



A Cluster-Based Small Cell On/Off Scheme for Energy Efficiency Optimization in Ultra-Dense Networks

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Abstract. Ultra-Dense Networks (UDN) can greatly meet the demand for explosively growing data traffic via deploying small cells (SCs) densely. However, the SCs densification causes higher energy consumption and more severe inter-cell interference (ICI). The SC on/off control is one of the effective ways to solve above problems, but the challenge is to maintain network coverage while avoiding degradation of the quality of service (QoS) of user equipment (UEs). In this paper, we formulate energy efficiency (EE) optimization problem in stochastic geometry-based network and take into consideration the QoS of UEs and ICI to maximize the EE. The solution is obtained by dividing the problem into SCs clustering and intra-cluster SC on/off control. We first use an improved K-means clustering algorithm to divide the dense SCs into disjoint clusters according to the distance and density of SCs. Then, within each cluster, selecting a SC as the cluster head (CH) is responsible for performing SC on/off operations under taking minimum rate of UEs and ICI as constraints. In addition, a heuristic search algorithm (HSA) is proposed for the intra-cluster SC on/off control. Simulation results demonstrate that the proposed scheme can effectively improve the network energy efficiency and suppress interference.

Keywords: UDN · Small cell on/off · Clustering · Energy efficiency

1 Introduction

With the proliferation of smart mobile devices and the development of real-time video streaming applications, a tremendous pressure on cellular networks has been put by the increasing capacity demands and explosive data traffic in the past decade [1, 2]. As a feasible solution, Ultra-Dense Networks (UDN) are envisioned to deal with the significantly increasing network capacity and data traffic problem via densifying communications infrastructure, viz., intensive deployment of the low-cost and low-power small cells (SCs) in hotspots (e.g., stadiums, airports, train stations, etc.) [3].

In UDN, the density of SCs is significantly increased. On one hand, this shortens the communication distance between the user equipment (UEs) and the base station to improve signal quality. On the other hand, this can spatially reuse the spectrum to increase capacity. However, with the densification of SCs, some problems in UDN arise such as redundant SCs energy consumption [4], the severe mutual interference between SCs [5] and limited backhaul capacity [6]. Among them, improving the energy efficiency (EE) of UDN by reducing energy consumption and interference has become the focus of research. Study in [7] has shown that the operation of SCs accounts for 60%–80% total energy consumption of network. As a result, all the SCs in the network remain open will waste a lot of energy as well as resulting in EE reduction. Moreover, the performance regimes in dense small cellular networks will gradually transition from noise-limited to dense interference-limited [8], which may further degrade the EE of UDN.

As an effective approach, SC on/off scheme (also known as SC sleep control) is used to save energy and promote EE [9]. It can turn off some specific SCs and traffic load of the sleeping SCs can transfer to neighbor SCs, which has shown that SC on/off mechanisms have great potential by reducing SCs' static power consumption [10]. However, when some SCs enter the sleep state, the average number of connections of active SCs will increase, which reduces the bandwidth obtained by the UEs and affects the QoS [11]. Therefore, many existing literatures have been devoted to studying the feasibility of SC on/off operation under QoS constraints. In [12], a random sleeping policy and a strategic sleeping policy based on multilevel sleep modes in heterogeneous cellular network were proposed to optimize EE. A strategic SCs sleeping mechanism according to the traffic demand was proposed in [13] to achieve energy saving, in which UEs associated with SCs in sleep close to the macro base station coverage area would be handed over to the macro-cell. Enhanced small inter-cell interference coordination was used to avoid QoS degradation. In [14] proposed a distributed SC on/off scheme that regularly checking the traffic load level and making sleep decisions under the constraints of QoS.

In addition, the number of possible the SC on/off combination grows exponentially with the number of SCs. So, some researches have focused on reducing the computational complexity of SC on/off operations [15–19]. The clustering approach was considered in [15, 16] to reduce the complexity of SC on/off. In [15], the locally coupled SCs was first grouped into clusters based on location and traffic load, and then the on/off algorithm was performed by local information in the cluster, wherein the SC with low traffic load was selected as the cluster head (CH). Another example is [16]. The difference is that it formed all SCs into a graph and then cut it into clusters. In [17], network-impact was introduced to decide to turn off SCs that minimize the increase in their neighbor load, in which SCs got turned on/off one by one. The author of [18] solved the energy-saving problem of SC on/off in two steps. It first adjusted the transmission power of active SCs and then introduced a state transition graph to reduce the switching cost incurred by the on/off. A single Q-Learning based probabilistic policy was proposed in [19] to obtain the optimal on/off switch policy, but this approach needs a long time for exploration, so as to get the optimal pattern. While these interesting efforts can effectively reduce complexity and power consumption, they lack the consideration of inter-cell interference (ICI) during SC on/off operations.

Therefore, we propose a cluster-based small cell on/off scheme in this paper to improve EE and mitigate ICI for UDN with low complexity. First of all, considering the increased network size of the UDN leads to more irregular coverage, we introduce stochastic geometry [20, 21] to capture the more realistic location distribution of the SCs and UEs. Then, a modified K-means clustering algorithm is proposed based on the distribution location of SCs. It can dynamically adjust the size of SCs clusters according to the density of SCs. After forming SCs clusters, one SC, in each cluster, is elected as a cluster CH and performs SC on/off scheme in its cluster to facilitate the reduction of signaling interactions. Finally, a heuristic search algorithm (HSA) is proposed for the intra-cluster SC on/off phase, which can be turned off without sacrificing the QoS requirements of UEs. The main contributions of this paper can be summarized as follows:

- (1) *Proposed a modified clustering algorithm in UDN:* We divide UDN into disjoint sub-area, which can classify NP-hard problem into many manageable sub-problems. Although performing SC on/off in each sub-area is still NP-hard, it can reduce the search space. Moreover, it can adaptively form clusters according to the location distribution of SCs to simplify the topology of the UDN.
- (2) *Reduced the complexity of SC on/off with HSA:* Based on the clustering results, each CH performs SC on/off scheme with QoS requirements of UEs and the interference constraints between SCs. The HSA is proposed to avoid the exponential complexity associated with obtaining the optimal SC on/off combination by exhaustive search. Furthermore, we also analyze the complexity of our scheme.

The remainder of this paper is organized as follows. Section 2 introduces the system model and gives the detailed problem formulation. In Sect. 3, we propose a SC on/off scheme based on clustering and theoretically analyze the complexity of our scheme. This is followed by the simulation experiments and performance analysis in Sect. 4. Section 5 concludes this paper with a summary. Also, the key notations and nomenclature used in the paper are listed in Table 1.

Table 1. List of key notations and nomenclature

Symbol	Explanation
UDN	Ultra-Dense Networks
PPP	Poisson Point Process
CH	Cluster Head
QoS	Quality of Service
Ψ_b	The set of SCs
Ψ_u	The set of UEs
ρ_{b_m}	The load of SC b_m
c_l	The l -th SC cluster
U_{c_l}	The set of UEs in cluster c_l
ε_{b_m}	The set of neighborhoods of SC b_m
γ_{b_m}	The density of SC b_m

2 System Model and Problem Formulation

2.1 System Model

We consider an UDN which are distributed according to a homogeneous PPP in a finite two-dimensional plane \mathfrak{R}^2 . Specifically, we use a homogeneous PPP with the density of λ_b to simulate the location distribution of SCs in the network and denoted by the set $\Psi_b = \{b_1, b_2, \dots, b_m\}$. Similarly, the location distribution randomly of single-antenna UEs are modeled as a homogeneous PPP $\Psi_u = \{u_1, u_2, \dots, u_n\}$ with the density of λ_u . Each UE is connected with SCs according to the closest distances while all other SCs act as interferers, thus the coverage areas of SCs comprise a Voronoi tessellation on the plane [21]. Due to the independent distribution of SCs and UEs and the coverage area of each SC, some SCs may have no users, which is called void cell [22]. Figure 1 shows an example of such a network.

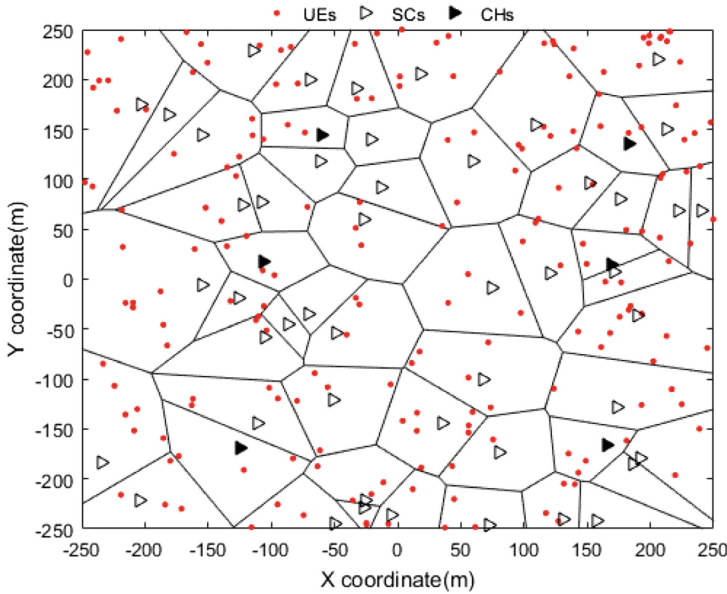


Fig. 1. A layout based on Poisson distributed small cells (SCs), user equipment (UEs) and cluster heads (CHs) on a 500 m * 500 m plane, with cell boundaries corresponding to a Voronoi tessellation.

To reduce energy consumption and co-tier interference in the UDN, each SC can be switched between working and sleeping. We use the set $X = \{x_{b_m}, \forall b_m \in \Psi_b\}$ to indicate the two different status of all SCs, where the binary variable $x_{b_m} = \{0, 1\}$, which is 0 if sleep mode and 1 if active mode. Assume all SCs transmit at a fixed power P_{Tx} , then, the received signal strength of UE u_n from SC b_m is determined by:

$$S_{b_m, u_n}^r = x_{b_m} P_{Tx} h_{b_m, u_n} d_{b_m, u_n}^{-\alpha} \tag{1}$$

where, h_{b_m, u_n} is an exponential random variable with mean 1 incorporating the effect of Rayleigh fading, d_{b_m, u_n} is the distance between the UE u_n and the SC b_m , and α is the

path loss factor of SCs, generally $\alpha > 2$ [20]. Then, the downlink Signal to Interference plus Noise Ratio (SINR) of UE u_n associated with SC b_m can be defined as in [18] as:

$$SINR_{b_m, u_n} = \frac{S_{b_m, u_n}^r}{\sum_{b_i \in \Psi_b \setminus \{b_m\}} S_{b_i, u_n}^r + \sigma^2} \quad (2)$$

where σ^2 is the noise power. According to the Shannon capacity, the achievable data rate of UE u_n associating with SC b_m is given by:

$$R_{b_m, u_n} = y_{b_m, u_n} W_{RB} \log_2(1 + SINR_{b_m, u_n}) \quad (3)$$

where y_{b_m, u_n} indicates the number of resource block (RB) required to meet the QoS of the UE u_n associated with SC b_m , W_{RB} represents the bandwidth per RB. Therefore, the number of RB required for the SC b_m to meet the minimum rate requirement of the UE u_n can be written as:

$$y_{b_m, u_n} = \left\lceil \frac{R_{\min}}{W_{RB} \log_2(1 + SINR_{b_m, u_n})} \right\rceil \quad (4)$$

Therefore, the SC should assign a certain amount of resources according to UEs' service rate to guarantee the QoS. Thus, the load of the SC b_m can be defined as the fraction of serving UEs resources to total resources:

$$\rho_{b_m} = \frac{\sum_{u_j \in \zeta_{b_m}} y_{b_m, u_j}}{RB_{b_m}^{total}} \quad (5)$$

where ζ_{b_m} represents the set of UEs associated with the SC b_m .

2.2 Problem Formulation

When no UEs are associated with the SC, the SC will enter sleep mode to save energy [22]. Not only that, our scheme will close the empty SC and then close the SCs with light load and heavy interference. Therefore, we discuss the problem of turn off those SCs to achieve more energy savings while ensuring the QoS of UEs. That is to find the best combination of SC on/off to maximize the EE, the EE maximization problem is computed as:

$$\max_{x, y} \left(\frac{\sum_{m=1}^{|\Psi_b|} x_{b_m} \sum_{u_j \in \zeta_{b_m}} R_{b_m, u_j}}{P_{total}} \right) \quad (6)$$

where P_{total} is the total power consumption of the entire network. The energy consumption of SCs are usually composed of power amplifiers, radio frequency circuit, power supplies and other power components according to the power consumption model descriptions in [14] and [18]. We divide the SCs power consumption P_{b_m} into dynamic power $P_{b_m}^{dy}$ and static power $P_{b_m}^{st}$, the total power consumption P_{total} can be calculated as:

$$P_{total} = \sum_{m=1}^{|\Psi_b|} P_{b_m} = \sum_{m=1}^{|\Psi_b|} P_{b_m}^{dy} + \sum_{m=1}^{|\Psi_b|} P_{b_m}^{st} \quad (7)$$

where the static power consumption includes fixed power consumption P_{fix} when SC is on and sleeping power consumption P_{off} when it is off. The dynamic power consumption consists of transmission power consumption and switching power consumption P^{sw} . Then, the power consumption and the power of each part of SC b_m can be expressed as:

$$P_{b_m}^{dy} = P_{b_m}^{sw} + x_{b_m} \partial_{b_m} \rho_{b_m} P_{Tx} \quad (8)$$

$$P_{b_m}^{st} = x_{b_m} P_{fix} + (1 - x_{b_m}) P_{off} \quad (9)$$

$$P_{b_m} = x_{b_m} (P_{fix} + \partial_{b_m} \rho_{b_m} P_{Tx}) + (1 - x_{b_m}) P_{off} + P_{b_m}^{sw} \quad (10)$$

where ∂_{b_m} is the power amplifier efficiency. P_{fix} and P_{off} respectively indicate the fixed power consumption when SC is turned on and off. $P_{b_m}^{sw}$ is the switching power consumption that can be regarded as the signal processing of the UEs when the SCs perform the switching operation [18]. Since the SC switching operation needs to ensure the QoS for each UE, the switching power consumption can be expressed a linear:

$$P_{b_m}^{sw} = (1 - x_{b_m}) |\zeta_{b_m}| P_o \quad (11)$$

where P_o is the power consumption that handles each UE re-associate to other SCs. Since given that the number of RB is a ceil integer and assume that the QoS can be maintained as long as the minimum throughput by each UE can be satisfied, we roughly consider the whole network throughput as a constant value and minimize network energy consumption and the number of required RBs while meeting users' the minimum demanded data rate to solve (6). The mathematical expression that minimizes problem η can be written as:

$$\begin{aligned} & \min \sum_{b_m \in \Psi_b} \sum_{u_n \in \Psi_n} (\mu_b P_{b_m} + \phi_b y_{b_m, u_n} k_{b_m, u_n}) \\ & s.t. \text{ C1: } \sum_{b_m \in \Psi_b} k_{b_m, u_n} = 1, \forall u_n \in \Psi_u \\ & \text{C2: } \sum_{u_n \in \Psi_u} k_{b_m, u_n} \cdot y_{b_m, u_n} \leq RB_{b_m}^{total}, \forall b_m \in \Psi_b \\ & \text{C3: } k_{b_m, u_n} \cdot R_{b_m, u_n} \geq R_{\min}, \forall u_n \in \Psi_u \\ & \text{C4: } k_{b_m, u_n} = \{0, 1\}, \forall b_m \in \Psi_b, \forall u_n \in \Psi_u \\ & \text{C5: } x_{b_m} = \{0, 1\}, \forall b_m \in \Psi_b \end{aligned} \quad (12)$$

where k_{b_m, u_n} is an indicator of the associated status. If UE u_n is served by SC b_m , there is $k_{b_m, u_n} = 1$, otherwise $k_{b_m, u_n} = 0$. μ_b and ϕ_b are the weight parameters that indicate the impact of energy consumption and RB on the problem. Constraint C1 determines that each UE can only be associated with one SC. Constraint C2 indicates that the UEs connected to the SC should not exceed the capacity of the SC. Constraint C3 ensures QoS for each UE. Note that the objective that minimize energy consumption and reduce the number of required RBs by selecting SCs among all the SCs to be turned on or off is a combination problem, which requires extremely high computational complexity in exhaustive combinational search for the optimal solution.

3 The Cluster-Based Small Cell On/Off Scheme

3.1 Overview

Network-level coordination in the UDN to determine the best SC on/off combination to address problem (12) is usually NP-hard and is nearly impossible to solve with a central controller for global optimization [4]. This solution in a fully centralized manner not only leads to excessive complexity, but the control overhead can be very large [9].

To address this problem, we split the whole UDN into multiple parts. The SC is selected in each part as the CH to act as the controller, and the CH asynchronously performs on/off control with reasonable overhead within the cluster. Specifically, we propose a cluster-based SC on/off scheme in UDN, which consists of SCs clustering and intra-cluster SC on/off control.

The overall procedure of the proposed scheme is shown in Fig. 2, which is divided into the following main steps:

- Step 1:** Calculate the location information of SCs to determine their density.
- Step 2:** Perform K-means clustering after performing max-min distance clustering.

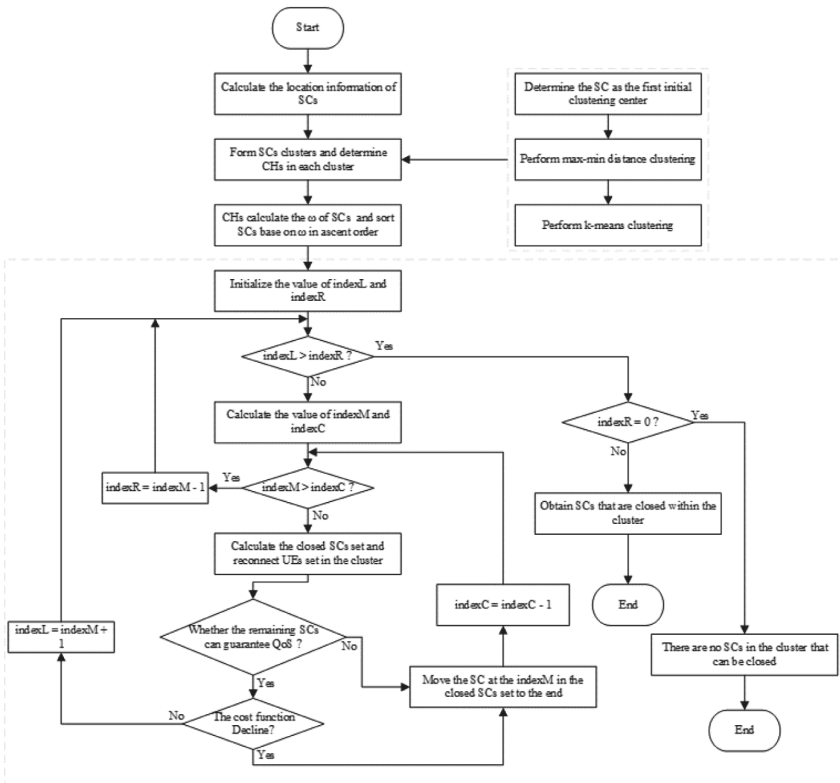


Fig. 2. The flow chart of cluster-based small cell on/off scheme

Step 3: An active SC closest to the final clustering center is selected as a CH in each cluster.

Step 4: CH collects coordination information within the cluster.

Step 5: Execute HSA.

In the following sub-sections, we describe the two phases of the proposed scheme. Specifically, steps 1 to 3 are the SC clustering and are described in detail in Sect. 3.2. Step 4 and 5 are the intra-cluster SC on/off control and are given in Sect. 3.3.

3.2 SCs Clustering

In general, the distance and density between SCs mirror their ability of collaborate and interference intensity. If several SCs that are far from each other form a cluster, the performance of the cluster cell on/off coordinated transmission is significantly reduced. Therefore, SCs that are close to each other preferentially form a cluster, and dense SCs are formed into different clusters by combining max-min distance clustering and K-means clustering algorithm. However, the traditional K-means clustering algorithm usually randomly selects the initial clustering center and the number of clusters needs to be preset, which leads to local optimum [15]. So, the number of pre-set clusters and the initial cluster centers are first obtained by the modified max-min distance clustering algorithm. Then, the output of the max-min distance is used as the initial value of the K-means clustering to obtain the final SCs cluster and CHs.

Firstly, we calculate the distance between the SCs before clustering to determine density of SCs, and the distance denoted by $d = [d_{b_m, b_i}, \forall b_m, b_i \in \Psi_b]$. The set of neighborhoods of the SC b_m is given by:

$$\varepsilon_{b_m} = \{b_i \in \Psi_b \mid d_{b_m, b_i} \leq d_{th}\} \quad (13)$$

where d_{th} is the threshold of distance. In addition, the density of the SC b_m can be calculated as:

$$\gamma_{b_m} = \sum_{b_k \in \varepsilon_{b_m}} |\varepsilon_{b_m}| \cdot \exp\left(\frac{-d_{b_m, b_k}}{(0.5d_{th})^2}\right) \quad (14)$$

We then choose the SC with the highest density as the initial cluster center of the max-min distance clustering, which ensures that there is at least one cluster formed by a group of dense SCs and avoids the inconsistent cluster results caused by randomly selecting the initial center.

Algorithm 1 SCs Clustering Algorithm**Input:** $\theta, \Psi_b, d_{b_m, b_i}, \forall b_m, b_i \in \Psi_b$ **Output:** $C = \{c_1, c_2, \dots, c_l\}$

- 1: Initialization: $D = \emptyset, Z = \emptyset,$
- 2: Calculate the density γ of each SC by Equation (14)
- 3: Find SC $b_m^* = \arg \max \gamma$ as the first clustering center,
 $z_1 \leftarrow b_m^*, \forall b_m \in \Psi_b$
- 4: Find SC $b_i^* = \arg \max_{i=1, \dots, m} d_{b_m^*, b_i}, z_2 \leftarrow b_i^*, D_{th} \leftarrow d_{b_m^*, b_i^*}$
- 5: $D = \{d_{z_l, b_i}, i = 1, \dots, m\}, l = 2$
- 6: **while** true **do**
- 7: $D_{z_l, b_p} = \{d_{z_l, b_p}, p = 1, \dots, m\},$
- 8: $D \leftarrow D \cup \{D_{z_l, b_p}\}$
- 9: $D_{th} \leftarrow \max_{b_p^*} \{\min D\}$
- 10: **if** $D_{th} > \theta \times d_{b_m^*, b_i^*}$ **then**
- 11: $l = l + 1, z_l \leftarrow b_p^*$
- 12: **else**
- 13: **break**
- 14: **end if**
- 15: **end while**
- 16: Using $Z = \{z_1, \dots, z_l\}$ and l as the initial value of K-means clustering to get the final cluster $C = \{c_1, c_2, \dots, c_l\}$

Finally, the cluster center and number obtained by the max-min distance algorithm are taken as the initial value of the K-means algorithm to obtain the final SCs clusters formed by set of SCs and denoted by $C = \{c_1, c_2, \dots, c_l\}$. The specific SCs clustering process is in Algorithm 1. Based on the clustering results, the CH within each cluster is responsible for SC on/off to facilitate the reduction of network state information and signaling interactions. Then we select the active SC closest to the clustering center as the CH.

3.3 Intra-cluster SC On/Off Control

After obtaining clusters of SCs according to Algorithm 1, the objective function of (12) can be divided into sub-problems corresponding to all clusters of SCs. That is, reducing the energy consumption and RBs of the entire network is approximately equal to minimizing the energy consumption and RB of each cluster. Then, the optimization problem η can be rewritten as:

$$\begin{aligned}
 & \sum_{c_l=1}^{|C|} \min \sum_{b_m \in c_l} \sum_{u_n \in \Psi_n} (\mu_b P_{b_m} + \phi_b y_{b_m, u_n} k_{b_m, u_n}) \\
 & s.t. \text{ C1: } \sum_{b_m \in \Psi_b} k_{b_m, u_n} = 1, \forall u_n \in \Psi_u \\
 & \text{C2: } \sum_{u_n \in \Psi_u} k_{b_m, u_n} \cdot y_{b_m, u_n} \leq RB_{b_m}^{total}, \forall b_m \in \Psi_b \\
 & \text{C3: } k_{b_m, u_n} \cdot R_{b_m, u_n} \geq R_{\min}, \forall u_n \in \Psi_u \\
 & \text{C4: } k_{b_m, u_n} = \{0, 1\}, \forall b_m \in \Psi_b, \forall u_n \in \Psi_n \\
 & \text{C5: } x_{b_m} = \{0, 1\}, \forall b_m \in \Psi_b \\
 & \text{C6: } \bigcup_{l=1}^{|C|} c_l = \Psi_b \quad \text{C7: } \bigcap_{l=1}^{|C|} c_l = \emptyset
 \end{aligned} \tag{15}$$

constraints C6 and C7 indicate that the SCs set in the entire UDN is divided into a number of SCs clusters and each SC can only be located in one cluster so as not to intersect, respectively.

For a given the set of SCs clusters, since there are only a few SCs per cluster, it becomes feasible to obtain the optimal on/off combination for each cluster by exhaustive search. However, this solution still has high search complexity, and we propose a heuristic search algorithm to solve the optimization problem.

In the cluster c_l , the SC b_m is able to close only if each of its UE can be served by other SCs in the same cluster. However, turning off the SCs with fewer service UEs will save more power consumption under the condition that the same number of SCs can be closed. On one hand, this avoids generating more switching power that is proportional to the number of service UEs. On the other hand, this avoids turning off the SCs with lots of UEs. Then, the additional dynamic power generated if the SC b_m is turned off is:

$$\omega_{b_m} = P_{sw_{b_m}} + \sum_{b_p \in c_l \setminus \{b_m\}} \partial \rho_{b_m \rightarrow b_p} P_{Tx} \tag{16}$$

where $\rho_{b_m \rightarrow b_p}$ is the load transferred to SC b_p when the SC b_m is switched off in the cluster. The actual load change of each SC is unknown before the shutdown occurs, so we approximately estimate the transferred load. It is assumed that the load transferred is related to the initial load of the SC b_m and its service UEs' interference which suffered from SC b_p . The interference of SC b_m suffered from the SC b_p can be expressed as $I_{b_m, b_p} = |\zeta_{b_m}| P_{Tx} G_{b_m, b_p}$, where G_{b_m, b_p} is the channel gain between SC b_m and b_p [23]. Furthermore, it may become useful signals for its users when the SC b_m is turned off. Thus, the relation can be given as:

$$\rho_{b_m \rightarrow b_p} = \rho_{b_m} \beta_{b_m, b_p} \mu \tag{17}$$

where $\beta_{b_m, b_p} = 1/I_{b_m, b_p}$, $\mu = 1 / \sum_{b_j \in c_l \setminus \{b_p\}} \beta_{b_m, b_j}$. We are acknowledged that a SC with less additional dynamic power generated, has a higher probability to be closed off. The specific HSA in intra-cluster SC on/off control is shown in Algorithm 2.

Algorithm 2 Heuristic Search Algorithm**Input:** c_l, U_{c_l} **Output:** The set c_l^{off} of SCs turned off in cluster

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1: Initialization:  $indexL = 1, indexR = |c_l|$ ,
2: calculate the value  $\omega$  of each SC in cluster  $c_l$  and sort
   them in ascending order as  $c_l^* = \{b_1, \dots, b_p\}$ ,
3: while  $indexL \leq indexR$  do
4:    $indexM = \lfloor \frac{indexL + indexR}{2} \rfloor; indexC = |c_l|$ 
5:   while  $indexC \geq indexM$  do
6:      $c_l^{off} \leftarrow$  SCs at 1 to  $indexM$  in set  $c_l^*$ 
7:      $U_{c_l}^{off} \leftarrow$  UEs associated with SCs in set  $c_l^{off}$ 
8:     if all UE  $\in U_{c_l}^{off}$  can be served by the remaining
       SCs  $\in c_l^{on} = c_l^* \setminus c_l^{off}$  and the  $\eta$  decrease then
9:        $indexL = indexM + 1$ 
10:      break
11:     else
12:       Move the SC at the  $indexM$  in set  $c_l^*$  to the
       end;  $indexC = indexC - 1$ 
13:     end if
14:   end while
15:   If  $indexM$  is greater than  $indexC$  then  $indexR$  equals
        $indexM$  minus 1
16: end while
17: if  $indexR$  is equal to zero then
18:   return  $c_l^{off} \leftarrow \emptyset$ 
19: else
20:   return  $c_l^{off} \leftarrow$  SCs at 1 to  $\lfloor \frac{indexL + indexR}{2} \rfloor$  in set  $c_l^*$ 
21: end if

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3.4 Computational Complexity Analysis

In this part, we analyze the complexity of the two stages of clustering and intra-cluster SC on/off in the proposed scheme. Assume that there are M SCs and L clusters are formed. Firstly, the max-min distance clustering algorithm needs to compare the distance between the existing cluster center node and other nodes to iteratively generate a new cluster center, thus the complexity of max-min distance can be calculated as $O(ML)$. Then the complexity of K-means clustering algorithm is $O(dMLt)$, $d = 2$ represents the two dimensional coordinate of SCs, and t is number of iterations of K-means algorithm. Finally, the time complexity of the first stage clustering is:

$$T_{clustering} = O(ML) + O(dMLt) \quad (18)$$

For the second stage of SC on/off operation, we assume that each SC serves P UEs. There are 2^M combinations if we get the optimal on/off combination by exhaustively searching each SC, and each UE will re-associate in $M - 1$ SCs when the SC is off. The

exhaustively searching algorithm time complexity is:

$$T_{optimal} = O(2^M P M) \quad (19)$$

In our proposed scheme, the SCs in each cluster are sorted in ascending order according to Eq. 16, and then closed by using the modified binary search. Assume that each cluster c_l contains S SCs. The complexity of binary search is $O(\log_2 S)$. The complexity of reconnecting the UEs to the remaining SCs at total search step is $PS[S/2(S - S/2) + S/2^2(S - S/2^2) + \dots + S/2^r(S - S/2^r)]$, which can be rewritten as $O(S^3 P)$, $r = \log_2 S$ indicates the number of searches. Therefore, the complexity of second stage is $O(S^3 P \log_2 S)$. As a result, the complexity of our proposed scheme is:

$$T_{proposed} = \max(O(dMLt), O(S^3 P L \log_2 S)) \quad (20)$$

It is worth noting that although SCs clustering increases computational complexity, they reduce the complexity of performing SC on/off in UND. Generally $M \gg L$ and $M \gg S$, thus the time complexity of our scheme is much lower than the optimal exhaustive search approach as the number of SCs increases.

4 Simulation Results

4.1 Parameters Settings

In order to simulate the performance of the proposed cluster-based SC on/off scheme, we consider a downlink scenario of ultra-dense network. It is composed of many SCs

Table 2. Major simulation parameters

Parameters	Value
Carrier frequency	2 GHz
Bandwidth	20 MHz
Total number of RBs per SC	100
Transmit power	30 dBm
Density of SCs	0.0002–0.002 SCs/m^2
Fixed power consumption	106 W [14]
Sleep power consumption	10 W [14]
P_o	30 dBm [18]
Traffic model	Full buffer
Path loss factor α	4 [21]
White noise power	–174 dBm/Hz
Minimum required rate per User	1 Mbps

and UEs randomly distributed within an area size of $500 \text{ m} \times 500 \text{ m}$. In this scenario, we set the density of users distributed in the area to 0.002 UE/m^2 , while the density of SCs continues to increase to the same density as UEs. The major parameters used for the simulation are listed in Table 2.

4.2 Result Analysis

We compare the other three schemes to evaluate the performance gain of the proposed scheme. The first is none SC on/off scheme [20] that all SCs are always on and there is no optimization method in the network, which is the benchmark compared with other scheme. The random SC on/off is the second scheme [12], which randomly choose to close a certain proportion of SCs in the network and switch users to the remaining SCs. If the closed SC has UEs, these users will switch to adjacent active SCs. The last one is void SC on/off scheme [22]: a SC will be turned on when it has at least one user to serve, otherwise it will be turned off.

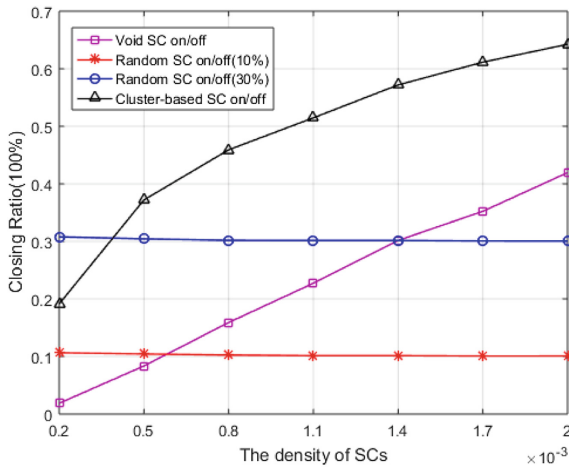


Fig. 3. The closing ratio under different densities of SCs

In Fig. 3, we compare the closing ratio of different SC on/off schemes under different distribution densities of SCs. It can be observed that the random SC on/off scheme always turns off a certain proportion of SCs regardless of the increase in the density of SCs. However, the proportion of SCs that are idle in the system is higher than about 30% as the density of SCs continues to increase, which results in the closing rate of the void SC on/off scheme will be higher than that of random SC on/off scheme. The closing ratio of cluster-based SC on/off scheme is always about 20% higher than that of the void SC on/off scheme with the increase of the density of SCs, that is, more SCs will be turned off to achieve higher power efficiency.

Figure 4 illustrates the total power consumption of all SCs in the network as the density of SCs increases. As can be seen from the figure, the network with the on/off scheme will save the power consumption of the SC. When the density of SCs is low,

the total power consumption of SCs realized by the four on/off schemes is almost equal. This is because a large amount of switching power consumption at this time replaces the energy saved by the SCs shutdown. That is to say, there are fewer SCs turned off when the density is low, but more users need to switch, leading to an increase in switching power consumption. However, as the density of the SCs increase, the number of SCs that are closed by the corresponding on/off scheme increases, so that power consumption is significantly reduced. When the density of SCs increases to the same density as the user, the total power consumption of SCs that achieved by the void SC on/off scheme will be reduced by about 38%, while 58% of the total power consumption can be saved through cluster-based SC on/off scheme.

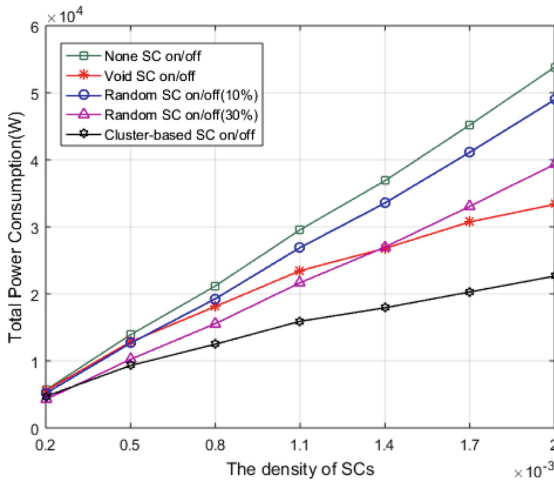


Fig. 4. The total power consumption under different densities of SCs

Figure 5 shows the network energy efficiency defined by Eq. 6. When the total throughput is almost constant, the energy efficiency of the network is determined by the total energy consumption. It can be seen from Figs. 2 and 3 that the total power consumption of the network is proportional to the number of SCs opened, and the impact of switching power consumption on the total power consumption will decrease as the density of SCs increases. Our proposed will close more SCs as the density of SCs increases, thus having better energy efficient than other on/off schemes.

Figure 6 implies the cumulative distribution function of SINR values of UEs in the case where the SCs and the user density are the same. As shown in the figure, the random on/off scheme does not improve SINR or even worse because it turns off SCs without guaranteeing the QoS of UEs. Both void SC on/off scheme and our scheme can suppress some interference, but our scheme can close more SCs and reduce more interference under the premise of guaranteeing the QoS of UEs, thus showing a better SINR of UEs than void SC on/off scheme.

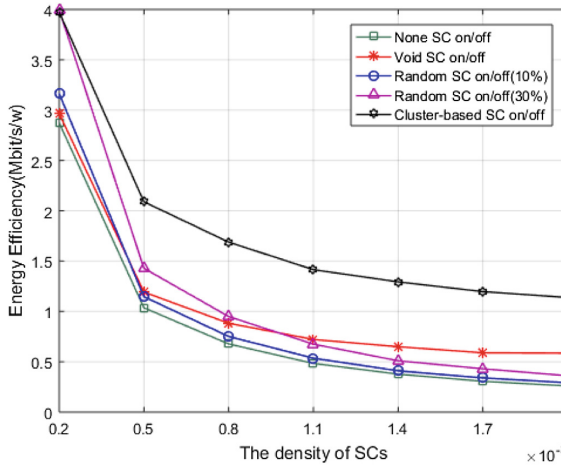


Fig. 5. The energy efficiency under different densities of SCs

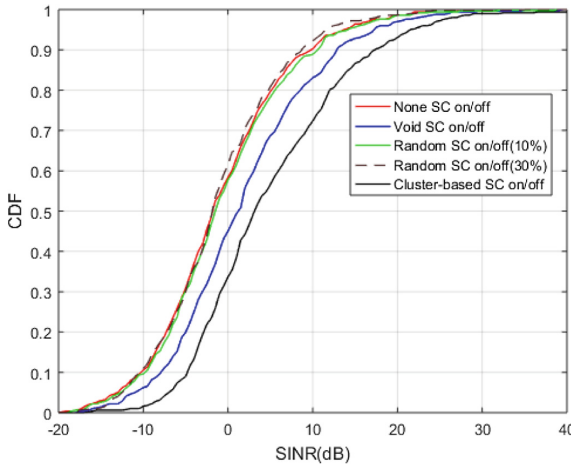


Fig. 6. The CDF of SINR values of UEs

The relationship between the SCs density and the RB cost of each on/off scheme is depicted in Fig. 7. It can be seen that there is no significant difference in the RB cost of none SC on/off scheme and random SC on/off scheme because their SINR levels are almost the same. Since closing some SCs can improve channel conditions, choosing to turn off the appropriate SCs can reduce the RB cost. Compared to the benchmark, our proposed scheme can reduce RB cost by about 50% when densities of UEs and SCs are the same.

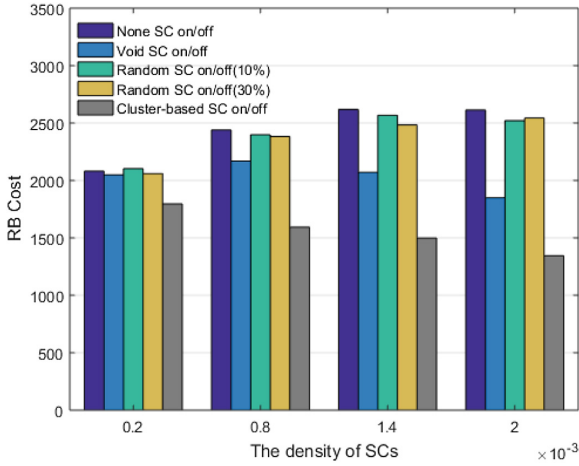


Fig. 7. The RB cost under different densities of SCs

5 Conclusions

In this paper, we propose a cluster-based SC on/off scheme for UDN. This scheme has two stages, viz., SCs clustering stage and intra-cluster SC on/off stage. In the SCs clustering stage, we firstly divide all SCs into multiple SC clusters by combining max-min distance clustering with K-means clustering algorithm. In the intra-cluster SC on/off stage, a HSA algorithm is proposed to turn SC on/off combo issues into selection questions, which is beneficial to reduce the computational complexity of searching the optimal combination of SC on/off. Simulation results show that the proposed scheme can effectively improve network energy efficiency, and this superiority is more obvious if the density of SCs is further increased in UDN.

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