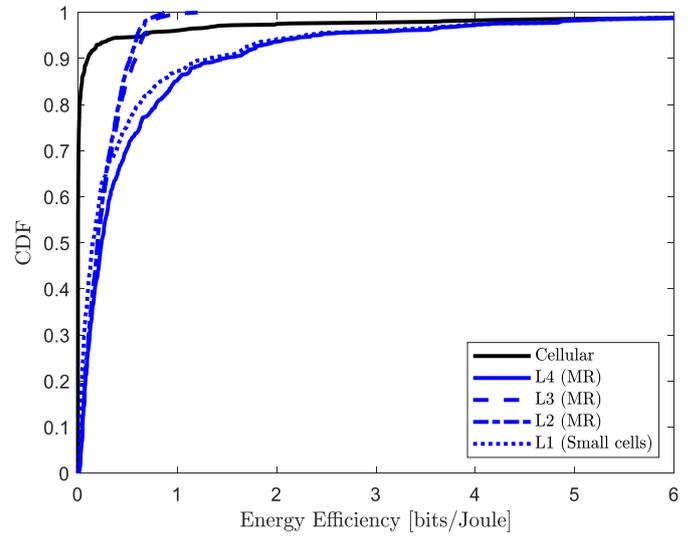
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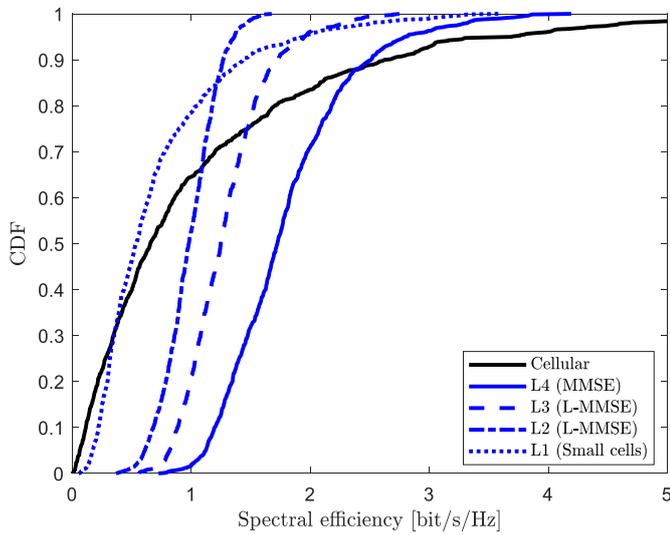


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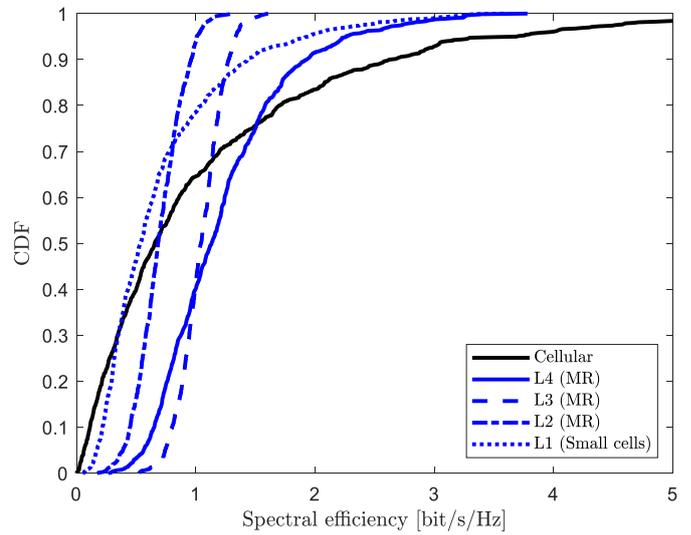


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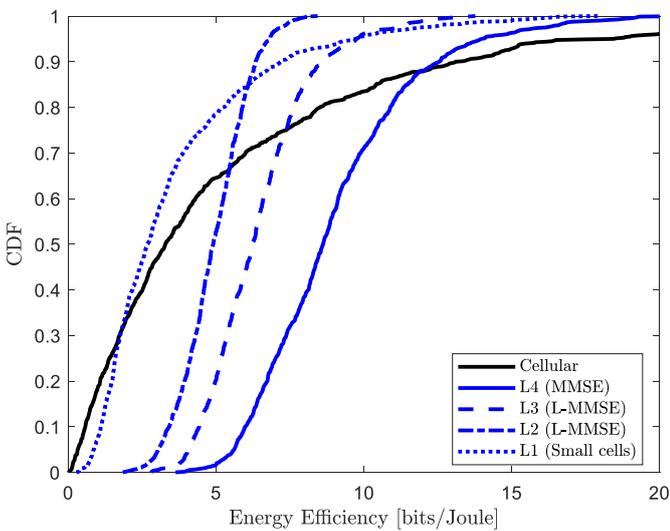
Figure 5 (a, b, c, d) : The SE and EE of cellular mMIMO and cell-Free mMIMO for 28 GHz-NLOS model when the BER= 10^{-8}



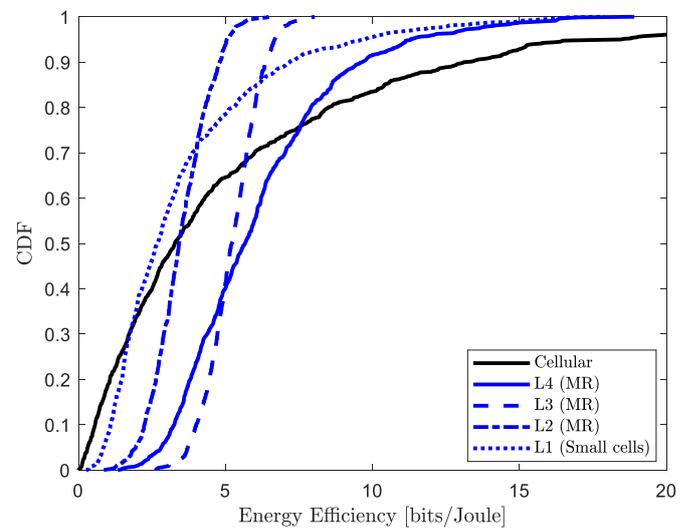
(a)



(b)



(c)



(d)

Figure 6 (a, b, c, d) : The SE and EE of cellular mMIMO and cell-Free mMIMO for 73 GHz-LOS model when the BER= 10^{-3}

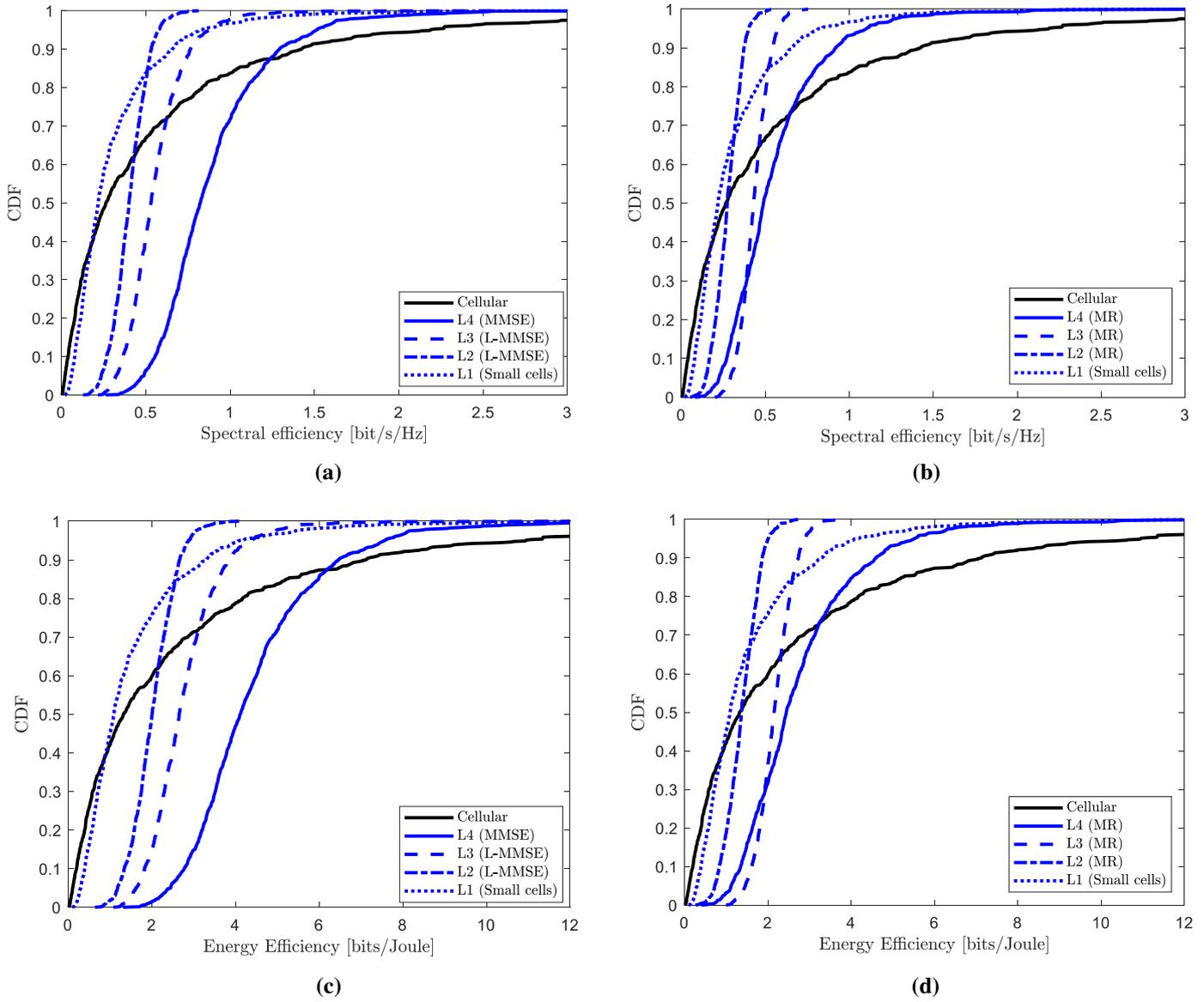
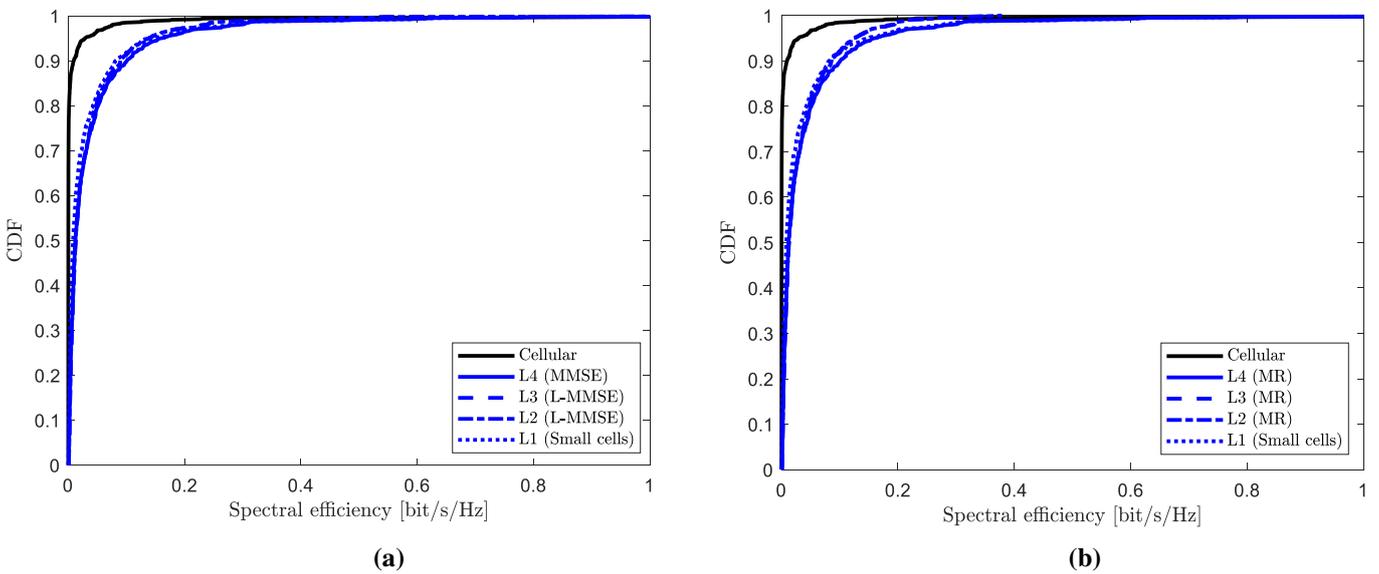
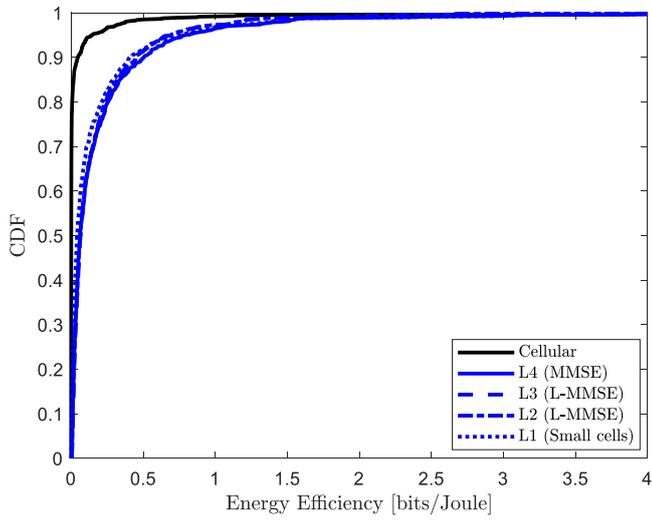


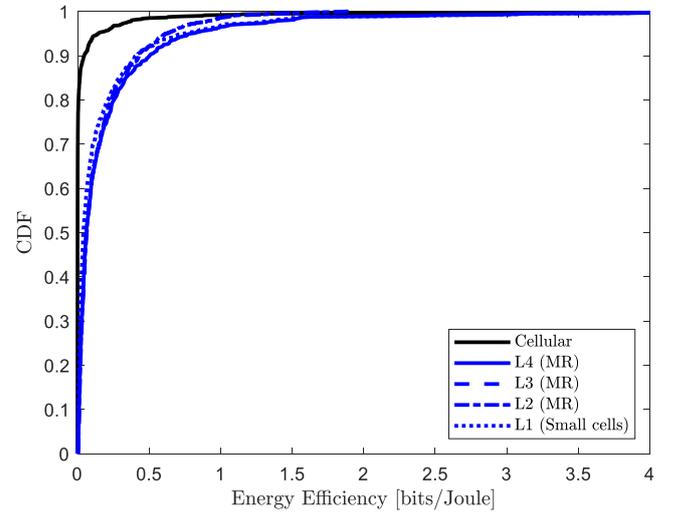
Figure 7 (a, b, c, d) : The SE and EE of cellular mMIMO and cell-Free mMIMO for 73 GHz-LOS model when the BER=10⁻⁸

Figure 6 and Figure 7 show SE and EE of cell-Free mMIMO system and cellular mMIMO when the LOS-73 GHz model is applied assuming that the BER is 10⁻³ and 10⁻⁸ respectively. From Figure 6 and Figure 7 it can be observed that the low BER value can provide a reliable communication system. Moreover, the Level 4 “fully centralized” can have a better performance than the cellular mMIMO when the MMSE or the MRC are applied. This is a unique characteristic to this propagation model. Figure 8, Figure 9, Figure 10, and Figure 11 displays the SE and EE performance of the MMSE and MRC in the cell-Free mMIMO for 73 GHz NLOS operation “Model 1 and Model 2” at different BER values.



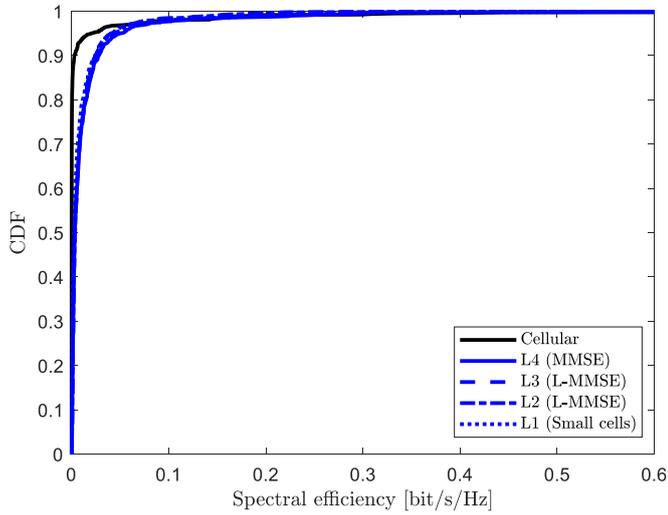


(c)

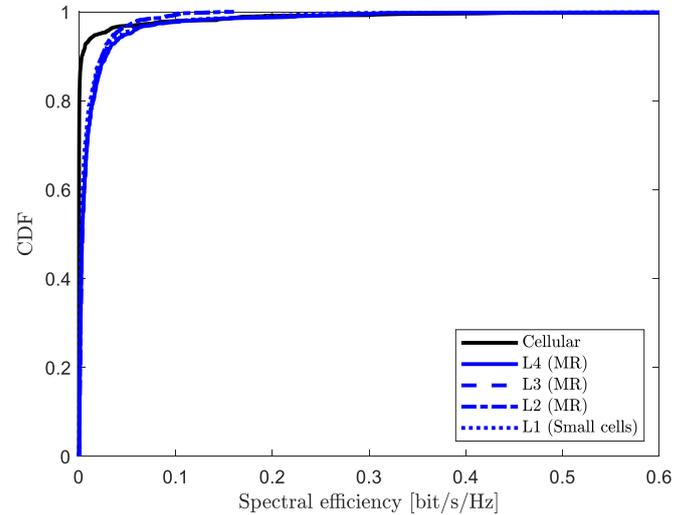


(d)

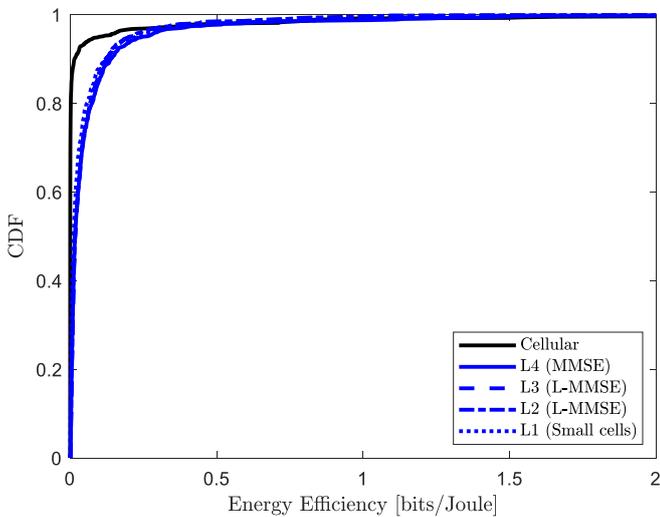
Figure 8 (a, b, c, d): The SE and EE of cellular mMIMO and cell-Free mMIMO for 73 GHz-NLOS model 1 when the $BER=10^{-3}$



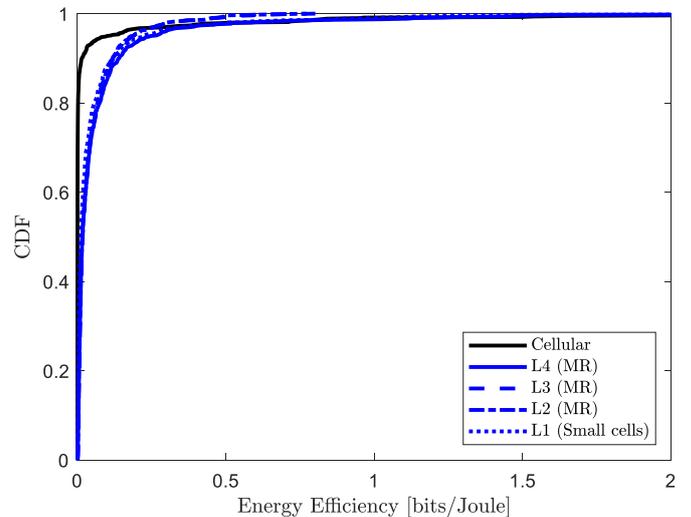
(a)



(b)

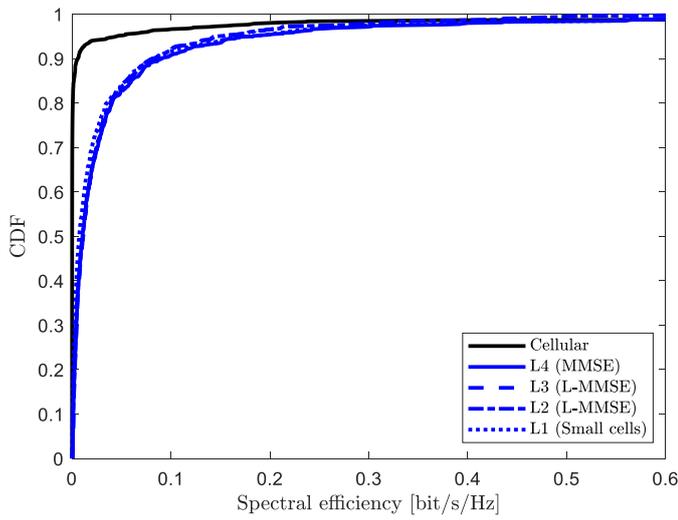


(c)

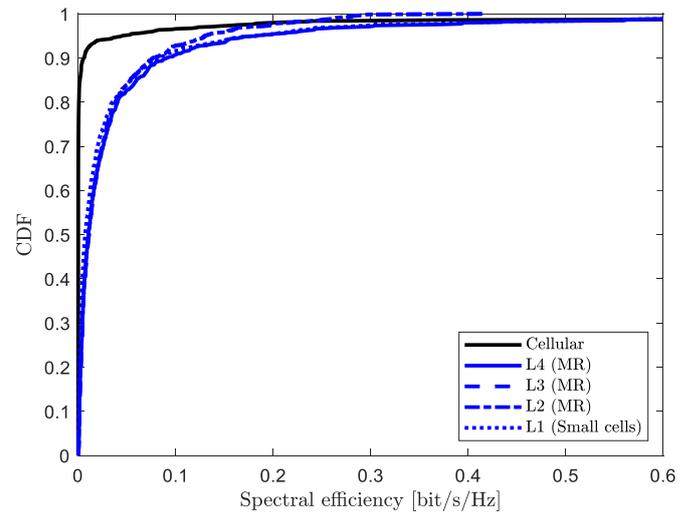


(d)

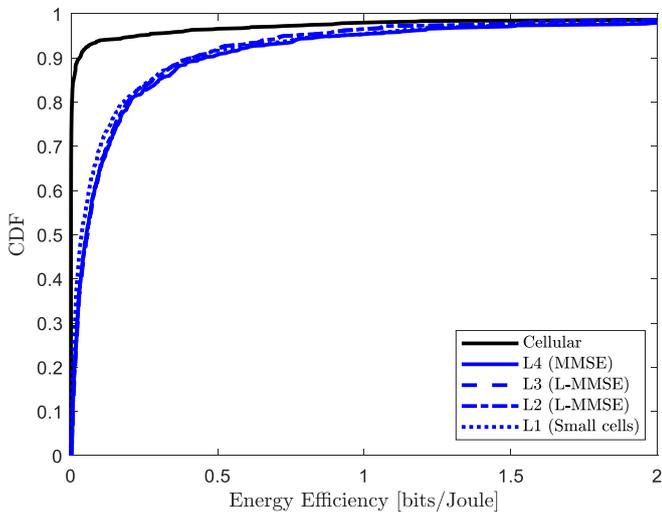
Figure 9 (a, b, c, d) : The SE and EE of cellular mMIMO and cell-Free mMIMO for 73 GHz-NLOS model 1 when the $BER=10^{-8}$



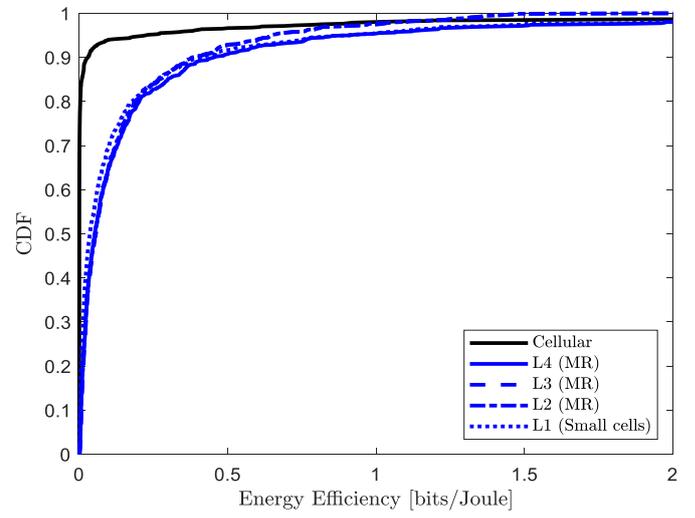
(a)



(b)

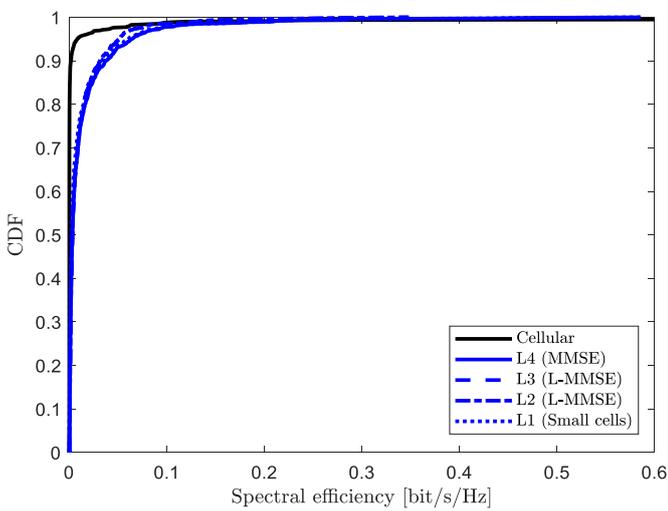


(c)

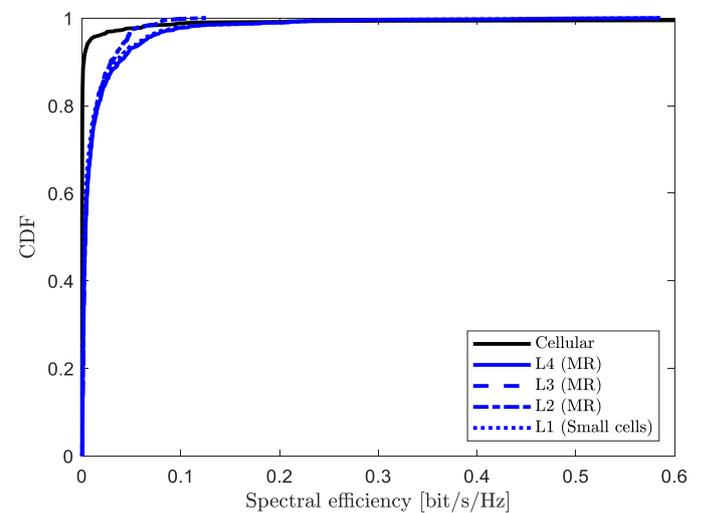


(d)

Figure 10 (a, b, c, d) : The SE and EE of cellular mMIMO and cell-Free mMIMO for 73 GHz-NLOS model 2 when the BER=10⁻³



(a)



(b)

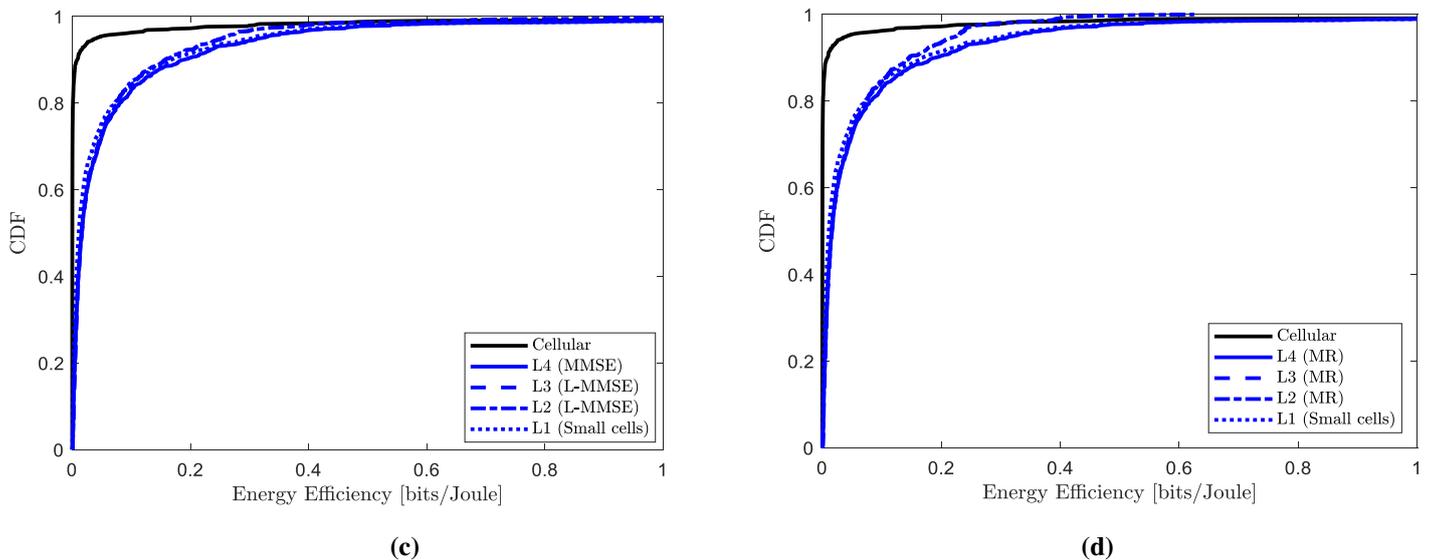


Figure 11 (a, b, c, d) : The SE and EE of cellular mMIMO and cell-Free mMIMO for 73 GHz-NLOS model 2 when the BER=10⁻⁸

From these figures, it can be concluded that the low BER results in a high reliable communication system. However, this results in low SE and EE values. The 73-GHz NLOS model 1 and model 2 can have a low SE and EE performance. However, the cell-Free mMIMO can provide a little better SE and EE performance than the cellular mMIMO. In general, the NLOS propagation models can let the mMIMO and their cell-Free mMIMO have a non-satisfied performance.

7. Conclusions

The cell-Free mMIMO network is simulated when the millimeter wave propagation models are applied. The NLOS propagation models can have a low SE and EE performance. On the other hand, level 4 in millimeter wave cell-Free mMIMO can provide a high performance than the cellular mMIMO especially for cell-edge users and shadowed users. The 73 GHz-LOS propagation model can provide a high SE and EE performance for the cellular mMIMO and the cell-Free mMIMO when either MMSE or MRC are applied.

Declarations

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

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There is no conflict between this work and other published work.

The Matlab code is available on reasonable request.

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