Optimum Jamming in User-Centric Cell-Free Networks

Ahmad Halimi Razlighi†, S. Mohammad Razavizadeh†, and Behrouz Maham‡
†School of Electrical Engineering, Iran University of Science and Technology, Iran
‡ Department of ECE, School of Engineering and Digital Sciences, Nazarbayev University, Kazakhstan
E-mails: halimirazlighi.ahmad@gmail.com, smrazavi@iust.ac.ir, and behrouz.maham@nu.edu.kz

2022 IEEE 96th Vehicular Technology Conference (VTC2022-Fall) | 978-1-6654-5468-1/22/$31.00 ©2022 IEEE | DOI: 10.1109/VTC2022-Fall57202.2022.10012721

***Abstract*—This paper investigates the optimum power allocation ratio of a jammer in order to ruin the sum spectral efficiency (SSE) of a user-centric cell-free network. In this regard, signal to interference plus noise ratio (SINR) is initially derived for each user in uplink, and then, a closed-form expression for SSE is provided. An optimization problem has been solved for two scenarios which finds the optimum power allocation that minimizes the SSE of the network, first for a single antenna jammer and next for a multi-antenna one. Additionally, the performance of the SSE has been studied in the presence of several single-antenna jammers in the proposed network and also one multi-antenna jammer. The result is compared with co-located multi-input multi-output (MIMO) network and it is found that unlike co-located MIMO, as the number of serving access points (APs) increases, the network becomes more robust against jamming. The effect of the jammer's antenna on power allocation ratio and spectral efficiency is further presented. Moreover, the impact of the number of jammers and the number of serving APs on the SE has been surveyed.**

***Index Terms*—Jamming, User-Centric, Cell-Free, Spectral Efficiency.**

I. Introduction

Massive multiple-input multiple-output (MIMO) has gained attention as a practical solution in 5G and beyond networks to provide higher quality of service (QoS), but the drop in the QoS experienced by cell-edge users, due to less channel gain and interference, has led to move towards new paradigms like distributed massive MIMO [1]. Cell-free (CF) networks are introduced as a promising massive MIMO technique to overcome poor QoS and handover issues at the cell-edge in cellular structures [2]. Clustering the serving access points (APs) based on users known as user-centric approach was introduced after the network-centric approach in CF networks in order to overcome the inter-cluster interference [3]. Besides, security in 5G networks and beyond is considered as a critical issue due to its various applications that rely on wireless communication. In this regard, physical layer security (PLS) has been introduced to secure communications by concentrating physical layer processing such as coding and beamforming [4].

In recent years, several aspects of CF networks like performance analysis, beamforming and power control have been widely studied in literature; however, investigating PLS in CF networks is still in its infancy. Pervious studies of PLS in CF networks are generally divided into two topics of "eavesdropping" and "jamming". Focusing on "eavesdropping", one should know that as CF networks as well as massive MIMO systems are robust against passive eavesdropping [5], active eavesdropping attacks have been studied in the literature. The secrecy rate in the presence of a single antenna eavesdropper (ED) for different scenarios of having limited and unlimited number of APs is studied in [6], where a power control algorithm is introduced to maximize secrecy rate. An algorithm based on the downlink pilot transmission is provided in [7] which limits the information leakage to a single-antenna ED and enhances the secrecy rate. Assuming that angle-of-arrival(AoA) information of all users and also the ED is available, [8] presents an AP selection scheme based on the AoA and proposes a channel estimation algorithm that results in an increase in secrecy rate. In order to inspect more realistic situations, [9] and [10] study the presence of a single-antenna ED in CF networks considering hardware impairments and spatially correlated rayleigh fading channels, respectively. The former shows that the effect of hardware impairments at APs vanishes as their number increases. Finally, an optimal power allocation approach to maximize the secrecy rate is provided by [11]. Heading towards "jamming", only [12] has recently investigated the presence of multiple single-antenna jammers in a CF network where all APs serve all users. It introduces two power control methods to reduce the destructive effect of jammers on spectral efficiency (SE). In addition, it reviews the effect of the transmission power of the jammers and their number on SE. Taking into account that not much work has been done on jamming in CF networks, this paper studies designing smart jammer(s) by finding optimum power allocation for the jammer(s) for both training and data transmission phases to have the most reducing effect on network SE. It has been tried to provide a holistic insight to jamming issue by considering single and multi-antenna jammer and also studying the effect of multiple jammers. The main contributions of this paper can be summarized as:

- Closed-form expressions of signal to interference plus noise ratio (SINR) for three different scenarios of one single-antenna, one multi-antenna and several single-antenna jammer(s) are derived.
- Convexity of the proposed optimization problem to find the optimal power allocation ration of the jammer is proved and the problem is solved through convex optimization tools.
- The impact of APs cluster size on power allocation strategy of the jammer is investigated in the presence of a single-antenna jammer and the result is compared with that of a co-located MIMO.
- The effect of the number of jammer's antenna on the power allocation strategy and sum spectral efficiency (SSE) of the network in case of both having fixed and variable cluster size is studied.
- The presence of several single-antenna jammers in the

This research was supported by the Faculty Development Competitive Research Grant (No. 240919FD3918), Nazarbayev University.

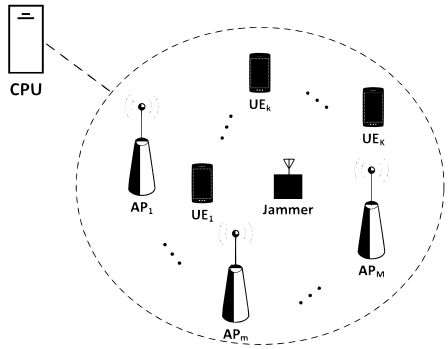

Fig. 1. A CF system with K single-antenna users, M single-antenna APs and a single-antenna jammer.

proposed network is considered and the result is compared with having one multi-antenna jammer.

Notation: Boldface symbols are used to refer to vectors and matrices. $(\cdot)^*$,$(\cdot)^T$,$(\cdot)^H$ and $()^\star$ are indicating conjugate, transpose, hermitian transpose and optimum value respectively. $\mathcal{CN}(\cdot,\cdot)$ denotes circular-symmetric complex Gaussian distribution. Finally, $\mathbb{E}\{\cdot\}$ is the expectation operator.

II. System Model

A user-centric CF network is considered as shown in Fig.1 where K legitimate single-antenna users are served by clusters of APs coming from M single-antenna APs geographically distributed in the proposed coverage area. All APs are connected to a central processing unit (CPU) via perfect fronthaul links. It is also considered that there exists a single-antenna jammer in the network trying to harm the system in the uplink transmission in both training and data transmission phases. Since the analysis hold almost the same for the situations that one multi-antenna jammer or several single-antenna jammers are present in the network, the differences are taken into consideration in Section III and here the analysis is provided for the presence of one single-antenna jammer.

The channel between k^{th} user and the m^{th} AP is assumed to be g_{mk}. Similarly, the channel between the jammer and the m^{th} AP is denoted by g_{mj}. Generally speaking, these single-input single-output (SISO) channels between each AP and the i^{th} device regardless of being legitimate or not are modeled as $g_{mi} = \beta_{mi}^{\frac{1}{2}}\tilde{g}_{mi}$ where $\tilde{g}_{mi}$ models the small-scale fading and $\beta_{mi}^{\frac{1}{2}}$ models the large-scale fading. It is also assumed that all channels are independent and identically distributed (i.i.d) in which $\tilde{g}_{mi}$ follows $\mathcal{CN}(0,1)$ distribution. β_{mi} models both path loss and shadowing. It is assumed that flat and slow fading hold in the system and channel realisations change independently from one coherence interval to another. Assuming decentralized implementation of user-centric CF network, all channel estimations are carried out at APs and after decoding the data, all the decoded data for each user from its serving APs are sent to CPU in order to estimate the final data of the intended user.

A. Training Phase and Channel Estimation

As it happens in a typical CF network, channels are estimated via uplink pilot transmission from the users. Assuming time division duplex (TDD) protocol, the estimated channels can be used in data transmission in downlink. The coherence interval under TDD protocol for uplink is divided to two intervals, one used for sending the pilot sequence and the other one for data. The coherence interval is indicated by T and τ is assigned for the pilot sequence length. Thus, the remaining interval, $T-\tau$, is used for data transmission. Theoretically, it is assumed τ symbols of the pilot sequence are chosen in a way that $\tau \geq K$ and as a result, orthogonal pilot sequences are available in the system [6]. The pilot sequence of the k^{th} user is defined as $\mathbf{\Phi}_k \in \mathbb{C}^{\tau\times 1}$. Moreover, it is assumed that $\mathbf{\Phi}_k^H\mathbf{\Phi}_k = 1$ and consequently $\mathbf{\Phi}_k^H\mathbf{\Phi}_{k'} = 0$ hold in the system where $k \neq k'$ and k and $k' \in \{1,...,K\}$. The received signal at the m^{th} AP in training phase will be as:

$$\mathbf{y_m} = \sum_{k=1}^{K}\sqrt{\tau p_t}g_{mk}\mathbf{\Phi}_k^T + \sqrt{\tau q_t}g_{mj}\mathbf{\Phi}_j^T + \mathbf{n}. \quad (1)$$

In (1), $\mathbf{\Phi}_j$ is the jammer's pilot sequence which is chosen randomly by the jammer because it is assumed that the jammer does not know the legitimate users' pilot sequences and as a result $\mathbb{E}\{(\mathbf{\Phi}_j^T\mathbf{\Phi}_k^*)^2\} = \frac{1}{\tau}$. In this way, the jammer can harm the training phase. In addition, p_t and q_t are the power that users and jammer use for training phase, respectively. In order to estimate the channel of a particular user, first $\mathbf{y_m}$ needs to be projected long $\mathbf{\Phi}_k$. Then by implementing $\mathbf{MMSE}$ estimation as introduced by [13], the estimated channel of the k^{th} user at the m^{th} AP is obtained:

$$\hat{g}_{mk} = c_{mk}\mathbf{y_m}\mathbf{\Phi}_k^*, \quad (2)$$

where c_{mk} is defined as:

$$c_{mk} = \frac{\sqrt{\tau p_t}\beta_{mk}}{(1+\tau p_t\beta_{mk}+q_t\beta_{mj})}. \quad (3)$$

It is clear that c_{mk} is different for the situations that multi-antenna jammer or several single-antenna jammers are present in the network. The differences are discussed later in Section III in details.

B. Data Transmission Phase

In this phase, users intend to send their data to the selected APs and simultaneously jammer transmits artificial noise signal. Transmitted symbol of the k^{th} user is indicated by x_k and for the jammer it is shown by s_k. Since decentralized implementation was considered, APs select a linear detection vector $\boldsymbol{\alpha}$ as a function of the estimated channels to detect the data of users that are receiving service from them. In order to find the received data from the k^{th} user, the k^{th} element of the received vector at m^{th} AP and the same element in detection vector are used as:

$$\begin{aligned} r_{mk} &= \sqrt{p_d}\alpha_{mk}^H g_{mk}x_k \\ &+ \sqrt{p_d}\sum_{\substack{i=1\\ i\neq k}}^{K}\alpha_{mk}^H g_{mi}x_i + \sqrt{q_d}\alpha_{mk}^H g_{mj}s + \alpha_{mk}^H n_m, \end{aligned} \quad (4)$$

where p_d and q_d are the portion of power each user and the jammer use for transmitting data and artificial noise, respectively. For the sake of simplicity and scalability maximum ratio combining (MRC) detection is used that means the estimated channels of the users are used for detection purposes ($\alpha_{mk} = \hat{g}_{mk}$). Using the expression in (4), the SINR equation for the k^{th} user can be written by (7). It is assumed that users and jammer have limited power budget denoted by P and Q, respectively. In order to design the jammer and find the

optimum power allocation, ζ and ρ parameters are introduced which are the fraction of the total power that the jammer and each user spend on the training phase. To illustrate it mathematically for the jammer, we have: $\zeta \triangleq \frac{\tau q_t}{TQ}$, which means it is considered that the power allocation between the two uplink phases are done as:

$$\tau q_t + (T-\tau) q_d = TQ. \tag{5}$$

In addition, the similar procedure can be applied to users.
In order to find the optimum power allocation for the jammer, as it was mentioned earlier in this paper, SSE of the network has been chosen as a metric of how the network is affected by jamming. Consequently, the SE for the k^{th} user is defined as [12]:

$$\mathcal{S}_k = (1 - \frac{\tau}{T}) \log_2(1 + \text{SINR}_k). \tag{6}$$

Moreover, the uplink SSE of the network is obtained by $\mathcal{S} = \sum_{k=1}^{K} \mathcal{S}_k$. Therefore, the SSE of the network introduced above is the objective function of the problem stated in Section IV. Moreover, a closed-form expression for the SINR_k is derived in (8) which lead to having a tangible expression for SSE of the network in presence of a jammer.

III. Extension to Other Scenarios

In this section the other two scenarios about the presence of jammer/jammers are considered. First the presence of a multi-antenna jammer is discussed and then the presence of several single-antenna jammers.

A. Single Multiple-antenna Jammer

In case of having a multi-antenna jammer in the network, it is assumed that the jammer has N_j antennas and its channels which are shown by g_{mn_j} are i.i.d and coming from $\mathcal{CN}(0,1)$ distribution. g_{mn_j} indicates the channel between the m^{th} AP and the n_j antenna of the jammer. Other system parameters about the location of the users and APs remain the same as the first scenario of having a single-antenna jammer. Further, it is assumed that the large-scale fading for the jammer's antennas is the same so, β_{mj} denotes the large-scale fading of the jammer. Also, a random pilot sequence is transmitted from each antenna of the jammer and $\mathbb{E}\{(\mathbf{\Phi}_{n_j}^T \mathbf{\Phi}_k^*)^2\} = \frac{1}{\tau}$ holds for all the transmitted pilots from the jammer. (8) for this scenario is derived in (10) on the top of the next page. The difference between (8) and (10) is obvious through the effect of the jammer's antennas indicated by N_j. Another difference takes place in channel estimation process in which for this case c_{mk} is defined:

$$c_{mk} = \frac{\sqrt{\tau p_t}\beta_{mk}}{\tau p_t \beta_{mk} + q_t N_j^2 \beta_{mj} + 1}. \tag{9}$$

B. Multiple Single-antenna Jammers

To consider the presence of multiple jammers in the network, it is assumed M_j single-antenna jammers are distributed uniformly in the coverage area and their channels are defined as $g_{mM_j} = \beta_{mM_j}^{\frac{1}{2}} \tilde{g}_{mM_j}$ where they are i.i.d. As the pervious scenarios, jammers transmit a random pilot sequence and $\mathbb{E}\{(\mathbf{\Phi}_{M_j}^T \mathbf{\Phi}_k^*)^2\} = 1$ holds. (3) for the channel estimation in this scenario changes as:

$$c_{mk} = \frac{\sqrt{\tau p_t}\beta_{mk}}{\tau p_t \beta_{mk} + q_t M_j \sum_{j=1}^{J} \beta_{mM_j} + 1}. \tag{12}$$

The closed form expression for the SINR of the k^{th} in this scenario is given by (11).

IV. Optimum Power Allocation

In this section the optimization problem to find the optimum power allocation ration ($\zeta^\star$) of the jammer in order to ruin the SSE of the network is introduced. It is assumed that the jammer is smart in a way that it knows the value of ρ and P of users so that its design be facilitated [14].So, the optimization problem is defined:

$$P: \begin{cases} \underset{\zeta}{\text{minimize}} & \mathcal{S} \\ \text{subject to} & 0 \le \zeta \le 1 \end{cases} \tag{13}$$

In order to deal with the optimization problem, its convexity is studied and it is proven that the proposed optimization problem is a convex one. Although three different scenarios have been studied so far, the convexity holds for all if it can be shown in one of the scenarios based on [15]. Firstly, $f_{mk}(\zeta)$ is defined as $f_{mk}(\zeta) \triangleq \frac{l(\zeta)}{\tau p_t \beta_{mk}^2}$ and regarding the presence of one single-antenna jammer in the network and rewriting the SINR equation based on ζ by substituting q_t and q_d from what we defined earlier and (5) as follows:

$$q_t = \frac{\zeta QT}{\tau} \quad and \quad q_d = \frac{(1-\zeta)QT}{T-\tau}, \tag{14}$$

$l(\zeta)$ will be defined as:

$$\begin{aligned} l(\zeta) \triangleq\ & (\tau p_t \beta_{mk} + \frac{\zeta QT}{\tau}\beta_{mj} + 1)(\sum_{i=1}^{K} \beta_{mi} + \frac{1}{p_d}) \\ & + \tau p_t \beta_{mk}^2 + \frac{(1-\zeta)QT}{T-\tau}(\tau p_t \beta_{mk} + \frac{3\zeta QT}{\tau}\beta_{mj} + 1)\beta_{mj} \end{aligned} \tag{15}$$

By the above consideration the problem(13) can be shown as:

$$P: \begin{cases} \underset{\zeta}{\text{minimize}} & (1 - \frac{\tau}{T}) \sum_{k=1}^{K} \sum_{\mu_L} \log_2(1 + \frac{1}{f_{mk}(\zeta)}) \\ \text{subject to} & 0 \le \zeta \le 1 \end{cases} \tag{16}$$

Using the composition rule in [15], the convexity will be proved as $\log(1+\frac{1}{x})$ is a convex and non-increasing function, and the second derivative of $l(\zeta)$ with respect to ζ is given as:

$$l''(\zeta) = -\frac{2(3)Q^2T^2\beta_{mj}^2}{\tau(T-\tau)p_d}, \tag{17}$$

which indicates that it is a concave function and by the composition rule, the optimization problem is a convex function and can be solved through convex optimization tool in MATLAB. Simulation results are provided in the next section.

V. Simulation Results

In this section, the behavior of the power allocation ratio of the jammer in the proposed user-centric CF network is evaluated through simulations and it is compared with its counterpart in a co-located MIMO system where the presence of jammer in a cellular co-located MIMO is studied. Also, the SSE performance of the system is provided for different scenarios of presence of a multi-antenna jammer and multiple single-antenna jammers in the network. The system model is deployed in a $500 \times 500\ m^2$ area and neither the users nor the jammer(s) can be located closer that $d_0 = 10\ m$ to the APs. The APs, users and jammer(s) are randomly and uniformly distributed in the defined area. It is assumed there

$$\text{SINR}_k = \sum_{\mu_L} \frac{p_d |\mathbb{E}\{\hat{g}_{mk}^H g_{mk}\}|^2}{p_d \sum_{i=1}^{K} \mathbb{E}\{|\hat{g}_{mk}^H g_{mi}|^2\} - p_d |\mathbb{E}\{\hat{g}_{mk}^H g_{mk}\}|^2 + \mathbb{E}\{||\hat{g}_{mk}^H||^2\} + q_d \mathbb{E}\{|\hat{g}_{mk}^H g_{mj}|^2\}}. \tag{7}$$

$$\text{SINR}_k = \sum_{\mu_L} \frac{\tau p_t \beta_{mk}^2}{(\tau p_t \beta_{mk} + q_t \beta_{mj} + 1)(\sum_{i=1}^{K} \beta_{mi} + \frac{1}{p_d}) + \tau p_t \beta_{mk}^2 + \frac{q_d}{p_d}(\tau p_t \beta_{mk} + 3 q_t \beta_{mj} + 1)\beta_{mj}}. \tag{8}$$

$$\text{SINR}_k = \sum_{\mu_L} \frac{\tau p_t \beta_{mk}^2}{(\tau p_t \beta_{mk} + q_t N_j^2 \beta_{mj} + 1)(\sum_{i=1}^{K} \beta_{mi} + \frac{1}{p_d}) + \tau p_t \beta_{mk}^2 + \frac{q_d}{p_d}(\tau p_t N_j \beta_{mk} + 3 N_j^2 q_t \beta_{mj} + N_j)\beta_{mj}}. \tag{10}$$

$$\text{SINR}_k = \sum_{\mu_L} \frac{\tau p_t \beta_{mk}^2}{(\tau p_t \beta_{mk} + q_t M_j \sum_{j=1}^{J} \beta_{mj} + 1)(\sum_{i=1}^{K} \beta_{mi} + \frac{1}{p_d}) + \tau p_t \beta_{mk}^2 + \frac{q_d}{p_d}(\tau p_t \beta_{mk} + 3 M_j q_t \sum_{j=1}^{J} \beta_{mj} + 1) \sum_{j=1}^{J} \beta_{mj}}. \tag{11}$$

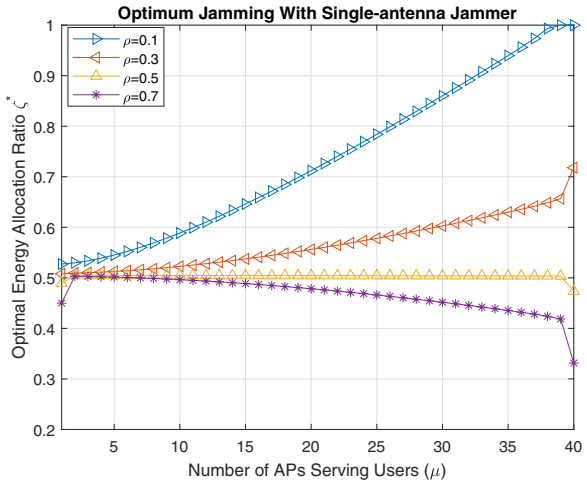

Fig. 2. Optimum power allocation ratio ($\zeta^\star$) of the single-antenna jammer versus the serving cluster size for different values of ρ. The jammer's power budget Q and the users' power budget P are set to be equal and 10 dB.

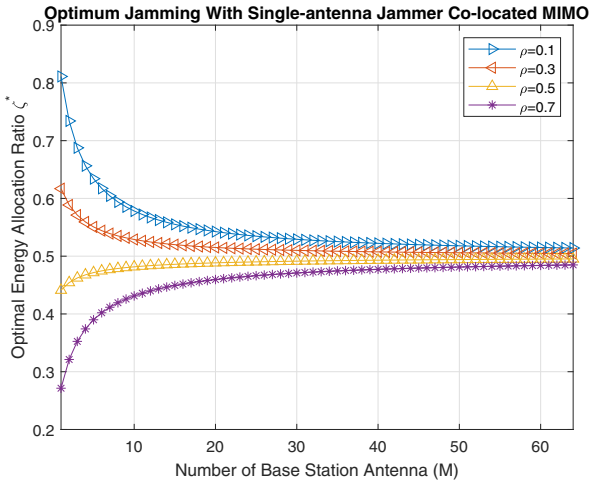

Fig. 3. Optimum power allocation ratio ($\zeta^\star$) of the single-antenna jammer versus the number of BS's antenna for different values of ρ. The jammer's power budget Q and the users' power budget P are set to be equal and 10 dB.

exist $M = 40$ APs and $K = 10$ users in the network. For all the mentioned scenarios, it is assumed that users and the APs are equipped with a single-antenna but jammer's number of antenna changes in the second scenario and its variation from one to ten antenna is studied. $\beta_{mi} = \frac{Z_{mi}}{(\frac{d_{mi}}{d_0})^n}$ is utilized to model the large-scale fading between the m^{th} AP and the i^{th} equipment in the network, in which its numerator models the shadow fading by Z that is a log-normal random variable and its denominator models the path loss and n is the path loss exponent. Parameters are set as, the coherence interval $T = 200$, by choosing the small number of users, the pilot sequence length is considered to be $\tau = K$, for the path loss exponent $n = 3.8$ is chosen and the for standard deviation of the shadowing $\sigma_{shad}^2 = 8$ dB. Regarding the normalization of the noise variance to one, the total power budget of the users and the jammer(s) are normalized and measured in dB.

Fig. 2 presents the optimum power allocation ration of a single-antenna jammer. It is obvious that jammer benefits the situation the most when each user only receives service from its nearest AP, by setting its power allocation ratio to $\zeta^\star = 0.5$ regardless of users' power allocation strategy. As the cluster size increases the situation becomes worse for the jammer and it must set different values for $\zeta^\star$ in accordance to the users' strategy. In comparison with Fig. 3 user-centric CF networks are more robust against jamming while in co-located MIMO, although it is expected that by increasing the number of antennas at BS the jammer's effect declines, the situation becomes suitable for it as $\zeta^\star$ for different strategies of the users reaches 0.5.

As it is presented in Fig. 4 in the same condition as Fig. 2, except that it is assumed that the power budget of the jammer increases with the number of its antennas, having multi-antenna jammer makes the situation suitable for jamming. As the number of jammer's antenna increases it does not matter that how users allocate their power for uplink transmission and the multi-antenna jammer only needs to set $\zeta^\star \simeq 0.5$. Simulations show that if the jammer's power budget remains constant and does not change by the increase in the number of antennas, there will be no gain to use multi-antenna jammer in the proposed network in case of ζ.

Finally, the performance of the SSE for the last two scenarios is presented separately in Fig. 5 and Fig. 6 when jammer(s) performs in their optimum state. The results shows that in a fixed cluster size, the use of a multi-antenna jammer will ruin the SSE more severely than using multiple single-antenna jammers. In addition, Increasing the number of serving APs or

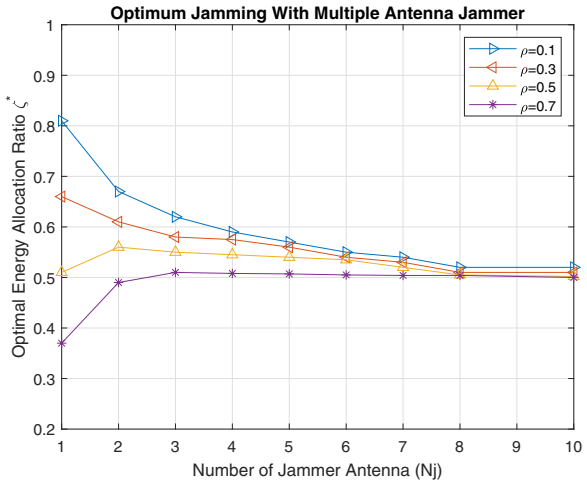

Fig. 4. Optimum power allocation ratio ($\zeta^{\star}$) of the multi-antenna jammer versus the number of jammer's antenna for different values of ρ. The users' power budget P is set to be 10 dB and the jammer's power budget is set to be $Q = N_j P$. The cluster size for this realization is set to be $\mu_l = 25$.

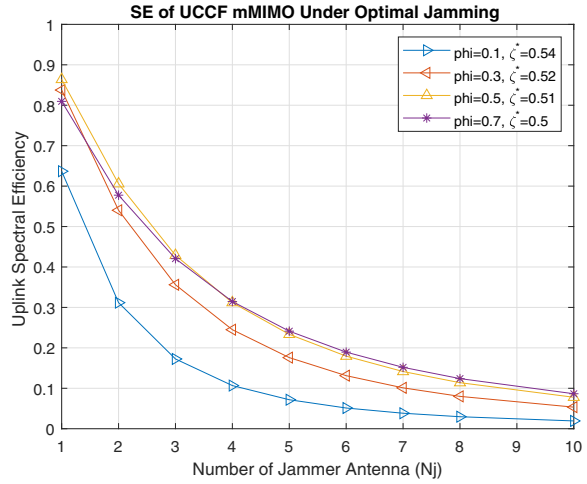

Fig. 5. Uplink SSE [bit/s/Hz] of the system in the presence of multi-antenna jammer and the cluster size is $\mu_L = 5$ and for the power budgets it is assumed $N_j P = Q = 10$ dB.

limiting the power of jammer(s) in both cases will not make any differences in the behavior of the SSE.

VI. Conclusion

The investigations in this paper have been carried out for the presence of a single-antenna jammer, multi-antenna jammer and several single-antenna jammers. It has been shown that when the AP cluster size is small the situation for the jammer is suitable and as the cluster size increases, jammer's situation becomes worse. For multi-antenna jammer, the increase in the number of antennas results in a better situation for the jammer which means it does not need to know the power allocation strategy of the users. Finally, It is proved that the network resists better when there are several single-antenna jammers than when there is a multi-antenna jammer. The study of the SSE shows that increasing the number of antennas at jammer causes an exponential decrease but increasing the number of single-antenna jammers does not do the same and as a result, increasing the AP cluster size to mitigate the effect of jamming, works better.

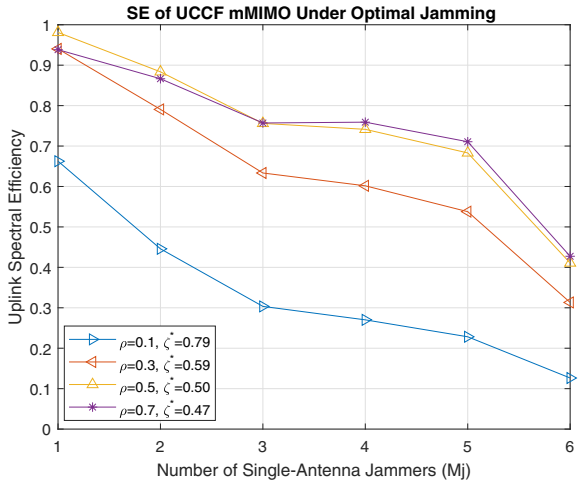

Fig. 6. Uplink SSE [bit/s/Hz] of the system in the presence of several single-antenna jammers and the cluster size is $\mu_L = 5$ and for the power budgets it is assumed $P = Q = 10$ dB.

References

[1] S. Elhoushy, M. Ibrahim, and W. Hamouda, "Cell-free massive MIMO: A survey," *IEEE Communications Surveys & Tutorials*, 2021.

[2] J. Zhang, E. Björnson, M. Matthaiou, D. W. K. Ng, H. Yang, and D. J. Love, "Prospective multiple antenna technologies for beyond 5G," *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 8, pp. 1637–1660, 2020.

[3] M. Giordani, M. Polese, M. Mezzavilla, S. Rangan, and M. Zorzi, "Toward 6G networks: Use cases and technologies," *IEEE Communications Magazine*, vol. 58, no. 3, pp. 55–61, 2020.

[4] Y. Wu, A. Khisti, C. Xiao, G. Caire, K.-K. Wong, and X. Gao, "A survey of physical layer security techniques for 5G wireless networks and challenges ahead," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 4, pp. 679–695, 2018.

[5] D. Kapetanovic, G. Zheng, and F. Rusek, "Physical layer security for massive MIMO: An overview on passive eavesdropping and active attacks," *IEEE Communications Magazine*, vol. 53, no. 6, pp. 21–27, 2015.

[6] S. Timilsina, D. Kudathanthirige, and G. Amarasuriya, "Physical layer security in cell-free massive MIMO," in *2018 IEEE Global Communications Conference (GLOBECOM)*. IEEE, 2018, pp. 1–7.

[7] S. Elhoushy and W. Hamouda, "Nearest aps-based downlink pilot transmission for high secrecy rates in cell-free massive MIMO," in *GLOBECOM 2020-2020 IEEE Global Communications Conference*. IEEE, 2020, pp. 1–6.

[8] J. Qiu, K. Xu, and X. Xia, "Secure transmission based on non-overlapping aoa in cell-free massive MIMO networks," in *2020 IEEE/CIC International Conference on Communications in China (ICCC)*. IEEE, 2020, pp. 588–593.

[9] X. Zhang, D. Guo, K. An, and B. Zhang, "Secure communications over cell-free massive MIMO networks with hardware impairments," *IEEE Systems Journal*, vol. 14, no. 2, pp. 1909–1920, 2019.

[10] X. Wang, Y. Gao, G. Zhang, and M. Guo, "Security performance analysis of cell-free massive MIMO over spatially correlated rayleigh fading channels with active spoofing attack," in *2020 International Conference on Wireless Communications and Signal Processing (WCSP)*. IEEE, 2020, pp. 540–545.

[11] T. M. Hoang, H. Q. Ngo, T. Q. Duong, H. D. Tuan, and A. Marshall, "Cell-free massive MIMO networks: Optimal power control against active eavesdropping," *IEEE Transactions on Communications*, vol. 66, no. 10, pp. 4724–4737, 2018.

[12] R. Sabbagh, H. Zhu, and J. Wang, "Cell-free massive MIMO systems under jamming attack," in *2021 IEEE International Conference on Communications Workshops (ICC Workshops)*. IEEE, 2021, pp. 1–6.

[13] S. M. Kay, *Fundamentals of statistical signal processing: estimation theory*. Prentice-Hall, Inc., 1993.

[14] H. Pirzadeh, S. M. Razavizadeh, and E. Björnson, "Subverting massive MIMO by smart jamming," *IEEE Wireless Communications Letters*, vol. 5, no. 1, pp. 20–23, 2015.

[15] S. Boyd, S. P. Boyd, and L. Vandenberghe, *Convex optimization*. Cambridge university press, 2004.