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On Power Allocation Strategy for Realistic Cellular Structured Cluster-wise Distributed MU-MIMO System

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Abstract With the demanding of higher capacity and higher data rate services in 5G-advanced systems, distributed multi-user multiple-input multiple-output (MU-MIMO) is a promising approach for radio access network (RAN). To avoid a prohibitively high signal processing complexity required for large-scale MU-MIMO, we have been studying cluster-wise distributed MU-MIMO for 5G advanced RAN. Multiple clusters are formed in each cell by K-means algorithm using user locations information. Unfortunately, cluster-wise distributed MU-MIMO introduces the inter-cluster-interference, thereby degrading the link capacity. In order to mitigate the capacity reduction, we recently proposed a sum capacity maximization-based power allocation strategy assuming an unrealistic square-shaped cellular structure.

It should be noted that the cluster shape may be different for a different cellular structure, resulting in a different inter-cluster interference. The aim of this paper is to evaluate the impact of sum capacity maximization-based power allocation strategy in the case of a realistic cellular structure. In this paper, a previously proposed modified K-means based cellular structuring method using antenna locations is considered. The link capacity evaluation is carried out by computer simulation assuming both the close-to-realistic cellular structure and the simple but unrealistic square-shaped cellular structure. It is shown that our previously proposed optimal power allocation strategy can effectively improve the link capacity even in the case of the close-to-realistic cellular structure.

Keywords 5G-advanced, Distributed antenna system, Clustering, K-means, Power allocation.

1. Introduction

In order to provide high-data rate services to the growing number of mobile users and devices, the frequency band is getting higher (e.g., the commercial 5G is using the millimeter wave band) and the deployment of base station (BS) antennas also tends to be denser. Then, aiming to avoid the frequently blockage of high frequency signal by obstacles because of the rectilinear propagation nature of higher frequency band signals, distributed antenna deployment is preferable than conventional co-located one to improve the coverage while further improving the energy efficiency. Moreover, considering the prohibitively high computational complexity of large-scale multiuser multi-input multi-output (MU-MIMO) communications, clustering method is utilized to divide the original large-scale MU-MIMO to several small-scale ones [1].

In such a cluster-wise distributed MU-MIMO, the cellular structuring and clustering methods may affect the system performance due to the different interference structure. In our previous study [2], we proposed a modified K-means [3] based cellular structuring method based on antenna locations to form the cells with the same number of antennas aiming at keeping the same signal processing power for all BSs. And the proposed cellular structuring method can obtain a realistic cellular structure rather than the simple square-shaped one which we used before. Based on that, also considering the processing capacity of the BS, in this paper, we further improve the clustering method from simple K-means to modified K-means, so that the number of users in each cluster does not exceed the allowable maximum number of multiplexed users.

In addition, inter-cell-interference and inter-cluster-interference strongly limits the cellular system capacity. So, in our previous study [4], we proposed an optimal power allocation (OPA) with total transmit power constraint. In the proposed OPA, the sequential quadratic programming (SQP) algorithm [5] is utilized for sum capacity maximization. We confirmed, by computer simulation, the effectiveness of our proposed OPA in a single square-shaped cell system. In this paper, as a further step, we introduce the proposed OPA to a multi-cell system having a new realistic cellular structure.

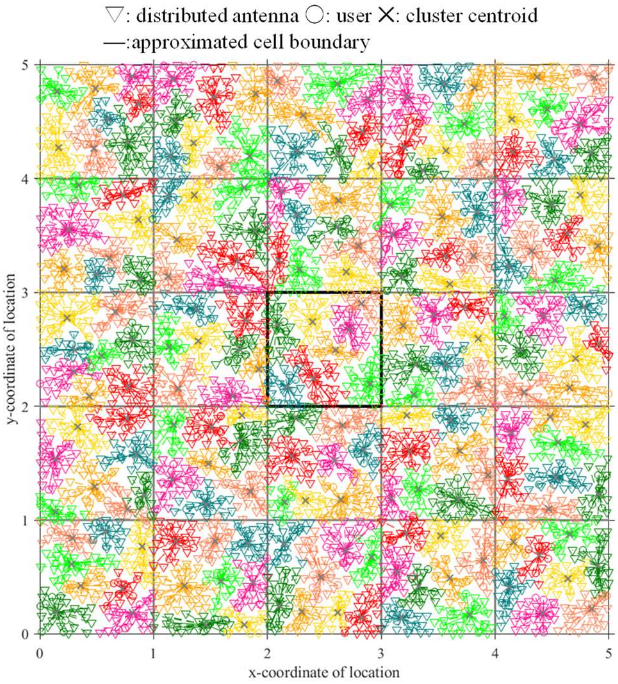
The rest of this paper is organized as follows. In Chapter

2, the cluster-wise distributed MU-MIMO is introduced. We give the examples of previously proposed modified K-means cellular structuring and compare with the square-shaped cellular structure. In Chapter 3, we formulate the sum capacity maximization-based power allocation algorithm with total power constraint and requirement of user experience. Then, in Chapter 4, we evaluate, by the simulation, the sum capacity and user capacity and compare our proposed OPA with equal power allocation (EPA) for the cases of modified K-means and square-shaped cellular structuring methods. Finally, some conclusions and future studies are given in Chapter 5.

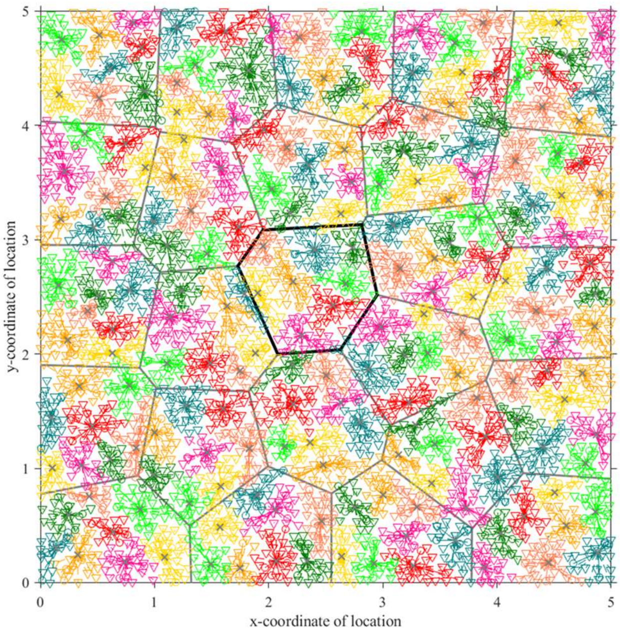
2. System model

As our assumption, U single-antenna users are randomly located following the uniform distribution in a normalized 5×5 square range service area. We set the antenna locations to maintain a certain spacing (AS) while meeting the random distribution, so as to achieve better coverage. For the square-shaped cellular structure, the service area is equally divided into M square cells, and $A_M=2U/M$ antennas are deployed in each cell. On the other hand, for modified K-means based cellular structuring, $A=2U$ antennas are firstly deployed over the service area and then, M equal-antenna-size cells are formed by modified K-means based on the antenna location information. As described in [3], the classic K-means clustering algorithm is equivalent to an iterative linear optimization problem. By adding the restriction of allowable minimum number of members in each cluster, the equal-size clusters (i.e., the same number of members per cluster) is realized [6]. For cellular structuring, the clustering object is the distributed antennas, and the clustering result is the cellular structure. The examples of two cellular structuring results are shown in Fig. 1, where the modified K-means based one can get hexagonal cell shape as the realistic system.

After the cellular structure is formed, each user is associated to a cell which has the closest antenna to it. Then, user location-based clustering is carried out by the modified K-means algorithm. Different from cellular structuring, the clustering object is changed to the users and the number of members is restricted to no more than the multiplexing capability [6]. It is worth noting that the colors in the Fig. 1 are only for the convenience of distinguishing clusters. In the actual communication process, each cell and clusters in each cell use the same radio resource at the same time, which means an existence of both inter-cell-interference and inter-cluster-interference.



(a) Square-shaped cellular structure



(b) Modified K-means based cellular structure

Fig. 1 Examples of cellular structuring result (U=1600, M=25, A=2×U, AS=0.625, K=8).

3. Sum capacity maximization-based power allocation

We consider the zero-forcing (ZF) based MU-MIMO transmission in each cluster. However, as we mentioned above, inter-cell and inter-cluster interference still exist which leads to the degradation of system capacity. Therefore, we introduce the previously proposed sum capacity maximization-based power allocation [4] into a cellular system constructed as we mentioned above. In this paper, a cell, which is closest cell to the center of service area and is indicated by black thick lines in Fig. 1, is considered as a target cell. The capacity for the u_kth user of the kth cluster in the target cell is computed by the Shannon's formula [7] given by Eq. (1), where γ_{uk} denotes the signal-to-interference-plus-noise ratio (SINR) of the u_kth user of the kth cluster. Both downlink and uplink capacity can be calculated by Eq. (1). Only the difference is the SINR due to different interference sources in the uplink and downlink. It should be noted that, in this paper, the perfect knowledge of each user's SINR is available.

$$C_{u_k} = \log_2(1+\gamma_{u_k}) \tag{1}$$

Using the above capacity formula, we try to maximize the sum capacity under the constraint of a total transmit power, single-antenna transmit power, and an allowable minimum user capacity. The optimal power allocation problem can be described as in Eq. (2). For simplicity, we also integrate the uplink and downlink constraints into a single function.

$$\begin{aligned}
&\max_{P_{u_k}} \sum_{k=0}^{K-1} \sum_{u_k=0}^{U_k-1} C_{u_k} \qquad (2)\\
&s.t.\ \mathbb{C}_1 : \sum_{k=0}^{K-1} \sum_{u_k=0}^{U_k-1} P_{u_k} = U \times P_{\text{target}}\\
&\quad \mathbb{C}_2 : C_{u_k} \geq C_{\text{allowable}},\\
&\qquad \forall k, u_k; k = \{0,1,\cdots,K-1\}, u_k = \{0,1,\cdots,U_k-1\}\\
&\quad \mathbb{C}_3 : \begin{cases} P_{a_k} \leq 5 \times P_{\text{target}}, & \text{in downlink}\\ \forall k, a_k; k = \{0,1,\cdots,K-1\}, a_k = \{0,1,\cdots,A_k-1\} & \\ \text{none,} & \text{in uplink} \end{cases}
\end{aligned}$$

where P_{target} is the target transmit power for each user, and the total transmit power is limited the P_{target} times the number of users in cell.

According to our previous study [4], cell-wise power constraint has a higher freedom of degree of power assignment to improve the probability to find solution and to obtain a higher achievable capacity. Then, the objective of sum capacity maximization will inevitably sacrifice the capacity of some users. So, it is also necessary to ensure that the user experience is above a certain level, as shown in condition 2. Moreover, due to the limited linear operating range of the power amplifier associated with each BS antenna, we also add the power limit of the downlink transmit powers per antenna to the conditions. As a preliminary study in this paper, the maximum downlink transmit power is set to e.g., 5 times the target transmission power. This condition 3 is introduced to make our algorithm practical.

To solve such a nonlinear inequality constrained optimization problem, we introduced the popular SQP algorithm to approximate the original problem by the quadratic programming subproblems which can be iteratively solved. It was confirmed [4] that the proposed SQP-based OPA can improve the sum capacity compared with EPA in the case of a small number of clusters and/or lower allowable minimum user capacity in the square-shaped single-cell system. How it works in modified K-means constructed multi-cell system is the topic of this paper. The simulation results are shown and discussed in the following chapter.

4. Simulation results

We carry out Monte-Carlo simulation with a fixed antenna location under 100 times randomly generated user locations to obtain the cumulative distribution function (CDF) of sum capacity and user capacity of the target cell. In addition to the link capacity comparison between OPA and EPA, the link capacities of the realistic cellular structure constructed by modified K-means algorithm and the square-shaped cellular structure are also compared. For a fair comparison of the sum capacity, we assume the same number of users in each cell for both cellular structures. Therefore, in the simulation, we first generated users of twice the predetermined total number within the service area and then randomly selected the predetermined number of users in each cell for subsequent clustering and power allocation.

The normalized transmit signal-to-noise ratio (SNR) per user is defined as the received signal-to-noise ratio of the receiver at the normalized distance of 1 from the transmitter. Then, the MIMO channel is characterized by distance-depended path loss, log-normal shadowing and frequency non-selective Rayleigh fading. The simulation setting is shown in Table 1. For each user location pattern, one-time generation of shadowing and fading is carried out to obtain the capacity samples. To obtain the CDF of the capacity, the user location patterns is changed 100 times.

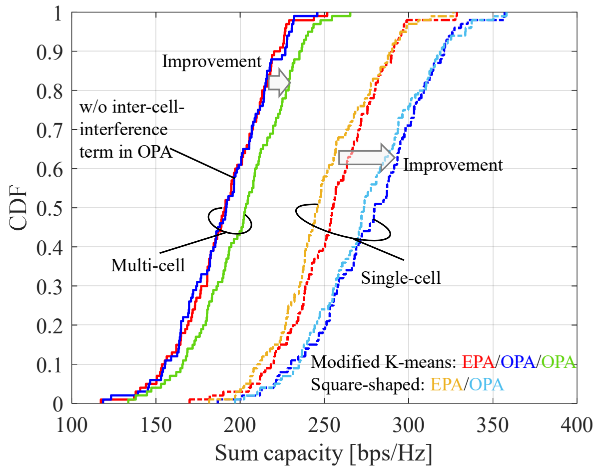
Table 1

Number of cells	25
Number of distributed antennas in each cell	128
Number of users in each cell	64
Number of clusters in each cell	8
Number of times of user location generations	100

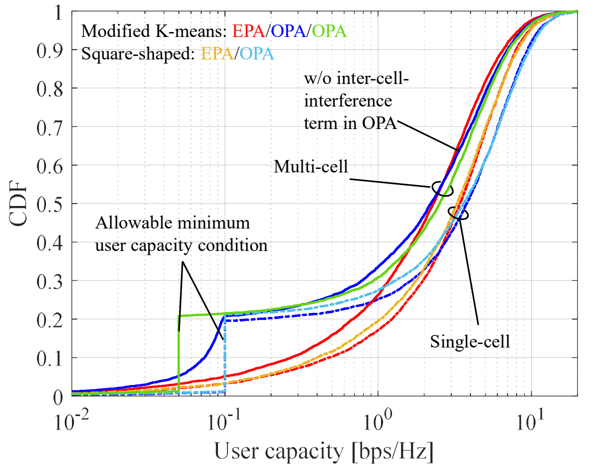
Path loss exponent	3.5
Shadowing standard deviation [dB]	8
Fading type	Rayleigh
Transmit power per user (P_{target})	1
Allowable minimum user capacity [bps/Hz]	0.1(single-cell), 0.05(multi-cell)
Starting point of OPA (SQP method)	EPA state

It should be noted that the start point for SQP iteration is EPA state and if the OPA has no solution, the capacity for that trial is calculated by EPA strategy. And to guarantee the user experience, we set an allowable minimum user capacity as 0.1 bps/Hz in the case of single-cell OPA.

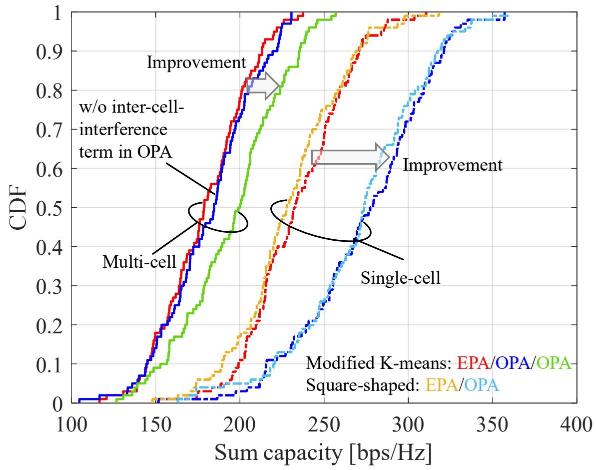
We compare the CDF of sum capacity and user capacity between EPA and OPA in Fig. 2.



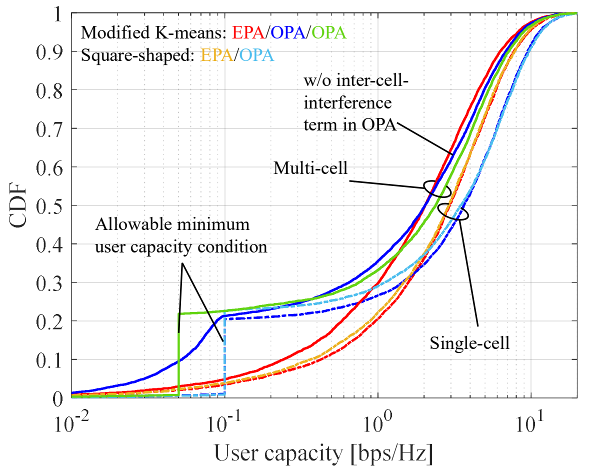
(a) Downlink sum capacity



(b) Downlink user capacity



(c) Uplink sum capacity



(d) Uplink user capacity

Fig. 2 CDF comparison of 2 power allocation strategies of target cell in 2 cellular structures

Firstly, we consider the single cell case (or isolated cell case). The results for EPA and OPA in square-shaped single-cell case and realistic single-cell cases are shown by the color lines on the right side of the figures above. As can be seen that, under such a setting (for the number of clusters and the allowable minimum user capacity), the proposed OPA can significantly improve sum capacity (around 10% @CDF=50%) in the single-cell case, regardless of uplink and downlink or any cell structure. Through the observation of user capacity, we can see that OPA does lower the capacity of some users to the allowable minimum (0.1 bps/Hz) to maximize the sum capacity. Also seen is that the capacity performance of modified K-means based cellular structure is better than that of square-shaped one under both EPA and OPA. This is because the interference level received by users near the cell boundary and corner is lower in realistic cellular structure than in square-shaped cellular structure. In other words, the users near the cell corner receive strong interference in the case of square-shaped cellular structure, leading to the capacity degradation. As for why the total capacity difference between the two cellular structures is not large in Fig. 2, this is because of clustering. As can be seen from Fig. 1, although the cellular structures are different, users receive not only the inter-cell-interference but also the inter-cluster-interference, which narrows the gap of the sum capacity between the two cellular structures.

Then, we extend the investigation to realistic multi-cell system which contains 25 cells as actually shown in Fig. 1 (b). If we apply the single-cell OPA (w/o the inter-cell interference term) to the multi-cell system, we obtain the CDF curves shown in the color lines on the left side in the Fig. 2. As can be seen, the sum capacity is significantly degraded (e.g., around 50% in downlink EPA) due to inter-cell-interference, and the single-cell OPA provides even worse capacity than EPA in the uplink. This is because the single-cell OPA does not consider the existence of inter-cell-interference. So, it is necessary to consider the inter-cell-interference in the optimization function. Because the inter-cell-interference will further limit the sum capacity, we reduce the allowable minimum user capacity by half in the multi-cell OPA, that is, 0.05 bps/Hz. The result when the multi-cell OPA is used is shown by the green line in the figures above. We can see that the multi-cell OPA (which considers the inter-cell-interference in the optimization process) improves the downlink sum capacity at CDF=50% by around 6% although it increases the probability of user capacity falling below a certain low value.

5. Conclusion

In this paper, we further investigated the previously proposed sum capacity maximization-based power allocation method. We introduced the modified K-means based multi-cell system to approximate the realistic cellular system. We also modified the clustering method from classic K-means to modified K-means in each cell. Also considering the practical application, the transmit power constraint to each antenna was introduced to the OPA function.

From Monte Carlo simulation, we showed that the proposed OPA can greatly improve the sum capacity in the single-cell (or isolated cell) system. Furthermore, we confirmed the effectiveness of the multi-cell OPA (which considers the inter-cell-interference).

In this paper, we considered the OPA operation in the target cell (center-cell on the area) only. In fact, the OPA decision by the target cell will change the inter-cell-interference to its surrounding cells and those cells optimize their own transmit powers by their OPA operations. Accordingly, the inter-cell-interference experienced by the target cell will change. Consequently, the coordinated inter-cell OPA is the next step of our study. In addition, parameter setting (e.g., number of clusters and allowable minimum user capacity) affects the solution domain of OPA. Finding the optimal way for parameter setting of sum capacity maximization is also an important topic for us.

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