Energy-Efficient Small Cell Cooperation in Ultra-Dense Heterogeneous Networks

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***Abstract*— This letter introduces a user-centric small cell clustering mechanism, which: 1) strengthens the received signal-to-interference-ratio (SIR) by small cell cooperation and 2) enables interference cancellation significantly through a user served by multiple cells in its vicinity. Consequently, we model this protocol with a Matérn cluster process (MCP) and present a new mathematical framework to study the average downlink rate of it. Then, a new formula for area spectral efficiency (ASE) with respect to cooperation number of the clustering mechanism is derived. Finally, the impact of cooperation number on energy efficiency (EE) is investigated. Simulation results demonstrate the optimal cooperation number which maximizes EE and validate the accuracy of theoretical analysis.**

***Index Terms*— Ultra-dense heterogeneous networks, Matérn cluster process, small cell cooperation, energy-efficient.**

I. Introduction

DENSER and closer deployment of small cells underlaid the traditional macro cells has been recognized as a promising approach to support a revolutionary growth in the network traffic and cope with the challenges posed by user mobility [1]. The densification of different types of small cells is defined as Ultra-Dense Networks (UDN), and the authors in [2] suggest a density over 10^3 $cells/km^2$ is considered as UND environments. The main challenges in UDN are serious interference and frequent handover among the neighboring small cells [3]. Meanwhile, power consumption of wireless communication infrastructure and information system rises markedly, of which clustering small cells is the major contributor [4].

To cope with aforementioned challenges, much attention has been drawn to small cell cooperation strategy due to its high data rate, anti-interference and extreme spatial reuse. The works in [4] and [5] investigated the interference-aware power coordination and energy cooperation between small cells, respectively. Authors in [6] and [7] introduced the description of user behavior into base station cooperation. However, these works mainly depend on rigorous simulations without tractable theory to explore the impact of cooperation size on energy efficiency.

Recently, stochastic geometry provides a statistical framework to quantify the network performance. Numerous researches have investigated small cell cooperation strategy and cluster size optimization problem using tools from it. A general and tractable model for average downlink rate and idle probability was derived in [8]. Authors in [9] presented a user-centric clustering solution and provided a comprehensive statistical framework for analyzing ASE and EE. Furthermore, the authors optimized cooperative radius which yielded a tradeoff between these two parameters. The works in [10] and [11] studied a small cell cooperation strategy for improving energy efficiency in terms of cluster area and base station density, respectively. These works pave the way to analyze the association of a user to more than one small cell and pose a theoretical way to the optimization for cluster size through homogeneous Poisson point process (PPP) [12]. However, PPP is not quite rigor for modeling user-centric small cell clustering scenario and there are very few researches on capturing the effects of clustering small cells in the theoretical analysis.

This motivates the urgent need to find a new mathematical framework which can accurately capture clustering features as well as coupling across the locations of users. For this reason, we model the spatial locations of small cells as Matérn cluster process (MCP) to study the user-centric small cell clustering mechanism. And then, develop a fundamental framework to facilitate the analysis of this protocol. Additionally, we explore the protocol in terms of energy efficiency and area spectral efficiency. The main contributions of this work are:

- a realistic mathematical framework to study the performance of user-centric small cell clustering mechanism is introduced.
- an accurate cumulative distribution function of the desired distance to the jth nearest small cell is employed.
- a tractable formula for the lower bound on the average downlink rate is derived.
- the optimal small cell cluster number that maximizes energy efficiency is investigated.

These results look into how small cells should be deployed by highlighting the impact of clustering features and adjusting ASE-EE tradeoff along with capacity guarantee. Numerical and Monte-Carlo simulation results confirmed our analytical performances and demonstrated the optimal cooperation number of small cells.

II. System Model

A. Network Architecture

As shown in Fig.1, the ultra-dense heterogeneous network is composed by two independent tiers with different type of cells and denoted by $k = \{m, s\}$. We start from the concept

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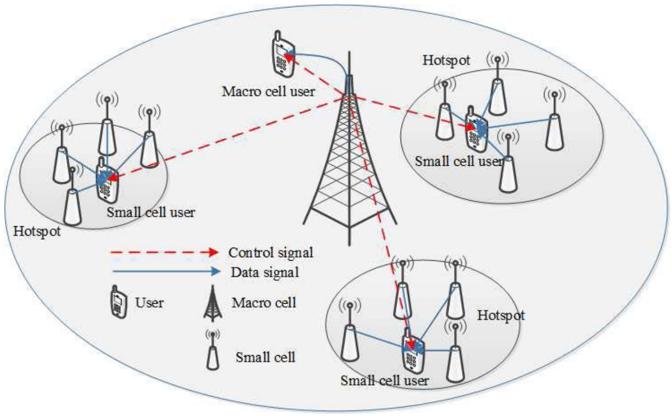

Fig. 1. System model.

of functionality separated networks [13], where the first tier is control network layer consisting of Macro cells for ubiquitous coverage and the other is data transmission layer consisting of ultra-dense small cells for high-speed.

1) Control Network Layer: The major responsibility of this layer is to transmit the control information of the whole network, including all necessary system information and functionalities. Moreover, in order to ensure the fairness of users in different locations and avoid frequent handovers among small cells, the data transmission of non-hotspot users and high-mobility users is guaranteed by Macro cells.

2) Data Transmission Layer: To support high-speed data transmission, massive amounts of small cells are expected to deploy in hotspots with very high density.

In this letter, we emphasize on a user-centric small cell clustering mechanism, in which a user connects to μ small cells clustering around it.

B. Mathematical Model and Assumptions

Without loss of generality, we consider the scale of control network layer is large enough. Both the small cells and users are assumed to be covered by the macro cells. Considering a user-centric small cells clustering mechanism, the distribution of small cells is modeled by an MCP Φ_s of density λ_s. In the MCP, hotspots forming a PPP Φ_p with density λ_p [12] as parent process, and then replace each point of Φ_p by a random finite set of small cells $\mathcal{Z}_x$ which are uniformly distributed in the circle of radius *D* around the users. The number of points in $\mathcal{Z}_x$ is identically independent Poisson distribution with mean μ, and the density function of daughter points is given by [12]

$$f(x) = \begin{cases} \frac{1}{\pi \mathcal{D}^2} & if \;\; \|x\| \le \mathcal{D} \\ 0 & otherwise \end{cases} \tag{1}$$

then we obtain the deployment density in data transmission layer by $\lambda = \lambda_p \mu$.

For notational simplicity, all users are equipped with single antenna, and the spatial location of users is assumed to be a homogeneous PPP Φ_u with density λ_u. Meanwhile, all small cells are equipped with single antenna. To eliminate the effect of interference, it is assumed that different types of cells work on orthogonal channels. Then we focus on the downlink transmission based on the standard path loss model $g(x) = \|x\|^{-\alpha}$ $(\alpha > 2)$, and the equivalent channel gains are assumed to be a Rayleigh fading with mean one, $h_i \sim exp(1)$ [14].

Subsequently, considering an interference-limited environment, SIR of the typical user while associated with the ith small cell in a serving cluster is then given by

$$SIR_i = \frac{P_s \, h_i \, r_i^{-\alpha}}{I_s} \tag{2}$$

where r_i is a random distance and I_s is aggregated interference, which can be expressed as

$$I_s = \sum\nolimits_{\Phi_s \setminus \mathcal{C}_s} P_s \, h_i \, r_i^{-\alpha} \tag{3}$$

where $\mathcal{C}_s$ is the set of serving cells.

The average power consumption of each cluster can be modeled as follows [9], [15]

$$\mathcal{P}_{cluster} = \mu \theta P_0 + \eta P_s + P_c \tag{4}$$

where η is the slope of the load-dependent power consumption, $\mu\theta$ is the small cells coefficient and θ $(0 \le \theta \le 1)$ is the implementation efficiency parameter which captures the performance gains from cooperation architecture of small cells. P_s, P_c and P_0 are the power consumed for transmitting downlink date by the user, circuit power at the user, fixed power consumption of each small cell in working mode, respectively.

III. Analysis of Performance Indicators

In this section, assuming there are enough macro cell antennas to guarantee the coverage probability under the functionality separation architecture, the main target is characterizing the performance indicators of the data transmission layer. Firstly, we derive the expression for the aggregate interference experienced by the typical user. Then we give the derivation of the average downlink rate. Besides, to further study how it behaves with different system parameters, a tractable lower-bound for average downlink rate will be explored.

A. Moments of Aggregate Interference

The mean aggregate interference at a typical user to its desired small cell during the single serving mode can be given according to Campbell's theorem [12] as follows:

$$\begin{aligned} \mathcal{M}_{single} &= \mathbb{E}(I) = \mathbb{E}\left(\sum\nolimits_{\Phi_s \setminus \mathcal{C}_s} P_s \, h_i \, r_i^{-\alpha}\right) \\ &= 2\pi\left(\lambda + \frac{\mu}{\pi^2 \mathcal{D}^4}\mathcal{A}(r)\right)\int_{\mathcal{D}}^{\infty} \mathbb{E}(H) \, r^{1-\alpha} \, dr \\ &= \frac{2\pi\left(\lambda + \frac{\mu}{\pi^2 \mathcal{D}^4}\mathcal{A}(r)\right)}{(\alpha-2)\,\mathcal{D}^{\alpha-2}} \end{aligned} \tag{5}$$

where $\mathcal{A}(r) = 2\mathcal{D}^2 \arccos\left(\frac{r}{2\mathcal{D}}\right) - r\sqrt{\mathcal{D}^2 - \frac{r^2}{4}}, 0 \le r \le \mathcal{D}$ is the disturbing interaction between two points belonging to the same cluster, which is not a contributor due to user-centric small cells clustering mechanism. Then the mean of the aggregate interference during this mode can be approximated as follows

$$\mathcal{M} = \frac{2\pi\lambda}{(\alpha-2)\,\mathcal{D}^{\alpha-2}} \tag{6}$$

B. Average Downlink Rate

Theorem 1: A lower-bound for the average downlink rate of the typical user from the jth small cell in the serving cluster can be given by

$$\underline{R_j} \geq \int_{r>0}\left(\int_{t>0}\exp\left(-\frac{r^{\alpha}\left(e^{t}-1\right)}{P_s}\mathcal{M}\right)dt\right)f_j\left(r\right)dr \tag{7}$$

where $f_j\left(r\right)$ is the distribution expression of the desired distance r to the jth nearest small cell in a serving cluster, and can be written as

$$f_j\left(r\right) = \frac{\frac{2}{\Gamma(j)}\left(\frac{\mu}{\mathcal{D}^2}\right)^j r^{2j-1}\,e^{-\mu r^2/\mathcal{D}^2}}{1-e^{-4\mu}} \tag{8}$$

and $\Gamma\left(n\right)=\int_0^{\infty}t^{n-1}e^{-t}dt$ is the gamma function.

Proof: The average downlink rate of the typical user from the connection to the jth nearest small cell can be defined as

$$R_j = \mathbb{E}_r\left[\mathbb{E}_{\Phi_s,\mathcal{H}}\left[\log\left(1+\frac{P_s\,h_i\,r_i^{-\alpha}}{I_s}\right)\middle|r\right]\right] \tag{9}$$

On the basis $\mathbb{E}\left(\mathcal{X}\right) = \int\limits_{t>0}\mathbb{P}\left(\mathcal{X}>t\right)dt$ for a positive random variable $\mathcal{X}$, the conditional expectation can be derived as follows.

$$\begin{aligned}
&\mathbb{E}_{\Phi_s,\mathcal{H}}\left[\log\left(1+\frac{P_s\,h_i\,r_i^{-\alpha}}{I_s}\right)\middle|r\right]\\
&\quad=\int\limits_{t>0}\mathbb{P}\left[\log(1+\frac{P_s\,h_i\,r_i^{-\alpha}}{I_s})>t\right]dt\\
&\quad=\int\limits_{t>0}\mathbb{P}\left[h>\frac{r^{\alpha}}{P_s}I\left(e^{t}-1\right)\right]dt\\
&\quad\overset{(a)}{=}\int\limits_{t>0}\mathbb{E}_I\left[\exp\left(-\frac{r^{\alpha}}{P_s}I\left(e^{t}-1\right)\right)\right]dt
\end{aligned} \tag{10}$$

where (a) follows from the exponential distribution of $\mathcal{H}$. Employing the Jensen's inequality and (6), we obtain

$$\mathbb{E}_I\left[\exp\left(-\frac{r^{\alpha}}{P_s}I\left(e^{t}-1\right)\right)\right] \geq \exp\left(-\frac{r^{\alpha}}{P_s}\mathcal{M}\left(e^{t}-1\right)\right) \tag{11}$$

Referring to all serving small cells are uniformly distributed with mean μ in the same cluster, the complementary cumulative distribution function (CCDF) of the desired distance to the jth nearest small cell under MCP can be approximated as a PPP with density $\frac{\mu}{\pi D^2}$ [12], which can be given by

$$\mathbb{P}_j = \frac{1-\exp\left(-\frac{\mu}{D^2}r^2\right)\sum\limits_{k=0}^{n-1}\frac{\left(\frac{\mu}{D^2}r^2\right)^k}{k!}}{1-e^{-4\mu}},\quad r<\mathcal{D} \tag{12}$$

where $1-e^{-4\mu}$ is a denominator to guarantee that the integration of the probability density function from 0 to $\mathcal{D}$ is not exceeding 1. Then taking the derivative, we get (8). Substituting (11) into (9) concludes the proof.

C. Area Spectral Efficiency

Area spectral efficiency is defined as the number of transmitted bits per second (bps) per Hz per unit area [8]. The lower bound on the average downlink rate can be applied to acquire a lower bound on the area spectral efficiency of the user-centric small cells clustering mechanism as

$$\tau_{ASE} = \lambda_u\sum_{j=1}^{\mu}\underline{R_j} \tag{13}$$

Notice that in this definition we assume there is no small cell belonging to the same cluster. In other words, a given small cell in the ultra-dense heterogeneous scenario serves at most one user.

D. Energy Efficiency

The clustering mechanism energy efficiency is defined to be as the ratio of throughput for each user from serving small cells and the average power consumption times the number of clustering small cells. Mathematically

$$\xi_{EE} = \frac{\sum_{j=1}^{\mu}\underline{R_j}}{\mu\theta P_0+\eta P_s+P_c} \tag{14}$$

The formula of area spectral efficiency is obviously an increasing function of μ, while the improvement of which comes at the expense of energy dissipation. This fact leads to an inevitable design question, i.e., how to determine the optimal cooperation number of clustering small cells in the ultra-dense heterogeneous networks, which maximizes energy efficiency while ensuring the area spectral efficiency.

Given the density of users, it is obvious that the area spectral efficiency and power consumption of the network are monotonically increasing functions of the cooperation number. However, an energy-efficient network would prefer a lower cluster number. Intuitively, the main job of the rest discussion is to seek out a balance between these two performance indicators by the simulation.

IV. Numerical Simulation and Discussion

In this section, we will validate the accuracy of our analysis through numerical simulation and Monte-Carlo simulation. We realize a MCP in a square with area of 1500×1500 and neglect the impact of noise. The parameters are set as $\eta=4$, $P_s=2W$, $P_0=6.8W$, $P_c=2.9W$ [15], [16], $\lambda_u=10^{-4}users/m^2$, $\lambda=10^{-3}cells/m^2$.

Fig.2 shows the average downlink rate of the typical user as a function of diverse cluster number. It verifies our observation that the rate increases with growing number of serving small cells. This is not hard to understand since more clustering small cells lead to higher useful signal and lower interference. Nevertheless, the reward of increasing cluster number to improve average downlink rate gets to be more and more marginal.

Fig.3 depicts the impact of cluster number on area spectral efficiency. The results of simulation and theoretical derivation are highly consistent, which verify the correctness of theoretical analyses. As with the curve of average downlink rate,

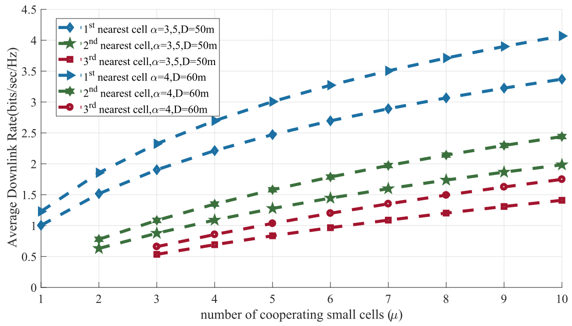

Fig. 2. Average downlink rate with varying cluster number of the connections from the first, second and third nearest cells to the typical user.

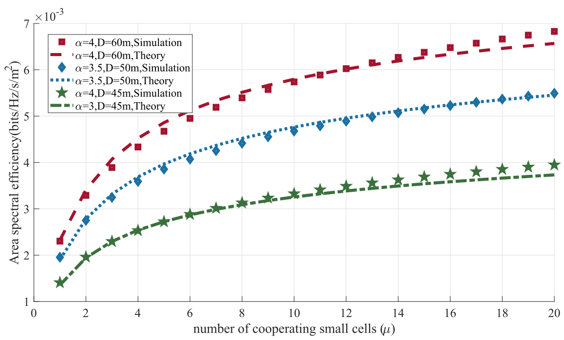

Fig. 3. Area spectral efficiency versus cluster number.

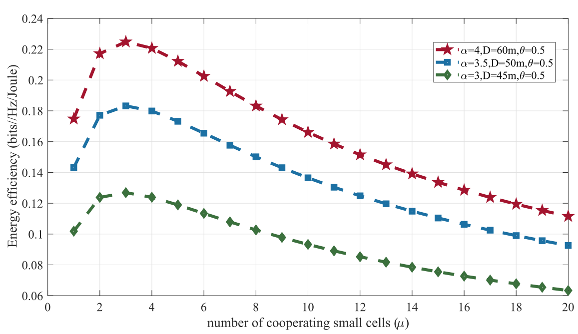

Fig. 4. Energy efficiency versus cluster number.

it monotonically increases with higher serving small cell number while the rises are diminishing. Nevertheless, power consumption is a linear function of cluster number. This means there exists an optimal cluster number which not merely maximizes the energy efficiency but also meet the minimum area spectral efficiency requirement. As indicated by Fig.4, numerical simulation results confirm our speculation. Thus, network deployment should consider the trade-off between these two performance indicators practically. On the condition that higher throughput is the more significant ingredient than power consumption, the choice of cluster number should be concentrated on area spectral efficiency. Under another condition that maximizing energy efficiency is the primary target, the selection of cluster number could focus on minimizing power consumption while throughput can be sacrificed partly.

V. Conclusion

This letter proposes a new mathematical framework to analyze the performance of user-centric small cell clustering mechanism, which models the distribution of small cells with MCP. Based on this framework, we have derived an accurate formula for the average downlink rate and a new distribution function of the desired distance. Furthermore, tractable formulas for the ASE and EE in terms of the cooperation number of small cells are investigated. In the future work, we will consider how to spread our newly framework to multi-tier heterogeneous networks.

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