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Research Article

Performance Analysis of Group Selection in UAV Networks with Backhaul-Aware Biasing

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The limited wireless backhaul capacity has become the major bottleneck for UAV communications, while in existing researches of UAV networks, the relation between cell selection and backhaul capacity has not been modeled. This paper proposes cell group selection with backhaul-aware biasing for UAV networks and analyzes system performance by deriving the rate outage probability via stochastic geometry, where the user's maximum data rate is constrained by backhaul capacity. Specifically, cell group selection is no longer distance-based and considered with backhaul capacity bias factor, where UAVs with higher backhaul capacity will have a larger bias factor to match the backhaul variance. In addition, the dynamic UAV group is organized with the N largest bias reference signal receiving power (BRSRP), where users can utilize the diversity gain by adjusting serving UAV dynamically as the channel conditions change. Analytical results show that the outage probability is decreased by 58% when cell group size $N = 3$ and UAV optimal density $\lambda_u = 600/\text{km}^2$ when UAV height $h = 150$ m.

1. Introduction

Radio equipment mounted on an unmanned aerial vehicle (UAV) can provide mobile wireless connectivity "from the sky" [1], which introduces paradigm innovation for traditional terrestrial network architecture. Owing to UAVs' prominent attributes including controlled mobility, flexible deployment [2], and dominant line-of-sight (LOS) connections, UAV networks hold significant potential to enhance network coverage, capacity, reliability, and energy efficiency [3] and provide on-demand wireless services. However, unlike terrestrial infrastructure which can be connected via wired backhaul links, UAVs can only depend on wireless backhaul connecting to the core networks, which become the major bottleneck that affects network performance [4]. In addition, owing to UAVs' severe cochannel interference and rate fluctuation caused by dominant LOS connections, how to guarantee the consistency of user service should be further considered.

Despite the fact that the variance of backhaul capacity greatly influences UAV network performance, most of the existing research on performance analysis takes the ideal backhaul assumption for granted. In [5, 6], the max reference signal receiving power (RSRP) rule is used for cell association, regardless of UAV backhaul capacity. Considering building obstacles, in [7], the 3D blockage effect is modeled in cell association, where the user equipment (UE) is connecting to the nearest visible UAV. To model the priority association (including the backhaul factor) in cell selection, [8] adopts the biased association in multitier UAV networks, where UAVs in the same tier have the same bias factor, while in a realistic scenario, the bias factor should vary with the backhaul capacities. Our previous job [9] characterized the relation of backhaul capacity and association bias in cellular networks, while how to model the impact of backhaul variance in UAV networks remains an open challenge.

There exist some studies focusing on joint optimization of system parameters such as UAV deployment positions, power allocation, and cache contents with the consideration of backhaul capacity constraints. Considering the congestion issue in backhaul, [10] develops a novel framework to jointly optimize the 3D placement of UAVs and the association of users with BSs for different QoS requirements. In [11], UAVs are connected to the core network through multihope wireless backhaul, and the joint optimization problem is formulated with power/bandwidth allocation and UAV placement locations for maximum throughput. [12] considers the integrated access and backhaul (IAB) architecture in UAV-assisted networks and proposes an interference management algorithm for sum rate maximization, while the impact of backhaul capacity of UAVs has not been modeled and theoretically analyzed in [10–12].

In addition to limited backhaul capacity, users' rate fluctuation is another important issue in UAV communication, due to UAVs' agility and LOS/NLOS channel variation. Therefore, single UAV cannot guarantee the service consistency, and multicell cooperation among UAVs [13] is of great importance for performance enhancement. Cell cooperation among UAVs, which organize a dynamical UAV group to provide service for each UE, can mine the potential of diversity gains, where the user can always connect to the UAV with the best channel conditions at any moment. In [14], user-centric network architecture is proposed for seamless service in UAV networks, and interference management is performed via a power control strategy. Nevertheless, [14] only considers distance-dependent UAV group selection, and how to accomplish the goal of flexible association with backhaul capacity constraints is still unsolved.

Taking all these challenges into account, this paper proposes cell group selection with backhaul-aware biasing for UAV networks, where UAVs with higher backhaul capacity will have a larger bias factor. The dynamic UAV group is organized with the N largest bias reference signal receiving power (BRSRP), where users can utilize the diversity gain by adjusting serving UAV dynamically as the channel conditions change. Using stochastic geometry, system performance is analyzed by deriving the rate outage probability.

2. System Model

2.1. Backhaul-Aware Cell Group Selection. The UAV selects a ground base station (BS) to establish a backhaul link for transmission. The ground BS acts as the medium between the UAV and the core network and transmits the content requested by UE to the UAV through the backhaul link. The UE selects a UAV to establish an access link, and the UAV will transmit the content received from the backhaul link to the UE through the access link. The access link and the backhaul link utilize orthogonal transmission resources. In addition, we ignore the thermal noise power because that it is negligible compared to the interference power.

The UAV selects the nearest BS as the best service BS and establishes a backhaul link with it. In this way, the selected station can obtain the strongest signal and ensure the maximum capacity of its backhaul link.

The common principle for UEs to select serving base stations (UAVs in this paper) is mostly based on RSRP received by UEs, and BSs with large reference signals are selected to ensure the best signal quality. However, in the superdense network, each small base station can allocate very limited backhaul capacity resources. When the number of UEs served by small base stations is too large, it will be difficult to allocate enough backhaul resources to newly connected UEs. At this time, not only will the main factor limiting the UE's actual rate be the signal quality but also the influence of the backhaul capacity should be taken into account. The small base station with poor signal but abundant backhaul resources may obtain better service quality, so that the backhaul resources of the whole network can be more fully and reasonably utilized. Therefore, this paper adopts a BRSRP-based strategy to select stations. The BRSRP is defined as

$$P_i = P_T B_i \left(r_i^2 + h^2\right)^{(-\alpha/2)}, \tag{1}$$

where P_i represents the BRSRP of the UAV with label i, P_T represents the signal transmitting power of the UAV, r_i represents the horizontal distance between the UAV and the UE, h represents the height of the UAV, and α is the path loss exponent. The impact factor B_i is added here to represent the backhaul capacity value of the UAV, and its detailed expression will be derived in the transmission rate part of the backhaul capacity.

Based on the BRSRP, the UE selects N UAVs with the largest BRSRP to form a UAV cluster serving this UE. For the designated user terminal, the BRSRP of each UAV received is sorted from the largest to the smallest. Based on the principle of $P_i > P_j$ and then $j > i$, the UAV cluster can be expressed as

$$\Phi = \left\{\mathrm{UAV}_i, i \in \{1, 2, 3, \cdots, N\}\right\}. \tag{2}$$

2.2. The Network Model. In the network of cooperative transmission between UAVs and BSs, a two-dimensional Poisson point process (PPP) is adopted in this paper. UAVs are distributed as PPP Ψ_u with density λ_u on an infinite two-dimensional plane located at height h. UEs are distributed as another PPP Ψ_c with density λ_c on an infinite two-dimensional plane on the ground. BSs are distributed as PPP Ψ_b with density λ_b on the same infinite two-dimensional plane on the ground. The three PPPs are independent of each other.

In traditional ground cellular wireless communication systems, a backhaul link is usually established between the macrobase stations and the small base stations, both of which are considered to be on the horizontal ground. That means that they are at the same level as the UE. In this scenario, due to the large loss caused by more building shielding, the small-scale fading is usually modeled by the Rayleigh fading channel. However, some researches show that the Nakagami-m distribution obtained by the experimental method of the field test has better adaptability to the description of the wireless channel. Therefore, in this paper, it is more appropriate to adopt Nakagami-m fading channel under the scenario of collaborative transmission among UAVs and BSs and UEs.

3. Outage Probability

This is the main analysis part of this paper, which deduces the rate outage probability of a user-centered UAV cluster network with backhaul capacity awareness. The rate outrage probability of UAVs is defined as the probability that the actual transmission rate T provided to the UE by all UAV in the cluster is less than threshold γ. In this case, the outage probability can be expressed as

$$\mathbb{P}_{o,N} = \mathbb{P}\left[\max_{i\in\{1,2,\cdots,N\}} T_i < \gamma\right] = \prod_{i=1}^{n} \mathbb{P}[T_i < \gamma], \tag{3}$$

where T_i is the actual transmission rate provided by UAV i in the cluster for UEs.

3.1. SIR and Transmission Rate. In this model, interference signals mainly come from signals sent by other BSs and UAVs, so the influence brought by other noises could be ignored in this paper. In the case of ignoring noise, the reception sensitivity of backhaul link and access link is mainly determined by the signal to interference radio (SIR). Therefore, SIR of the backhaul link can be expressed as

$$\mathrm{SIR}_b = \frac{g_n \omega_n^{-\alpha}}{\sum_{i\in\Psi_b\setminus\{\mathrm{BS}_n\}} g_i \omega_i^{-\alpha}}, \tag{4}$$

where n represents the BS that is carrying out the backhaul transmission for the UAV, ω represents the distance between the BS and the UAV, $\omega_n^{-\alpha}$ represents the impact of large-scale fading, and g represents the impact of small-scale fading. Since the transmission from BS to UAV and the transmission from UAV to UE both belong to the transmission between the high altitude and the low altitude, the more universal Nakagami-m fading is adopted in the small-scale fading in this scenario.

Similarly, the SIR of access link can be expressed as

$$\mathrm{SIR}_b = \frac{g_n \omega_n^{-\alpha}}{\sum_{i\in\Psi_u\setminus\{\mathrm{UAV}_n\}} g_i \omega_i^{-\alpha}}. \tag{5}$$

The transmission rate (capacity) of the access link and the backhaul link is defined as

$$R = \log_2(1 + \mathrm{SIR}_a), \tag{6}$$

$$B = \log_2(1 + \mathrm{SIR}_b). \tag{7}$$

In the process of transmission, the core network receives and sends the UE's request data to UAV by the backhaul link, and then, the data is sent by the UAV through the access link to the UE. Therefore, in this process, the actual transmission rate possessed by users is affected by both the capacity of the access link and the capacity of the backhaul link. This actual transmission rate is defined in this paper as the smaller value of the two, i.e.,

$$T = \min\,(R, B). \tag{8}$$

In order to determine the backhaul link capacity, we first analyze the SIR of the backhaul link.

Since the backhaul link capacity of each UAV is independent of each other, we can analyze a specific UAV, which establishes a backhaul link with the nearest BS on the ground. At this time, the signals sent by other BSs on the ground are regarded as interference. The relative spatial position of the UAV and the nearest BS can be simplified as follows:

r is the horizontal distance between the UAV and the nearest BS, so the BS distribution should satisfy a condition that there are no other BSs in the circular area with radius r as the center of the UAV's projection on the horizontal ground. In other words, it has to satisfy (9) in the case of a two-dimensional PPP.

$$\mathbb{P}[r > R] = \mathbb{P}[\text{No BS closer than } R] = e^{-\lambda_b \pi R^2}. \tag{9}$$

The probability distribution function of r is expressed as

$$\mathbb{P}[r \le R] = F_r(R) = 1 - e^{-\lambda_b \pi R^2}. \tag{10}$$

ω is the distance between UAV and the nearest BS, so we can get that $\omega^2 = h^2 + r^2$. It can be further obtained that the probability density function (PDF) of r and ω can be, respectively, expressed as

$$f_r(r) = \frac{dF_r(r)}{dr} = 2\pi\lambda_b r e^{-\lambda_b \pi r^2}, \tag{11}$$

$$f_\omega(\omega) = 2\pi\lambda_b \omega e^{-\lambda_b \pi\left(\omega^2 - h^2\right)}. \tag{12}$$

Given the PDF of ω, it can be further expressed that the distribution of SIR of the backhaul link is

$$\begin{aligned}\mathbb{P}_c[\mathrm{SIR}_b > \beta] &= \mathbb{E}_\omega[[\mathrm{SIR}_b > \beta \mid \omega]] \\ &= \int_h^\infty \mathbb{P}[\mathrm{SIR}_b > \beta \mid \omega] 2\pi\lambda_b \omega e^{-\lambda_b \pi\left(\omega^2 - h^2\right)} d\omega.\end{aligned} \tag{13}$$

According to (12) and the channel characteristics of Nakagami-m fading, we can further derive the conditional probability distribution expression of the backhaul link SIR as follows:

$$\begin{aligned}\mathbb{P}_c[\mathrm{SIR}_b > \beta] &= \mathbb{E}_I[\mathbb{P}[g_n > \beta\omega^\alpha I \mid \omega, I]] \\ &\overset{(a)}{=} \mathbb{E}_I\left[\frac{\Gamma(m, m\beta\omega^\alpha I)}{\Gamma(m)} \mid \omega, I\right] \\ &\overset{(b)}{=} \mathbb{E}_I\left[\sum_{k=0}^{m-1} \frac{(m\beta\omega^\alpha)^k}{k!} e^{-m\beta\omega^\alpha I} \mid \omega, I\right] \\ &= \sum_{k=0}^{m-1} \frac{(-m\beta\omega^\alpha)^k}{k!}\left[\frac{\partial^k}{\partial s^k} L_I(s \mid \omega)\right],\end{aligned} \tag{14}$$

where (a) is derived from the complementary probability distribution function of random variable g_n in the Nakagami-m fading channel, (b) comes from the integer value for m gamma function definitions, and $L_I(s \mid \omega)$ is the Laplace transform of interference signal intensity I. Here is the derivation of the Laplace transform of I.

$$\begin{aligned}
L_I(s \mid \omega) &= \mathbb{E}_I\left[e^{-sI} \mid \omega, I\right] = \mathbb{E}_{\Psi_b,\{g_i\}}\left[\exp\left(-s\sum_{i\in\Psi_b\{n\}} g_i \omega_i^{-\alpha}\right) \mid \omega, I\right] \\
&= \mathbb{E}_{\Psi_b,\{g_i\}}\left[\prod_{i\in\Psi_b\{n\}} \exp\left(-s g_i \omega_i^{-\alpha}\right) \mid \omega, I\right] \\
&\overset{(a)}{=} \mathbb{E}_{\Psi_b}\left[\prod_{i\in\Psi_b\{n\}} \mathbb{E}_g\left[\exp\left(-s g \omega_i^{-\alpha}\right)\right] \mid \omega, I\right] \\
&\overset{(b)}{=} \exp\left(-2\pi\lambda_b \int_r^\infty \left(1 - \mathrm{E}_g\left[\exp\left(-sg \times \left(h^2 + v^2\right)^{-\alpha/2}\right)\right]\right) v dv\right)_{v=\sqrt{\omega^2 - h^2}} \\
&\overset{(c)}{=} \exp\left(-2\pi\lambda \int_r^\infty \left(1 - \left(1 + \frac{s\left(h^2+v^2\right)^{-\alpha/2}}{m}\right)^{-m}\right) v dv\right),
\end{aligned} \tag{15}$$

where (a) is obtained based on the independent and identical distribution of the small-scale fading g_i of each UAV and g_i is independent of the BSs' Poisson point process Ψ_b. (b) obeys the probability generation functional (PFGL) of the PPP; that is, for the function $f(x)$, we have $\mathbb{E}[\prod_{x\in\Psi} f(x)] = \exp\left(-\lambda \int_{\mathbb{R}^2} (1 - f(x)) dx\right)$; since the interference signal comes from the BSs outside the circular region of radius R, the bounds of integration here are from R^2 to infinity. (c) is obtained according to the Laplace transform of small-scale fading g of the Nakagami-m fading channel $L_g(s) = (m/(m+s))^m$.

To sum up, the SIR probability distribution of the backhaul link in the UAV scenario is expressed as (24).

By analyzing the SIR probability distribution of the backhaul link, it is not difficult to find that the final expression is not a closed expression, and this form is not conducive to the final quantitative analysis. Therefore, we first carry out the appropriate simplification and approximation to the formula, so as to facilitate the further derivation and analysis. Taking path loss exponent $\alpha = 4$ and parameter $m = 1$, we can get the simplified SIR probability distribution expression of the backhaul link:

$$\mathbb{P}(\mathrm{SIR}_b > \beta) = \frac{\exp\left(-\pi\lambda_b h^2 \sqrt{\beta}\left((\pi/2) - \arctan\left(1/\sqrt{\beta}\right)\right)\right)}{1 + \sqrt{\beta}\left((\pi/2) - \arctan\left(1/\sqrt{\beta}\right)\right)}. \tag{16}$$

Correspondingly, the backhaul link rate (capacity) distribution can be expressed as

$$\mathbb{P}(B > x) = \xi(x) = \frac{\exp\left(-\pi\lambda_b h^2 \sqrt{2^x - 1}\left((\pi/2) - \arctan\left(1/\sqrt{2^x - 1}\right)\right)\right)}{1 + \sqrt{2^x - 1}\left((\pi/2) - \arctan\left(1/\sqrt{2^x - 1}\right)\right)}, \tag{17}$$

where x is the threshold of the backhaul link transmission rate.

3.2. UAV Group Selection. In the traditional BS selection criteria based on RSRP or distance, the probability density function of the distance between the serving BS and the UE can be obtained directly from the nature of the PPP. However, under the BRSRP selection criteria in this paper, the distribution of the UAV selected by the user in the air will be different from the BS distribution in the backhaul link; that is, we cannot directly obtain the PDF of the distance between the UAV and the UE within the cluster only through the properties of the PPP.

In this part, according to the characteristics of BRSRP station selection criteria, we analyze the characteristics of the distance between the UAV and the UE in the cluster and the requirements that the distance should meet. Finally, we derive the PDF of the distance between the UAV and the UE by using random geometry tools. So we get the SIR probability distribution expression of the access link in the derivation of the transmission terminal rate. Since the UAV cluster is in a plane with a fixed height, we only need to consider the horizontal distance between the UAV and the UE. Let $\{r_i\}(i = 1, 2, 3 \cdots)$ represent the horizontal distance set of UAV and the specific UE based on BRSRP sorting. In this section, we first consider the distribution of serving UAV in the case of group size $N = 1$, that is, the PDF of r_1. Then, based on this result, we will extend it to the case of group size $N \geq 2$ and obtain the expression that is applicable to any value of group size.

First, we discuss the case where the group size $N = 1$. Since the PDF of r_1 is difficult to be derived directly, the problem is divided into the following steps according to the characteristics of r_1: (1) derivate the probability expression that the BRSRP of all UAVs in the circle with radius r_1 is less than that of UAV_1; (2) derivate the probability expression that the BRSRP of all the UAVs outside the circle with radius $(r_1 + dr_1)$ is smaller than that of UAV_1; and (3) multiply the results obtained in the first two steps; then, the probability that BRSRP is less than the BRSRP of UAV_1 except for the $O(r_1, r_1 + dr_1)$ region in the plane is obtained, that is, the probability that UAV_1 is located in the $O(r_1, r_1 + dr_1)$ region, and the expression of the latter is obtained by the proportional relation between the result and the PDF of r_1.

According to the ideas above, in the circular region with specific ground user projection as the center of the circle and r_1 as the radius, we first deduce the probability that the BRSRP of all UAVs is less than the BRSRP of UAV_1 (P_1):

$$\begin{aligned}
&\mathbb{P}\left[B_k\left(r_k^2 + h^2\right)^{-\alpha/2} < B_1\left(r_1^2 + h^2\right)^{-\alpha/2}, \forall \mathrm{UAV}_k \text{ in } \mathbb{C}(r_1)\right] \\
&\quad = \sum_{K=0}^{\infty} \frac{\left(\pi\lambda_u r_1^2\right)^K e^{-\pi\lambda_u r_1^2}}{K!} \cdot \mathbb{E}_{r_{\tilde{1}}, r_{\tilde{2}}, \cdots, r_{\tilde{K}}, B_1}\left[\mathbb{P}\left[\max_{k\in\{\tilde{1},\tilde{2},\cdots,\tilde{K}\}} P_k < P_1\right]\right].
\end{aligned} \tag{18}$$

The probability that the BRSRP of any UAV in this circular region is less than P_1 is

$$\begin{aligned}\mathbb{E}_{r_k,B_1}[\mathbb{P}[P_k<P_1]]&=1-\mathbb{E}_{B_1}\left[\int_0^{r_1}\xi\left(B_1\left(\frac{r_k^2+h^2}{r_1^2+h^2}\right)^{\alpha/2}\right)f_{r_k}(r_k)dr_k\right]\\&=1-\int_0^{\infty}f_{B_1}(B_1)\int_0^{r_1}\frac{2r_k}{r_1^2}\xi\left(B_1\left(\frac{r_k^2+h^2}{r_1^2+h^2}\right)^{\alpha/2}\right)dr_kdB_1\\&=1-\frac{2(r_1^2+h^2)}{\alpha r_1^2}\int_0^{\infty}\frac{f_{B_1}(B_1)}{B_1^{2/\alpha}}\int_{B_1\left(h^2/\left(r_1^2+h^2\right)\right)^{\alpha/2}}^{B_1}\xi(r)r^{(2/\alpha)-1}drdB_1\\&=1-\theta_1,\end{aligned}\tag{19}$$

where $\xi(x)$ is the complementary probability distribution function of the capacity of the backhaul link deduced in (17). It should also be noted that according to the characteristics of the Poisson point process in a given region, the PDF of r_k is $f_{r_k}(r_k)=2r_k/r_1^2$.

According to $\xi(x)$, the PDF of the capacity of the backhaul link is

$$f_{B_1}(B_1)=\frac{d(1-\xi(B_1))}{dB_1}.\tag{20}$$

Because each UAV's backhaul link capacity is independent of each other, so

$$\mathbb{E}_{r_1,r_2,\cdots,r_K,B_1}\left[\mathbb{P}\left[\max_{k\in\{1,2,\cdots,K\}}P_k<P_1\right]\right]=\left\{\mathbb{E}_{r_k,B_1}[\mathbb{P}[P_k<P_1]]\right\}^K.\tag{21}$$

Thus, (18) can be further simplified as

$$\begin{aligned}&\mathbb{P}\left[B_k\left(r_k^2+h^2\right)^{-\alpha/2}<B_1\left(r_1^2+h^2\right)^{-\alpha/2},\forall\text{UAV }k\text{ in }\mathbb{C}(r_1)\right]\\&\quad=\exp\left(\pi\lambda_u r_1^2(1-\theta_1)\right)\exp\left(-\pi\lambda_u r_1^2\right)=\exp\left(-\pi\lambda_u r_1^2\theta_1\right).\end{aligned}\tag{22}$$

To find the expression for the probability that BRSRP in the UAV plane region $R^2/\mathbb{C}(r_1+dr_1)$ is less than P_1, we first define

$$\begin{aligned}e_1&=\inf_{k\in\mathbb{R}^2/\mathbb{C}(r_1+dr_1)}\mathrm{I}(B_1{r_1}^{-\alpha}-B_k{r_k}^{-\alpha}>0)\\&=1-\sup_{k\in\left(\mathbb{R}^2/\mathbb{C}(r_1+dr_1)\right)}\mathrm{I}(B_1{r_1}^{-\alpha}-B_k{r_k}^{-\alpha}\le 0),\end{aligned}\tag{23}$$

where $I(\cdot)$ represents the indicator function. At this point, the probability that BRSRP of UAV in the plane region $R^2/\mathbb{C}(r_1+dr_1)$ is less than P_1 can be expressed as (25).

$$\begin{aligned}\mathbb{P}[\mathrm{SIR}_b>\beta]&=\int_h^{\infty}2\pi\lambda_b\omega e^{-\lambda_b\pi\left(\omega^2-h^2\right)}\sum_{k=0}^{m-1}\frac{(-m\beta\omega^{\alpha})^k}{k!}\\&\quad\cdot\left[\frac{\partial^k}{\partial s^k}\exp\left(-2\pi\lambda\int_r^{\infty}\left(1-\left(1+\frac{s\left(h^2+v^2\right)^{-\alpha/2}}{m}\right)^{-m}\right)vdv\right)\right]_{s=m\beta\omega^{\alpha}}d\omega,\end{aligned}\tag{24}$$

$$\begin{aligned}&\mathbb{P}\left[B_k\left(r_k^2+h^2\right)^{-\alpha/2}<B_1\left(r_1^2+h^2\right)^{-\alpha/2},\forall\text{UAV}_k\text{ in }\frac{\mathbb{R}^2}{\mathbb{C}(r_1+dr_1)}\right]=\mathbb{P}[e_1=1]\\&\quad=\mathbb{P}\left[\left\{\sup_{k\in\left(\mathbb{R}^2/C(r_1+dr_1)\right)}\mathrm{I}\left(B_1\left(r_1^2+h^2\right)^{-\alpha/2}-B_k\left(r_k^2+h^2\right)^{-\alpha/2}\le 0\right)\right\}\le 0\right]\\&\quad=\exp\left(-2\pi\lambda_u\int_{r_1}^{\infty}\mathrm{I}\left(\mathrm{I}\left(B_1\left(r_1^2+h^2\right)^{-\alpha/2}-B_k\left(r_k^2+h^2\right)^{-\alpha/2}\le 0\right)>0\right)dr_k\right)\\&\quad=\exp\left(-2\pi\lambda_u\int_{r_1}^{\infty}\mathbb{P}\left[B_1\left(r_1^2+h^2\right)^{-\alpha/2}-B_k\left(r_k^2+h^2\right)^{-\alpha/2}\le 0\right]dr_k\right)\\&\quad=\exp\left[-\pi\lambda_u r_1^2\int_0^{\infty}f_{B_1}(B_1)\int_{r_1}^{\infty}\frac{2r_k}{r_1^2}\xi\left(B_1\left(\frac{r_k^2+h^2}{r_1^2+h^2}\right)^{\alpha/2}\right)dr_kdB_1\right]\\&\quad=\exp\left(-\pi\lambda_u r_1^2\theta_2\right),\end{aligned}\tag{25}$$

$$\begin{aligned}A_1(r_1)&=\mathbb{P}\left[B_k\left(r_k^2+h^2\right)^{-\alpha/2}<B_1\left(r_1^2+h^2\right)^{-\alpha/2},\forall\text{SBS}_k\text{ in }\frac{\mathbb{R}^2}{\mathrm{O}(r_1,r_1+dr_1)}\right]\\&=\mathbb{P}\left[B_k\left(r_k^2+h^2\right)^{-\alpha/2}<B_1\left(r_1^2+h^2\right)^{-\alpha/2},\forall\text{UAV}_k\text{ in }\frac{\mathbb{R}^2}{\mathbb{C}(r_1+dr_1)}\right]\cdot\mathbb{P}\\&\quad\cdot\left[B_k\left(r_k^2+h^2\right)^{-\alpha/2}<B_1\left(r_1^2+h^2\right)^{-\alpha/2},\forall\text{UAV}_k\text{ in }(r_1)\right]\\&=\exp\left(-\pi\lambda_u r_1^2(\theta_2+\theta_1)\right),\end{aligned}\tag{26}$$

$$\begin{aligned}A_i(r_i)&=\mathbb{P}\left[(i-1)\text{ UAV in }\frac{\mathbb{R}^2}{O(r_i,r_i+dr_i)}\text{ with the BRSRP larger than }P_i\right]\\&=\sum_{N_1=0}^{i-1}\exp\left(-\pi\lambda_u r_i^2\theta_1\right)\frac{\left(\pi\lambda_u r_i^2\theta_1\right)^{N_1}}{N_1!}\exp\left(-\pi\lambda_u r_i^2\theta_2\right)\frac{\left(\pi\lambda_u r_i^2\theta_2\right)^{i-1-N_1}}{(i-1-N_1)!}=\exp\\&\quad\cdot\left(-\pi\lambda_u r_i^2(\theta_1+\theta_2)\right)\frac{1}{(i-1)!}\sum_{N_1=0}^{i-1}\frac{(i-1)!}{N_1!(i-1-N_1)!}\left(\pi\lambda_u r_i^2\theta_1\right)^{N_1}\left(\pi\lambda_u r_i^2\theta_2\right)^{i-1-N_1}\\&=\frac{\left(\pi\lambda_u r_i^2(\theta_1+\theta_2)\right)^{i-1}}{(i-1)!}\exp\left(-\pi\lambda_u r_i^2(\theta_1+\theta_2)\right).\end{aligned}\tag{27}$$

In order to further derive the probability density function of r_1, it can be obtained from (22) and (25) that the probability that the BRSRP of UAV in the region $R^2/O(r_1,r_1+dr_1)$ is less than P_1 is (26).

According to the proportion relation and the property of PDF $f_{r_1}(r_1')dr_1'/f_{r_1}(r_1')dr_1'=A_1(r_1')2\pi r_1'dr_1'/A_1(r_1')2\pi r_1'dr_1'$, $\int_0^{\infty}f_{r_1}(r_1)dr_1=1$, we can get that the PDF of r_1 is

$$f_{r_1}(r_1)=\frac{\exp\left(-\pi\lambda_u r_1^2(\theta_2+\theta_1)\right)r_1}{\int_0^{\infty}\exp\left(-\pi\lambda_u r_1^2(\theta_2+\theta_1)\right)r_1dr_1}.\tag{28}$$

Second, we discuss the case where the group size $N\ge 2$. When the UAV group size $N\ge 2$, we need to discuss the PDF of r_i at $i>1$. This is different from r_1 in that we need to consider that there are $i-1$ UAVs in other regions of the plane whose BRSRP is larger than that of the UAVs located at r_i, and they may be located inside or outside the circle of radius r_i. Therefore, we should analyze the problem in the following steps: (1) derivate the probability that the BRSRP of N_1 UAVs in the circle with radius r_i is larger than that of UAV$_i$; (2) derivate the probability expression that the BRSRP of $i-1-N_1$ UAVs outside the circle with radius (r_i+dr_i) is larger than that of UAV$_i$; and (3) multiply the results obtained in the first two steps; then, the probability that

BRSRP is less than the BRSRP of UAV_i except for the $O(r_i, r_i + dr_i)$ region in the plane is obtained, that is, the probability that UAV_i is located in the $O(r_i, r_i + dr_i)$ region, and the expression of the latter is obtained by the proportional relation between the result and the PDF of r_i.

In the circular region with specific ground user projection as the center of the circle and r_i as the radius, we deduce the probability that the BRSRP of $N-1$ UAVs is less than the BRSRP value of $\mathrm{UAV}_i(P_i)$ in (29) following the steps above.

$$\begin{aligned}
&\mathbb{P}[N_1 \text{ UAV in } \mathbb{C}(r_i) \text{ with the BRSRP larger than } P_i] \\
&= \sum_{N_t=N_1}^{\infty} C_{N_t}^{N_1} \frac{\left(\pi\lambda_u r_i^2\right)^{N_t} e^{-\pi\lambda_u r_i^2}}{N_t!} \\
&\quad \cdot \left\{\mathbb{E}_{r_k,B_i}[\mathbb{P}[P_k \le P_i]]\right\}^{N_t-N_1} \left\{\mathbb{E}_{r_k,B_i}[\mathbb{P}[P_k > P_i]]\right\}^{N_1} \\
&= \sum_{N_t=N_1}^{\infty} \frac{\left\{\mathbb{E}_{r_k,B_i}[\mathbb{P}[P_k \le P_i]]\right\}^{N_t-N_1}}{(N_t-N_1)!} \left(\pi\lambda_u r_i^2\right)^{N_t} \cdot e^{-\pi\lambda_u r_i^2} \\
&\quad \cdot \frac{\left\{\mathbb{E}_{r_k,B_i}[\mathbb{P}[P_k > P_i]]\right\}^{N_1}}{N_1!} = \exp\left(-\pi\lambda_u r_i^2\theta_1\right) \frac{\left(\pi\lambda_u r_i^2\theta_1\right)^{N_1}}{N_1!},
\end{aligned} \tag{29}$$

where N_t is the number of UAVs in $\mathbb{C}(r_i)$.

$$\begin{aligned}
&\mathbb{P}[R_i \ge \gamma \mid r_i] = \mathbb{P}[\mathrm{SIR}_a \ge 2^\gamma - 1 \mid r_i] \\
&= \sum_{k=0}^{m-1} \frac{\left(-m(2^\gamma-1)\left(r_i^2+h^2\right)^{\alpha/2}\right)^k}{k!} \cdot \left[\frac{\partial^k}{\partial s^k} \exp\left(-2\pi\lambda \int_r^\infty\right.\right. \\
&\quad \left.\left.\cdot \left(1-\left(1+\frac{s\left(h^2+v^2\right)^{-\alpha/2}}{m}\right)^{-m}\right) v dv\right)\right]_{s=m(2^\gamma-1)\left(r_i^2+h^2\right)^{\alpha/2}},
\end{aligned} \tag{30}$$

$$\begin{aligned}
\mathbb{P}_{o,N} &= \prod_{i=1}^{N} \mathbb{P}[T_i < \gamma] \\
&= \prod_{i=1}^{N} \left[1 - \frac{\exp\left(-\pi\lambda_b h^2 \sqrt{2^\gamma-1} \arctan\left(\sqrt{2^\gamma-1}\right)\right)}{1+\sqrt{2^\gamma-1} \arctan\left(\sqrt{2^\gamma-1}\right)}\right. \\
&\quad + \int_\gamma^\infty \int_0^\infty \left(1-\exp\left(-\pi\lambda_u \sqrt{2^\gamma-1}\left(r_i^2+h^2\right) \arctan\right.\right. \\
&\quad \left.\left.\cdot\left(\sqrt{2^\gamma-1}\right)\right)\right) f_{r_i}(r_i) f_{B_i}(B_i) dr_i dB_i \Bigg].
\end{aligned} \tag{31}$$

In order to get the probability that the BRSRP of N_2 UAV is larger than P_i in the region $R^2/\mathbb{C}(r_i + dr_i)$, we need to prove the following Lemma 1: UAVs whose BRSRP is larger than P_i are on the circular area $\mathbb{C}(\Theta)$, where Θ is a value large enough. See Appendix A for detailed proof.

Consider condition (2) first. According to the derivation of (25), we can similarly derive

$$\mathbb{P}\left[P_k < P_i, \forall \mathrm{UAV}_k \in \frac{\left\{\mathbb{R}^2/\mathbb{C}(r_i+dr_i)\right\}}{\bigcup_{n_2} O\left(r_{n_2}, r_{n_2}+dr_{n_2}\right)}\right] = \exp\left(-\pi\lambda_u r_i^2\theta_2\right), \tag{32}$$

where $R^2/\mathbb{C}(r_i + dr_i)$ means UAVs whose BRSRP is larger than P_i in $O(r_i + dr_i, \Theta)$.

Then, considering condition (1), the probability that there are only N_2 UAVs in the region $O(r_i + dr_i, \Theta)$ whose BRSRP value is larger than P_i is

$$\begin{aligned}
&\mathbb{P}[N_2 \text{ UAV in } O(r_i+dr_i, \Theta) \text{ with the BRSRP larger than } P_i] \\
&= \exp\left(-\pi\lambda_u r_i^2\theta_2\right) \frac{\left(\pi\lambda_u r_i^2\theta_2\right)^{N_2}}{N_2!}.
\end{aligned} \tag{33}$$

See Appendix B for detailed proof.

It can be obtained from (29) and (33) that the probability that BRSRP of UAV in the region $R^2/O(r_i, r_i + dr_i)$ is less than P_i is (26).

According to the proportion relation and the property of PDF $f_{r_i}(r_i')dr_i'/f_{r_i}(r_i')dr_i' = A_i(r_i')2\pi r_i' dr_i'/A_1(r_i')2\pi r_i' dr_i'$, $\int_0^\infty f_{r_i}(r_i)dr_i = 1$, we can get that the PDF of r_i is

$$f_{r_i}(r_i) = \frac{\left(\left(\pi\lambda_u r_i^2(\theta_1+\theta_2)\right)^{i-1}/(i-1)!\right) r_i \exp\left(-\pi\lambda_u r_i^2(\theta_1+\theta_2)\right)}{\int_0^\infty \left(\left(\pi\lambda_u r_i^2(\theta_1+\theta_2)\right)^{i-1}/(i-1)!\right) r_i \exp\left(-\pi\lambda_u r_i^2(\theta_1+\theta_2)\right) dr_i}, \tag{34}$$

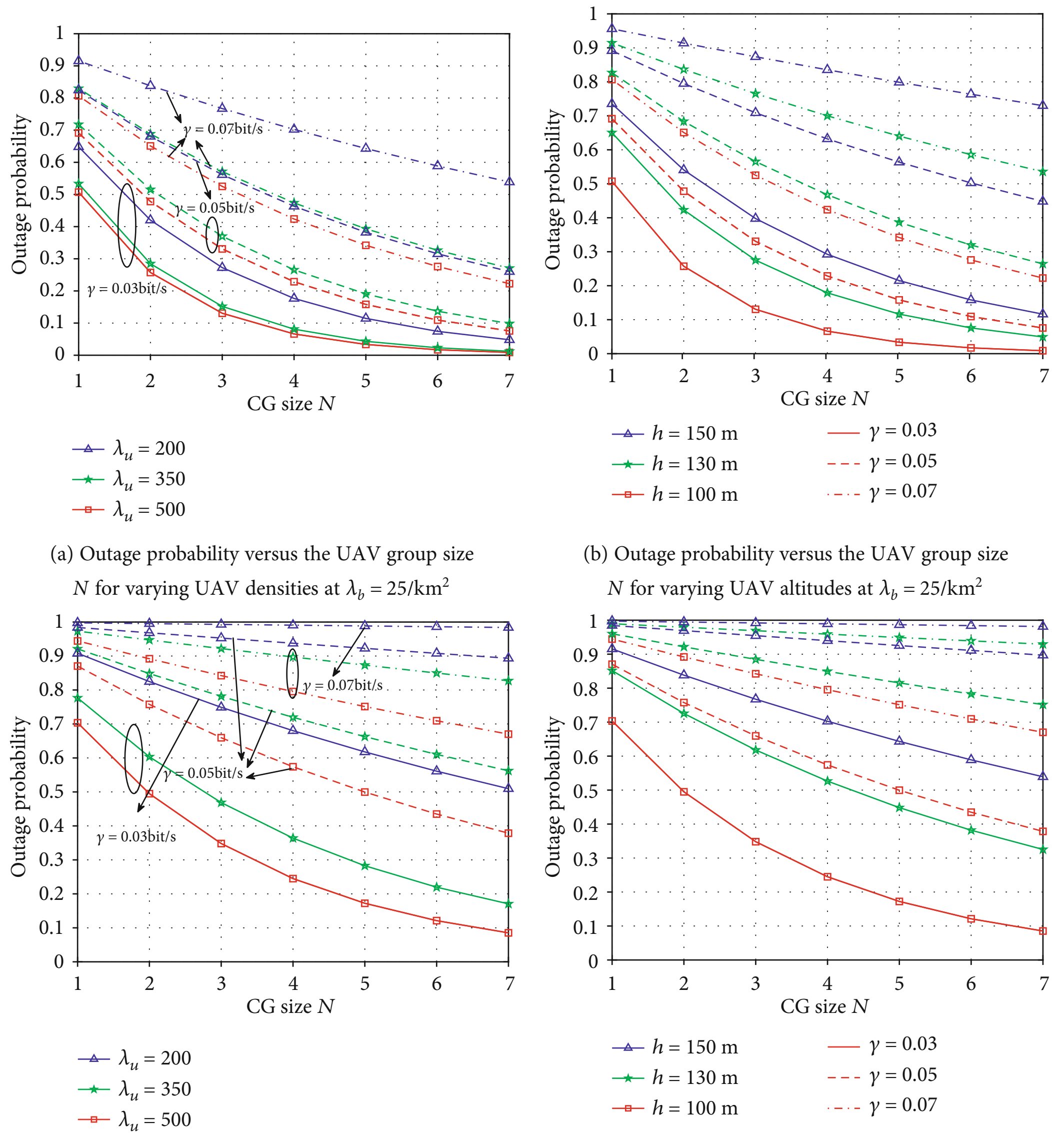
where $i \ge 2$.

Above all, we can get that the probability density function of $r_i (i = 1, 2, \cdots)$ is

$$f_{r_i}(r_i) = \frac{\left(\left(\pi\lambda_u r_i^2(\theta_1+\theta_2)\right)^{i-1}/(i-1)!\right) r_i \exp\left(-\pi\lambda_u r_i^2(\theta_1+\theta_2)\right)}{\int_0^\infty \left(\left(\pi\lambda_u r_i^2(\theta_1+\theta_2)\right)^{i-1}/(i-1)!\right) r_i \exp\left(-\pi\lambda_u r_i^2(\theta_1+\theta_2)\right) dr_i}. \tag{35}$$

By observing (35), it can be seen that in the UAV scene containing the parameter height h, the expression contains an integral term that is difficult to be simplified, so an accurate closed solution cannot be obtained. However, we can still derive the outrage probability from this expression.

3.3. Outrage Probability. As can be seen from the above, in order to obtain the expression of outrage probability, the joint influence of two aspects should be considered. On the one hand, the actual transmission rate of each UAV in the cluster should be considered; on the other hand, the actual transmission rate is jointly restricted by the capacity of the



(a) Outage probability versus the UAV group size N for varying UAV densities at $\lambda_b = 25/\mathrm{km}^2$

(b) Outage probability versus the UAV group size N for varying UAV altitudes at $\lambda_b = 25/\mathrm{km}^2$

(c) Outage probability versus the UAV group size N for varying UAV densities at $\lambda_b = 100/\mathrm{km}^2$

(d) Outage probability versus the UAV group size N for varying UAV altitudes at $\lambda_b = 100/\mathrm{km}^2$

FIGURE 1: Outage probability as a function of UAV group size N and rate thresholds under different UAV densities or different UAV altitudes.

access link and backhaul link. Therefore, for any UAV_i in the cluster, its rate outrage probability can be expressed as

$$\begin{aligned}\mathbb{P}[T_i < \gamma] &= \mathbb{P}[R_i < B_i < \gamma] + \mathbb{P}[R_i < \gamma, B_i > \gamma] + \mathbb{P}[R_i > B_i, B_i < \gamma] \\ &= \mathbb{P}[B_i < \gamma] + \mathbb{P}[R_i < \gamma, B_i > \gamma].\end{aligned} \tag{36}$$

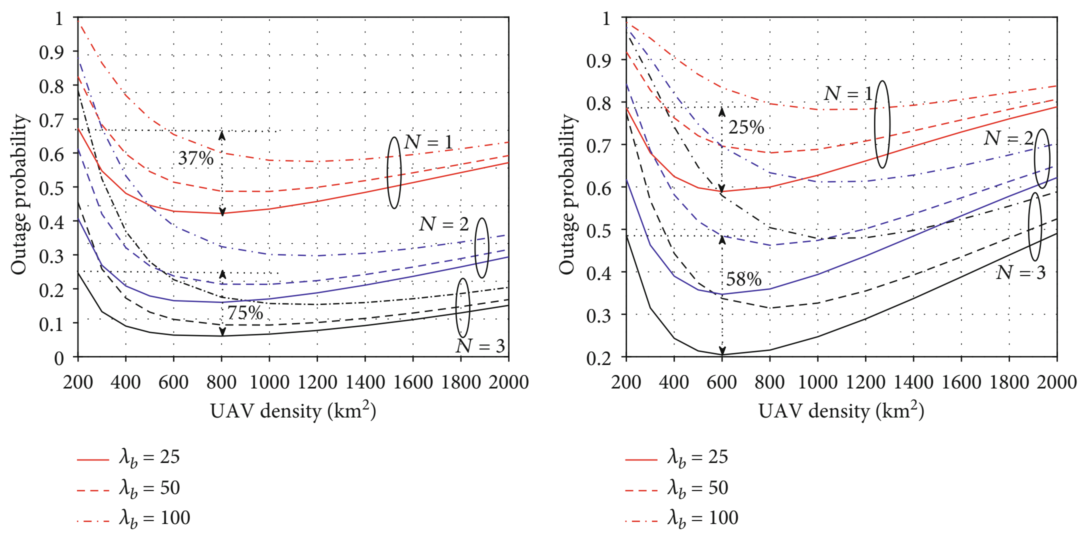
The latter part of (36) can be expressed as

$$\mathbb{P}[R_i < \gamma, B_i > \gamma] = \int_\gamma^\infty \int_0^\infty (1 - \mathbb{P}[R_i \geq \gamma \mid r_i]) f_{r_i}(r_i) f_{B_i}(B_i) dr_i dB_i. \tag{37}$$

Under the premise that the horizontal distance r_i is known, the conditional probability distribution function of the capacity R_i of the access link is similar to the derivation of the backhaul link, which can be obtained by analogy as (30). To sum up, the rate outrage probability of the UE can be expressed as

$$\begin{aligned}\mathbb{P}_{o,N} &= \prod_{i=1}^{N} \mathbb{P}[T_i < \gamma] = \prod_{i=1}^{N} \\ &\cdot \left[1 - \mathbb{P}[\mathrm{SIR_b} > 2^\gamma - 1] + \int_\gamma^\infty \int_0^\infty (1 - \mathbb{P}[\mathrm{SIR}_a \geq 2^\gamma - 1 \mid r_i]) f_{r_i}(r_i) f_{B_i}(B_i) dr_i dB_i\right].\end{aligned} \tag{38}$$

In the quantitative analysis of the next part, we reasonably simplify the results of (38) by making the path loss exponent $\alpha = 4$ and the parameter $m = 1$. In this case, we get (31).



(a) $h = 100$ m

(b) $h = 150$ m

Figure 2: Outage probability versus UAV density λ_u for varying CG size N.

4. Numerical Result

In this section, we use our proposed model to analyze the effects in outage probability for different network parameters such as the altitude of the UAVs, the UAV group size, the path loss exponent of channel, and the rate threshold γ. The simulation parameters and their default values are as follows. In the following paper, BS density is set to $\lambda_b = 50/\text{km}^2$. We also set $\lambda_u = 500/\text{km}^2$, $\lambda_c = 5000/\text{km}^2$, $h = 0.1$ km, $\alpha = 4$, and $\gamma = 0.02$ bit/s.

First, we study the outage probability versus the UAV group size N for different rate thresholds in Figure 1. As UAV group size N increases, there are more UAVs' optional services of the base station as the user base station. If the current UAV base stations provide users with the actual transmission rate which is less than the minimum speed threshold, more UAV BSs can be provided to the user and outage probability is reduced. However, excessive increase in the size of the UAV group will cause resource waste. In other words, for fixed γ and λ_u, increasing the UAV group size leads to saturation of the coverage probability; that is, we can no longer reduce the outage probability by increasing N beyond a certain value. As can be seen from Figure 1, when N reaches a certain value, the downward trend of the curve tends to be flat after the UAV group size N continues to increase, and the ratio of gain and resources consumed brought by increasing the UAV group size N will decrease. The comparison of Figures 1(a) and 1(b) shows that when $\lambda_b = 25/\text{km}^2$, the change of UAV altitude has a greater effect on the outage probability than the UAV density. In addition, as shown in Figures 1(c) and 1(d), when λ_b increases to 100 /km^2, changing UAV density can also greatly affect the outage probability, and the UAV flying altitude should be lowered in denser networks to mitigate higher level of interference.

As the UAV density increases, the change trend of outage probability is not monotonic and it decreases first and then increases, which is illustrated in Figure 2. When the UAV density is within the small value range below 600/km^2, the change trend of outage probability is mainly affected by the useful signal strength of the service UAV. As the deployment density of UAVs at high altitude increases, the distance between the user's base station group of service UAVs and the user is relatively close. In this way, the useful signal strength of the base station of service UAVs received by the user is relatively high, and the outage probability will decrease correspondingly. However, when the density of UAVs is within the larger value range of 600/km^2 or above, the interference of other UAVs in the network to the communication link of users will have an increasing impact on the changing trend of outage probability. Therefore, as the deployment density of UAVs at high altitude increases, outage probability will show an upward trend. Furthermore, the comparison between Figures 2(a) and 2(b) shows that when $h = 100$ m, outage probability changes more obviously. For example, when $N = 3$ and $\lambda_b = 25/\text{km}^2$, the outage probability is decreased by 58% at $h = 150$ m but by 75% at $h = 100$ m.

5. Conclusion

This paper proposes cell group selection with backhaul-aware biasing for UAV networks and analyzes system performance by deriving the rate outage probability via stochastic geometry, where a user's maximum data rate is constrained by backhaul capacity. Specifically, cell group selection is no longer distance-based and considered with a backhaul capacity bias factor, where UAVs with higher backhaul capacity will have a larger bias factor to match the backhaul variance. In addition, the dynamic UAV group is organized with the N largest BRSRP, where users can utilize the diversity gain by adjusting serving UAV dynamically as the channel conditions change.

Appendix

A. Proof of Lemma 1

In the plane of the UAVs, the probability that at least a UAV's BRSRP is larger than P_i in $O(r_k, r_k + dr_k)$ is

$$\frac{2\pi r_k dr_k}{\xi\left(B_i\left(\left(r_k^2+h^2\right)/\left(r_i{}^2+h^2\right)\right)^{\alpha/2}\right)}. \tag{A.1}$$

As r_k goes to infinity, we can find that

$$\frac{2\pi r_k}{\xi\left(B_i\left(\left(r_k^2+h^2\right)/\left(r_i{}^2+h^2\right)\right)^{\alpha/2}\right)} \longrightarrow 0. \tag{A.2}$$

Therefore, there exists $\Theta > 0$, such that

$$\frac{2\pi r_k}{\xi\left(B_i\left(\left(r_k^2+h^2\right)/\left(r_i{}^2+h^2\right)\right)^{\alpha/2}\right)} < \varepsilon(\forall \varepsilon > 0, \forall r_k > \Theta). \tag{A.3}$$

If we set $\varepsilon = 1/r_k^z (z \geq 2)$, we get

$$\begin{aligned}
&\mathbb{P}\left[\exists \mathrm{UAV}_k,\ \text{such that}\, P_k > P_i \,\text{and}\, \mathrm{UAV}_k \in \frac{\mathbb{R}^2}{\mathbb{C}(\Theta)}\right] \\
&\quad \leq \frac{\int_\Theta^\infty 2\pi r_k}{\xi\left(B_i\left(\left(r_k^2+h^2\right)/\left(r_i{}^2+h^2\right)\right)^{\alpha/2}\right) dr_k} < \int_\Theta^\infty \varepsilon dr_k \\
&\quad = \frac{1}{(m-1)\Theta^{m-1}}.
\end{aligned} \tag{A.4}$$

When Θ is large enough, the right side of the equation converges to zero. Therefore, we may safely draw the conclusion that there is no UAV whose BRSRP is larger than P_i outside the area $\mathbb{C}(\Theta)$.

B. Proof of (33)

Assume that N_3 is a sufficiently large positive integer and the $O(r_i + dr_i, \Theta)$ area is divided into the N_3 area of the same circle. Since N_3 is large enough, all points in the same circle can be considered to be equidistant from the center of the circle. In addition, since the area $\pi(\Theta^2 - r_i^2)/N_3$ of each circle is small enough, it can be considered that there is only one or no UAV in each circle whose BRSRP value is larger than P_i. The probability that there is a UAV with a BRSRP value greater than P_i in the circle area is

$$\lambda_u \mathbb{E}_{r_k, B_i}[\mathbb{P}[P_k > P_1]] \frac{\pi\left(\Theta^2 - r_i^2\right)}{N_3}. \tag{B.1}$$

From the properties of PPP in a given region and the previous derivation, we can obtain (B.1) and (B.2).

$$f_{r_k}(r_k) = \frac{2r_k}{\Theta^2 - r_i^2}, \tag{B.2}$$

$$\begin{aligned}
\mathbb{E}_{r_k, B_i}[\mathbb{P}[P_k > P_1]] \frac{\pi\left(\Theta^2 - r_i^2\right)}{N_3} &= \int_0^\infty f_{B_1}(B_1) \int_{r_i + dr_i}^{\Theta} \xi \\
&\quad \cdot \left(B_i \left(\frac{r_k^2 + h^2}{r_1^2 + h^2}\right)^{\alpha/2}\right) f_{r_k}(r_k) dr_k dB_1 \\
&= \frac{r_i^2 \theta_2}{\Theta^2 - r_i^2}.
\end{aligned} \tag{B.3}$$

And then, we get

$$\begin{aligned}
&\mathbb{P}[N_2\ \text{UAVs in}\ O(r_i + dr_i, \Theta)\ \text{have the BRSRP larger than}\ P_i] \\
&\quad = C_{N_3}^{N_2} \left(\lambda_u \frac{r_i^2 \theta_2}{\Theta^2 - r_i^2} \frac{\pi\left(\Theta^2 - r_i^2\right)}{N_3}\right)^{N_2} \overset{(a)}{=} \frac{\left(\pi \lambda_u r_i^2 \theta_2\right)^{N_2}}{N_2!}.
\end{aligned} \tag{B.4}$$

The derivation of (a) is based on when N_3 is large enough, and it can be obtained that

$$C_{N_3}^{N_2} = \frac{N_3(N_3 - 1) \cdots (N_3 - N_2 + 1)}{N_2!} \approx \frac{N_3{}^{N_2}}{N_2!}. \tag{B.5}$$

Finally, the proof is completed by multiplying formula (33) in the main body with formula (B.4) in the appendix.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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