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Incorporation of MU-MIMO Technology into User-centric Cell-Free mMIMO System

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Abstract Recently, cell-free massive multiple-input-multiple-output (CF-mMIMO) system has been attracting a great attention. CF-mMIMO system is designed to accommodate a relatively small number of users by using a large number of antennas. From the practical perspective of computational complexity and fronthaul capacity, a user-centric antenna clustering approach is taken, i.e., each user is served by an antenna cluster which is a set of antennas with high channel gain. However, as the number of users increases, the interference tends to degrade the transmission performance. To improve the transmission performance under a densely populated user environment, we propose to incorporate the multi-user MIMO (MU-MIMO) technology into user-centric CF-mMIMO, which is called clusters-centric CF-mMIMO in this paper. In cluster-centric CF-mMIMO, user-clusters are first formed and a set of antennas is associated with each user cluster for performing MU-MIMO communication in parallel. We will show by computer simulation of user capacity that the proposed cluster-centric CF-mMIMO outperforms the user-centric CF-mMIMO under a densely populated user environment.

Keywords Cell free massive MIMO, user clustering, signal processing

1. Introduction

The massive multiple-input-multiple-output MIMO (massive MIMO) [1,2] is considered the most effective technology to significantly improve the spectrum efficiency (SE) of mobile communication systems. There are two types of massive MIMO according to the deployment manner of antennas. One is the centralized massive MIMO system which deploys large-scale antenna array at the base station (BS) [1]. The other one is distributed massive MIMO which spatially deploys a large number of antennas over the BS coverage area called the cell and connects these distributed antennas via mobile fronthaul [3].

Recently, a so-called cell-free massive MIMO (CF-mMIMO) system has been attracting a great attention [4-6]. CF-mMIMO is actually a special realization based on the concept of distributed massive MIMO. Like its name, CF-mMIMO deploys a large number of access points or distributed antennas over a wide communication service area to serve a relatively small number of users compared to the number of antennas, rather than dividing the service area into a number of cells. Scalability is the main challenge for the CF-mMIMO implementation due to the prohibitively high computational complexity of signal processing and fronthaul capacity due to the large-scale network [5]. Therefore, in [5], a user-centric antenna clustering approach was proposed to realize the scalable implementation of CF-mMIMO. Specifically, in the user-centric antenna clustering, each user is served by an antenna cluster which is a set of high channel gain antennas. Since user-centric antenna clusters for different users are inevitably overlapped, the interference problem arises. Hence, the multi-user precoding/postcoding based interference mitigation is taken for each user signal transmission. In [5], the partial MMSE was proposed to partially mitigate the interference from other users. However, in the above scenario, as the number of users increases, the transmission performance tends to degrade due to severer inter-user interference.

In this paper, to improve the transmission performance under a densely populated user environment, we propose to incorporate the multi-user MIMO (MU-MIMO) technology into user-centric CF-mMIMO, which means that, instead of user-centric approach, user-cluster centric approach is taken. Such a CF-mMIMO is called cluster-centric CF-mMIMO in this paper. In cluster-centric CF-mMIMO, user clusters are first formed and then, a set of antennas is associated with each user cluster. The set of antennas for each user-cluster is allowed to overlap to those of other user-clusters.

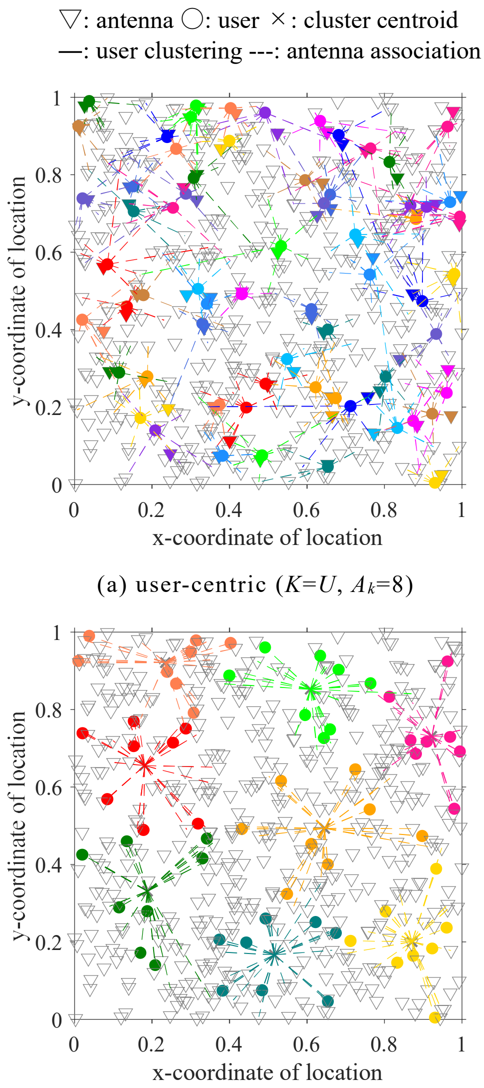
The rest of this paper is organized as follows. In Section 2, we introduce the system model and show how we construct the user-clusters and associate antennas with each user-cluster by comparing the user-centric approach. Then, in Section 3, the CF-mMIMO transmission model based on zero-forcing (ZF) multiuser multiplexing [7,8] and the generalized signal-to-interference-plus-noise-ratio (SINR) expression is derived, which is applicable to both cluster-centric and user-centric CF-mMIMO transmissions. In Section 4, computer simulation results are presented to demonstrate the effectiveness of proposed cluster-centric CF-mMIMO transmission. Finally, we give some conclusions and future study in Section 5.

2. System model

We consider a CF-mMIMO system which serves U single-antenna users by using A distributed antennas in a normalized 1×1 square-shaped service area. A antennas and U users are assumed to be randomly located in the coverage area. We consider to form K user-clusters in the CF-mMIMO system. For the user-centric approach, K=U, because it can be considered that the user-centric approach is single-user clustering. On the other hand, for the proposed cluster-centric approach, the number of users in the kth cluster is denoted by U_k, which is determined by the signal processing power required for multiuser multiplexing. It should be noted that the user-clusters are disjointed and U_k=U/K when U users are equally divided into K clusters. The number of antennas associated with the kth cluster is denoted by A_k. It should also be noted that a set of antennas associated with different user-clusters are allowed to overlap.

As we mentioned above, to make the CF-mMIMO system scalable, a user-centric antenna clustering was proposed in [5]. A set of antennas for each user is based on channel gains between each user and antennas. The antenna clusters are allowed to overlap each other, as illustrated in Fig. 1 (a). However, as the user density increases and approaches that of antennas, the residual inter-user-interference becomes stronger since the number of antennas per user is limited.

In this paper, we introduce the user-cluster-wise MU-MIMO to effectively mitigate the inter-user-interference in the dense user environment. In our proposed cluster-centric approach, user cluster is first constructed by modified K-means method [9,10] based on the user location information. By denoting the user set $\mathcal{S}_k \subset \{1,\ldots u,\ldots,U\}$ that belongs to the kth cluster, then, $|\mathcal{S}_k| = U_k$. Moreover, the user clusters are non-overlapped, i.e., $\mathcal{S}_k \cap \mathcal{S}_i = \varnothing$. After that, antenna association is carried out. In order to clearly compare cluster-centric and user-centric approaches, we also associate antennas with each user cluster based on channel gain. Then, for cluster-centric approach, each user in the cluster needs to be fairly associated with antennas to ensure the quality of service, that is, each user associates the same number (A_k/ U_k) of antennas to form its antenna cluster. The antenna association method is based on the strongest channel gain criterion. Similar to user-centric approach, a set of antennas for each user cluster can also be overlapped. The proposed cluster-centric approach is illustrated in Fig.1 (b).



(a) user-centric (K=U, A_k=8)

(b) cluster-centric (K=8, A_k=16)

Fig. 1 An example of antenna association.

(A=512, U=64).

It should be noted that a set of antennas associated with each cluster is different for user-centric and cluster-centric approaches as seen in the above Fig.1.

3. ZF-based MU-MIMO transmission model for CF-mMIMO system

In this section, we present the ZF-based MU-MIMO transmission scenario for CF-mMIMO. Here, we derive the expressions for the pre/postcoding weight vector and those for the achievable SINR for cluster-centric CF-mMIMO. It is worth noting that, same as in Section. 2, the user-centric approach is regarded as a special case of the cluster-centric one (i.e., single-user cluster), so the formula deduced below is general. First, inspired by the literature [5], we define the antenna association matrix for the kth cluster as $\mathbf{D}_k \in \mathbb{C}^{A\times A} = diag(d_1,\ldots,d_a,\ldots,d_A)$. If the ath antenna is associated with the kth cluster, the element d_a of $\mathbf{D}_k$ is set to 1, otherwise it is set to 0. Based on this, the antenna set associated with the kth cluster is denoted by $\mathcal{M}_k \subset \{1,\ldots a,\ldots,A\}$ with $|\mathcal{M}_k| = A_k$. The MIMO channel is characterized by distance-depended path loss, log-normal shadowing and Rayleigh fading. The uplink channel vector for the u_kth user in the kth cluster is denoted by $\mathbf{h}_{u_k}$ of size $A\times 1$. Then, the uplink channel postcoding weight vector for the u_kth user in the kth cluster can be represented as

$$\mathbf{w}_{u_k} = \mathbf{h}_{u_k}^H \mathbf{D}_k \left(\sum_{i=1}^{K} \sum_{v_i=1}^{U_i} \mathbf{D}_k \mathbf{h}_{v_i} \mathbf{h}_{v_i}^H \mathbf{D}_k \right)^{-1}. \quad (1)$$

In the process of multi-user detection, considering the scalability of computational complexity and the adaptability of interference source superposition, the number of antennas associated with each cluster in the dense user environment is much smaller than the number of interfering users in the service area. Refer to [5], we calculate the weight vector from the antenna dimension. For convenience, we use uplink channel vector for postcoding weight derivation. Note that according to the duality of uplink and downlink channels, the downlink channel vector and precoding vector are the transposition of $\mathbf{h}_{u_k}$ and $\mathbf{w}_{u_k}$, respectively. As can be seen from Eq. (1), the matrix inversion is necessary for each cluster. It should be pointed out that the user-centric approach requires U/K times larger number of matrix inversion operations than the cluster-centric approach. Hence, the proposed cluster-centric approach has an advantage of reduced computational complexity compared to the user-centric approach.

When the power spectral density of AWGN at user and antenna side is considered as 1, the SINR of the u_kth user in the kth cluster can be derived as

$$\mathrm{SINR}_{u_k} = \begin{cases} \dfrac{P_{u_k} \left| \mathbf{w}_{u_k} \mathbf{D}_k \mathbf{h}_{u_k} \right|^2}{\sum_{i=1,}^{K} \sum_{v_i=1}^{U_i} P_{v_i} \left| \mathbf{w}_{u_k} \mathbf{D}_k \mathbf{h}_{v_i} \right|^2 - P_{u_k} \left| \mathbf{w}_{u_k} \mathbf{D}_k \mathbf{h}_{u_k} \right|^2 + \left\| \mathbf{v}_{u_k} \right\|_F^2}, \mathrm{UL} \\ \dfrac{\dfrac{P_{u_k} \left| \mathbf{h}_{u_k}^T \mathbf{D}_k \mathbf{w}_{u_k}^T \right|^2}{\left\| \mathbf{w}_{u_k}^T \right\|_F^2}}{\sum_{i=1}^{K} \sum_{v_i=1}^{U_i} \dfrac{P_{v_i} \left| \mathbf{h}_{u_k}^T \mathbf{D}_i \mathbf{w}_{v_i}^T \right|^2}{\left\| \mathbf{w}_{v_i}^T \right\|_F^2} - \dfrac{P_{u_k} \left| \mathbf{h}_{u_k}^T \mathbf{D}_k \mathbf{w}_{u_k}^T \right|^2}{\left\| \mathbf{w}_{u_k}^T \right\|_F^2} + 1}, \mathrm{DL} \end{cases}. \quad (2)$$

In Eqs. (1) and (2), all users are assumed to interfere to each other. However, the interference from faraway users is sufficiently weak due to the pathloss. Therefore, following [5], we consider only strong interfering users in the weight calculation, which is called partial ZF. The uplink postcoding weight vector of partial ZF for the u_kth user in the kth cluster is given as

$$\mathbf{w}_{u_k}^{\text{partial}} = \mathbf{h}_{u_k}^H \mathbf{D}_k \left(\sum_{v_i \in \mathcal{N}_k} \mathbf{D}_k \mathbf{h}_{v_i} \mathbf{h}_{v_i}^H \mathbf{D}_k \right)^{-1}, \quad (3)$$

where $\mathcal{N}_k$ is the set of interested users (consisting cluster members and interference users) for partial ZF weight calculation of the kth cluster. It should be noted that relative to partial ZF, the ZF detection in Eq. (1) is called full detection because all the users are considered in the weight calculation. It is worth noting that the interested user set $\mathcal{N}_k$ is different for user-centric and cluster-centric approaches. To be more precise, for user-centric approach, users who share the same antenna are interfering users [5], i.e., they are taken into account when computing the correlation matrix for matrix inversion shown in Eq. (3). In this paper, for cluster-centric approach, we determine a union of interfering users of the user-centric approach as the interfering users for computing the correlation matrix). This is to ensure that the channel estimation complexity for the cluster-centric approach becomes equivalent to the user-centric approach.

4. Numerical results

In this section, we evaluate and discuss the performance of user-centric and cluster-centric approaches. We carry out Monte-Carlo simulation to compute the user capacity, the sum capacity, and the user fairness [11] achievable with user-centric and cluster-centric MU-MIMO for each user location pattern. For each generation of user location pattern, the pathlosses, the shadowing losses, and the Rayleigh fading gains between users and antennas are generated once. Then, the cumulative distribution function (CDF) of the capacity is obtained by changing the user location pattern 100 times randomly for a fixed antenna location pattern. In our simulation, equal transmit power allocation among users is utilized. The transmit power is represented by the normalized transmit signal-to-noise ratio (SNR) which is the received SNR when the transmitter-receiver distance is equal to the side length of the normalized 1×1 square-shaped area. The simulation parameters setting is shown in Table 1.

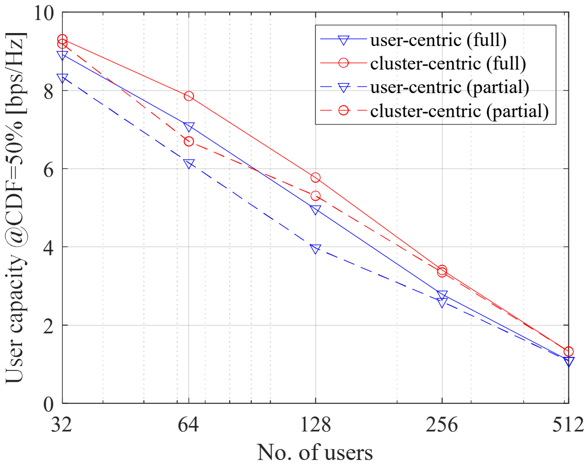
Table 1

	User-centric [5]	Cluster-centric
Number of distributed antennas (A)	512	
Number of users (U)	32, 64, 128, 256, 512	
No. of users per cluster (U_k)	1	8
Number of clusters (K)	U	U/8
No. of antennas per cluster (A_k)	8	16
Number of times of user location generations	100	
Path loss exponent	3.5	
Log-normal shadowing standard deviation [dB]	8	
Fading type	Rayleigh	
Transmit SNR per user (P) [dB]	-30	

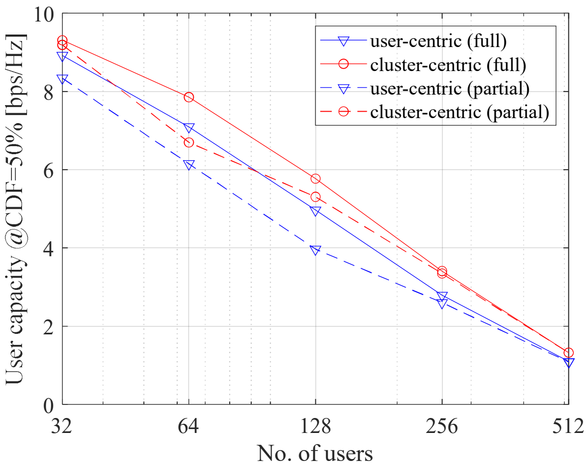
As shown in Table 1, the number U_k of users to be multiplexed in the kth cluster is set to 8 for the cluster-centric approach. Regarding the antenna association method, the channel gain threshold is used in [5] to find the antennas to associate with each user, so the number of antennas per user is different among users. However, in this paper, the number of antennas per user is set to 8 for all users. This is to make a clear comparison between user-centric and cluster-centric approaches. According to Eq. (1) and [5,8], the total computational complexity for obtaining the weight vectors is about $\sum_{k=1}^{K} O(A_k^3)$ for the case of cluster-centric CF-mMIMO irrespective of the value of U_k. For the case of user-centric CF-mMIMO, A_k=8 and K=U and accordingly, the total computational complexity becomes $U \times O(8^3)$. Therefore, to make the computational complexity equal, the number of antennas per cluster of the cluster-centric CF-mMIMO is given by A_k=16 when U_k=8.

Fig. 2 plots the user capacity, the sum capacity, and the user fairness at the CDF of 50% as a function of the number of users. As the benchmark, the results of user-centric approach taking into account all users in service area as interference sources (labelled as user-centric (full)) are indicated as blue solid lines. The results of our cluster-centric approach (cluster-centric (full)) are indicated as the red solid lines. It is clearly seen that our cluster-centric approach achieves higher capacity and user fairness than the user-centric approach. We analyze the reason by plot the heat map of received signal strength for all the users in service area from the antennas belong to a target user in Fig. 3. In the Fig. 3, the colored solid circle represents the received signal strength, and the hollow circle indicates the users considered for weight calculation. In case of full user detection, all users are circled, and the arrow indicates the target user. By comparing Fig. 3 (a) and (b), we can see that in cluster-centric case, the received signal strength of users in the same cluster as the target user is very low, indicating that the interference of the target user is effectively suppressed inside the cluster. In addition, compared with user-centric case, the interference caused by target users to other users in cluster-centric is also low in general. This is because our proposed cluster-centric approach fairly associates antennas which have high channel gain with each user in the cluster, which can effectively form the null beams to cancel the interference inside the cluster. On the other hand, our proposed cluster-centric approach uses larger number of antennas per cluster (16 antennas for cluster-centric approach while 8 antennas for user-centric approach) and therefore, more null beams can be formed to better cancel the interference from users outside the cluster of interest. However, full user detection requires the knowledge of channel state information for all users in the service area and may not be scalable and practical.

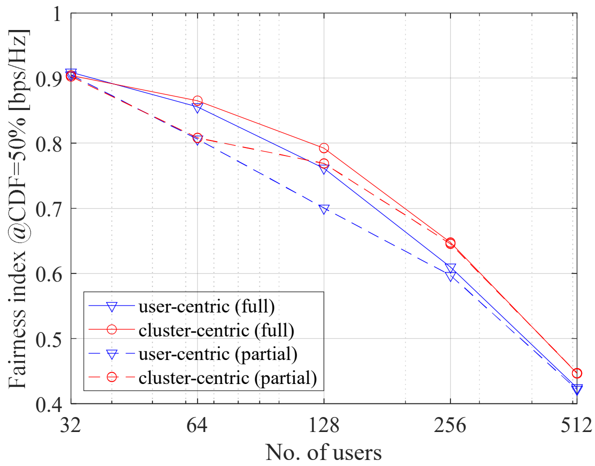
Next, the results of the partial ZF-based MU-MIMO (i.e., taking into account interfering users near each cluster instead of all of interfering users) are plotted as the dash lines for both user-centric and cluster-centric approaches in Fig. 2. It can be observed that the use of partial ZF-based MU-MIMO reduces the capacity and fairness for both user-centric and cluster-centric approaches because only a part of interference users is considered in the pre/postcoding weight vector. The reason for this capacity reduction is discussed in the following. When the number of users is small e.g., U=64 while A=512, probability of overlapping the antenna clusters for the user-centric approach is very small although some of users whose antennas are not overlapped with a user of interest give strong interference to that user. This can be understood by comparing Fig. 3 (a) and (c) (also Fig. 3 (b) and (d)) and combining with Fig. 1. However, it should be noted that the cluster-centric approach still gives higher capacity and fairness than the user-centric approach.



(a) User capacity

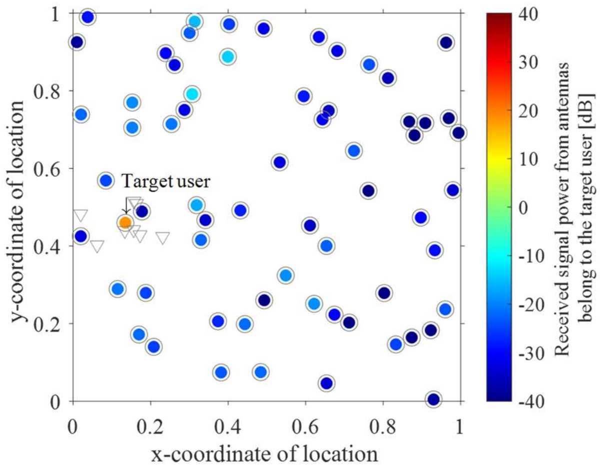


(b) Sum capacity

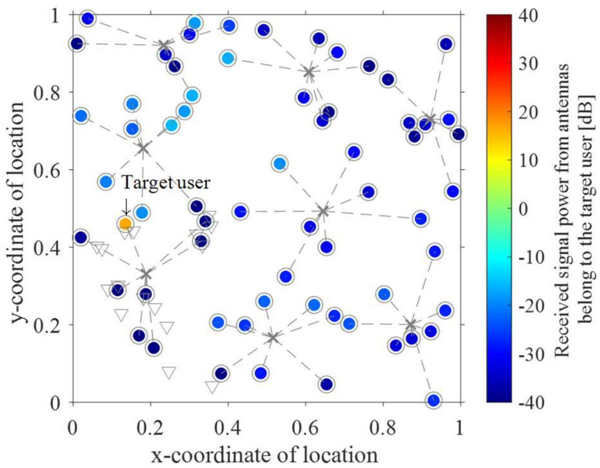


(c) User fairness

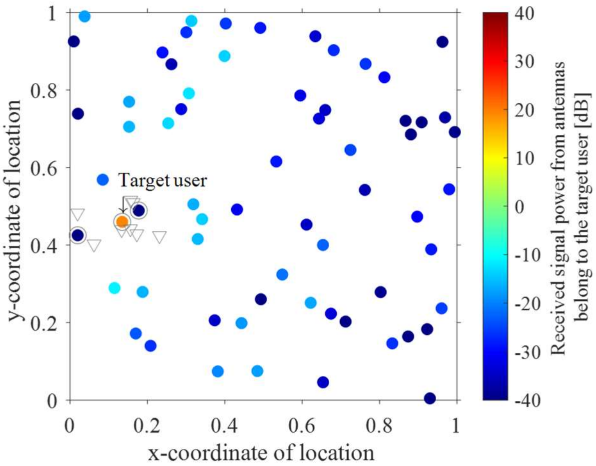
Fig. 2 Downlink system performance of user-centric and cluster-centric approaches with full and partial MU-MIMO processing.



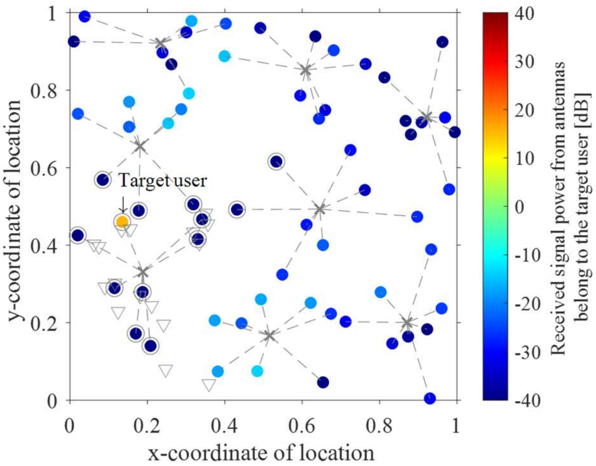
(a) User-centric (full)



(b) Cluster-centric (full)

_

(c) User-centric (partial)



(d) Cluster-centric (partial)

Fig. 3 Heatmap of received signal level of each user. (U=64 and A=512 as assumed in Fig. 1)

So far, we have shown the results of the downlink transmission. We have also confirmed by the simulation that the uplink performance can be similar to the downlink performance and also that our cluster-centric approach provides higher uplink capacity and fairness than the user-centric approach.

5. Conclusion

In this paper, we proposed the cluster-centric approach for CF-mMIMO system. We derived the full and partial ZF-based pre/postcoding weight vectors. The user-centric CF-mMIMO is a special case of our proposed cluster-centric CF-mMIMO. We also derived the general expression for the received SINR which can be applicable to both cluster-centric and user-centric approaches. We confirmed by Monte-Carlo simulation that the cluster-centric approach provides higher capacity and user fairness than user-centric approach in both downlink and uplink transmissions.

Optimization of the user-clustering and antenna association is left as our future study. Also interesting is to find the optimal number of users per user-cluster for the given user-to-antenna ratio.

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