Cooperative Transmission with Power Control in the Hyper-cellular Network

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Abstract. In response to the challenge of no difference coverage in seamless wide-area coverage scenarios, the 5G hyper-cellular network (HCN) is proposed to ensure user mobility and traffic continuity. In this network, Control Base Station (CBS) is responsible for control coverage, and the traffic base stations (TBSs) take care of high-speed data transmission. Firstly, this paper analyzes the spectral efficiency of different users by dividing the center region and edge region based on Poisson Voronoi Tessellation (PVT) model. For central users, a power control scheme is used to optimize the transmit power of TBSs. For edge users, a cooperative transmission technology and a power control scheme are employed to increase the spectral efficiency. In addition, the TBS sleeping strategy is used to further reduce inter-cell interference. Then, the analytical expressions of the spectral efficiency are derived by using random geometry. The simulation results illustrate that this scheme has a good effect on improving the spectral efficiency of the users with constant mobile velocity.

Keywords: Hyper-cellular network · Random model · Cooperative transmission technology · Power control · Spectral efficiency

1 Introduction

In order to make full use of spectral resources and the ever-increasing capacity demand, a new hyper-cellular network (HCN) architecture is proposed, which has the advantage of being able to cope with the differentiated service requirements of users, flexibly configuring network resources. The core idea is moderately separate the control signaling and service data transmission on the coverage [1]. The control base station (CBS) manages the user's access request and is the global information master of the network; the traffic base station (TBS) is used for high-speed data transmission to the user, which is flexible and efficient. With

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This work was supported by the National S&T Major Project (No. 2018ZX03001011).

J. Zheng et al. (Eds.): ADHOCNETS 2019, LNICST 306, pp. 162–173, 2019.
https://doi.org/10.1007/978-3-030-37262-0_13

the separation architecture, CBS can wake up the corresponding TBS when there is service demand, achieving joint optimization of energy efficiency and resources.

However, as the number of base stations increases, inter-cell interference is a key obstacle to achieve higher spectral efficiency. As a solution to the green cellular network, a cooperative transmission technique is proposed that converts interference into the useful signal by neighbor cell cooperation according to changes in the environment [2]. It ensures less disruption to the user experience, allowing for spectrum reuse in dense areas with interference limited. The power control scheme can better control mutual co-channel interference by optimizing the transmit power between multiple base stations.

Cooperative transmission technology and power control scheme are extensively studied in literature. In [3], a power control algorithm based on the average channel gain matrix is proposed. This algorithm minimizes the transmit power of the base station, while ensuring the signal to interference plus noise ratio (SINR) and increases the system capacity, but this scheme is too singular and does not fully optimize user performance. To increase system capacity and cell edge capacity, [4] proposes a scheme that combines cooperative transmission with quality of service guaranteed and multi-cell coordinated power control, but does not give specific implementation details. [5] is an adaptive modulation scheme that defines three different joint transmission modes based on the number of cooperative base stations, which increases the flexibility of cooperative transmission, but did not consider the power consumption.

Considering the randomness and density of distribution of users and base stations in actual scenarios, random geometry is a novel and useful method to provide instructive results for SINR and the spectral efficiency [6]. Both base stations and users are modeled as a Poisson Point Process (PPP) in [7], comparing the average spectral efficiency of conventional distributed antenna systems (DAS) and user-centric DAS. Further considering cooperative transmission to improve network performance, [8] comprehensively analyzed the average spectral efficiency of uplink transmission and downlink transmission. In addition, [9] obtains the capacity expression under cooperative transmission considering the change of user distribution density. In [10], a partitioning method suitable for the edge user and the central user is proposed in random networks, and analyze the impact of user density on coverage probability by two resource allocation methods. In [11], the edge users are divided based on the method of [10], and a cooperative cluster is formed by Voronoi diagram to improve the throughput of the edge users.

From the research results in the introduction, it can be found that on the one hand, some cooperation schemes are relatively simple, the spectral efficiency improvement is limited or the implementation details of the scheme are not given in the actual topology of the network, on the other hand, performance analysis is not performed for users who are moving at high speed for actual scenarios. Therefore, this paper mainly studies the downlink edge spectral efficiency and average spectral efficiency in HCN. The power control scheme related to the distance is applied to optimize the transmit power of the TBS and improve the received signal quality of the central user. The edge users further eliminate serious interference from neighboring TBSs by cooperative transmission technique to improve edge spectral efficiency. The new expressions for downlink spectral efficiency are obtained by random distribution features. Finally, simulation analysis demonstrates that this scheme can greatly improve the spectral efficiency of users.

The rest of this paper is organized as follows. Section 2 describes the system model of the HCN and establishes the average spectral efficiency expression of the central user and the edge user. Section 3 defines the center user and the edge user, the analytical expressions for edge spectral efficiency and average spectral efficiency are obtained. In Sect. 4, numerical simulation evaluates the edge spectral efficiency and the average spectral efficiency. In the end, this paper is summarized in Sect. 5.

2 System Model

Considering a PVT model in HCN which consists of a CBS and multiple TBSs, the active state and transmit power of TBSs are controlled by CBS, and the whole space is divided by voronoi diagram. The TBS set and the user set are denoted by Φ_{b} and Φ_u, and the corresponding respectively Poisson distribution densities are λ_b and λ_u. In this paper, cooperative transmission technology is only used to enhance the receiving power of the edge users. Furthermore, CBS selects the cooperative TBSs for the edge user according to the distance between TBSs and the edge user (Fig. 1).

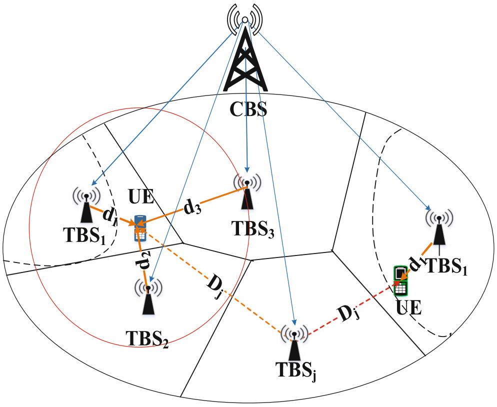

Fig. 1. Downlink cooperative transmission for central users and edge users in HCN, where the red solid line represents the desired signal, the red dotted line is the interference signal, the blue line is the backhaul link, and the black dotted line denotes the boundary line of the center area and the edge area. (Color figure online)

Assuming that a randomly selected edge user is at the origin, there are n cooperative TBSs to provide services, the cooperative TBSs are sequentially sorted according to the distance $(d_1 < d_2 < \cdots < d_n)$, where the distance between the edge user and the i-th cooperative TBS is d_i, and the distance from the j-th interfering TBS is D_j. The channel gain experienced by the users from the serving TBS is assumed to follow Rayleigh distribution with mean 1. In order to optimize the transmission power of the TBSs, which is expressed in a functional form proportional to the distance between the user and the serving TBS i.e., $P = pd^{\rho\alpha}$, where d is distance between service TBS and the user, p is the initial power of each TBS and ρ is the power control factor.

According to the above conditions, the $SINR_c$ of the central user with non-cooperative transmission and the $SINR_e$ of the edge user with cooperative transmission are

$$SINR_c = \frac{P_d}{I_d + N} = \frac{ph_1 d_1^{\rho\alpha} {d_1}^{-\alpha}}{\sum\limits_{j\in\Phi_b, j\neq 1} ph_j d_j^{\rho\alpha} {D_j}^{-\alpha} + \sigma^2} \tag{1}$$

and

$$SINR_e = \frac{P_d}{I_d + N} = \frac{\sum\limits_{i\in B_0} ph_i d_i^{\rho\alpha} {d_i}^{-\alpha}}{\sum\limits_{j\in\Phi_b \backslash B_o} ph_j d_j^{\rho\alpha} {D_j}^{-\alpha} + \sigma^2} \tag{2}$$

where d_1 is the distance between the user and the local service TBS, and h follows the exponential distribution with μ^{-1}. P_d is the total received power of the desired signal, I_d is the received power of the interference signal, and σ^2 is the variance of Gaussian white noise. B_o denotes a circular area with the user as the origin and the distance d_n as a radius. Assuming each TBS transmitting signal is the Gaussian signal, the spectral efficiency of the center user and the edge user are derived from (1) and (2), respectively,

$$SE_c' = E_{\Phi_b,h}\left[In\left(1 + SINR_c\right)\right] \tag{3}$$

$$SE_e' = E_{\Phi_b,h}\left[In\left(1 + SINR_e\right)\right] \tag{4}$$

Next, (3) and (4) are transformed by the Laplace transform to find more exact expressions. Then, we get the integral expression of the spectral efficiency of the edge user and the central user according to the definition of Laplace transform [7]

$$SE_c' = \int_0^\infty \frac{e^{-s\sigma^2/p}}{s} L_{c\_I}(s)\left(1 - L_{c\_S}(s)\right) ds \tag{5}$$

$$SE_e' = \int_0^\infty \frac{e^{-s\sigma^2/p}}{s} L_{e\_I}(s)\left(1 - L_{e\_S}(s)\right) ds \tag{6}$$

3 The Spectral Efficiency

It can be seen from (5) and (6) that only the Laplace transform of the desired signal P_d and the interference signal I_d is required, and the corresponding spectral efficiency expression can be obtained. Further considering the selection probability of the central user and the edge user in the cell and the distance distribution function between the users and the TBSs, the average spectral efficiency expression of the final central user and the edge user can be obtained.

$$SE_c = P_c \int\limits_{d_1 > 0} SE_c' f_c(d_1) dd_1 \tag{7}$$

$$SE_e = P_e \int\limits_{d_1 > 0} \dots \int\limits_{d_n > d_{n-1}} SE_e' f_e(d_1) \dots f_e(d_n) dd_1 \dots dd_n \tag{8}$$

Therefore, this paper is divided into four parts to solve these two expressions.

3.1 Selection Probability of the Central User and the Edge User

Assume that only one user is scheduled in a given time slot. The user selection probability indicates the probability that a randomly selected user is allocated a corresponding resource and served by the TBS. Since the distance between TBSs is random, the fixed distance threshold cannot be used to define edge users and central users. Considering the cell is voronoi structure, the distance d_1 and d_2 between the user and the nearest two TBSs have a specific ratio, and the central user and the edge user can be divided according to the proportional threshold R. If $d_1/d_2 > R$, the user is defined as the edge user, otherwise it is the central user [10]. We can get the joint probability density function (PDF) of the distance between the user and the nearest two TBSs is [12] (Fig. 2)

$$f(d_1, d_2) = (2\pi\lambda_b)^2 d_1 d_2 \exp\left(-\pi\lambda_b d_2^2\right) \tag{9}$$

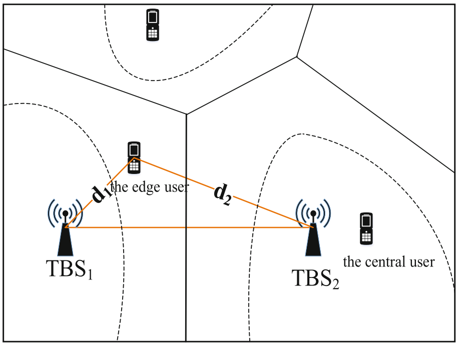

Fig. 2. An example of dividing edge users and central users

The selection probability of the edge user is obtained

$$\begin{aligned} P_e &= 1 - P\left[d_1/d_2 \leq R\right] \\ &= 1 - \int_0^{\infty}\int_0^{d_2 R} f(d_1, d_2) dd_1 dd_2 \\ &= 1 - \mathrm{R}^2 \end{aligned} \tag{10}$$

The selection probability of the central user is $P_c = R^2$.

3.2 Distance Distribution Function Between the User and TBSs

The central user uses the nearest TBS as the service TBS. Thus, the PDF of d_1 can be obtained

$$f_c(d_1) = 2\pi\lambda_b d_1 e^{-\lambda_b \pi d_1^2},\ d_1 > 0 \tag{11}$$

The edge user has n closer TBSs to provide service. Let the distance of the i-th cooperative TBS and the selected edge user be ς_i, no other TBSs can be closer than ς_i, so the cumulative distribution function (CDF) of d_i is [8]

$$\begin{aligned} F_{\varsigma_i}(d_i) &= 1 - P(d_i \leq \varsigma_i) \\ &= 1 - \sum_{t=0}^{i-1} e^{-\pi\lambda_b {d_i}^2} \frac{\left(\pi\lambda_b {d_i}^2\right)^t}{t!} \end{aligned} \tag{12}$$

and the expression of the PDF of d_i can be obtained as

$$f_e(d_i) = 2\pi\lambda_b d_i e^{-\pi\lambda_b {d_i}^2} \frac{\left(\pi\lambda_b {d_i}^2\right)^{i-1}}{(i-1)!},\ i \in [1, ..., n] \tag{13}$$

3.3 Laplace Transform of Desired Signal

We can obtain $P_i \sim E({d_i}^{\alpha(\rho-1)}\mu)$ by $h_i \sim E(\mu)$, then the Laplace transform of the desired signal of the central user is

$$\begin{aligned} L_{c\_S}(s) &= \int_0^{\infty} e^{-sP_i} {d_i}^{\alpha(\rho-1)} \mu e^{-{d_i}^{\alpha(\rho-1)}\mu P_i} dP_i \\ &= \frac{1}{1 + s\mu^{-1}{d_1}^{\alpha(1-\rho)}} \end{aligned} \tag{14}$$

The edge user receives signals from n cooperative TBSs in a maximum ratio combining manner, i.e. $P_d = \sum_{i=1}^{n} h_i {d_i}^{\alpha(\rho-1)}$. The Laplace transform of the desired signal of the edge user can be obtained by Eq. (14) as follows

$$L_{e\_S}(s) = \prod_{i=1}^{n} L_{c\_S}(s) \tag{15}$$

3.4 Laplace Transform of Interference Signal

In a given time slot, there may be no users who need services in the neighboring cells and the TBSs can be controlled to be in a sleep state. Therefore, the sleeping probability that the TBS does not have any user in need of service in its coverage in a time slot. This probability can sparse the λ_b of the interference TBSs. Assuming the number of users in the cell is M, the sparse TBS density λ' can be obtained from the proposition 1 in [9]

$$\begin{aligned} \lambda' &= \lambda_b \left(1 - P\left(M = 0\right)\right) \\ &= \lambda_b \left[1 - \left(1 + 3.5^{-1} \frac{\lambda_u}{\lambda_b}\right)^{-3.5}\right] \end{aligned} \tag{16}$$

Therefore, the Laplace transform of the interference signal is

$$\begin{aligned} L_{e\_I}(s) &= E_{\Phi_b^I,h}\left[\exp\left(-s\sum_{j\in\Phi_b^I} h_j d_j^{\rho\alpha} D_j{}^{-\alpha}\right)\right] \\ &= \mathrm{E}_{\Phi_b^I}\left\{\prod_{j\in\Phi_b\backslash\beta_o} E_h\left[exp(-sh_j d_j^{\rho\alpha} D_j{}^{-\alpha})\right]\right\} \\ &= \exp\left(-\pi^2\lambda'\lambda_b\int_{d_n^2}^{\infty}\int_{0}^{\infty}\frac{e^{-\pi\lambda_b x}}{1+\mu s^{-1}x^{-\rho\alpha/2}y^{\alpha/2}}dxdy\right) \end{aligned} \tag{17}$$

where (17) is derived from the probability generating function of PPP and h following the exponential distribution.

For the central user, laplace transform of the interference signal is

$$L_{c\_I}(s) = \exp\left(-\pi^2\lambda'\lambda_b\int_{d_1^2}^{\infty}\int_{0}^{\infty}\frac{e^{-\pi\lambda_b x}}{1+\mu s^{-1}x^{-\rho\alpha/2}y^{\alpha/2}}dxdy\right) \tag{18}$$

After the above series of calculations, we can respectively obtain the spectral efficiency of the central user and the spectral efficiency of the edge user.

Combining with the selection probability of the central user and the edge user, the average spectral efficiency of the user is

$$SE = (1 - P_e)SE_c + P_e SE_e. \tag{19}$$

4 Simulation Results and Performance Evaluation

To simplify the analysis, consider a microcell coverage scenario in the HCN in a time slot i.e., $\lambda_\mathrm{b} > \lambda_\mathrm{u}$. In this paper, we use the derived edge spectral efficiency (ESE) and average spectral efficiency (ASE) mathematical expressions and numerical simulation methods to discuss user's performance. The setting of the simulation parameters is generally $\lambda_\mathrm{b} = 0.2$, $\lambda_\mathrm{u} = 0.1$, $\alpha = 4$, $\mu = 1$ and

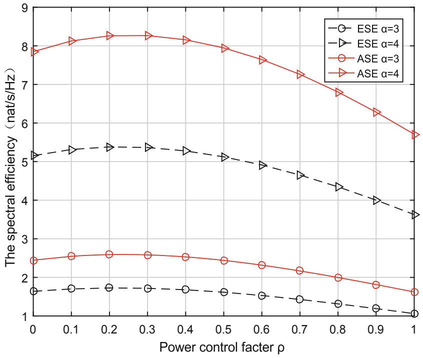

Fig. 3. Downlink edge spectral efficiency and average spectral efficiency as a function of ρ.

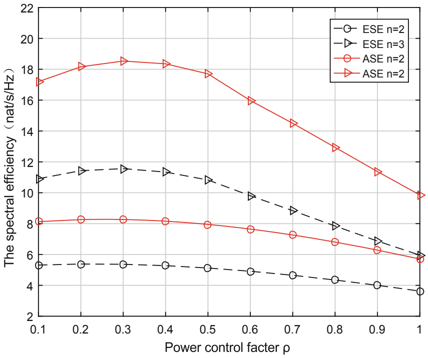

Fig. 4. Downlink edge spectral efficiency and average spectral efficiency as a function of n.

$\sigma^2 = \sqrt{2}$. The central user and the edge user partition threshold R of the edge user is set to 2/3 [12].

Figure 3 shows the effect of the power control factor on spectral efficiency. First, as the ρ increases, the edge spectral efficiency and the average spectral efficiency both increase first and then decrease. Therefore, the transmit power of the TBS has an optimal value $\rho = 0.2$ and is obtained at $\lambda_b = 0.2$. The reason for the increase is transmission power of the TBSs increases as the ρ increases, leading to increased spectral efficiency, but the transmission power of interference TBSs also increases sharply and causes the SINR to decrease drastically, and the spectral efficiency shows the descending trend.

Comparing the two curves with different α, the spectral efficiency shows an upward trend. That is because the interference TBSs are farther away from the user and the interference power is attenuated faster so that the spectral efficiency shows an overall upward trend. As shown in Fig. 4, as the number n

of cooperative TBSs increases, inter-cell interference further decreases, and the edge spectral efficiency and the average spectral efficiency are improved.

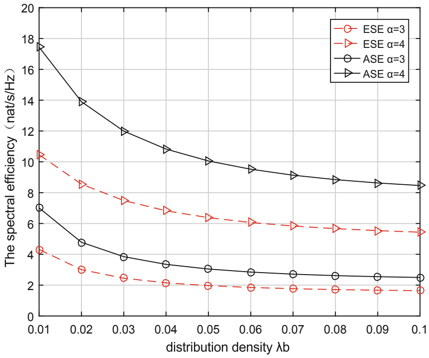

Fig. 5. Downlink edge spectral efficiency and average spectral efficiency as a function of λ_b.

In Fig. 5, we can find that the distance between the user and the TBSs decreases and interference increase as λ_b increase, which causes the spectral efficiency to decline. In the later stage, because received power of the desired signal and interference signal simultaneously increase, the spectral efficiency eventually shows a steady decline.

Since the user may bring about frequent handover during the mobile process, resulting in the transmission delay. Therefore, this paper evaluates the spectral efficiency of mobile users by describing the switching cost due to users moving at high speed. The handover cost is defined according to the normalized handover delay and it is given [13]

$$D = \min\left(H_t \times T, 1\right) \tag{20}$$

where H_t is the handover rate per unit time and T is the delay time in each handover. For the general trajectory and moving model, the handover rate of the homogeneous network based on the PPP is verified as $H_t = 4v\sqrt{\lambda_b}/\pi$ [13], where v is the mobile velocity. Then, by quantifying the effect of the handover cost on the spectral efficiency, it is expressed as

$$SE_i = SE_i \times (1 - D), i = \{c, e\} \tag{21}$$

Figures 6 and 7 are the comparison of the spectral efficiency of the three schemes when velocity is 120 km/h and T = 1 ms. The first scheme only considers power control. The second traditional cooperative transmission scheme, all cooperative TBSs are transmitted with the initial power, and the third is the proposed scheme. Comparing the three curves, it can be clearly seen that when $\lambda_b < 0.2$, the second scheme is better than the other two schemes. This is

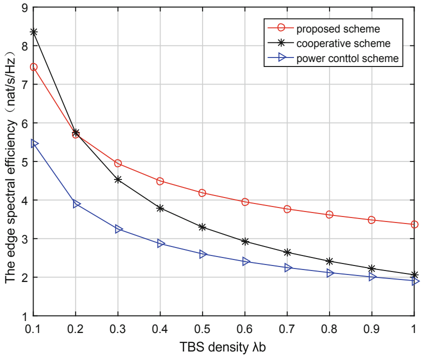

Fig. 6. Comparison of the edge spectral efficiency under three schemes.

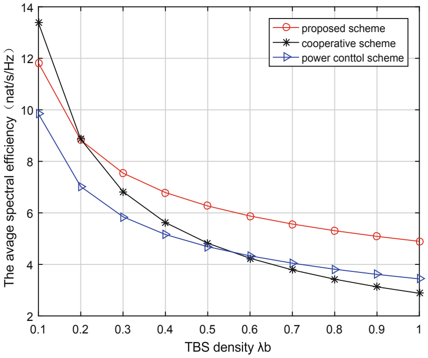

Fig. 7. Comparison of the average spectral efficiency under three schemes.

because when λ_b is small, the transmission power of the TBS is larger, and the quality of the received signal of the user is better. Thus, the spectral efficiency is also increased. However, when $\lambda_b \geq 0.2$, as the density of TBSs increases, the inter-cell interference is larger as transmission power increases. The power control scheme can be used to select the optimal transmission power to reduce the interference and the cooperative transmission can increase receiving quality of the signal, improving the spectral efficiency of the user, so the proposed scheme is best.

In Fig. 7, it can be observed from the simulation of average spectral efficiency that the second scheme is better than the second scheme when $\lambda_b < 0.6$, indicating that the cooperative scheme has a significant effect on improving the edge spectral efficiency and the average spectral efficiency, However, when the λ_b continues to increase, more users are concentrated in the central area of the cell. At this time, the power control scheme is more conducive to the improvement of the average spectral efficiency than the cooperative transmission scheme.

It can be calculated that the edge spectral efficiency of the third scheme is increased by 60% compared with the first scheme, and the average spectral efficiency is improved by 34%. The third scheme has an improvement of 29% in the edge spectral efficiency and an improvement of 32% in average spectral efficiency compared to the second scheme.

5 Conclusion

Aiming at the serious inter-cell interference problem in seamless wide-area coverage scenarios, this paper proposes a joint power control and cooperative transmission technology based on the PVT model under HCN. For the cell center user, the power control scheme and the sleeping scheme are applied to reduce the interference from the neighboring TBSs. For the cell edge user, we joint cooperative transmission and power control to reduce serious inter-cell interference. Then, the analytical expression of the spectral efficiency of the edge user and the average spectral efficiency are derived by the random geometry. The simulation results demonstrate that this scheme can significantly improve edge spectral efficiency and average spectral efficiency compared to other schemes. It is suitable for high mobility and seamless connectivity in the seamless wide-area coverage scenario, providing users with comprehensive coverage of high-speed service experience.

References

1. Niu, Z., Gong, J., Zhou, S.: Research on hyper cellular mobile communication system based on energy efficiency and resource optimization. Telecommun. Sci. **30**(12), 34–47 (2014)
2. Maxwell, C.: A Treatise on Electricity and Magnetism, 3rd edn. Clarendon, Oxford (1892)
3. Jacobs, S., Bean, P.: Fine particles, thin films and exchange anisotropy. Magnetism **3**, 271–350 (1963)
4. Hoshino, K., Fujii, T.: Multi-cell coordinated power control with adjacent cell cooperative transmission considering actual environment. In: 2011 IEEE 73rd Vehicular Technology Conference (VTC Spring), pp. 1–5. Yokohama (2011)
5. Cui, Q., Song, H., Wang, H., Valkama, M., Dowhuszko, A.: Capacity analysis of joint transmission CoMP with adaptive modulation. IEEE Trans. Veh. Technol. **66**(2), 1876–1881 (2016)
6. ElSawy, H., Hossain, E., Haenggi, M.: Stochastic geometry for modeling, analysis, and design of multi-tier and cognitive cellular wireless networks: a survey. IEEE Commun. Surv. Tutorials **15**, 996–1019 (2013)
7. Lin, Y., Yu, W.: Downlink spectral efficiency of distributed antenna systems under a stochastic model. IEEE Trans. Wirel. Commun. **13**(12), 6891–6902 (2014)
8. Cai, J.: Application of random geometry theory in cellular networks. Nanjing University of Posts and Telecommunications, Doctor (2016)
9. Yu, M., Kim, L.: Downlink capacity and base station density in cellular networks. In: 2013 11th International Symposium and Workshops on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt), Tsukuba Science City, pp. 119–124 (2013)

10. Mankar, D., Das, G., Pathak, S.: Load-aware performance analysis of cell center/edge users in random HetNets. IEEE Trans. Veh. Technol. **67**(3), 119–124 (2018)
11. Park, J., Lee, N., Heath, W.: Cooperative base station coloring for pair-wise multicell coordination. IEEE Trans. Commun. **64**(1), 402–415 (2016)
12. Moltchanov, D.: Distance distributions in random networks. Ad Hoc Netw. **10**(6), 1146–1166 (2012)
13. Arshad, R., Elsawy, H., Sorour, S., et al.: Handover management in 5G and beyond: a topol-ogy aware skipping approach. IEEE Access **4**, 9073–9081 (2016)