Spectrum Sharing between UAV-based Wireless Mesh Networks and Ground Networks

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***Abstract*—The unmanned aerial vehicle (UAV)-based wireless mesh networks can economically provide wireless services for the areas with disasters. However, the capacity of air-to-air communications is limited due to the multi-hop transmissions. In this paper, the spectrum sharing between UAV-based wireless mesh networks and ground networks is studied to improve the capacity of the UAV networks. Considering the distribution of UAVs as a three-dimensional (3D) homogeneous Poisson point process (PPP) within a vertical range, the stochastic geometry is applied to analyze the impact of the height of UAVs, the transmit power of UAVs, the density of UAVs and the vertical range, etc., on the coverage probability of ground network user and UAV network user, respectively. The optimal height of UAVs is numerically achieved in maximizing the capacity of UAV networks with the constraint of the coverage probability of ground network user. This paper provides a basic guideline for the deployment of UAV-based wireless mesh networks.**

***Index Terms*—Spectrum Sharing; Unmanned Aerial Vehicle; Wireless Mesh Networks; Ground Networks.**

I. Introduction

Since unmanned aerial vehicles (UAVs) have flexible maneuverability and large coverage, the UAV-mounted base stations (BSs) are widely applied to provide ubiquitous wireless connections [1]. The UAV-mounted BSs relieve the mismatch between the diverse traffic load and the fixed infrastructures [2]. For example, the demand for mobile and flexible wireless connections is urgent in the areas with traffic congestions or concerts. UAV-mounted BSs can be deployed in this scenario to offload the cellular traffic to the UAVs [3]. In the areas with disasters, the ground infrastructures are destroyed and the UAV-mounted BSs can be deployed to provide communication services to the rescue persons and vehicles on ground [4], [5].

In the UAV-mounted BS system, multiple small UAVs can provide more economical wireless coverage than a single large UAV [6]. Li *et al.* in [7] developed a two-UAV relaying system to extend the communication range of UAV networks. They have verified the feasibility of realizing multi-UAV communications. Chand *et al.* in [8] designed a UAV-based wireless mesh network for the scenarios of disaster management and military environment. The project loon established by Alphabet Inc. aims to provide Internet access to remote areas using balloons which form an aerial mesh network [9]. In [10], we have realized the UAV-based wireless mesh network, where multiple UAVs provide wireless coverage to the users on ground. Meanwhile, the UAVs form an aerial ad hoc network. With one UAV accessing the Internet via the gateway, all the users on ground can access the Internet.

According to Gupta and Kumar's theory [11], the per-node capacity of ad hoc networks is a decreasing function of the number of hops. For the aerial tier in the UAV-based mesh network, the multi-hop transmissions bring severe capacity shortage problem for each UAV. Spectrum sharing is an effective technology in improving the capacity of wireless networks via enhancing the spectrum utilization. Fortunately, the UAV networks and ground networks such as cellular networks are spatially separated, which creates a unique opportunity for the spectrum sharing between them [12]. Zhang *et al.* in [14] studied the spectrum sharing between the drone small cell networks and the cellular networks. Sboui *et al.* in [15] optimized the transmit power to maximize the energy efficiency when a UAV shares the spectrum of primary users. Lyu *et al.* in [16] designed the orthogonal spectrum sharing between UAV and ground BS. Yoshikawa *et al.* in [17] studied the spectrum sharing between UAVs and radar systems. Huang *et al.* in [18] designed the routing schemes for the aerial cognitive radio networks.

Although many prior works have studied the issue of spectrum sharing between UAVs and other wireless systems, to the best of the authors' knowledge, very few studies have considered the issue of spectrum sharing between the UAV-based wireless mesh networks and the ground networks, such as cellular networks. Motivated by this, in this paper, the spectrum sharing is studied in the air-to-air communications of UAVs to improve the capacity of UAV networks. Considering the distribution of UAVs as a three-dimensional (3D) homogeneous Poisson point process (PPP), stochastic geometry is applied to analyze the coverage probability of UAV network users and ground network users. As a result, the optimal height of UAVs can be found with the constraint of the coverage probability of ground network users.

The remainder of this paper is organized as follows. In Section II, the system model is introduced. Section III analyzes

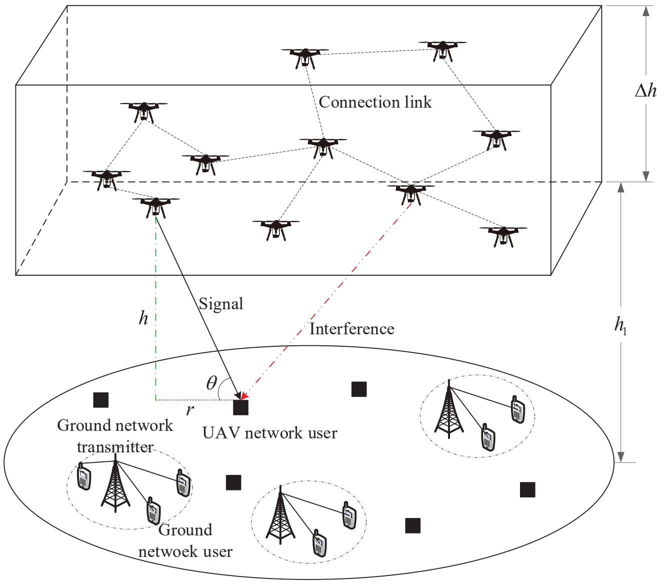

Fig. 1. System model of UAV-ground spectrum sharing.

the performance of spectrum sharing of UAV-ground networks using stochastic geometry. The simulation results are provided in Section IV. Finally, we summarize this paper in Section V.

II. System Model

When multiple UAVs provide wireless services to the users on ground, the UAVs should form a wireless mesh network to improve the coverage of the multiple UAVs. In this scenario, each UAV acts as an aerial BS and the multiple UAVs form an aerial ad hoc network. With one UAV connecting to the gateway via backhaul link, all the UAVs can provide Internet connections for the UAV network users. In the aerial ad hoc networks, multi-hop transmissions are required to forward data from sources to destinations. Since multi-hop transmissions bring severe capacity shortage problem for each UAV, the communications among UAVs share the spectrum of the ground networks to improve the network capacity. While the spectrum of the air-to-ground communications is different from the spectrum of the ground networks to avoid the severe interference between them.

A. Network model

As illustrated in Fig. 1, the distribution of the transmitters (TXs) of ground network, such as the BSs of cellular network[1], follows a two-dimensional (2D) homogeneous PPP Φ_d with density λ_d. The distribution of UAVs follows a 3D homogeneous PPP Φ_u with density λ_u. The minimum and maximum heights of UAVs are h_1 and $h_1 + \Delta h$, respectively. Δh is defined as the vertical range of the UAVs. In the UAV network, the Aloha protocol is applied as the medium access control (MAC) protocol.

[1]In this paper, the general ground networks including, but not limited to cellular network, are considered.

B. Channel model

Both path-loss and small scale fading are considered. The path-loss exponent of the ground-to-ground link is α_d. The path-loss exponent of the air-to-ground link is α_u. The power gain of small scale fading is an exponential distributed random variable with unit mean. Additive white Gaussian noise is considered with mean zero and variance N. The transmit power of the UAV and the TX of ground network are P_u and P_d, respectively. Both the line-of-sight (LoS) and non-line-of-sight (NLoS) propagations in the air-to-ground communications are considered. The received signal strength at the UAV network user can be expressed as [19], [20]

$$P_{r,g} = \begin{cases} P_u |d_{ug}|^{-\alpha_u} & \text{LoS} \\ \eta P_u |d_{ug}|^{-\alpha_u} & \text{NLoS} \end{cases}, \tag{1}$$

where d_{ug} is the distance between the UAV and the UAV network user. η is an attenuation factor because of the NLoS propagation [19]. The probability of LoS propagation is as follows [20].

$$P_{\text{LoS}} = \frac{1}{1 + C \exp\left(-B(\theta - C)\right)}, \tag{2}$$

where B and C are environmental dependent constants. θ is the elevation angle. As illustrated in Fig. 1, with h being the height of a UAV and r being the distance between the projection of the UAV on ground and the UAV network user, the value of θ is

$$\theta = \frac{180}{\pi} \arctan(\frac{h}{r}). \tag{3}$$

III. Spectrum Sharing of UAV-Ground Networks

With the spectrum sharing between the UAV network and the ground network, we derive the coverage probabilities of ground network user and UAV network user respectively.

The coverage probability is defined as the probability of successful communication. Define β as the threshold of signal-to-interference-plus-noise ratio (SINR) at the receiver for successfully communication. The coverage probability is the probability $P(\gamma > \beta)$ with γ being the SINR of the receiver.

A. The coverage probability of ground network user

Define $\gamma_{gu} = \frac{P_d d_0^{-\alpha_d} g_0}{I_{gu}^c + I_u + N}$ as the received SINR of a typical ground network user at the origin $\{\mathbf{0}\}$, where g_0 is the power gain of small scale fading. d_0 is the distance between the typical ground network user and its associated TX. I_{gu}^c and I_u are the interference generated by the TXs of ground network and the UAVs, respectively.

$$I_{gu}^c = \sum_{d_i \in \Phi_d \backslash \{\mathbf{0}\}} P_d d_i^{-\alpha_d} g_i, \tag{9}$$

$$\begin{aligned} I_u &= I_{u,LoS} + I_{u,\text{NLoS}} \\ &= \sum_{x_i \in \Phi_u} P_{\text{LoS}} P_u x_i^{-\alpha_d} g_i + \sum_{x_i \in \Phi_u} \left(1 - P_{\text{LoS}}\right) \eta P_u x_i^{-\alpha_d} g_i, \end{aligned} \tag{10}$$

where g_i is the small scale fading gain of the interference link. d_i is the distance between the ith TX of ground network and

$$L_{I_{gu}^c}(\frac{\beta {d_0}^{\alpha_d}}{P_d}) = \exp(-\frac{2\lambda_d \pi^2 (\beta)^{2/\alpha_d} {d_0}^2}{\alpha_d \sin(2\pi/\alpha_d)}) \tag{4}$$

$$\begin{aligned} L_{I_{u,LOS}}(\frac{\beta d_0^{\alpha_d}}{P_d}) &= \exp(-\lambda_u \int_V (1 - \frac{1}{1+\frac{\beta d_0^{\alpha_d}}{P_d} P_u P_{LOS} x_i^{-\alpha_u}})dx) \\ &= \exp(-\lambda_u \int_{h1}^{h2}\int_0^{2\pi}\int_0^{\infty} (1 - \frac{1}{1+\frac{\beta d_0^{\alpha_d}}{P_d} P_u (\sqrt{r^2+z^2})^{-\alpha_u} \frac{1}{1+C\exp(-B(\frac{180}{\pi}\arctan(z/r)-C))}}) r dr d\phi dz) \\ &= \exp(-2\pi\lambda_u H_1(\beta, d_0, h, \alpha_d, \alpha_u)). \end{aligned} \tag{5}$$

$$\begin{aligned} L_{I_{u,\mathrm{NLoS}}}(\frac{\beta d_0^{\alpha_d}}{P_d}) &= \exp(-2\pi\lambda_u \int_{h1}^{h2}\int_0^{\infty} (1 - \frac{1}{1+\frac{\beta d_0^{\alpha_d}}{P_d} P_u \eta (\sqrt{r^2+z^2})^{-\alpha_u} (1 - \frac{1}{1+C\exp(-B(\frac{180}{\pi}\arctan(z/r)-C))})}) r dr dz) \\ &= \exp(-2\pi\lambda_u H_2(\beta, d_0, h, \alpha_d, \alpha_u)). \end{aligned} \tag{6}$$

$$H_1(\beta, d_0, h, \alpha_d, \alpha_u) = \int_{h1}^{h2}\int_0^{\infty} (1 - \frac{1}{1+\frac{\beta d_0^{\alpha_d}}{P_d} P_u (\sqrt{r^2+z^2})^{-\alpha_u} \frac{1}{1+C\exp(-B(\frac{180}{\pi}\arctan(z/r)-C))}}) r dr dz. \tag{7}$$

$$H_2(\beta, d_0, h, \alpha_d, \alpha_u) = \int_{h1}^{h2}\int_0^{\infty} (1 - \frac{1}{1+\frac{\beta d_0^{\alpha_d}}{P_d} P_u \eta (\sqrt{r^2+z^2})^{-\alpha_u} (1 - \frac{1}{1+C\exp(-B(\frac{180}{\pi}\arctan(z/r)-C))})}) r dr dz. \tag{8}$$

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the typical ground network user. x_i is the distance between the ith UAV and the typical ground network user.

With the definition of the coverage probability, the coverage probability of a typical ground network user is

$$\begin{aligned} P_1 &= P(\gamma_{gu} > \beta), \\ &\overset{(a)}{=} \exp(-\frac{\beta d_0^{\alpha_d}(I_{gu}^c + I_u + N)}{P_d}) \\ &= \exp(-\frac{\beta d_0^{\alpha_d} I_{gu}^c}{P_d}) \exp(-\frac{\beta d_0^{\alpha_d} I_u}{P_d}) \exp(-\frac{\beta d_0^{\alpha_d} N}{P_d}) \\ &= L_{I_{gu}^c}(\frac{\beta d_0^{\alpha_d}}{P_d}) L_{I_u}(\frac{\beta d_0^{\alpha_d}}{P_d}) \exp(-\frac{\beta d_0^{\alpha_d} N}{P_d}), \end{aligned} \tag{11}$$

where (a) is obtained from the exponential distribution of g_0. $L_A(*)$ is the Laplace transform of the random variable A.

With the considered path-loss model (1), I_u can be re-expressed as

$$I_u = I_{u,\mathrm{LoS}} + I_{u,\mathrm{NLoS}}. \tag{12}$$

The Laplace function of I_u then can be expressed as

$$L_{I_u}(\frac{\beta d_0^{\alpha_d}}{P_d}) = L_{I_{u,\mathrm{LoS}}}(\frac{\beta d_0^{\alpha_d}}{P_d}) L_{I_{u,N\mathrm{LoS}}}(\frac{\beta d_0^{\alpha_d}}{P_d}). \tag{13}$$

Since g_i is a random variable independent of the point process Φ_u, we have

$$\begin{aligned} & L_{I_{u,\mathrm{LoS}}}(\frac{\beta d_0^{\alpha_d}}{P_d}) = E_{I_{u,\mathrm{LoS}}}[\exp(\frac{\beta d_0^{\alpha_d}}{P_d} I_{u,\mathrm{LoS}})] \\ &= E_{g_i,\Phi_u}[\prod_{x_i \in \Phi_u \backslash \{\mathbf{0}\}} \exp(\frac{\beta d_0^{\alpha_d}}{P_d} g_i P_u P_{\mathrm{LoS}} x_i^{-\alpha_u})] \\ &= E_{\Phi_u}[\prod_{x_i \in \Phi_u \backslash \{\mathbf{0}\}} E_{g_i}[\exp(\frac{\beta d_0^{\alpha_d}}{P_d} P_u P_{\mathrm{LoS}} x_i^{-\alpha_u})]] \\ &= E_{\Phi_u}[\prod_{x_i \in \Phi_u \backslash \{\mathbf{0}\}} \frac{1}{1+\frac{\beta d_0^{\alpha_d}}{P_d} P_u P_{\mathrm{LoS}} x_i^{-\alpha_u}}], \end{aligned} \tag{14}$$

and

$$\begin{aligned} & L_{I_{u,\mathrm{NLoS}}}(\frac{\beta d_0^{\alpha_d}}{P_d}) \\ &= E_{\Phi_u}[\prod_{x_i \in \Phi_u \backslash \{\mathbf{0}\}} \frac{1}{1+\frac{\beta d_0^{\alpha_d}}{P_d} P_u (1-P_{\mathrm{LoS}}) \eta x_i^{-\alpha_u}}]. \end{aligned} \tag{15}$$

Hence, $L_{I_u}(\frac{\beta d_0^{\alpha_d}}{P_d})$ is derived as follows.

$$\begin{aligned} L_{I_u}(\frac{\beta d_0^{\alpha_d}}{P_d}) &= E_{\Phi_u}[\prod_{x_i \in \Phi_u} \frac{1}{1+\frac{\beta d_0^{\alpha_d}}{P_d} P_u P_{\mathrm{LoS}} x_i^{-\alpha_u}}] \\ &\times E_{\Phi_u}[\prod_{x_i \in \Phi_u} \frac{1}{1+\frac{\beta d_0^{\alpha_d}}{P_d} P_u (1-P_{\mathrm{LoS}}) \eta x_i^{-\alpha_u}}]. \end{aligned} \tag{16}$$

Applying the probability generating function of PPP [14]

$$E(\prod_{x_i \in \Phi} f(x)) = \exp(-\lambda_d \int_V [1-f(x)]dx), \tag{17}$$

then $L_{I_{gu}^c}(\frac{\beta d_0^{\alpha_d}}{P_d})$ can be derived as (4) [13]. $L_{I_u}(\frac{\beta d_0^{\alpha_d}}{P_d})$ can

$$
\begin{aligned}
L_{I^c_{u,\text{LoS}}}(\frac{\beta x_0^{\alpha_u}}{P_u}) &= \exp(-\lambda_u \int\limits_V (1-\frac{1}{1+\beta x_0^{\alpha_u} P_{\text{LoS}} x_i^{-\alpha_u}})dx) \\
&= \exp(-\lambda_u \int_{h1}^{h2}\int_0^{2\pi}\int_0^{\infty} (1-\frac{1}{1+\beta x_0^{\alpha_u}(\sqrt{r^2+z^2})^{-\alpha_u}\frac{1}{1+C\exp(-B(\frac{180}{\pi}\arctan(z/r)-C))}})rdrd\phi dz) \\
&= \exp(-2\pi\lambda_u H_3(\beta, x_0, h, \alpha_u)).
\end{aligned} \tag{18}
$$

$$
\begin{aligned}
L_{I^c_{u,\text{NLoS}}}(\frac{\beta x_0^{\alpha_u}}{P_u}) &= \exp(-2\pi\lambda_u \int_{h1}^{h2}\int_0^{\infty} (1-\frac{1}{1+\beta x_0^{\alpha_u}\eta(\sqrt{r^2+z^2})^{-\alpha_u}(1-\frac{1}{1+C\exp(-B(\frac{180}{\pi}arctan(z/r)-C))})})rdrdz) \\
&= \exp(-2\pi\lambda_u H_4(\beta, x_0, h, \alpha_u)).
\end{aligned} \tag{19}
$$

$$
H_3(\beta, x_0, h, \alpha_u) = \int_{h1}^{h2}\int_0^{\infty} (1-\frac{1}{1+\beta x_0^{\alpha_u}(\sqrt{r^2+z^2})^{-\alpha_u}\frac{1}{1+C\exp(-B(\frac{180}{\pi}\arctan(z/r)-C))}})rdrdz. \tag{20}
$$

$$
H_4(\beta, x_0, h, \alpha_u) = \int_{h1}^{h2}\int_0^{\infty} (1-\frac{1}{1+\beta x_0^{\alpha_u}\eta(\sqrt{r^2+z^2})^{-\alpha_u}(1-\frac{1}{1+C\exp(-B(\frac{180}{\pi}\arctan(z/r)-C))})})rdrdz. \tag{21}
$$

be derived using (5) and (6), where $H_1(\beta, d_0, h, \alpha_d, \alpha_u)$ and $H_2(\beta, d_0, h, \alpha_d, \alpha_u)$ are provided in (7) and (8), respectively.

B. The coverage probability of UAV network user

The coverage probability of a typical UAV network user is defined as

$$
P_2 = P(\gamma_{uu} > \beta), \tag{22}
$$

where γ_{uu} is the received SINR of the UAV network user and β is the SINR threshold[2]. With the considered path-loss model (1), P_2 can be expressed as

$$
\begin{aligned}
P_2 &= P_{\text{LoS}} P(\frac{P_u x_0^{-\alpha_u} g_i}{I_u^c} > \beta) + P_{\text{NLoS}} P(\frac{\eta P_u x_0^{-\alpha_u} g_i}{I_u^c} > \beta) \\
&= P_{\text{LoS}} \exp(-\frac{\beta x_0^{\alpha_u} I_u^c}{P_u}) + (1-P_{\text{LoS}})\exp(-\frac{\beta x_0^{\alpha_u} I_u^c}{\eta P_u}) \\
&= P_{\text{LoS}} L_{I_u^c}(-\frac{\beta x_0^{\alpha_u}}{P_u}) + (1-P_{\text{LoS}}) L_{I_u^c}(-\frac{\beta x_0^{\alpha_u}}{\eta P_u}),
\end{aligned} \tag{23}
$$

where x_0 is the distance between the typical UAV user and its associated UAV. The term I_u^c is the received interference from UAVs and we have

$$
\begin{aligned}
I_u^c &= I^c_{u,\text{LoS}} + I^c_{u,\text{NLoS}} \\
&= \sum_{x_i \in \Phi_u \setminus \{\mathbf{0}\}} P_{\text{LoS}} P_u x_i^{-\alpha_u} g_i + \\
&\sum_{x_i \in \Phi_u \setminus \{\mathbf{0}\}} (1-P_{\text{LoS}})\eta P_u x_i^{-\alpha_u} g_i.
\end{aligned} \tag{24}
$$

Similar to the derivation of the coverage probability of ground network user, we have

$$
\begin{aligned}
L_{I_u^c}(\frac{\beta x_0^{\alpha_u}}{P_u}) &= L_{I^c_{u,\text{LoS}}}(\frac{\beta x_0^{\alpha_u}}{P_u}) L_{I^c_{u,\text{NLoS}}}(\frac{\beta x_0^{\alpha_u}}{P_u}) \\
&= E_{\Phi_u}[\prod_{x_i \in \Phi_u \setminus \{\mathbf{0}\}} \frac{1}{1+\beta x_0^{\alpha_u} P_{\text{LoS}} x_i^{-\alpha_u}}] \times \\
&E_{\Phi_u}[\prod_{x_i \in \Phi_u \setminus \{\mathbf{0}\}} \frac{1}{1+\beta x_0^{\alpha_u}(1-P_{\text{LoS}})\eta x_i^{-\alpha_u}}].
\end{aligned} \tag{25}
$$

The $L_{I^c_{u,\text{LoS}}}(\frac{\beta x_0^{\alpha_u}}{P_u})$ and $L_{I^c_{u,\text{NLoS}}}(\frac{\beta x_0^{\alpha_u}}{P_u})$ can be derived in (18) and (19), where $H_3(\beta, x_0, h, \alpha_u)$ and $H_4(\beta, x_0, h, \alpha_u)$ are provided in (20) and (21), respectively.

IV. Numerical Results and Analysis

This section provides the numerical results of the coverage probabilities of UAV network user and ground network user. Besides, the transmission capacity of UAV network is defined and maximized. The parameters in the simulations are summarized in Table 1.

A. The coverage probability of ground network user

The coverage probability of a typical ground network user, namely, P_1 is illustrated in Fig. 2 as a function of h_1 and Δh. The 20-point Monte Carlo simulation results are provided in Fig. 2. Each point undergoes 1000 times Monte Carlo simulations. It is verified that the theoretical results, namely, the surface fits well with the points. Notice that when h_1 is large, for example, when h_1 is close to 100 m, P_1 is large. This is due to the fact that when the UAVs are high above the ground, the interference from UAVs to the typical ground network user is small, which will increase the value of P_1. When Δh is increasing, P_1 is decreasing because the probability of LoS propagation from UAVs to the ground network user is increasing. This discovery is also observed

[2]Note that although we use the same parameter β for the SINR threshold, the values of β for ground network and UAV network can be different.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
P_u	5 W
P_d	0.1 W
α_u	3
α_d	4
B and C	0.136 and 11.95
β	0.1
η	0.1
λ_u	10^{-4} per square meter
λ_d	10^{-3} per square meter
d_0	10 m
N	10^{-9} W

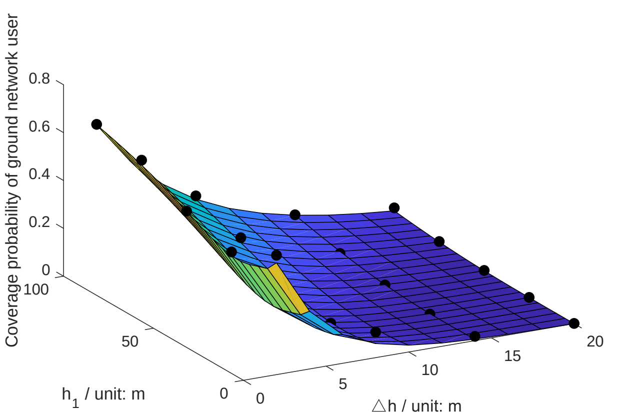

Fig. 2. The coverage probability of ground network user versus h_1 and Δh.

in Fig. 3, which depicts the relation between P_1 and h_1 with different values of Δh. In Fig. 3, when h_1 is increasing from 0, P_1 is firstly decreasing because the probability of LoS propagation between the UAV and the ground network user is increasing. When h_1 exceeds a threshold, P_1 is increasing with the increase of h_1 because the propagation path between the UAV and the ground network user becomes long in this case, which will decrease the interference from UAVs to ground network user.

B. The coverage probability of UAV network user

The coverage probability of UAV network user, namely, P_2 is illustrated in Fig. 4. The 20-point Monte Carlo simulation results are provided in Fig. 4. Each point undergoes 1000 times Monte Carlo simulations. Notice that the theoretical results, namely, the surface fits well with the points. The P_2 fluctuates with the increase of h_1. For each Δh, there exists an optimal h_1 to maximize P_2. Besides, with the increase of Δh, P_2 is decreasing because the signal link is long. A critical observation is that the when $\Delta h \to 0$, namely, when UAVs are distributed in 2D plane, P_2 has maximum value in Fig. 4.

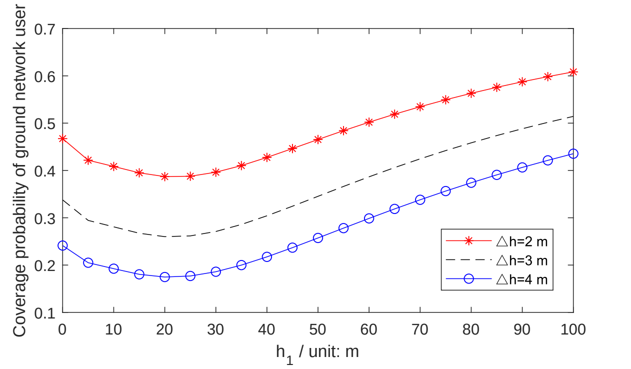

Fig. 3. The relation between the coverage probability of ground network user and h_1 with different values of Δh.

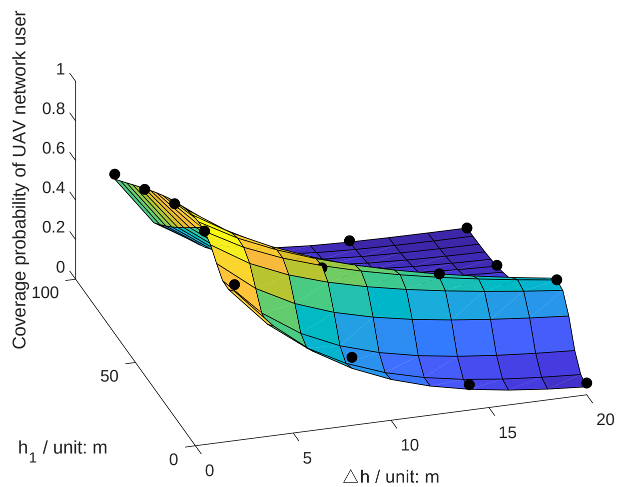

Fig. 4. The coverage probability of UAV network user versus h_1 and Δh.

C. The optimal height of UAVs

The definition of transmission capacity (TC) in [14] is applied to verify the performance of UAV network, which is as follows [14].

$$T_u = \lambda_u P(\gamma_{uu} > \beta)\log(1+\beta), \tag{26}$$

where γ_{uu} is the SINR of the UAV network user and T_u denotes the TC of UAV network. With the constraint of the coverage probability of ground network user, the optimal height of UAVs, defined as h_1, can be found to maximize the TC of UAV network. The optimization model is as follows.

$$\begin{aligned} &\max_{h_1}\ T_u \\ &s.t.\quad P_1 \geq \alpha. \end{aligned} \tag{27}$$

Although the form of (27) is simple, the object function and constraint condition are complex. It is difficult to derive a closed-form solution. Hence the optimal solution of h_1 is derived numerically.

With $\alpha = 0.4$, the relation between the TC of UAV network and h_1 is illustrated in Fig. 5. The optimal h_1 to maximize the TC of UAV network can be searched. It is verified that with

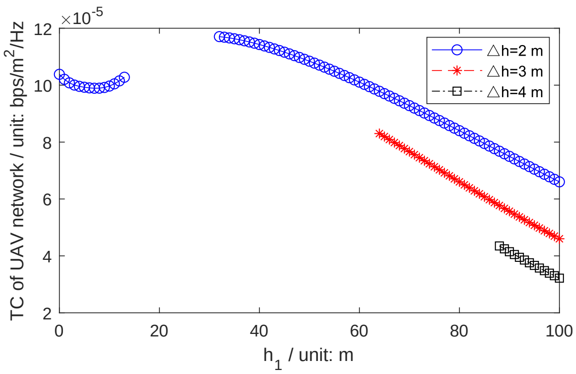

Fig. 5. The relation between the transmission capacity of UAV network user and h_1 with $\alpha = 0.4$ and different values of Δh.

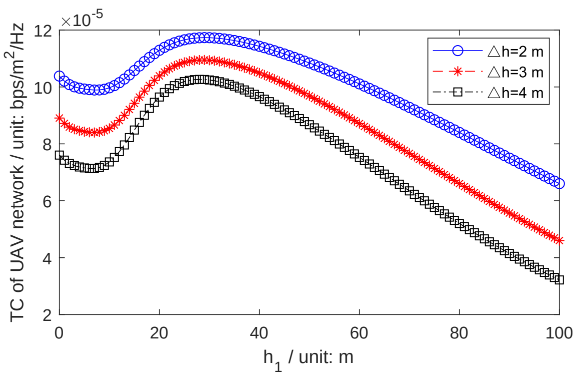

Fig. 6. The relation between the transmission capacity of UAV network user and h_1 with $\alpha = 0.1$ and different values of Δh.

the decrease of Δh, the TC of UAV network increases. When $\Delta h \to 0$, namely, the UAVs are distributed in a 2D plane, the TC of UAV network is maximum. With the constraint $\alpha = 0.4$, there are vacant segments where the h_1 does not satisfy the constraint of (27). However, when the constraint $\alpha = 0.1$, all the values of h_1 in Fig. 6 are feasible solutions. In this case, the optimal h_1 can still be searched to maximize the TC of UAV network.

V. Conclusion

In this paper, the spectrum sharing between UAV-based wireless mesh networks and ground networks is analyzed using stochastic geometry. The impact of the height of UAVs, the transmit power of UAVs, the density of UAVs and the vertical range on the coverage probability of ground network user and UAV network user is analyzed. Then the optimal height of UAVs is achieved to maximize the transmission capacity of UAV networks. This paper provides fundamental analysis for the spectrum sharing of UAV-based wireless mesh networks, which may motivate the study of spectrum sharing for more aerial wireless mesh networks.

Acknowledgment

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