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Study on cluster formation for distributed MU-MIMO

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Abstract: Deploying a large number of spatially distributed antennas (DAs) is a promising solution to improve the link capacity while keeping the coverage of 5G systems which utilize a high frequency band. And clustering is a promising method to mitigate the extremely high computational complexity due to a large-scale multi-user multiple-input multiple-output (MU-MIMO). User-clustering and antenna-clustering are two clustering approaches. In this paper, we utilize K-means algorithm in clustering and propose two cluster member assignment (CMA) methods to assign corresponding DAs or users into user-clusters or antenna-clusters. Then, we evaluate the achievable downlink and uplink capacities through computer simulation to find the optimum combination of clustering approach and CMA.

Keywords: distributed antenna, MU-MIMO, user-antenna clustering

Classification: Wireless Communication Technologies

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1 Introduction

High frequency band e.g. mmWave band, where broad bandwidth is available, is adopted in 5th generation (5G) systems to alleviate the increasing mobile data

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traffic. However, it has a nature of rectilinear propagation and large pathloss which cause a problem in achieving the high link capacity while keeping the base station (BS) coverage. One promising solution is to deploy a large number of spatially distributed antennas (DAs) to improve the link capacity or the spectral efficiency. Besides, a large-scale MU-MIMO has a problem of high computational complexity. To mitigate this problem, dividing large-scale MIMO into small-scale ones through clustering is a good solution. There are two clustering approaches, user-clustering and antenna-clustering, for distributed MIMO. In [1], user-clustering based on K-means algorithm [2] and antenna selection were proposed to form cluster-wise MU-MIMO. On the other hand, in [3], flexible antenna clustering (FAC) and ordered user selection were considered to improve spectral efficiency of a large-scale distributed antenna system (L-DAS).

In this paper, we introduce K-means algorithm in clustering and propose two cluster member assignment (CMA): user-antenna-distance based CMA (UAD-CMA) and cluster-centroid-distance based CMA (CCD-CMA) methods to assign corresponding DAs or users into user-clusters or antenna-clusters. Assuming zero-forcing (ZF) based MU-MIMO [4], we try to find the best combination of clustering and CMA for cluster-wise MU-MIMO through the link capacity evaluation by computer simulation.

The rest of the paper is organized as follows. In Sect. 2, algorithms of clustering and CMA are described. Sect. 3 gives the signal presentation for cluster-wise ZF-based MU-MIMO. Then, in Sect. 4, the simulation results on the link capacity achievable with the cluster-wise ZF-based MU-MIMO are presented and the best combination of clustering and CMA is found. Finally, some conclusions are given in Sect. 5.

2 Clustering and CMA methods

In this paper, we first cluster either users or antennas into a predetermined number of clusters by using K-means algorithm [2] (the former is called UC and the latter is called AC). Then we assign DAs or users by two CMA methods. Therefore, there are $2 \times 2 = 4$ possible combinations to form the cluster-wise MU-MIMO. In this paper, a single square-shaped BS coverage area (cell) is considered. The total number of users and that of antennas in the BS cell are denoted by U and A, respectively. It is assumed that $U \leq A$ and $U_k \leq A_k$ because of ZF-based cluster-wise MU-MIMO, where A_k and U_k represent the number of antennas and that of users assigned to the kth cluster, respectively.

First, the K number of clusters is predetermined. In both UC and AC, the location-based K-means clustering is initialized by selecting K random positions as the centroids among users or DAs. We calculate the distance of each user or DA to all cluster-centroids and add users or DAs into the closest cluster. Then, the cluster centroids are updated based on the positions of their members. This process is repeated until the cluster centroids no longer change.

After either UC or AC is completed, CMA shown in Fig. 1 is respectively carried out to assign DAs or users to each cluster. UAD-CMA procedure is described first and then followed by CCD-CMA.

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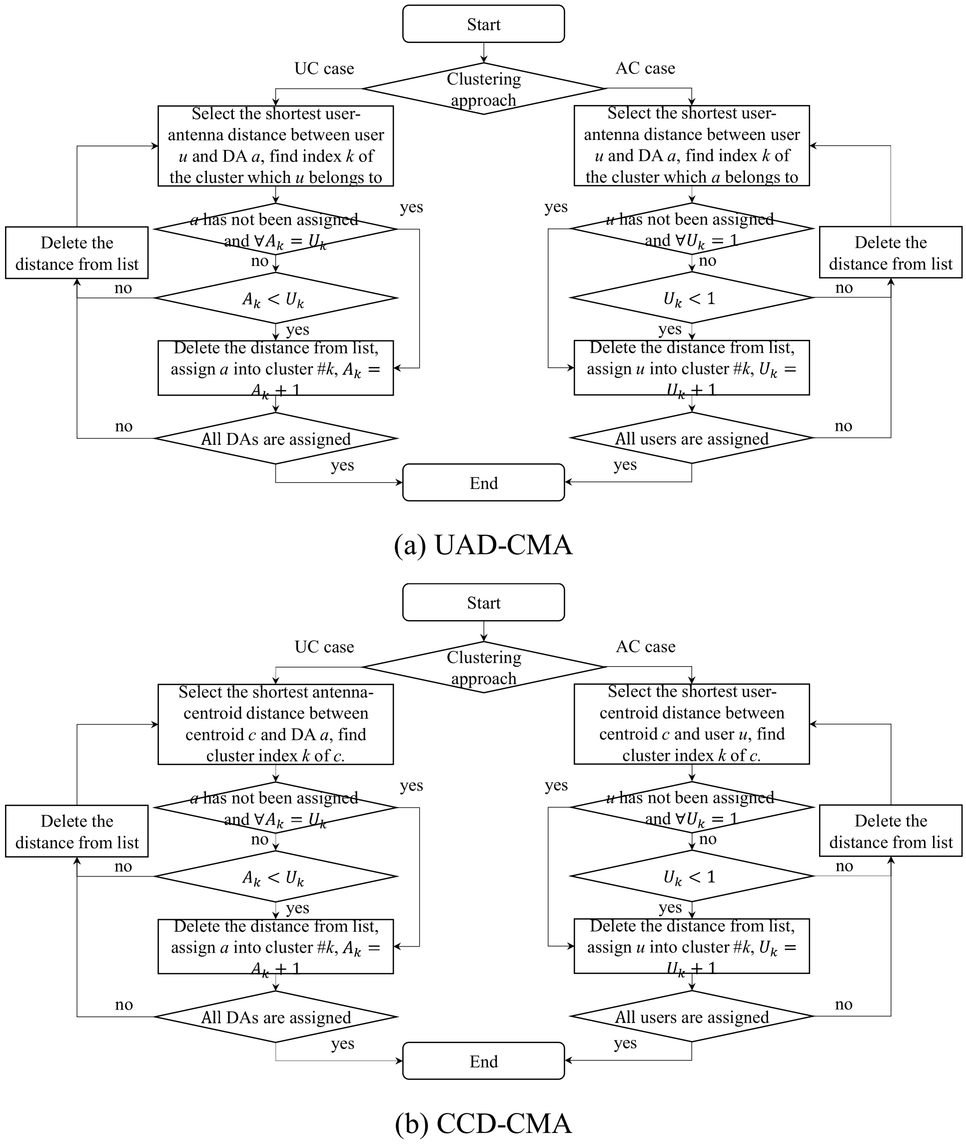

Fig. 1. CMA procedure.

Here, we consider a two-step procedure in both UAD-CMA and CCD-CMA. The first step is to assign user or antenna members based on ascending distance to meet the constraint on the number of users and antennas in each cluster, i.e., $1 \leq U_k \leq A_k$. The second step is to assign remaining users or antennas to the closest cluster. The assignment is based on *user-antenna distance* in the case of UAD-CMA and is based on *antenna (or user)-cluster-centroid distance* in the case of CCD-CMA.

3 Cluster-wise MU-MIMO and link capacity formula

Before evaluating the link capacity achievable with cluster-wise ZF-based MU-MIMO, the signal representation for downlink and uplink transmissions is presented. Then, the link capacity formula for the given MU-MIMO channel realization is presented with the consideration of inter-cluster interference. In this paper, the perfect knowledge of MU-MIMO channels is assumed.

Fig. 2 shows the transmission system model of cluster-wise ZF-based MU-

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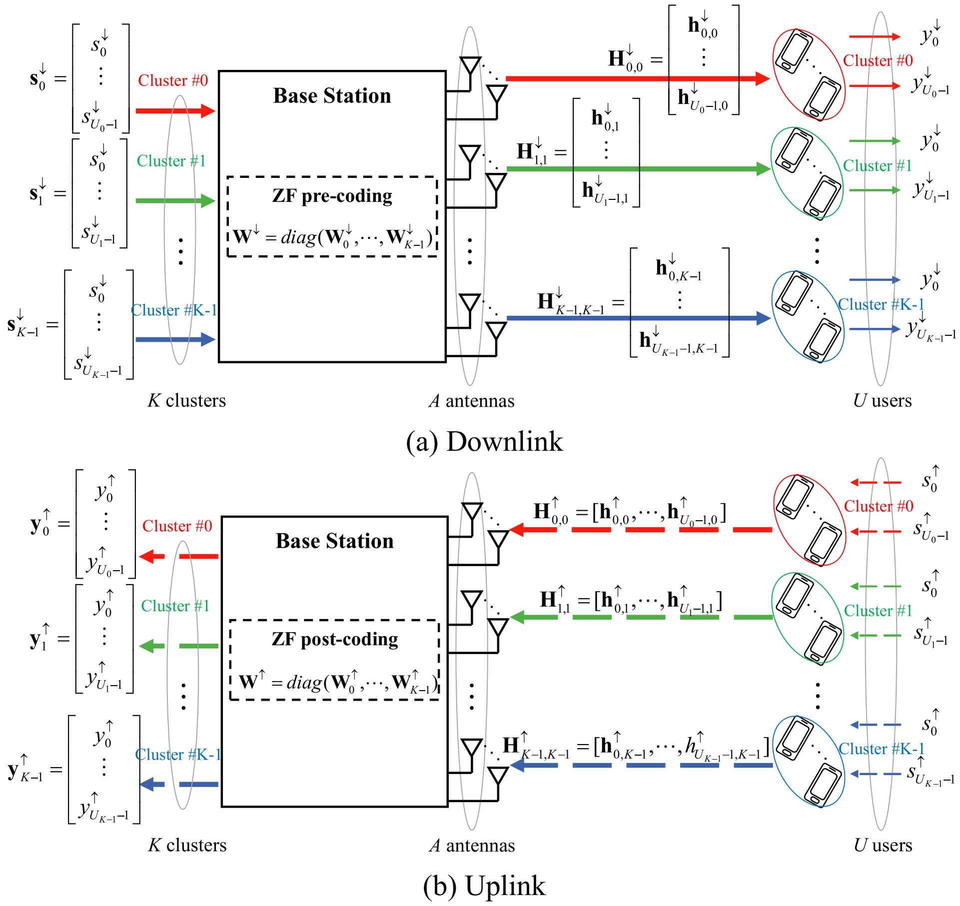

Fig. 2. Transmission system model for cluster-wise ZF based MU-MIMO.

MIMO. Letting $\mathbf{H}_{k,k}^{\downarrow}$ and $\mathbf{H}_{k,k}^{\uparrow}$ be respectively the downlink and uplink MU-MIMO channel matrices of the kth cluster, the downlink ZF pre-coding matrix and the uplink ZF post-coding matrix can be expressed as

$$\begin{cases} \mathbf{W}_k^{\downarrow} = (\mathbf{H}_{k,k}^{\downarrow})^{\dagger} = \mathbf{H}_{k,k}^{\downarrow}{}^{H}(\mathbf{H}_{k,k}^{\downarrow}\mathbf{H}_{k,k}^{\downarrow}{}^{H})^{-1} \\ \mathbf{W}_k^{\uparrow} = (\mathbf{H}_{k,k}^{\uparrow})^{\dagger} = (\mathbf{H}_{k,k}^{\uparrow}{}^{H}\mathbf{H}_{k,k}^{\uparrow})^{-1}\mathbf{H}_{k,k}^{\uparrow}{}^{H} \end{cases}, \tag{1}$$

where $\mathbf{A}^H$ denotes the conjugate transpose of matrix $\mathbf{A}$. Assuming that inter-user-interference is perfectly eliminated by ZF, the baseband equivalent representation for the received signal of the u_kth user in the kth cluster is given by

$$\begin{cases} y_{u_k}^{\downarrow} = \sqrt{\beta_k P_k} s_{v_k}^{\downarrow} + \sum\limits_{m=0, m\neq k}^{K-1} \sum\limits_{j_m=0}^{U_m-1} \mathbf{h}_{u_k,m}^{\downarrow} \mathbf{W}_m^{\downarrow}(:, j_m)\sqrt{\beta_m P_m} s_{j_m}^{\downarrow} + n_{u_k} \\ y_{u_k}^{\uparrow} = \sqrt{P_{u_k}} s_{v_k}^{\uparrow} + \sum\limits_{m=0, m\neq k}^{K-1} \sum\limits_{j_m=0}^{U_m-1} \mathbf{W}_k^{\uparrow}(u_k, :)\mathbf{h}_{j_m,k}^{\uparrow}\sqrt{P_{j_m}} s_{j_m}^{\uparrow} + \mathbf{W}_k^{\uparrow}(u_k, :)\mathbf{n}_k \end{cases}, \tag{2}$$

where the second and third terms are inter-cluster-interference and noise, respectively. In Eq. (2), $\mathbf{h}_{u_k,k}^{\downarrow} \in \mathbf{H}_{k,k}^{\downarrow}$ and $\mathbf{h}_{u_k,k}^{\uparrow} \in \mathbf{H}_{k,k}^{\uparrow}$ are the downlink channel row vector and uplink channel column vector for the u_kth user in the kth cluster, respectively. $\mathbf{W}_k^{\downarrow}(:, u_k)$ and $\mathbf{W}_k^{\uparrow}(u_k, :)$ represent the u_kth column and row vectors in $\mathbf{W}_k^{\downarrow}$ and $\mathbf{W}_k^{\uparrow}$, respectively. $\beta_k = 1/\|\mathbf{W}_k^{\downarrow}\|_F^2$ denotes the normalization factor for the ZF

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pre-coding in the kth cluster, where $\|\mathbf{A}\|_F$ denotes the Frobenius norm of matrix $\mathbf{A}$. It is assumed that uplink transmit signal-to-noise ratio (SNR) is equal for all users, i.e., $\forall P_{u_k} = P$, and accordingly, total downlink transmit SNR over A_k DAs in the kth cluster is $P_k = U_k \times P$. s_{u_k} represents the data symbol of the uth user in the kth cluster with $E[|s_{u_k}|^2] = 1$. The additive white Gaussian noise (AWGN) component at the u_kth user in downlink and the AWGN vector at DAs in the kth cluster in uplink are represented by n_{u_k} and $\mathbf{n}_k$, respectively. The downlink and uplink sum capacities are computed using the Shannon capacity formula as

$$\begin{cases} C_{sum}^{\downarrow} = \sum_{k=0}^{K-1}\sum_{u_k=0}^{U_k-1}\log_2\left(1+\dfrac{\beta_k P_k}{\sum\limits_{m=0,m\neq k}^{K-1}\sum\limits_{j_m=0}^{U_m-1}\beta_m P_m|\mathbf{h}_{u_k,m}^{\downarrow}\mathbf{W}_m^{\downarrow}(:,j_m)|^2+1}\right), \\ C_{sum}^{\uparrow} = \sum_{k=0}^{K-1}\sum_{u_k=0}^{U_k-1}\log_2\left(1+\dfrac{P_{u_k}}{\sum\limits_{m=0,m\neq k}^{K-1}\sum\limits_{j_m=0}^{U_m-1}P_{j_m}|\mathbf{W}_k^{\uparrow}(u_k,:)\mathbf{h}_{j_m,k}^{\uparrow}|^2+\|\mathbf{W}_k^{\uparrow}(u_k,:)\|^2}\right) \end{cases}. \tag{3}$$

4 Sum capacity evaluation

The BS cell is normalized to a 1 by 1 square-shaped area. $P = 0\,\text{dB}$ represents the normalized transmit SNR, which is equivalent to the received SNR at the distance equal to the side length of BS cell from the transmitter. $U = 64$ users equipped with single-antenna and $A = 128$ DAs are randomly deployed in the BS cell. $K = 8$ clusters are formed by K-means based clustering and proposed CMA methods to perform cluster-wise ZF-based MU-MIMO. All users and DAs share the same frequency resource among BS cell in this paper.

The link capacity is evaluated for four possible realizations of cluster-wise MU-MIMO with consideration of the inter-cluster interference. Throughout this simulation, a randomly generated certain deployment pattern of $A = 128$ DAs is fixed. The propagation channel is composed of distance-dependent path loss, log-normal shadowing loss, and frequency non-selective Rayleigh fading. Hence, the downlink channel gain $h_{u_k,a_k}^{\downarrow} \in \mathbf{H}^{\downarrow}$ between the u_kth user and the a_kth DA with their distance $d_{u_k,a_k}(\leq \sqrt{2})$ normalized by the side length of square-shaped BS cell can be expressed as

$$h_{u_k,a_k}^{\downarrow} = \sqrt{d_{u_k,a_k}^{-\alpha}10^{-\frac{\varphi}{10}}}\,g, \tag{4}$$

where α and φ represent the path loss exponent and the shadowing loss (in dB) following the Gaussian distribution, respectively. In this paper, $\alpha = 3.5$ and φ is assumed as a zero-mean Gaussian variable with standard deviation $\sigma = 8$. The variable g denotes the Rayleigh fading gain characterized by a zero-mean complex Gaussian random variable with unit variance. The locations of $U = 64$ users are randomly generated 1000 times. For every set of users' locations, clustering and CMA are carried out and set of shadowing losses is generated 10 times. Then, for each set of shadowing losses, a set of Rayleigh fading gains is generated 10 times

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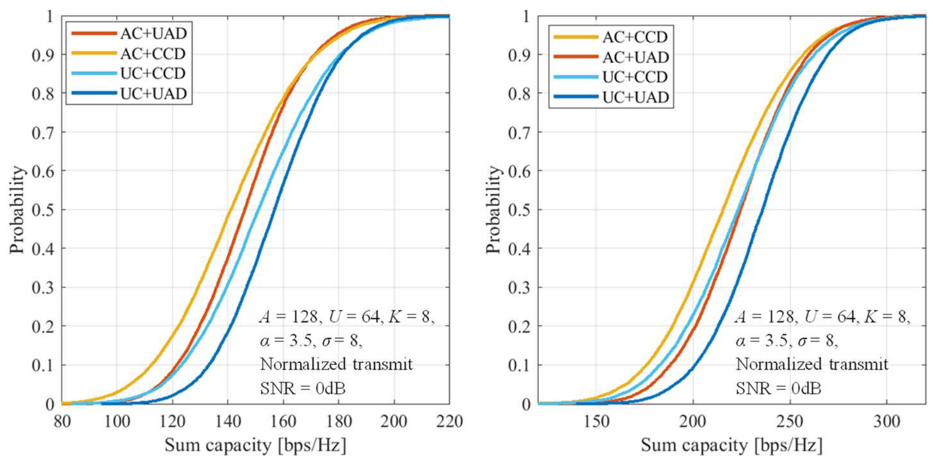
to obtain the local averaged sum capacity (i.e., the sum capacity computed by using Eq. (3) is averaged over 10 sets of Rayleigh fading gains for each given path loss and shadowing loss).

Fig. 3 plots the cumulative distribution function (CDF) of sum capacities of total four combination of clustering approaches and CMA methods. Below, we compare the two approaches of clustering. It can be seen from Fig. 3 that UC performs better than AC for both downlink and uplink, and the difference of capacity are both about 11 bps/Hz at CDF = 50%. This is because $A = 2U$ is assumed in this paper, which means that users are distributed more sparsely than DAs. This leads to a high degree of freedom when assigning DAs to UCs and a high multiplexing gain can be obtained to mitigate the ICI well. In addition, since the users' locations change while the antennas' locations are fixed, user clustering approach can form clusters adaptively according to the changes in user locations.

Next, we compare the two proposed CMA methods. In both downlink and uplink cases, UAD performs better irrespective of AC or UC. This is because the allocation criterion based on the shortest user-antenna distance can guarantee almost always each user can find at least one antenna which is very close to it to obtain high signal-to-interference-plus-noise ratio (SINR). Note that we evaluated the sum capacity for different antenna deployment patterns and confirmed that the CDF curves are almost similar to those shown in Fig. 3. Moreover, we also evaluated the sum capacity when $K = 4$, 16, and 32 and compared the combinations of clustering and CMA. Similar to $K = 8$, UC + UAD achieves the highest capacity.



(a) Downlink (b) Uplink

Fig. 3. Comparison of the sum link capacity.

5 Conclusion

In this paper, we studied the cluster formation based on K-means algorithm for performing cluster-wise MU-MIMO in a distributed MU-MIMO system. K-means algorithm was used to form UCs or ACs, to which antennas or users were assigned by proposed CMA methods. It was confirmed by sum capacity evaluation that a combination of UC and UAD is the best.

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In this paper, the perfect knowledge of MIMO channels and the same transmit powers for all users were assumed. Channel estimation and power allocation are left as our future study.

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