IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received November 13, 2019, accepted December 1, 2019, date of publication December 6, 2019, date of current version December 23, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2958100

User-Centric Intelligent UAV Swarm Networks: Performance Analysis and Design Insight

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This work was supported in part by the Beijing Natural Science Foundation under Grant L182035, in part by the National Science Foundation of China under Grant 61971064 and Grant 61901049, and in part by the Fundamental Research Funds for the Central Universities under Grant 2019PTB-008.

ABSTRACT To enhance the network coverage and capacity, unmanned aerial vehicle (UAV) communication has become a promising technology thanks to the high mobility and the flexible deployment of UAVs. However, the consistency of the service is not guaranteed due to the limitation single UAV base station (BS), leading to the research for the user-centric UAV swarm networks. This paper derives the semi-closed-form expressions of coverage probability and average achievable rate for the user-centric UAV swarm networks to characterize the performance gain obtained from the increased UAV swarm diversity. Especially, the user-centric UAV swarm networks organize a dynamic UAV swarm for each user consisting of potential serving UAVs in user's vicinity, which gives the design of boundaryless cells to serve each user seamlessly without user's involvement. By modeling the locations of the UAVs as Poisson point process (PPP) and modeling the channel fading as Nakagami-m distribution, the analytical results are calculated under two transmission modes, depending on whether cell coordination is considered or not. The results show that the coverage performance can be improved by 30% without cell coordination and 50% with cell coordination in comparison with traditional cell-centric networks when the UAV altitude is 100 m and SINR threshold is 0 dB.

INDEX TERMS User-centric UAV swarm networks, coverage probability, average achievable rate, Poisson point process.

I. INTRODUCTION

Unmanned aerial vehicle (UAV) communication has became one of the most important candidates in 5G and beyond (B5G) [1], thanks to its high mobility, inexpensiveness and flexibility [2]. To provide temporary connectivity in the short-term scenarios, such as natural disasters, sports events, and concerts, deployment of UAV may be faster and more cost effective compared to terrestrial base stations (BSs) [3].

Due to its controlled mobility [4] and strong line-of-sight (LoS) links [5], UAV networks can provide significant solutions for enhanced network coverage and capacity in B5G. This is because that UAV has a larger angle of elevation, leading to higher probability for LoS links [6]. Meanwhile, the controlled mobility can provide LoS link by adjusting the locations of the UAVs with blocked links [7]. On the other hand, the high mobility and LoS feature of UAV networks also lead to the fluctuation of channel quality, and therefore, the wireless communication link from the single UAV can not guarantee the consistency of service [8].

User-centric UAV swarm network is proposed in [9] for seamless coverage and enhanced throughput. Especially, the definition of user-centric network (UCN) is proposed in [10], where the network architecture is shifted from traditional cell-centric to user-centric. UCN is defined by introducing the philosophy of the network serving user and the "de-cellular" method [11]. In [12], a general result of UCN performance is analyzed to characterize the gain obtained from the increased BS diversity. The results show the signal-to-interference-plus-noise ratio (SINR) can be improved by 75% in comparison with traditional cell-centric networks.

The most significant difference between the cell-centric architecture and user-centric architecture is the resource

The associate editor coordinating the review of this manuscript and approving it for publication was Jiankang Zhang.

allocation approach. Traditional cell-centric network techniques construct the network only based on the distribution and condition of base stations without taking users' distribution and traffic condition into full account [13]. By contrast, user-centric networks let the user feel like the network is always following it and the network shall intelligently recognize the user's wireless communication environments, and then flexibly organizes the required cell group and resource to serve the user [14]. Besides, UAV swarm networks can realize much wider coverage, better monitoring and understanding of interested area, smarter decision-making, and thus to better support diverse applications compared to terrestrial networks [15].

Therefore, to overcome the limitation of single UAV and to achieve the diversity gain of potential UAVs, user-centric UAV swarm networks will intelligently organize the UAV in the vicinity of the user equipment (UE). Compared to terrestrial networks, UAV networks can organize its resource more flexibly by adjusting the altitude of UAV and by increasing the UAV density temporarily.

A. RELATED WORKS

The user-centric architecture for traditional terrestrial networks has been widely investigated in recent literature, in terms of network architecture [10], mobility enhancement [14], [16], and performance analysis [11], [12], *et. al.*. In [10], dynamic access point grouping is proposed as the core function of UCN for providing satisfactory and secure service through the user's trajectory. The dual connectivity [14] and multi-connectivity [16] are applied in UCN with control-plane/user-plane split architecture to reduce the handover probability and handover failure rate. In [11] and [12], the locations of BSs are model as Poisson point process (PPP) which is a tractable analytical model for explicit expressions in cellular networks first proposed in [17] by Jeffrey G. Andrews *et. al.*. Especially, the expression of the coverage probability is derived with power control strategy to mitigate the inter-cell interference.

In UAV networks, the communication links between the serving UAV and UE are quite different from that in terrestrial networks. The LoS link probability is considered in [2] and [19] due to the less shadowing. Besides, the channel fading gain is usually modeled as Nakagami-m fading, which is a generalized model that mimics various fading environments [18], instead of Rayleigh fading in terrestrial networks. Moreover, the locations of UAVs are usually modeled in 3D space [20] or in 2D plane with fixed altitude [8]. However, the user-centric network architecture does not taken into consideration in the literature mentioned above.

However, few works consider the UAV swarm networks to achieve the diversity gain. Through the investigation, only [21], [22] and [9] analyze the capacity performance in UAV swarm networks. In [21], a cooperative UAV cluster is developed within a cylinder to offload UEs from ground BSs. However, the UAV cluster is formed according to the distance between the projection and UE, without considering the user-centric network architecture and the diversity gain of the potential UAVs. A user-centric cooperative scheme for UAV assisted wireless networks is analyzed in [22], where the UAV and the terrestrial BSs can serve the edge UE cooperatively. However, for UE that connected to the UAV or the terrestrial BS, the potential radio resource of the BSs in the vicinity is not organized effectively. In contrast, the UAVs around the UE form a transmission point group in [9] and cooperate with each other within the UAV swarm through power control strategy. One of the defect in [9] is that the result only applicable to the power control strategy as it proposed in the system model. The general result is not obtained for user-centric UAV swarm networks.

B. CONTRIBUTIONS

In this paper, the expressions of coverage probability and average achievable rate are derived in the user-centric UAV swarm networks. Two transmission modes are considered in this paper, according to whether cell coordination is considered or not. Our main contributions can be summarized as follows:

- A user-centric UAV swarm network is proposed in this paper where the UAVs in the vicinity provided potential radio resource form a UAV swarm to serve the UE seamlessly. The UAV that provides average received signal strength larger than the threshold is selected for the UE-specific UAV swarm.
- Two transmission modes are taken into consideration. In the first mode, the interference is mitigated with cell coordination, and in the second mode, a general result for user-centric UAV swarm networks is obtained without cell coordination.
- With the locations of the UAVs modeled as a PPP and the channel fading modeled as Nakagami-m fading, the expressions of coverage probability and average achievable rate are derived. What's more, semi-closed-form expressions are derived by simplifying the channel fading as Rayleigh model. Simulation is conducted to validate the correctness and usefulness of our analysis.

II. SYSTEM MODEL

A. NETWORK MODEL

UAVs are deployed to act as aerial BS in a two-dimensional plane for providing wireless service. Considering the simplicity of calculation, we assume that UAVs are deployed on the same height H_0. The distribution of UAVs follows a 2D-PPP with density λ in the infinitive plane Φ, which is defined as $\Phi = \{ (x, y, z) : x, y \in \mathbb{R}, z = H_0\}$. The locations of UEs are also modelled as 2D-PPP Φ_u with density λ_u.

This paper considers a user-centric network architecture as defined in [11], where multiple UAVs around the UE form a UAV swarm to serve the specific UE. This network architecture is suitable for the scenarios where the ability of a single UAV is usually blocked or the resource of the

UAVs is abundant. For example, in dense urban, since the communication links is more likely to be blocked by the building, user-centric UAV swarm network can provide multiple potential serving UAV and thus improve the LoS probability.

We define the UAVs inside the UAV swarm of the UE as ϕ. That is termed as user-centric UAV swarm networks. We assume that the UAV j is in the UAV swarm of UE i if and only if

$$P_T d_{ij}^{-\alpha(z)} = P_T \left(r_{ij}^2 + H_0^2\right)^{-\frac{\alpha(z)}{2}} > \gamma_{th}, \tag{1}$$

where P_T is the transition power of UAVs, r_{ij} is the distance of UE i to the projection of the UAV j on the ground, $d_{ij} = \sqrt{r_{ij}^2 + H_0^2}$ is the distance of UAV j to UE i, γ_{th} denotes the threshold of the average received signal strength for the UE-specific UAV swarm, and $\alpha(z)$ is path loss exponent at a certain height z, where $z = H_0$ as it is mentioned before. The path loss exponent $\alpha(z)$ is denoted as [2]

$$\alpha(z) = \max\left(a - bz + c/z, 2\right), \tag{2}$$

where parameters a, b, and c are constants to model the terrain types, and the suitable parameters are $a = 4.6$, $b = 0.0075$, $c = 12.6$ [2]. $\alpha(z)$ is about equal to 2 when the altitude z is large enough, because there is few blockages.

Based on (1), whether the UAV j is in the UAV swarm of UE i or not depends on the distance between the UAV j and UE i. That is, the threshold of the distance between the UE i and the projection of UAV j is given by

$$R_{th} = \sqrt{\left(\frac{P_T}{\gamma_{th}}\right)^{-2/\alpha(z)} - H_0^2}. \tag{3}$$

Therefore, the size of UAV swarm is determined by the power threshold γ_{th}, which means that the UE can adjust the size of UAV swarm by changing the radius of UAV swarm. What's more, the number of UAVs in the UE-specific UAV swarm is random according to the property of UAV.

In our analysis, we assume that the UAV that transmits data to the UE is selected from UAV swarm instead of the whole UAV set Φ. However, the UAV that is the closest one to the UE may not have the best transmission quality and any UAV of the UAV swarm can be chosen as the serving UAV for diversity gain. In this paper, we assume that the UAV with the largest backhaul capacity in the user-centric swarm is the serving UAV. What's more, the backhaul capacity is independent of the UAV's location. Thus, the location of the serving UAV follows uniform distribution in the given UAV swarm as derived in [23].

B. PROPAGATION MODEL

In this paper, a path loss plus fading propagation model is assumed. The received signal strength of UE i from UAV j is expressed as

$$P_{ij} = P_T h_{ij} d_{ij}^{-\alpha(z)} \tag{4}$$

where h_{ij} is the small scale fading that is model as Nakagami-m distribution, and $\alpha(z)$ is path loss exponent at a certain height z as explained in (2). Nakagami-m distribution is a special Gamma distribution which can be used to express the general small scale fading [2], so h_{ij} can be denoted as $h_{ij} \sim G(m, \frac{1}{m})$. And the probability density function of h_{ij} is given by

$$f_N(h) = \frac{m^m h^{m-1}}{\Gamma(m)} e^{-mh}. \tag{5}$$

In our analysis, we use m_0 and m to represent the Nakagami-m fading parameter of serving link and interference link.

C. SINR MODEL

In the user-centric UAV swarm networks, the SINR of UE is given by

$$\begin{aligned} SINR_i &= \frac{P_T h_i d_i^{-\alpha(z)}}{\sum\limits_{j\in\phi} P_T h_{ij} d_{ij}^{-\alpha(z)} + \sum\limits_{k\in\Phi/\phi} P_T h_{ik} d_{ik}^{-\alpha(z)} + \sigma^2} \\ &= \frac{h_i d_i^{-\alpha(z)}}{I_{in} + I_{out} + \sigma^2/P_T} \end{aligned} \tag{6}$$

where h_i and d_i denote the channel gain and the distance from the serving UAV of UE i, respectively, $I_{in} = \sum\limits_{j\in\phi} h_{ij} d_{ij}^{-\alpha(z)}$ and $I_{out} = \sum\limits_{k\in\Phi/\phi} h_{ik} d_{ik}^{-\alpha(z)}$ represent the interference from UAVs within the UAV swarm and that from UAVs outside the UAV swarm, respectively, and σ^2 is the noise power. For simplicity, we assume noise can be neglected since it is relatively low compared to the interference experienced at the receiving UE.

In this paper, we consider two transmission modes for the user-centric UAV swarm networks:

- Transmission with cell coordination: In user-centric UAV swarm networks, UAVs in the same UAV swarm can transmit jointly and cooperatively or employ inter-cell interference coordination. In this case, there will be no interference between the UAVs in the same UAV swarm.
- Transmission without cell coordination: Considering a general result of user-centric UAV swarm networks, the cell coordination with the UAV swarm is not employed.

Based on the two transmission modes mentioned above, we can infer that all the UAVs outside the UAV swarm are interference UAV. In the case that cell coordination is considered, there is no interference from the UAVs within the same UAV swarm and I_{in} can be neglected. While when the cell coordination is not considered, I_{in} should be taken into account.

III. COVERAGE PROBABILITY

According to Slivnyak's theorem, the typical UE located at the origin is analyzed for the network performance without loss of generality.

According to the property of PPP, UAVs are distributed uniformly and independently over the given area. Assuming that there are n UAVs in the UAV swarm ϕ, the distribution of these n UAVs are independent and uniform. What's more, UAVs outside the UAV swarm ϕ are also distributed independently and uniformly. The PDF of the distance from the serving UAV to UE i is expressed as [12]

$$f_{r_i}(r_i) = \frac{2r_i}{R_{th}^2} \tag{7}$$

where r_i is the horizontal distance between the UE and the serving UAV, and $0 \le r_i \le R_{th}$. The coverage probability for UE i is defined as

$$\begin{aligned} P_c &= P\left(SIR_i \ge \theta\right) \\ &= E_{r_i}\left[P\left(SIR_i \ge \theta | r_i\right)\right] \\ &= \int_0^{R_{th}} P\left(SIR_i \ge \theta | r_i\right) f_{r_i}\left(r_i\right) dr_i \end{aligned} \tag{8}$$

where θ represents the SIR threshold. Then we discuss the coverage probability in two transmission modes: with/without cell coordination.

A. TRANSMISSION WITH CELL COORDINATION

The interference within the UAV swarm is neglected in this case. SIR can be further expressed as

$$SIR_i^{(w)} = \frac{h_i d_i^{-\alpha(z)}}{I_{out}} \tag{9}$$

Then the coverage probability can be further derived, as shown in Theorem 1.

Theorem 1: Based the system model in Section II, the coverage probability in the user-centric UAV swarm networks with cell coordination is given by (10), as shown at the bottom of this page.

Proof: The coverage probability can be derived as

$$\begin{aligned} P_c^{(w)} &= \int_0^{R_{th}} P(SIR_i \ge \theta | r_i) f_{r_i}(r_i) dr_i \\ &= \int_0^{R_{th}} P\Big(\frac{h_i d_i^{-\alpha(z)}}{I_{out}} \ge \theta | r_i\Big) f_{r_i}(r_i) dr_i \\ &= \int_0^{R_{th}} P(h_i \ge \theta d_i^{\alpha(z)} I_{out} | r_i) \frac{2r_i}{R_{th}^2} dr_i \\ &\overset{(a)}{=} \int_0^{R_{th}} E_{I_{out}}\left[\frac{\Gamma\left(m_0, m_0\theta d_i^{\alpha(z)} I_{out}\right)}{\Gamma\left(m_0\right)}\right] \frac{2r_i}{R_{th}^2} dr_i \\ &\overset{(b)}{=} \int_0^{R_{th}} E_{I_{out}}\left[\sum_{k=0}^{m_0-1} \frac{\left(m_0\theta d_i^{\alpha(z)} I_{out}\right)^k}{k!} e^{-m_0\theta d_i^{\alpha(z)} I_{out}}\right] \frac{2r_i}{R_{th}^2} dr_i \\ &\overset{(c)}{=} \int_0^{R_{th}} \sum_{k=0}^{m_0-1} \frac{\left(-m_0\theta d_i^{\alpha(z)}\right)^k}{k!} \left[\frac{\partial^k}{\partial s^k} \mathcal{L}_{I_{out}}(s)\right]_{s=m_0\theta d_i^{\alpha(z)}} \frac{2r_i}{R_{th}^2} dr_i. \end{aligned} \tag{11}$$

where (a) is satisfied because of complementary cumulative distribution function (CCDF) of gamma random variable h_i, (b) follows the definition of incomplete gamma function when m_0 is an integer, (c) follows the definition Laplace transform.

The Laplace transform of I_{out} is given by

$$\begin{aligned} \mathcal{L}_{I_{out}}(s) &= E_{I_{out}}\left[e^{-sI_{out}}\right] \\ &= E_{I_{out}}\left[\exp\left(-s \sum_{k\in\Phi\backslash\phi} h_k d_k^{-\alpha(z)}\right)\right] \\ &= E_{\Phi,h_k}\left[\prod_{k\in\Phi\backslash\phi} \exp\left(-s h_k d_k^{-\alpha(z)}\right)\right] \\ &= E_{\Phi}\left[\prod_{k\in\Phi\backslash\phi} E_{h_k}\left[\exp\left(-s h_k d_k^{-\alpha(z)}\right)\right]\right] \\ &\overset{(a)}{=} E_{\Phi}\left[\prod_{k\in\Phi\backslash\phi} \left(1 + \frac{s d_k^{-\alpha(z)}}{m}\right)^{-m}\right] \\ &\overset{(b)}{=} e^{-2\lambda\pi \int_{R_{th}}^{\infty}\left[1-\left(1+\frac{s\left(\sqrt{u^2+H_0^2}\right)^{-\alpha(z)}}{m}\right)\right] u du} \end{aligned} \tag{12}$$

where (a) follows the moment generating function (MGF) of gamma random variable h_k, (b) follows probability generating functional (PGFL) of PPP, and u denotes the distance between the typical user and the interference UAV. Substituting the result of (12) into (11), we can get the final result of coverage probability. ■

If we assume $m_0 = m = 1$, which means that the channel gain becomes Rayleigh fading, h will follow an exponential distribution with unit mean 1, i.e., $h \sim \exp(1)$. Based on this assumption, we can simplify the coverage probability, as shown in corollary 1.

Corollary 1: Assuming that the channel gain h follows Rayleigh distribution, the coverage probability of UE i can

$$P_c^{(w)} = \frac{2}{R_{th}^2}\int_0^{R_{th}} r_i \sum_{k=0}^{m_0-1} \frac{\left[-m_0\theta\left(\sqrt{r_i^2+H_0^2}\right)^{\alpha(z)}\right]^k}{k!} \left[\frac{\partial^k}{\partial s^k} e^{-2\lambda\pi \int_{R_{th}}^{\infty}\left[1-\left(1+\frac{s\left(\sqrt{u^2+H_0^2}\right)^{-\alpha(z)}}{m}\right)\right] u du}\right]_{s=m_0\theta d_i^{\alpha(z)}} dr_i \tag{10}$$

be derived as

$$P_{c'}^{(w)} = \int_0^{R_{th}} \mathcal{L}_{I_{out}}\left(\theta d_i^{\alpha(z)}\right)\frac{2r_i}{R_{th}^2}dr_i = \frac{2}{R_{th}^2}\int_0^{R_{th}} r_i \exp\left[-\lambda\pi d_i^2\theta^{\frac{2}{\alpha(z)}}\int_\tau^\infty \frac{1}{1+x^{\alpha(z)/2}}dx\right]dr_i \tag{13}$$

where $\tau = \frac{R_{th}^w + H_0^2}{\theta^{2/\alpha(z)}d_i^2}$.

Proof: According to the definition in (8) and equation (10), the coverage probability can be simplified as

$$\begin{aligned} P_{c'}^{(w)} &= \int_0^{R_{th}} P(SIR_i \geq \theta|r_i)f_{r_i}(r_i)dr_i \\ &= \int_0^{R_{th}} P(h_i \geq \theta d_i^{\alpha(z)} I_{out}|r_i)f_{r_i}(r_i)dr_i \\ &= \int_0^{R_{th}} \mathcal{L}'_{I_{out}}\left(\theta d_i^{\alpha(z)}\right)\frac{2r_i}{R_{th}^2}dr_i \end{aligned} \tag{14}$$

where the Laplace transform can be derived as

$$\begin{aligned} &\mathcal{L}'_{I_{out}}(s) \\ &= E_\Phi\left[\prod_{k\in\Phi\backslash\phi} E_{h_k}\left[\exp\left(-sh_k d_k^{-\alpha(z)}\right)\right]\right] \\ &= E_\Phi\left[\prod_{k\in\Phi\backslash\phi}\frac{1}{1+sd_k^{-\alpha(z)}}\right] \\ &= \exp\left\{-2\lambda\pi\int_{R_{th}}^\infty\left[1-\frac{1}{1+s\left(\sqrt{u^2+H_0^2}\right)^{-\alpha(z)}}\right]udu\right\} \\ &= \exp\left[-\lambda\pi d_i^2\theta^{\frac{2}{\alpha(z)}}\int_\tau^\infty\frac{1}{1+x^{\alpha(z)/2}}dx\right] \end{aligned} \tag{15}$$

and in the last step, we assume that $\tau = \frac{R_{th}^w + H_0^2}{\theta^{2/\alpha(z)}d_i^2}$.

Therefore, the simplified coverage probability in (13) can be obtained. ■

B. TRANSMISSION WITHOUT CELL COORDINATION

In this subsection, we consider a general scenario where the cell coordination is not applied. Hence, there is interference from the UAVs within the same UAV swarm. To calculate the interference of the whole network, the interference can be divided into three parts: 1) Interference from the UAVs in the UAV swarm whose distance to the UE is less than d_i, denoted as I_{in1}; 2) Interference from the UAVs in the UAV swarm whose distance to the UE is larger than d_i, denoted as I_{in2}; 3) Interference outside the UAV swarm. The coverage probability is given in the following theorem.

Theorem 2: Considering a general scenario in user-centric UAV swarm networks where the UE can receive the interference from the UAVs within the same UAV swarm, the coverage probability is given by (16), as shown at the bottom of this page.

Proof: Similarly, the coverage probability can be derived based on the definition in (8), as given by

$$\begin{aligned} P_c^{(wo)} &= \int_0^{R_{th}} P(SIR_i \geq \theta|r_i)f_{r_i}(r_i)dr_i \\ &= \int_0^{R_{th}} P\left(\frac{h_i d_i^{-\alpha(z)}}{I_{in1}+I_{in2}+I_{out}} \geq \theta|r_i\right)f_{r_i}(r_i)dr_i \\ &= \int_0^{R_{th}} P\left(h_i \geq \theta d_i^{\alpha(z)} I_{to}|r_i\right)\frac{2r_i}{R_{th}^2}dr_i \\ &= \int_0^{R_{th}} E_I\left[\frac{\Gamma\left(m_0, m_0\theta d_i^{\alpha(z)} I_{to}\right)}{\Gamma(m_0)}\right]\frac{2r_i}{R_{th}^2}dr_i \\ &= \int_0^{R_{th}} E_I\left[\sum_{k=0}^{m_0-1}\frac{\left(m_0\theta d_i^{\alpha(z)} I_{to}\right)^k}{k!}e^{-m_0\theta d_i^{\alpha(z)} I_{to}}\right]\frac{2r_i}{R_{th}^2}dr_i \\ &= \int_0^{R_{th}}\sum_{k=0}^{m_0-1}\frac{\left(-m_0\theta d_i^{\alpha(z)}\right)^k}{k!}\left[\frac{\partial^k}{\partial s^k}\mathcal{L}_{I_{to}}(s)\right]_{s=m_0\theta d_i^{\alpha(z)}} \\ &\quad \frac{2r_i}{R_{th}^2}dr_i \end{aligned} \tag{17}$$

Then the Laplace transform of I_{to} can be calculated as multiplication of three parts, which are $\mathcal{L}_{I_{in1}}$, $\mathcal{L}_{I_{in2}}$ and $\mathcal{L}_{I_{out}}$. That is, $\mathcal{L}_{I_{to}}(s) = \mathcal{L}_{I_{in1}}(s)\mathcal{L}_{I_{in2}}(s)\mathcal{L}_{I_{out}}(s)$. The Laplace transform of I_{out} is obtained in (12). The derivations of $\mathcal{L}_{I_{in1}}$ and $\mathcal{L}_{I_{in2}}$ are similarly. Therefore, we can obtain the expression of $\mathcal{L}_{I_{to}}$ as

$$\begin{aligned} &\mathcal{L}_{I_{to}}(s) \\ &= \exp\left\{-2\lambda\pi\int_0^{r_i}\left[1-\left(1+\frac{m_0\theta d_i^{\alpha(z)}\left(\sqrt{u^2+z_j^2}\right)^{-\alpha(z)}}{m}\right)\right]udu\right. \\ &\quad -2\lambda\pi\int_{r_i}^{R_{th}}\left[1-\left(1+\frac{m_0\theta d_i^{\alpha(z)}\left(\sqrt{u^2+z_j^2}\right)^{-\alpha(z)}}{m}\right)\right]udu \end{aligned}$$

$$P_c^{(wo)} = \frac{2}{R_{th}^2}\int_0^{R_{th}} r_i\sum_{k=0}^{m_0-1}\frac{\left(-m_0\theta d_i^{\alpha(z)}\right)^k}{k!}\left[\frac{\partial^k}{\partial s^k}e^{-2\lambda\pi\int_0^\infty\left[1-\left(1+\frac{m_0\theta d_i^{\alpha(z)}\left(\sqrt{u^2+H_0^2}\right)^{-\alpha(z)}}{m}\right)\right]udu}\right]_{s=m_0\theta d_i^{\alpha(z)}} dr_i \tag{16}$$

$$-2\lambda\pi\int_{R_{th}}^{\infty}\left[1-\left(1+\frac{m_0\theta d_i^{\alpha(z)}\left(\sqrt{u^2+z_j^2}\right)^{-\alpha(z)}}{m}\right)\right]udu\Bigg\}$$

$$= e^{-2\lambda\pi\int_0^{\infty}\left[1-\left(1+\frac{m_0\theta d_i^{\alpha(z)}\left(\sqrt{u^2+z_j^2}\right)^{-\alpha(z)}}{m}\right)\right]udu} \quad (18)$$

By inserting (18) into (17), the coverage probability in (16) is derived. Proof is complete. ■

Similarly, assuming $m_0 = m = 1$, the distribution of channel gain h is simplified from Nakagami-m distribution to Rayleigh distribution, which follows an exponential distribution with unit mean 1, i.e., $h \sim \exp(1)$. In this case, the coverage probability is simplified, showing in Corollary 2.

Corollary 2: Assuming that the channel gain h follows Rayleigh distribution and the cell coordination is not applied, the coverage probability of UE i can be derived as

$$\begin{aligned} P_{c'}^{(wo)} &= \int_0^{R_{th}} \mathcal{L'}_{I_{to}}\left(\theta d_i^{\alpha(z)}\right)\frac{2r_i}{R_{th}^2}dr_i \\ &= \frac{2}{R_{th}^2}\int_0^{R_{th}} r_i \exp\left[-\lambda\pi d_i^2\theta^{\frac{2}{\alpha(z)}}\int_{\varsigma}^{\infty}\frac{1}{1+\varsigma^{\alpha(z)/2}}dx\right]dr_i \end{aligned} \quad (19)$$

where $\varsigma = \frac{u^2+H_0^2}{\theta^{2/\alpha(z)}d_i^2}$.

Proof: Based on the definition of coverage probability in (8), the simplified coverage probability without cell coordination is given by

$$\begin{aligned} P_{c'}^{(wo)} &= \int_0^{R_{th}} P(SIR_i \geq \theta|r_i)f_{r_i}(r_i)dr_i \\ &= \int_0^{R_{th}} P(h_i \geq \theta d_i^{\alpha(z)}I_{to}|r_i)f_{r_i}(r_i)dr_i \\ &= \int_0^{R_{th}} \mathcal{L'}_{I_{to}}\left(\theta d_i^{\alpha(z)}\right)\frac{2r_i}{R_{th}^2}dr_i \end{aligned} \quad (20)$$

where $\mathcal{L'}_{I_{to}}(s)$ is the Laplace transform of the interference from the whole network, which is also equal to $\mathcal{L'}_{I_{in1}}(s)\mathcal{L'}_{I_{in2}}(s)\mathcal{L'}_{I_{out}}(s)$. The simplified Laplace transform of I_{out} is derived in (15). $\mathcal{L'}_{I_{in2}}(s)$ and $\mathcal{L'}_{I_{out}}(s)$ can be derived in the same approach. Therefore, $\mathcal{L'}_{I_{to}}(s)$ can be calculated as

$$\begin{aligned} &\mathcal{L'}_{I_{to}}(s) \\ &= \mathcal{L'}_{I_{in1}}(s)\mathcal{L'}_{I_{in2}}(s)\mathcal{L'}_{I_{out}}(s) \\ &= \exp\left\{-2\lambda\pi\int_0^{r_i}\left[1-\frac{1}{1+s\left(\sqrt{u^2+H_0^2}\right)^{-\alpha(z)}}\right]udu\right. \\ &\quad -2\lambda\pi\int_{r_i}^{R_{th}}\left[1-\frac{1}{1+s\left(\sqrt{u^2+H_0^2}\right)^{-\alpha(z)}}\right]udu \\ &\quad \left. -2\lambda\pi\int_{R_{th}}^{\infty}\left[1-\frac{1}{1+s\left(\sqrt{u^2+H_0^2}\right)^{-\alpha(z)}}\right]udu\right\} \\ &= \exp\left\{-2\lambda\pi\int_0^{\infty}\left[1-\frac{1}{1+s\left(\sqrt{u^2+H_0^2}\right)^{-\alpha(z)}}\right]udu\right\} \\ &= \exp\left[-\lambda\pi d_i^2\theta^{\frac{2}{\alpha(z)}}\int_{\varsigma}^{\infty}\frac{1}{1+\varsigma^{\alpha(z)/2}}dx\right] \end{aligned} \quad (21)$$

where in the last step, we assume that $\varsigma = \frac{u^2+H_0^2}{\theta^{2/\alpha(z)}d_i^2}$.

By inserting (21) into (20), the coverage probability in (19) is derived. Proof is complete. ■

IV. AVERAGE ACHIEVABLE RATE

The average achievable rate is one of the most important parameters to evaluate the network capacity and is analyzed in this part. The average achievable rate is denoted as R_{avg} in this paper. We first get the relationship between coverage probability and the average achievable rate as followed

$$\begin{aligned} R_{avg} &= E_{SIR_i}\left[\ln(1+SIR_i)\right] \\ &\overset{(a)}{=} E_{d_i}\left[\int_0^{\infty} P\left(\ln(1+SIR_i) > \eta\right)d\eta\right] \\ &= E_{d_i}\left[\int_0^{\infty} P\left(SIR_i > \left(e^{\eta}-1\right)\right)d\eta\right] \\ &\overset{(b)}{=} E_{d_i}\left[\int_0^{\infty}\frac{P(SIN_i > \theta)}{\theta+1}d\theta\right] \\ &= \int_0^{\infty}\frac{E_{d_i}\left[P(SIN_i > \theta)\right]}{\theta+1}d\theta \\ &= \int_0^{\infty}\frac{P_c}{\theta+1}d\theta \end{aligned} \quad (22)$$

where (a) is satisfied because $\ln(1+SIN_i)$ is a strictly positive random variable, and in step (b), we use θ to replace $e^{\eta}-1$ which is also the SIR threshold as mentioned above. Then we derive the average achievable rate in the two transmission modes as assumed above.

A. TRANSMISSION WITH CELL COORDINATION

The average achievable rate under Nakagami-m fading with cell coordination can be achieved by inserting (10) into (22). The expression is given by (23), as shown at the bottom of the next page.

Then, by simplifying the channel fading h into Rayleigh fading, the simplified coverage probability can be achieved from corollary 1, which is given by (24), as shown at the bottom of the next page.

B. TRANSMISSION WITHOUT CELL COORDINATION

In the general transmission mode, the average achievable rate under Nakagami-m fading without cell coordination can be

TABLE 1. Notation parameters.

Parameters	Description	Values
θ	SIR threshold	-5 dB
λ	UAV density	10^{-6}, 10^{-5}, 5×10^{-5} /m^2
H_0	UAV altitude	100, 250, 350 m
R_{th}	UAV swarm radius threshold	400, 600, 800 m

achieved by inserting (16) into (22). The expression is given by (25), as shown at the bottom of this page.

Then, by simplifying the channel fading h into Rayleigh fading, the simplified coverage probability can be achieved from corollary 2, which is given by (26), as shown at the bottom of this page.

V. NUMERICAL RESULTS

Numerical results are conducted in this section and shows how different parameters influence the coverage probability and average achievable rate. Due to the complexity of expression in Nakagami-m fading channel, the results is shown in the condition when Nakagami-m parameter $m = 1$. The parameters for the results are listed in Table 1.

A. ANALYSIS RESULTS FOR COVERAGE PROBABILITY

Fig. 1 shows the effect of UAV density, UAV altitude and UAV swarm radius threshold on the coverage probability. In Fig. 1(a) and Fig. 1(d), with cell coordination, the coverage probability decreases with the increase of density because of the assumption that only one UAV will transmit data to the typical user and interference will increase with the increase of density. Without cell coordination, the coverage probability also decreases with the increase of density. However, it drops more quickly than that with cell coordination because of the interference within the UAV swarm.

Fig. 1(b) and Fig. 1(e) demonstrate the coverage probability with UAV altitude. Coverage probability will increase with the increase of height. Although received power of data link and interference both will decrease with the increase of altitude, the interference decreases more. Therefore, the overall SIR will increase, leading to the increase of coverage probability. Besides, the trend of curves changes to stationary phase at around 350 m. This is because that the path loss exponent reduces to 2 and doesn't reduce with the increased altitude, as described in the system model.

Fig. 1(c) and Fig. 1(f) show the relationship between the coverage probability and UAV swarm radius threshold. Coverage probability decreases with the increase of threshold because of the assumption that the location of the serving UAV is distributed randomly inside UAV swarm. However, UAV that is closer to the typical UE has a better SIR in the calculation. Therefore, the chosen UAV is more likely to be further to the typical UE with the increase of UAV swarm size and the SIR will be smaller.

B. ANALYSIS RESULTS FOR AVERAGE ACHIEVABLE RATE

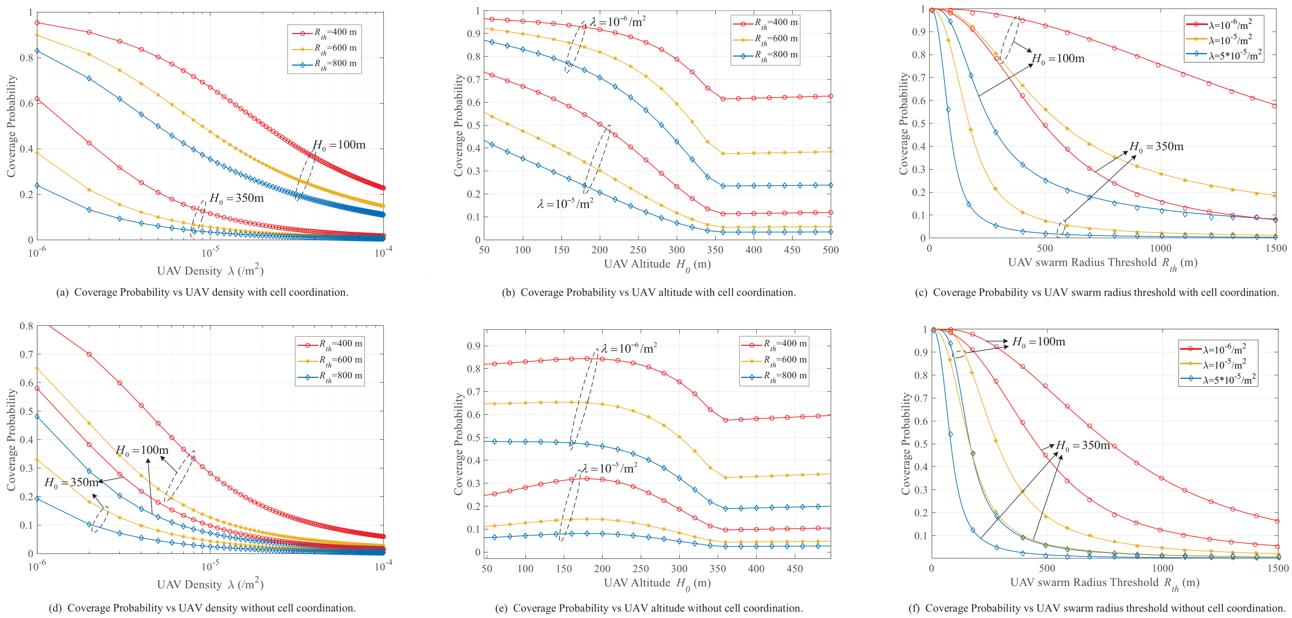
Fig. 2 shows the average achievable rate in user-centric UAV swarm networks. In Fig. 2(a) and Fig. 2(d), it can be seen

$$R_{avg}^{(w)} = \frac{2}{R_{th}^2}\int_0^\infty \frac{1}{\theta+1}\int_0^{R_{th}} r_i \sum_{k=0}^{m_0-1} \frac{\left[-m_0\theta\left(\sqrt{r_i^2+H_0^2}\right)^{\alpha(z)}\right]^k}{k!} \left[\frac{\partial^k}{\partial s^k}\exp\left\{-2\lambda\pi\int_{R_{th}}^\infty\left[1-\left(1+\frac{s\left(\sqrt{u^2+H_0^2}\right)^{-\alpha(z)}}{m}\right)\right]udu\right\}\right]_{s=m_0\theta d_i^{\alpha(z)}} dr_i d\theta. \tag{23}$$

$$R_{avg'}^{(w)} = \frac{2}{R_{th}^2}\int_0^\infty \frac{1}{\theta+1}\int_0^{R_{th}} r_i \exp\left[-\lambda\pi d_i^2\theta^{\frac{2}{\alpha(z)}}\int_{\frac{R_{th}^2+H_0^2}{\theta^{2/\alpha(z)}d_i^2}}^\infty \frac{1}{1+x^{\alpha(z)/2}}dx\right]dr_i d\theta \tag{24}$$

$$R_{avg}^{(wo)} = \frac{2}{R_{th}^2}\int_0^\infty \frac{1}{\theta+1}\int_0^{R_{th}} r_i \sum_{k=0}^{m_0-1} \frac{\left(-m_0\theta d_i^{\alpha(z)}\right)^k}{k!} \left[\frac{\partial^k}{\partial s^k}\exp\left\{-2\lambda\pi\int_0^\infty\left[1-\left(1+\frac{m_0\theta d_i^{\alpha(z)}\left(\sqrt{u^2+H_0^2}\right)^{-\alpha(z)}}{m}\right)\right]udu\right\}\right]_{s=m_0\theta d_i^{\alpha(z)}} dr_i d\theta \tag{25}$$

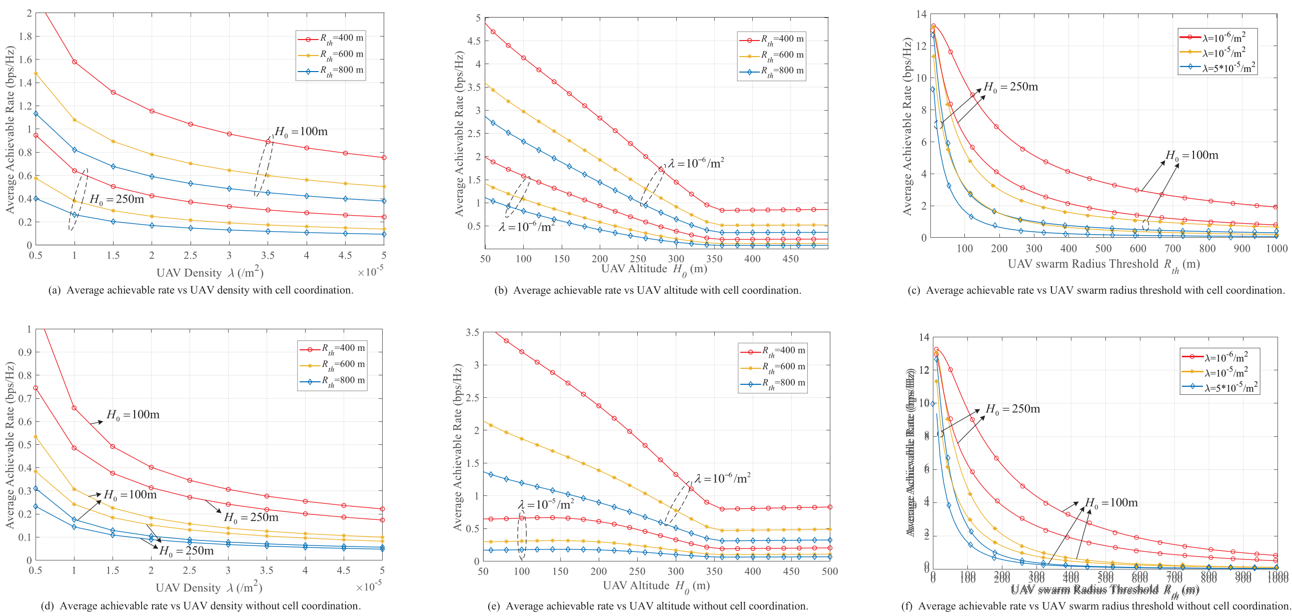
$$R_{avg'}^{(wo)} = \frac{2}{R_{th}^2}\int_0^\infty \frac{1}{\theta+1}\int_0^{R_{th}} r_i \exp\left[-\lambda\pi d_i^2\theta^{\frac{2}{\alpha(z)}}\int_{\frac{z^2}{\theta^{2/\alpha(z)}d_i^2}}^\infty \frac{1}{1+x^{\alpha(z)/2}}dx\right]dr_i d\theta \tag{26}$$



(a) Coverage Probability vs UAV density with cell coordination. (b) Coverage Probability vs UAV altitude with cell coordination. (c) Coverage Probability vs UAV swarm radius threshold with cell coordination.

(d) Coverage Probability vs UAV density without cell coordination. (e) Coverage Probability vs UAV altitude without cell coordination. (f) Coverage Probability vs UAV swarm radius threshold without cell coordination.

FIGURE 1. Coverage probability in user-centric UAV swarm networks.



(a) Average achievable rate vs UAV density with cell coordination. (b) Average achievable rate vs UAV altitude with cell coordination. (c) Average achievable rate vs UAV swarm radius threshold with cell coordination.

(d) Average achievable rate vs UAV density without cell coordination. (e) Average achievable rate vs UAV altitude without cell coordination. (f) Average achievable rate vs UAV swarm radius threshold without cell coordination.

FIGURE 2. Average achievable rate in user-centric UAV swarm networks.

that the average achievable rate decreases with the increase of UAV density. Since this paper assumes that only one UAV serves the UE, the interference increases with the increase of density, leading to the decrease of the average achievable rate. It can also be seen that if path loss exponent is a constant, average achievable rate will increase with the increase of height.

Fig. 2(b) and Fig. 2(e) show the relationship between the average achievable rate and the UAV altitude. Although received signal strength and interference both decrease with the increase of the UAV altitude, the interference decreases more. Therefore, the overall SIR increases, leading to the increase of coverage probability.

Fig. 2(c) and Fig. 2(f) show the effect of UAV swarm radius threshold on the average achievable rate. It can be seen that average achievable rate will decrease with the increase of UAV swarm radius because the location of the serving UAV is random. However, the distance between the serving UAV and the typical UE is more likely to be further when the UAV swarm size is increased. Therefore, the UE's SIR is lower. It can also be seen that with the increase of UAV swarm radius, impact of the UAV altitude is getting smaller.

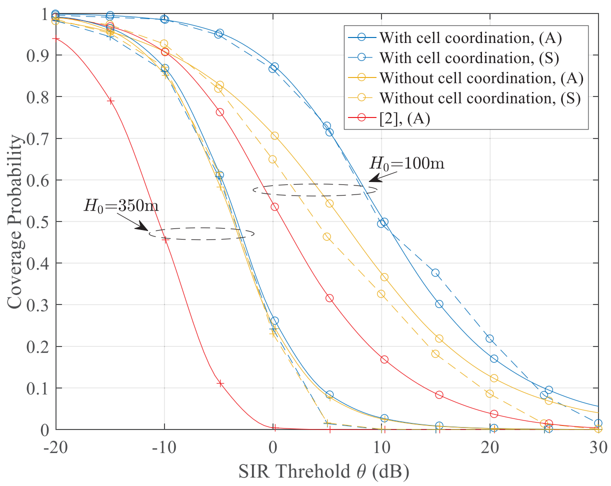


FIGURE 3. **Coverage probability vs SIR threshold in user-centric UAV swarm networks with/without cell coordination.**

C. SIMULATION RESULTS

Fig. 3 shows the analysis and simulation results of coverage probability versus SIR threshold with/without cell coordination in user-centric UAV swarm networks. We also compare the results with the performance of cell-centric UAV networks analyzed in [2], which assumes that the closest UAV to the typical UE is chosen as the serving UAV. The simulation results validate our analysis and it can be seen that user-centric UAV swarm networks have better coverage probability than cell-centric UAV networks. This is because in traditional cell-centric networks, there is a probability that the link is blocked by buildings and the throughput is limited by the backhaul capacity. Expectedly, the coverage probability decreases with the increase of SIR threshold. This is because the greater threshold is, the harder the UE received signal strength is able to meet the requirements. When SIR threshold is 0 dB, the coverage probability of user-centric UAV swarm networks without cell coordination achieves an increase of 30% gains over traditional cell-centric UAV networks, and that with cell coordination achieves 60% gain due to the decreased interference.

VI. CONCLUSION

In order to achieve the diversity gain by taking advantage of the radio resource of the potential serving UAVs in the vicinity of UE, user-centric UAV swarm network is proposed in this paper, where multiple UAVs around the UE form a UE-specific UAV swarm to provide user-centric service. Two transmission modes are considered in this paper, which are transmission with cell coordination where interference is mitigated within the same UE-specific UAV swarm and transmission without cell coordination where a general result for user-centric UAV swarm networks is obtained, respectively. Semi-closed-form expressions of coverage probability and average achievable rate are derived with the locations of the UAVs modeled as PPP and the channel fading model as Nakagami-m distribution. The results show that user-centric UAV swarm networks can achieve at least 30% gain for coverage probability. For further study, the transmission scheme and the backhaul capacity can be further investigated for improving the network capacity.

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