A Clustering-Based Spectrum Resource Allocation Algorithm for Dense Small Cell Networks

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Abstract. This paper considers the spectrum resource allocation problem for dense small cell networks, and focuses on a system scenario where small cells are non-uniformly distributed in a macro cell. A clustering-based spectrum resource allocation (CSRA) algorithm is proposed to perform resource allocation for both macro-cell user equipments and small cell user equipments with the objective to maximize the system capacity. To minimize both intra-tier and inter-tier interferences in the system, the concept of clusters is introduced into spectrum resource allocation, and a few principles are correspondingly set for clustering. Moreover, an upper limit for the cluster size is set in for clustering to avoid the formation of a too large cluster, which otherwise would consume a large number of physical resource blocks (PRBs) and thus affect the system capacity. To increase spectrum utilization, all PRBs are allowed to be used by all users in the system. Simulation results show that the proposed CSRA algorithm can significantly increase the system capacity as compared with an existing CDRA algorithm.

Keywords: Clustering · Resource allocation · Small cell

1 Introduction

Dense small cell networks have been widely considered as a key technology for future cellular networks [1–3]. However, the extensive deployment of small cells would cause a sharp increase in interference between small cells and macro cells (inter-tier interference) and between neighboring small cells (intra-tier interference). Resource allocation is an efficient way to manage the inter-cell interference in a dense small cell network. Considerable studies have been conducted to find efficient solutions to resource allocation for mitigating the inter-cell interference [4–9]. In our previous work [9], we presented a clustering-based downlink resource allocation (CDRA) algorithm for a system scenario where small cells are uniformly distributed in a macro cell. For a non-distributed system scenario, however, the CDRA algorithm cannot well address the spectrum resource allocation, which motivated us to conduct this work.

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In this paper, we study the spectrum resource allocation problem in dense small cell networks. In particular, we consider a system scenario where small cells are non-uniformly distributed in a macro cell. To minimize both intra-tier and inter-tier interferences, we introduce the concept of clusters into spectrum resource allocation, and correspondingly set a few principles for clustering. Unlike [9], an upper limit for the cluster size is set to avoid the formation of a too large cluster, which otherwise would cause the consumption of a large number of physical resource blocks (PRBs) and thus affect the system capacity. Moreover, all PRBs are allowed to be used by all users in the system, both MUEs and SUEs. Based on these strategies, a clustering-based spectrum resource allocation (CSRA) algorithm is proposed to perform PRB allocation for MUEs and SUEs with the objective to maximize the system capacity. Simulation results are shown to evaluate the performance of the proposed CSRA algorithm.

The rest of the paper is organized as follows. Section 2 formulates the resource allocation problem considered in this paper. Section 3 presents the proposed CSRA algorithm for dense small networks. Section 4 evaluates the performance of the CSRA algorithm based on simulation results. The paper is concluded in Sect. 5.

2 System Model and Problem Formulation

This section describes the system model and formulates the resource allocation problem considered in this paper.

2.1 System Model

Figure 1 illustrates a small cell network system considered in this paper, which consists of one macro cell and multiple small cells. A macro cell base station (MBS) is located in the center of the system, and multiple small cell base stations (SBS) are non-uniformly distributed within the macro cell. Each SBS is connected to the MBS through a backhaul network. Thus, the MBS can share common channel state and resource allocation status information (CSI) with all SBS. The macro cell contains multiple macro-cell user equipments (MUEs) and each small cell contains multiple small-cell user equipments (SUEs), which are randomly distributed in the coverage area of the macro cell and each small cell, respectively. Moreover, orthogonal frequency division multiplexing (OFDM) is employed for data transmission in the system. In spectrum resource allocation, the basic unit is one physical resource block (PRB). All PRBs in the system can be used by all SUEs and MUEs.

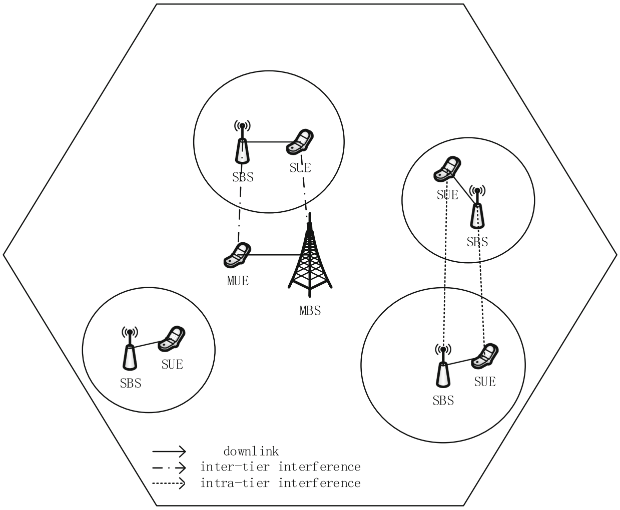

Fig. 1. System model

2.2 Problem Formulation

In this paper, we consider downlink spectrum resource allocation in the dense small cell network system shown in Fig. 1. In resource allocation, we focus on minimizing the inter-tier interference between MUEs and an SUEs sharing the same PRBs, and the intra-tier interference between SUEs in different small cells sharing the same PRBs. Thus, we assume that different MUEs in the macro cell are allocated different PRBs and different SUEs in the same small cell are allocated different PRBs. Meanwhile, different SUEs in different small cells are allowed to share the same PRBs. In this way, there is no interference between different MUEs in the macro cell and between different SUEs in the same small cell. The interference only exists between an MUE in the macro cell and an SUE in a small cell or between different SUEs in different small cells if they share the same PRBs.

Further, we assume that there are N small cells in the macro cell, which are denoted by i ($i = 1, 2, \ldots, N$). There are U_0 MUEs in the macro cell and there are U_i SUEs in small cell i. Thus, the total number of users in the system is

$$U_{Total} = \sum\nolimits_{i=0}^{L} U_i \tag{1}$$

where $i = 0$ stands for the macro cell. Also, we assume that there are M PRBs available in the system, which are denoted by $k(k = 1, 2, \ldots, M)$. In addition, we assume that each user only needs one PRB for communication in resource allocation.

For resource allocation, we define a resource sharing distribution matrix for each cell, i.e.,

$$\prod\nolimits_{i} = [\pi_{jk}]_{\mathrm{K}_i \times \mathrm{M}}, i = 0, 1, 2, \ldots, N; k = 1, 2, \ldots, M; j = 1, 2, \ldots U_i \tag{2}$$

where row j represents the jth user (MUE j or SUE j) in cell i and column k represents the kth PRB, $\pi_{jk} = 1$ indicates that user j is allocated PRB k while $\pi_{jk} = 0$ indicates user j is not allocated PRB k.

For *user j* in cell i, its data rate, denoted by R_{ij}, is given by

$$R_{ij} = \log_2\left(1 + SINR_{ij}\right) \tag{3}$$

where $SINR_{ij}$ represents the signal to interference plus noise ratio (SINR) of user j in cell i, and is given by

$$SINR_{ij} = \frac{P_{ij}G_{ij}}{I_{ij} + N_0} \tag{4}$$

where P_{ij} represents the transmission power from BS i to user j in cell i, G_{ij} represents the channel gain from BS i to user j in cell i, I_{ij} represents the interference at user j in cell i, and N_0 represents the additive white Gaussian noise power.

For SUE j in cell i ($i = 1,\ldots N$), I_{ij} is caused by the transmissions from the MBS and the SBSs of other small cells, who share the same PRB. Thus, I_{ij} is given by

$$I_{ij} = \pi_{0j}P_{0j}h_{0j} + \sum_{i'=1, i' \neq i}^{N} \pi_{i'j}P_{i'j}G_{i'j},\ \forall i, 1 \leq i \leq N \tag{5}$$

where the first item represents the interference from the MBS while the second represents the interference from other small cells.

For MUE j in cell 0, I_{0j} is given by

$$I_{0j} = \sum_{i=1}^{N} \pi_{ij}P_{ij}h_{ij}. \tag{6}$$

Obviously, I_{0j} is only caused by the SBSs of the small cells.

With the above assumptions and analyses, the downlink resource allocation problem considered in this paper is to find a set of resource allocation matrices $\prod_i (i = 0, 1, 2, \ldots, N)$ so that the sum-rate of all users in the system is maximized, i.e.,

$$\max \sum_{j=1}^{U_0} R_{0j} + \sum_{i=1}^{N} \sum_{j=1}^{U_i} R_{ij} \tag{7}$$

subject to

$$Z_0 \cup Z_1 \cup \ldots \cup Z_i \cup \ldots \cup Z_N \subseteq Z \tag{8}$$

$$\sum_{j=0}^{U_i} P_{ij} \leq P_{\max,i}, \forall i \tag{9}$$

$$P_{ij} \geq 0, \forall i, j \tag{10}$$

where Z represents a set of PRBs available in the system, Z_i represents a set of PRBs allocated to the MUEs or SUEs in small cell i; constraint (8) specifies that the number of PRBs allocated to MUEs and SUEs should not be larger than that of the PRBs available in the system; constraint (9) specifies that the maximum sum power of the base station transmitting to all users in cell I is $P_{\max,i}$; constraint (10) enforces that the power used is always non-negative.

3 Clustering-Based Spectrum Resource Allocation Algorithm

This section presents the proposed CSRA algorithm to address the resource allocation problem described in the previous section.

3.1 Overview

The CSRA algorithm is a heuristic algorithm for allocating PRBs for the MUEs and SUEs in the small cell system shown in Fig. 1. It aims to minimize the intra-interference and inter-interference so that the total system capacity is maximized. In a small cell system, if two small cells are close to each other and two SUEs respectively belonging to the two small cells share the same PRB, it would cause a big interference between the two SUEs. The smaller the distance between the two small cells, the bigger the interference. To avoid severe interference between two SUEs in different two small cells, it is expected to allocate different PRBs to such two SUEs in resource allocation. To implement this, we introduce the concept of clusters in PRB allocation. Here, a cluster is defined as a group of small cells, which are close to each other in distance. To avoid intra-tier interferences between SUEs, the SUEs in different small cells within the same cluster should not be allocated the same PRBs in resource allocation.

The CSRA algorithm consists of three components: small cell clustering, small cell priority determination, and spectrum resource allocation. Next we describe the three components in more details.

3.2 Small Cell Clustering

With the introduction of clusters, clustering must be performed before spectrum resource allocation is performed. For this purpose, it is necessary to have reasonable clustering principles first.

As mentioned, if two small cells are close to each other, the intra-tier interference would be severe if the SUEs in the two small cells share the same PRBs. To avoid the potential intra-tier interference, if the distance between two SBSs is smaller than a given threshold, the two small cells should be included in the same cluster, as shown in Fig. 1. Thus, we obtain the first principle for clustering, i.e., the distance between any two small cells in a cluster must be smaller than a given threshold. The threshold value depends on several system parameters, including the transmission power of an SBS, the macro cell radius, and the channel state.

Based on the first principle, a number of clusters could be formed in the system, and different combinations of clusters could be obtained, which means that the clustering result is not unique. In clustering, it is usually expected to include multiple small cells in one cluster in order to mitigate intra-tier interferences between SUEs; on the other hand, in a non-uniformly distributed dense small cell network system, a cluster could include many small cells, which would cause the consumption of a large number of PRBs. Thus, to avoid the formation of such clusters, the size of a cluster or the number of small cells included in a cluster should be limited by a given value. Based on this analysis, we obtain the second principle for clustering, i.e., a cluster can include multiple small cells, but has an upper limit.

Based on the first two principles, it is found that a small cell could belong to several different clusters. Thus, we obtain the third principle for clustering, i.e., a small cell is allowed to belong to different clusters.

Given the three clustering principles, the MBS can perform clustering to form all small cells in the system into a set of clusters. The main clustering procedures include the following steps:

(1) For each small cell, find out all other small cells with a distance to the small cell smaller than a given threshold.
(2) Find out a set of clusters which may include the current small cell based on the clustering principles.
(3) Repeat steps (1) and (2) until all small cells in the system are considered.
(4) Determine a set of clusters for resource allocation by finding the union of all sets of clusters obtained in steps (1)–(3).

3.3 Small Cell Priority Determination

After clustering, the MBS is supposed to determine the priority of each small cell for resource allocation before resource allocation is performed. In determining the priority of a small cell, two factors are taken into account: one is the size of the largest cluster the small cell belongs to and the other is the number of clusters the small cell belongs to. In general, a small cell in a cluster with a larger size should be assigned a higher priority than a small cell in a cluster with a smaller size. This is because in a larger cluster there are more small cells, which would cause more serious interferences between SUEs if they share the same PRBs. On the other hand, in each cluster, a small cell belonging to more clusters should be assigned a higher priority than other small cells in the cluster. This is because a small cell belonging to more clusters may affect the resource allocation for more small cells. If two small cells belong to the same number of clusters, one of them is randomly selected and is assigned a higher priority than the other. Once the priority of each small cell is determined, the MBS will broadcast the clustering information and small cell priority information to the system. In addition, the MBS itself is assigned a higher priority than all small cells.

3.4 Spectrum Resource Allocation

After the priority of each small cell is determined, the MBS and each SBS will perform PRB allocation for each MUE and SUE, respectively, based on their priorities. To minimize inter-tier and intra-tier interferences between different MUEs and/or SUEs, PRB allocation should adhere to the following allocation principles:

(1) Use orthogonal resources or different PRBs as many as possible;
(2) Allocating different PRBs to MUEs in the macro cell.
(3) Allocating different PRBs to SUEs in the same cluster.
(4) Allowing SUEs in a cluster share PRBs with SUEs not in the same cluster or with MUEs not in the coverage of the cluster if there are no more orthogonal PRBs remaining.

Based on the above allocation principles, the main resource allocation procedures include the following steps:

(1) The MBS performs PRB allocation for MUEs in the macro cell as follow:
    (a) Allocate orthogonal PRBs to all MUEs in the system;
    (b) Once the allocation is completed, the MBS broadcasts a signaling message to inform the system of its completion and the PRB allocation information;
(2) Once receiving the signaling message, the SBS of the small cell with the highest priority among all small cells not allocated will perform PRB allocation for its SUEs:
    (a) Allocate those orthogonal PRBs that have not been allocated first;
    (b) If no orthogonal PRB is available, share PRBs that have been allocated to those SUEs not in the same cluster the SBS belongs to, or share PRBs that have been allocated to those MUEs who are not in the coverage of the same cluster the SBS belongs to;
    (c) Once the SBS of the current small cell completes its resource allocation, it broadcasts a signaling message to inform the system of its completion;
(3) Repeat (2) until resource allocation for all small cells is performed.

4 Simulation Results

This section evaluates the performance of the proposed CSRA algorithm based on simulation results. The simulation experiments were conducted on a simulator that we developed using C++. For evaluation, we compare the CSRA algorithm with the CDRA algorithm proposed in [9] in terms of the total system capacity, i.e., the sum-rate of all users in the system. In the simulation experiments, we used the channel gain path loss model given in [10], i.e.,

$$PL = 20\lg(d[m]) + 20\lg(f[MHz]) - 27.56 \tag{11}$$

The upper limit of the cluster size is set to one third of the number of small cells in the system. For simplicity, we assume that the number of SUEs in each small cell is equal. The parameters used in the simulation experiments are summarized in Table 1.

Table 1. Simulation Parameters

Parameter	Value
MBS transmission power	43 dBm
SBS transmission power	24 dBm
Number of PRBs	100
Macro cell radius	500 m
Small cell radius	50 m
Distance threshold	200 m
Spectrum frequency	2 GHz
PRB bandwidth	180 kHz
White noise power	−174 dB/Hz

Figure 2 shows the total system capacity with CSRA and CDRA, respectively, under different number of SUEs in each small cell. It is seen that CSRA can basically achieve a larger system capacity than CDRA. On the other hand, when the number of SUEs in each small cell is smaller, the total system capacities with both CSRA and CDRA increase as well. This is because in this case there are sufficient PRBs available for the SUEs. When the number of SUEs in each small cell increases beyond a certain number, the system capacities start to decline after reaching a peak. This is because in this case the number of PRBs in the system cannot accommodate the larger number of SUEs. More PRBs are shared and more interference is caused, resulting in the decrease of the total system capacity.

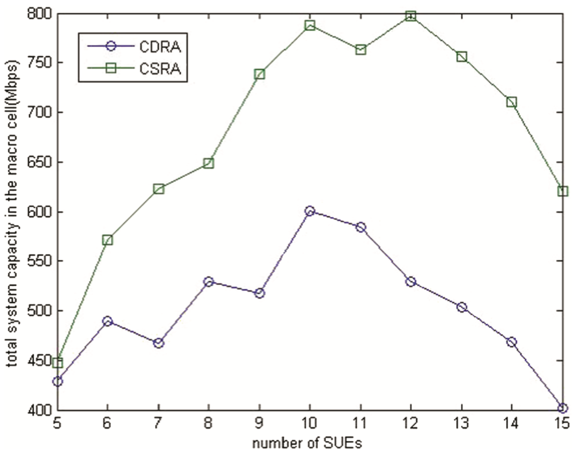

Fig. 2. Total system capacity vs number of SUEs in each small cell ($U_0 = 80$)

Figure 3 shows the total system capacity with CSRA and CDRA, respectively, under different numbers of MUEs in the macro cell. It is seen that CSRA can basically achieve a larger system capacity than CDRA. On the other hand, when the number of MUEs is smaller, the total system capacities with both CSRA and CDRA increase as well. This is because in this case there are sufficient PRBs available for the MUEs. When the number of MUEs increases beyond a certain number, the system capacities start to decline after reaching a peak. This is because in this case the number of PRBs in the system cannot accommodate the larger number of MUEs. More PRBs are shared and more interference is caused, resulting in the decrease of the total system capacity.

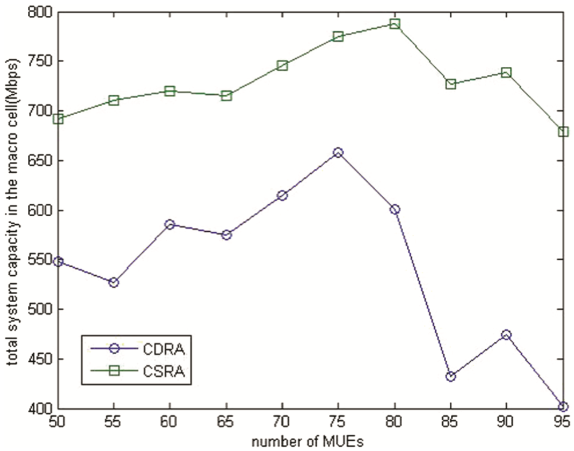

Fig. 3. Total system capacity vs number of MUEs ($U_i = 10$)

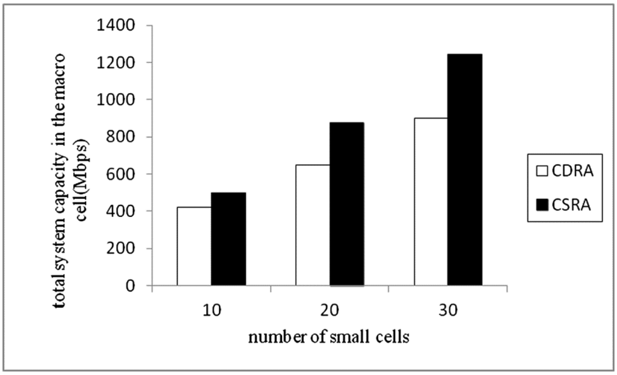

Fig. 4. Total system capacity vs number of small cells ($U_0 = 80$, $U_i = 12$)

Figure 4 shows the total system capacity with CSRA and CDRA, respectively, under different numbers of small cells in the system. It is seen that as the number of small cells in the system increases, the total system capacities with both ACDRA and CDRA increase as well. Meanwhile, the total system capacity with CSRA is larger than that with CDRA. The difference of the total system capacities with the two algorithms becomes larger as the number of small cells in the system increases.

Figure 5 shows the cumulative distribution function (CDF) of the system capacity with CSRA and CDRA, respectively. It is seen that CSRA outperforms CDRA in terms of the system capacity. With CDRA, the data rates of about 40% users in the system are lower than 0.5 bps. In contrast, with CSRA, almost no user has a data rate lower than 0.5 bps.

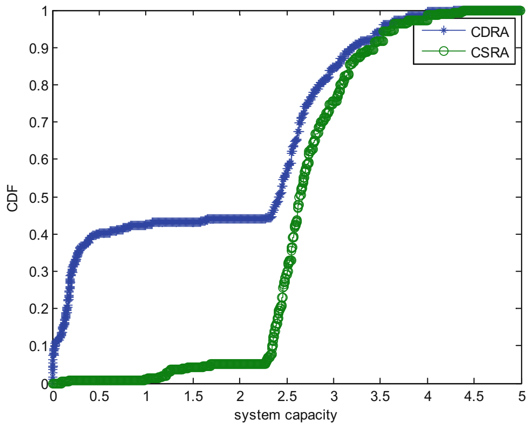

Fig. 5. CDF of system capacity ($U_0 = 90$, $U_i = 7$)

5 Conclusions

In this paper, we studied the spectrum resource allocation problem in dense small cell networks, and focused on a system scenario where small cells are non-uniformly distributed in a macro cell. The CSRA algorithm is proposed to perform PRB allocation for MUEs and SUEs with the objective to maximize the system capacity. To minimize both intra-tier and inter-tier interferences, we introduced the concept of clusters into spectrum resource allocation, and correspondingly set a few principles for clustering. Unlike [9], an upper limit for the cluster size is set to avoid the formation of a too large cluster, which otherwise would consume a large number of physical resource blocks (PRBs) and thus affect the system capacity. Moreover, all PRBs are allowed to be used by all users in the system, both MUEs and SUEs. Simulation results show that the proposed CSRA algorithm out performs the CDRA algorithm in terms of the system capacity.

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