On Cellular Structure for Ultra-dense Distributed Antenna-based 5G-advanced Systems

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Abstract Compared with the traditional cellular structure based on centralized antennas, the distributed antenna-based cellular structure has advantages in terms of low latency, high capacity, and low energy consumption. Especially when using the millimeter wave bands, it can effectively reduce the signal blockage problem frequently encountered in urban areas. Therefore, it can be considered as a promising cellular structure for 5G-advanced systems. The system performance may be strongly affected by the cellular structure. So, how to construct base station coverage areas called cells is quite important. In this paper, we propose a cellular structure method by modified K-means clustering algorithm to construct a given number of cells each having the same number of distributed antennas. It is shown by the computer simulation that, compared with cellular structures of simple square-shaped cells and that constructed by an original K-means algorithm, the proposed cellular structure method achieves higher link capacity, higher fairness of user capacity, and lower delay when user scheduling is considered.

Keywords Distributed antenna system, cell structure, K-means algorithm, 5G-advanced system

1. Introduction

Recently, with a rapid popularization of broadband mobile data services, densifying the base station antennas and utilizing higher frequency bands are the promising solutions to guarantee the service quality. Nevertheless, because of the rectilinear propagation nature of high frequency band signals, the transmitted signals are easily blocked by obstacles, especially in urban areas. Distributed antenna-based cellular structure which deploys a number of antennas over the base station coverage area called cell can solve this problem very well and also has advantages of latency, capacity, and energy efficiency [1].

This paper considers how to construct the cellular structure after base station antennas are densely deployed in a certain service area. We first assume that each base station has the same signal processing capacity. Starting from this, we propose a modified K-means algorithm [2] to construct the cells each having the same number of distributed antennas. Furthermore, the number of users that the base station can serve simultaneously is limited due to the available signal processing power. If the number of users in a cell exceeds the upper limit, we utilize the user scheduling to divide the users into several sets to give the signal transmitting/receiving opportunity to user sets sequentially.

The rest of this paper is organized as follows. In Chapter 2, we present ultra-dense distributed antenna-based system model and then, describe our proposed antenna-based cellular structuring method using modified K-means algorithm. We show examples of cellular structure constructed for different user and antenna distribution and compare them with two other cellular structures: the simple square-shaped cells and a cellular structure constructed by an original K-means algorithm [3]. Furthermore, the three cellular structures are evaluated in terms of user capacity, fairness of user capacity and scheduling loss (delay) which are the system performance of interest. In Chapter 3, in order to adaptively follow the variations in the traffic density caused by the users' movement, we also consider the user-based cellular structuring method and analyze it from the perspective of realizability with the comparison of antenna-based method proposed in the previous chapter. Finally, we give some conclusions and future works in the Chapter 4.

2. Antenna-based cellular structuring method

As we mentioned in Chapter 1, cellular structure significantly affects system performance in a distributed antenna system. We first consider to construct cells based on antenna location information. Below, three methods are considered: a simple square-shaped division, original K-means, and modified K-means. After describing our system model, we will construct three cellular structures by using the above three methods and evaluate the system performance.

2.1. System model

Over a certain service area of a 5×5 square range, 2×U distributed antennas and U single-antenna users are randomly located following the same uniform distribution. And the allowable minimum distance between antennas is set to 0.01. According to the three methods, a given number (K) of cells are constructed based on antennas. Then, each user is associated with a cell having antenna closest to that user. An example of proposed modified K-means cell structure is shown in Fig. 1, the detail of structuring method will be introduced in following section.

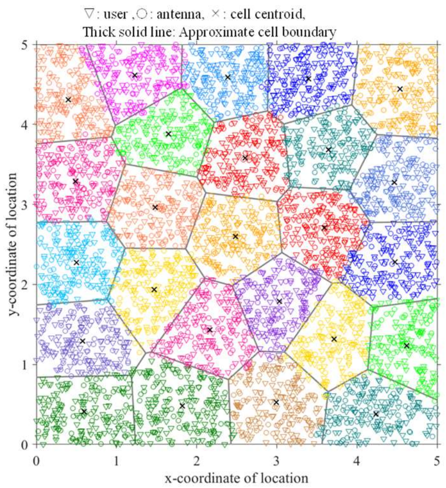


Fig. 1 An example of cellular structure formed by the proposed modified K-means (U=1600, K=25, A=2×U)

Due to the limited base station processing capacity, user scheduling mechanism is utilized in each cell to allocate users to different time slots to perform zero-forcing (ZF) [4] based Multi-User Multiple-Input Multiple-Output (MU-MIMO) communication with all antennas in the cell. In the user scheduling, users in a cell are grouped into several time slots and the transmitting and receiving opportunity is allocated sequentially from one group to the other (this is called the round-robin type scheduling). And the scheduling mechanism is described in Fig. 2. In this paper, the base station signal processing capacity is expressed as the number of users which can be simultaneously multiplexed by MU-MIMO. Letting M, U_i, and N_i be the number of users to be multiplexing limited by the signal processing power at each base station, the number of users in the ith cell, and the number of required time slots for the ith cell, respectively, we have $N_i = \lceil U_i/M \rceil$. Users in the ith cell are first randomly grouped into N_i exclusive user sets. If U_i is not an integer multiple of M, r=U_i - M (N_i-1) users are remained. To fill the last slot, (M-r) users are randomly selected from previous slots. Then, the scheduling period T is set as the least common multiple of the number of slots required by each cell, i.e., T=lcm (N_1, N_2, …, N_i, …, N_K).

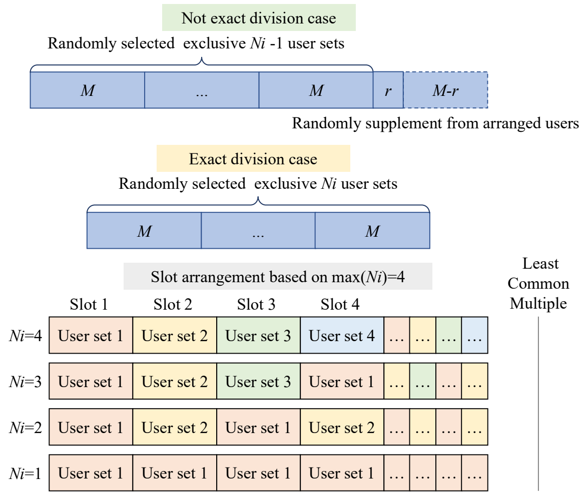


Fig. 2 Scheduling mechanism

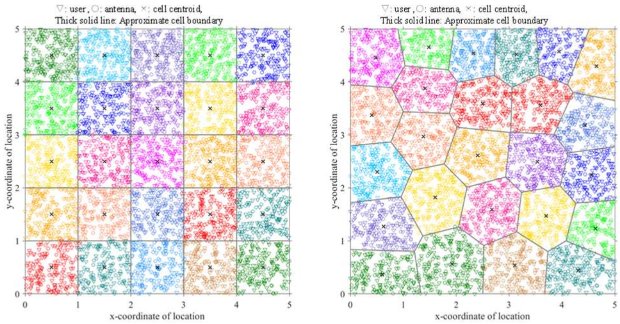
2.2. Cellular structuring methods and graphic results

The simplest method to construct a cellular structure to use geometric division, such as square. Regardless of the location and density of the antennas, the service area is simply divided into K equal square-shaped cells, and the antennas in each cell area is controlled by the base station of that cell. In this paper, because of the limited signal processing power, MU-MIMO is considered to multiplex M single-antenna users. Therefore, the number of cells, K, is given by the ratio of a total number of predicted users in a service area of interest and M, i.e., K=U/M. An example of this square-shaped cellular structure is shown in Fig. 3 (a), where U=1600, M=64, K=25, A=2×U.

Furthermore, considering the influence of antenna location, the nearby partition is a more reasonable method. We apply the well-known K-means algorithm [3] based on antenna locations to get compact cell structure. This is called the original K-means method in this paper.

The number of antennas in each cell is different although its average is the same. In this paper, we apply a modified K-means described in [2] to guarantee that each cell has the same number of antennas. An example of cellular structure constructed by the proposed method is already shown in Fig. 1.

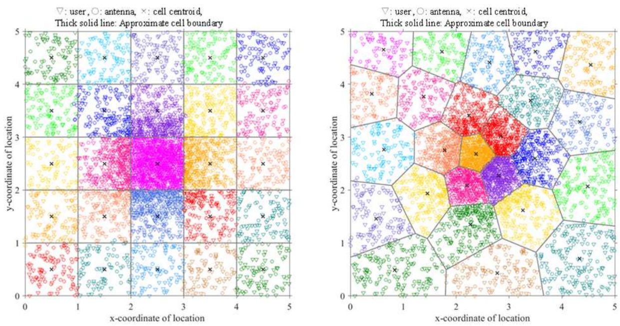
The cellular structures constructed by the latter two methods depend on the location and density of the antennas. They are close to the hexagonal structure often modelled for the traditional cellular systems. In addition, compared with the original K-means method, the modified K-means method ensures the uniform number of antennas in each cell.



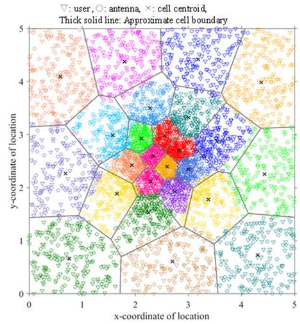
(a) square-shaped division (b) original K-means

Fig. 3 Examples of cellular structure constructed by two contrast methods under uniform user antenna distribution (U=1600, K=25, A=2×U)

We further compare three methods in the case of non-uniform user and antenna distribution in Fig. 4. In this non-uniform distribution case, more antennas should be deployed in an area where more users are located. So, in this paper, it is assumed that the users and antennas are populated according to the same distribution. Here, we assume that 3/8 of users and antennas are uniformly distributed in the 5×5 service area and the rest 5/8 are gathered near the center of the service area according to the two-dimensional Gaussian distribution whose mean and covariance matrix are coordinate (2.5,2.5) and diag(0.25, 0.25).



(a) square-shaped division (b) original K-means



(c) modified K-means

Fig. 4 Examples of cellular structure constructed by three methods under non-uniform user antenna distribution (U=1600, K=25, A=2×U)

As we can see, the original K-means method and the modified K-means method can construct the cellular structure adaptively following the density or distribution of antennas, where the modified K-means performs better to construct more small cells in the area with higher density. On the other hand, since the square-shaped division constructs the cell structure by simply dividing the service area into the fixed number of equal areas, a large number of users gather in a few cells. In the center cell of Fig.4 (a), a large number of time slots are needed, which reduces the user capacity and increase the time delay, resulting in degradation of the system performance. Therefore, in the next chapter, we will evaluate the three methods from the perspective of capacity and delay.

2.3. Simulation and numerical results

After the cellular structuring and scheduling are determined, each cell is assumed to perform ZF-based MU-MIMO transmission to multiplex M=64 users simultaneously. Therefore, the inner-cell interference is perfectly eliminated, but the inter-cell interference exists. The capacity of the uth user in the service area of interest is computed using Shannon's formula [4] as shown in Eq. (1), where $t\in(1, \ldots, T)$ and $\gamma_{u,t}$ denotes the slot index and signal-to-interference-plus-noise ratio of uth user in the tth slot.

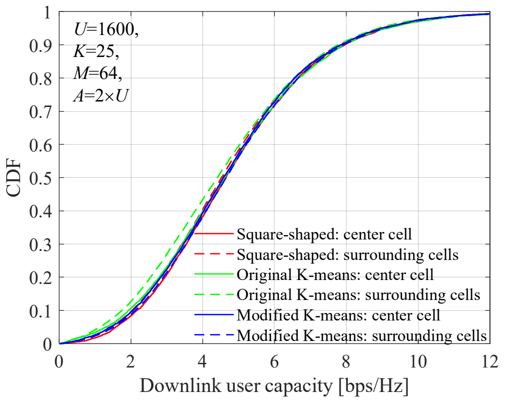
$$C_u = \frac{1}{T}\sum_{t=1}^{T} C_{u,t}, C_{u,t} = \begin{cases} \log_2(1+\gamma_{u,t}), \text{ if user has oppotunity} \\ 0, \text{ otherwise} \end{cases} \quad (1)$$

Accordingly, we can evaluate the fairness of user capacity by Jain's fairness index [5] as

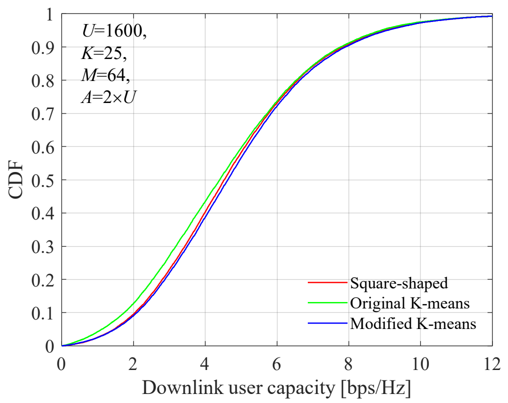
$$J = \frac{(\sum_{u=1}^{U} C_u)^2}{U \bullet \sum_{u=1}^{U} C_u^2}. \quad (2)$$

In simulation, we fix an antenna distribution and construct the cellular structure by using three methods. Then, the user distribution is generated 100 times. For each user distribution pattern, shadowing loss and Rayleigh loss are generated once to evaluate the user capacity, fairness index, and delay (i.e., necessary scheduling slots).

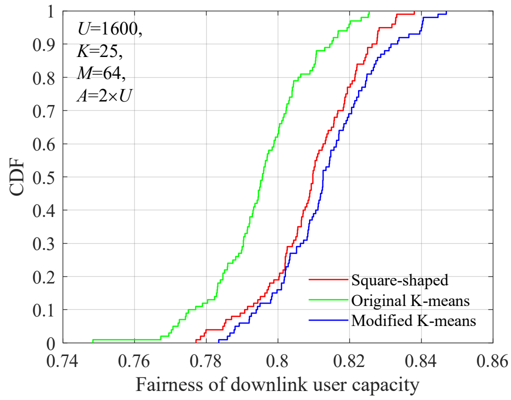
The simulation results for the case of users and antennas being uniformly distributed in service area, are shown in Fig. 5. In order to compare more comprehensively the user capacity, we take two constructs of comparison: one is to compare the capacity of the cell closest to the service area center with that of its surrounding cells. This is to measure the difference of service quality between two types of cells, as shown in Fig. 5 (a). The other is to compare the total user capacity within a fixed range ($x, y \in (1,4)$), which can more directly show the impact of the three structures on the system performance as shown in Fig. 5 (b). In addition, the fairness index in Fig. 5 (c) is measured by data sets in Fig. 5 (b). It can be understood from Fig. 5 and also from Figs. 1 and 3 that when users and antennas are uniformly distributed, the cell size and user antenna density of three methods are basically the same, so the system performance is almost the same.



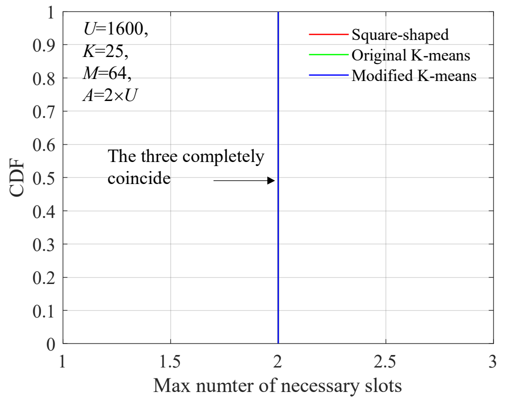
(a) capacity of users in center and surrounding cells



(b) capacity of users in the target range



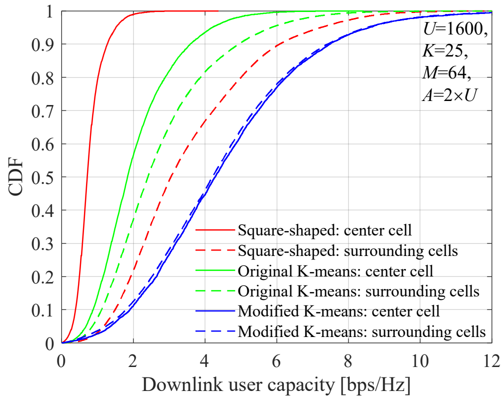
(c) fairness of target range user capacity



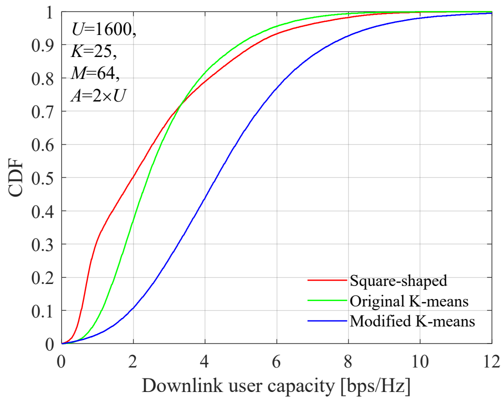
(d) delay of users in the target range

Fig. 5 Comparison among three structure methods (uniform user antenna distribution)

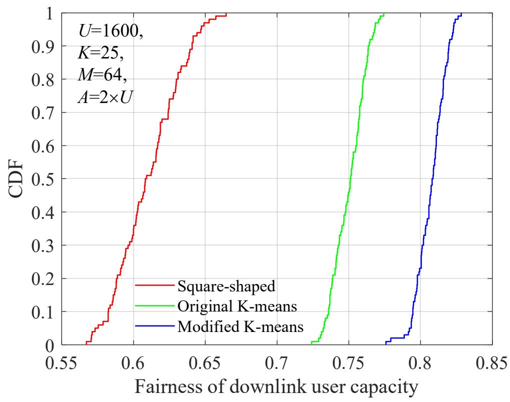
The simulation results when users and antennas are non-uniformly distributed are shown in Fig. 6. In the case of square-shaped structure, a large number of users gather in the central cell as shown in Fig. 3 and hence, users must be divided into many time slots. Accordingly, the user capacity in this cell reduces significantly due to the scheduling loss. On the other hand, the number of users in the surrounding cells is small, so the capacity degradation is not significant. Therefore, we observe a serious difference between the cells in terms of system performance. Original K-means method also has a similar situation, but the difference in system performance between cells is not seriously large although the center cell is still affected by the scheduling loss. The proposed method ensures that the number of antennas in each cell is exactly the same, then the cell size can change adaptively with the density, and the number of users in the cell is almost the same, so there is almost no difference in system performance between cells.



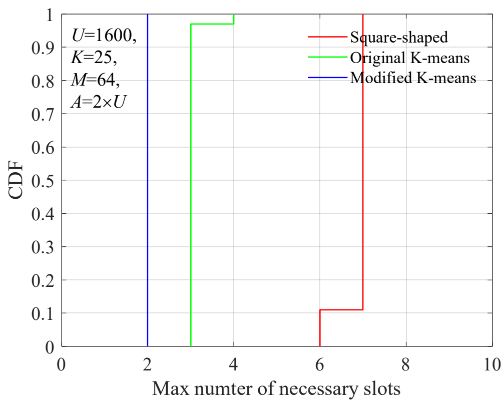
(a) capacity of users in center and surrounding cells



(b) capacity of users in the target range



(c) fairness of target range user capacity



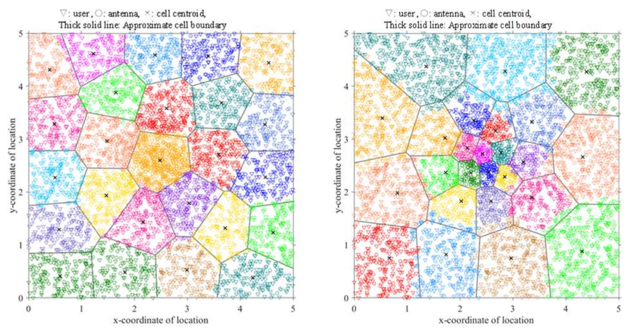
(d) delay of users in the target range

Fig. 6 Comparison among three structure methods (non-uniform user antenna distribution)

It can also be seen from Figs.5 and 6 that the cellular structure constructed by the proposed method is least affected by the scheduling loss. In the area where users are populated densely, the cellular structure constructed by the proposed method ensures that users are able to experience the highest capacity, the highest fairness and the lowest delay. Moreover, the proposed method can construct the cellular structure which ensures that the capacity and fairness remain unchanged under uniform and non-uniform distribution.

3. Discussion on user-based cellular structuring method

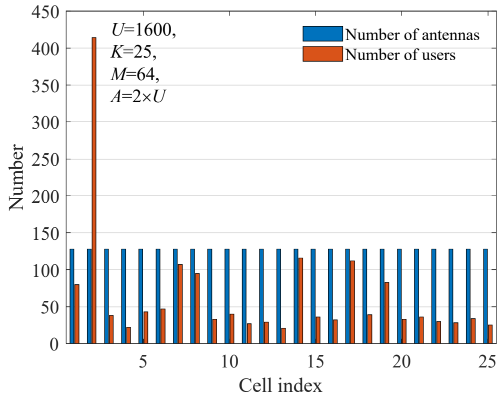
Up to now, we discussed the cellular structure construction methods using antenna location information based on the assumption that antennas are deployed following users' distribution. The simulation results indicate that the proposed modified K-means based cell structuring method is the best in general. Actually, once antennas are deployed, they remain unchanged. However, user or traffic density may vary in time. Therefore, cellular structuring method based on the user location information may be more dynamic and can follow changing user distribution, thereby leading to better system performance. Below, we consider a modified K-means based cellular structuring method using user location information. We assume uniform distribution of antennas while users are non-uniformly distributed, i.e., users are gathered in a center area as assumed in Chapter 2. The examples of cellular structure constructed by user-based and antenna-based modified K-means are shown in Fig. 7.



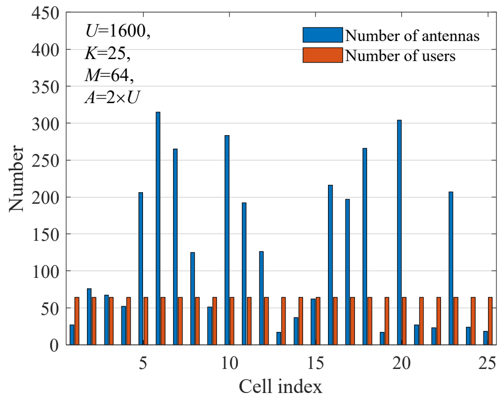
(a) antenna-based (b) user-based

Fig. 7 Examples of user-based and antenna-based cell structure. Uniform distribution of antennas and non-uniform distribution of users. (U=1600, K=25, A=2×U)

It can be understood from Fig. 7 that the modified K-means method is also applicable to construction of the user-based cellular structure. The cellular structure consisting of cells of different sizes according to the user density.



(a) antenna-based



(b) user-based

Fig. 8 Number of users and antennas in each cell

By presenting number of users and antennas in each cell in Fig. 8, we find that the antenna shortage problem is serious when the antenna distribution and user distribution are different. Specifically, for antenna-based cellular structure, although the total number of cells with insufficient antennas is small, still the necessary number of slots in scheduling is larger than 2 (in same user and antennas distribution case). In addition, for user-based cellular structure, since nearly half of the cells have insufficient antennas, more time slots are necessary to mitigate the antenna insufficiency, so the degradation of system performance may become more serious.

However, it does not mean that user-based method cannot be accepted. If more antennas are deployed, this antenna shortage problem can also be alleviated. Therefore, it is worth discussing how the overall user-antenna ratio in the service area affects the system performance for user-based and antenna-based construction. This is left as our future study.

4. Conclusion

In this paper, we considered the cellular structure method for ultra-dense distributed antenna-based 5G-advanced system. We proposed a modified K-means method to divide the same size of neighbor antennas as cells aiming to keep the same processing capacity for each base station. It was compared with simple square-shaped method and original K-means method while assuming user and antenna distribution are consistent.

The simulation results indicated that the proposed method was adapted to both uniform and non-uniform distribution to get corresponding cell size and shape and provide the best system performance in terms of user capacity, fairness and delay, especially in non-uniform case.

Finally, we simply analyzed reliability of user-based cell structuring method and found the antenna shortage problem under our current parameter setting. Therefore, the impact of user-antenna ratio on system performance, and how to determine the number of cells and the upper limit of base station processing capacity are reserved for our future research.

5. Acknowledgement

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