Correspondence

The Outage-Free Replacement Problem in Unmanned Aerial Vehicle Base Stations

Bhola, Chuan-Chi Lai, *Member, IEEE*, and Li-Chun Wang, *Fellow, IEEE*

***Abstract*—Thanks to the feature of on-demand and flexible deployment, unmanned aerial vehicle base stations (UAV-BS) can enhance coverage and capacity beyond current 5 G cellular networks. The main challenge in deploying UAV-BS lies in the fact that the limited battery in UAB-BS cannot support long-time reliable services. Therefore, a serving UAV-BS being running out its power needs to be replaced with a new fully-charged UAV-BS. This is called UAV-BS replacement process. However, most existing UAV-BS replacement methods ignore the link outage problem during the replacement. Thus the outage-free replacement problem (OFRP) for UAV-BSs arises. We provide a method to calculate the outage probability of the UAV replacement approach. We further formulate the Outage Probability Minimization Problem (OPMP) for UAV-BS replacement. To solve this problem, a 3-Dimensional Outage-Free Replacement Approach (3D-OFRA) is presented, which exploits different heights of swapping UAV-BSs during the replacement process. More importantly, we provide the guidelines of determining the distance between two UAV-BSs to minimize the link outage possibility during the UAV-BS replacement process. Our numerical results show that with the recommended distance between two UAV-BSs based on 3D-OFRA, the outage probability of the served UEs approaches to zero, compared with 40% of the traditional direct replacement approach.**

***Index Terms*—UAV Base station, replacement, hotspot, seamless service, outage probability.**

I. Introduction

Unmanned Aerial Vehicle mounted Base Station (UAV-BS) gets much more attention recently and becomes a promising solution to meet the outburst traffic demand by expanding coverage and capacity for 5 G and beyond networks [1] [2]. The deployment of UAV-BS is much more flexible than conventional ground base stations (GBS). Compared with GBS, UAV-BS can also possibly provide better communication quality to terrestrial users by propagating signals through the line-of-sight (LoS) link. Many existing works have used UAV-BSs to provide wireless applications with different concerns: number of served users [3], trajectory optimization [4], power control [5], interference management [6] [7], and frequency utilization [8] [9], etc.

However, UAV-BS faces many challenges, especially battery capacity issues. Generally, the service time of UAV-BS is about 15 to 30 minutes only [1], so cellular operators need to prepare a backup UAV-BS to replace the UAV-BS before its battery runs out. The replacement UAB-BS has become necessary for long-term communication services.

In the literature, the UAV-BS replacement is a hot research topic [10] [11]. The authors in [10] proposed a scheduler aorithm to schedule multiple UAV-BS replacements for long-term (several hours) UAV-BS communication services to the users in the hot spots. In order to increase the service time of the UAV-BS group, [11] proposed a model of swapping the positions of the UAV-BS with low residual battery and the adjacent UAV-BS with high remaining battery.

Nevertheless, the existing UAV-BS replacement approaches cannot provide reliable communication services during the UAV-BS replacement process. As shown in Fig. 1, due to the mobility/movement of UAV-BSs during the replacement procedure, UEs in the shaded area will be covered by none of UAVs for a short period of time and then experience the link outage issue. Such a problem is called *Outage-Free Replacement Problem* (OFRP).

To solve OFRP, we propose a *3-Dimensional Outage-Free Replacement Approach* (3D-OFRA), which utilizes the height of UAV-BS to ensure that all ground hotspot users can always connect to UAV-BS. In the proposed OFRA, we first analyze the outage probability of the direct replacement approach, and then formulate the OFRP as an *Outage Probability Minimization Problem* (OPMP). After that, we also suggest a condition, this is the upper limit of the horizontal distance between two UAV-BSs, so that the outage probability can be zero during the entire UAV-BS replacement process. In this way, all users in the hotspot area can seamlessly transfer the association to the new upcoming UAV-BS.

Numerical results show that there is usually a nonlinear relationship between the outage probability and the horizontal distance between two UAV-BSs. In addition, the results verify that the outage probability is zero when the recommended distance condition is met. This means that the proposed OFRA can effectively solve OPMP.

The main contributions of this paper are summarized as follows:

- Compare with the existing solutions of UAV replacement, this work is the first one to identify and solve the Outage-Free Replacement Problem (OFRP), and we believe that this work can lead an important contribution to related research field.
- We suggest a horizontal distance condition between two UAV-BSs for ensuring the proposed 3-Dimensional Outage-Free Replacement Approach (3D-OFRA) can guarantee zero outage to UEs in the target hotspot area.
- With the proposed 3D-OFRA, the collision problem of UAV-BSs during the replacement procedure can be avoided since two UAV-BSs fly at different altitudes and follow the suggested horizontal distance condition.
- The simulation result indicates that the proposed 3D-OFRA indeed provides the optimal solution for the Outage Probability Minimization Problem (OPMP) modeled from OFRP, under the suggested (upper-bound) horizontal distance condition.

The rest of letter is organized as follows. Section II presents considered system model with some assumptions. Section III presents the

Manuscript received March 5, 2021; revised July 10, 2021; accepted September 7, 2021. Date of publication September 30, 2021; date of current version December 17, 2021. This research was supported in part by Ministry of Science and Technology under the Grants MOST 110-2634-F-009-021-, MOST 110-2221-E-A49-039-MY3, and MOST 110-2222-E-035-004-MY2, Taiwan. This work was also supported in part by the Center for Open Intelligent Connectivity from The Featured Areas Research Center Program within the framework of the Higher Education Sprout Project by the Ministry of Education (MOE) in Taiwan. The review of this article was coordinated by Prof. Zhu Han. *(Corresponding author: Li-Chun Wang.)*

Bhola is with the Electrical Engineering and Computer Science International Graduate Program, National Yang Ming Chiao Tung University, Hsinchu 30010, Taiwan (e-mail: bhola.eed06g@nctu.edu.tw).

Chuan-Chi Lai is with the Department of Information Engineering and Computer Science, Feng Chia University, Taichung 40724, Taiwan (e-mail: chuanclai@fcu.edu.tw).

Li-Chun Wang is with the Department of Electrical and Computer Engineering, National Yang Ming Chiao Tung University, Hsinchu 30010, Taiwan (e-mail: wang@nycu.edu.tw).

Digital Object Identifier 10.1109/TVT.2021.3116701

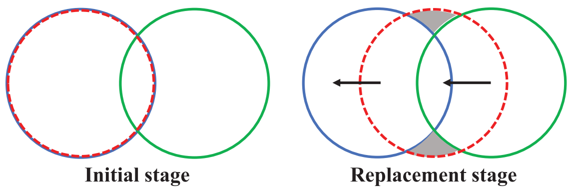

Fig. 1. The scenario of coverage outage (shaded area) during the replacement process, where red dot circle is the target hotspot area, the blue circle is the coverage of the leaving UAV-BS, the green circle is the coverage of the upcoming fully charged UAV-BS, the black arrows indicate that the two UAV-BS are moving in the same direction and speed.

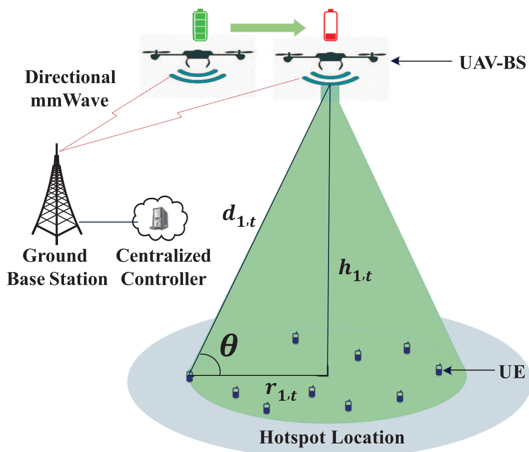

Fig. 2. The UAV-BS replacement scenario for serving the hotspot area.

problem formulation. Section IV explains the proposed approach with the algorithm, example, and analysis in detail. In Section V, we show the simulation results and validate the performance of the proposed algorithm in various situations. Finally, the conclusion remarks of this work are given in Section VI.

II. System Model

As shown in Fig. 2, we consider the scenario that the centralized network controller/cellular operator wants to replace the UAV-BS U_1 with a fully charged UAV-BS U_2. We assume that the target hotspot area is given as a circular coverage area, $T_A = (x_A, y_A, r_A)$, where (x_A, y_A) is the horizontal coordinates of T_A and r_A is the coverage radius. A set of stationary user equipments (UEs), $E = \{u_1, u_2, \ldots, u_M\}$, are uniformly distributed in T_A. We denote $u_m = (x_m, y_m)$ as the coordinates of a ground UE, where $m = 1, 2, \ldots, M$. UAV-BS U_i is allowed to fly within a predefined allowable altitudes, $h_{i,t} \in [h_{\min}, h_{\max}]$, where $i \in \{1, 2\}$. The 3D location of a UAV-BS at time t is denoted as $U_{i,t} = (x_{i,t}, y_{i,t}, h_{i,t}), i \in \{1, 2\}, t \in [0, T]$, where T is the complete time of the UAV-BS replacement.

In this work, we adopt the air-to-ground channel model [12], so the average path loss of the LoS and non-LoS (NLoS) signals respectively are

$$L^{\text{LoS}}_{h_{i,t},r_{i,m,t}} = 20\log_{10}\left(\frac{4\pi f_c d_{i,m,t}}{c}\right) + \eta_{LoS}$$

and

$$L^{\text{NLoS}}_{h_{i,t},r_{i,m,t}} = 20\log_{10}\left(\frac{4\pi f_c d_{i,m,t}}{c}\right) + \eta_{NLoS}.$$

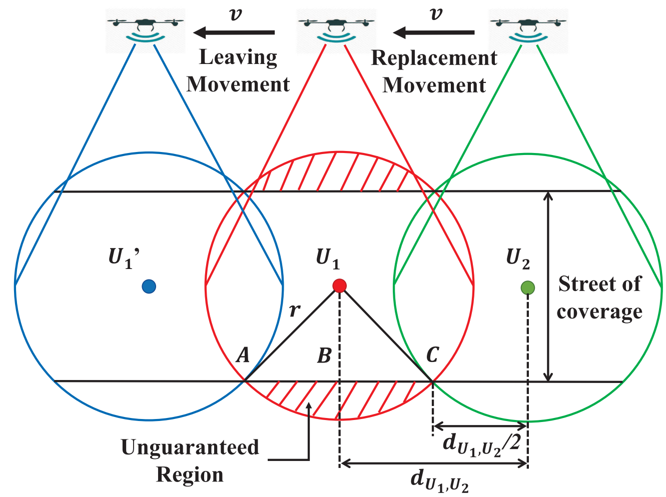

Fig. 3. The outage area of the straightforward UAV-BS replacement approach.

Note that η_{LoS} and η_{NLoS} are the free space propagation loss which depends on the environment, c is the speed of light, f_c is the carrier frequency, and $d_{i,m,t} = \sqrt{r^2_{i,m,t} + h^2_{i,t}}$ is the Euclidean distance between UAV-BS U_i and UE u_m at time t. The probability of LoS signals from U_i to u_m is

$$P^{\text{LoS}}_{h_{i,t},r_{i,m,t}} = \frac{1}{1 + a\exp\left(-b\left(\frac{180}{\pi}\theta_{i,m,t} - a\right)\right)}$$

where $\theta_{i,m,t} = \tan^{-1}(\frac{h_{i,t}}{r_{i,m,t}})$ is the elevation angle of the UAV-BS; a and b are the constant factors depend on the different environments (rural, urban, dense urban, etc.); and $r_{i,m,t} = \sqrt{(x_{i,t} - x_m)^2 + (y_{i,t} - y_m)^2}$ is the horizontal distance between UAV-BS U_i and UE u_m at time t. With $P^{\text{LoS}}_{h_{i,t},r_{i,m,t}}$, the probability of NLoS signals from U_i to u_m is $P^{\text{NLoS}}_{h_{i,t},r_{i,m,t}} = 1 - P^{\text{LoS}}_{h_{i,t},r_{i,m,t}}$. In summary, the average path loss of the signal from U_i and u_m will be

$$\begin{aligned} L_{h_{i,t},r_{i,m,t}} &= P^{\text{LoS}}_{h_{i,t},r_{i,m,t}} \times L^{\text{LoS}}_{h_{i,t},r_{i,m,t}} \\ &\quad + P^{\text{NLoS}}_{h_{i,t},r_{i,m,t}} \times L^{\text{NLoS}}_{h_{i,t},r_{i,m,t}} \\ &= 20\log_{10}(d_{i,m,t}) + \alpha \times P^{\text{LoS}}_{h_{i,t},r_{i,m,t}} + \beta \end{aligned} \quad (1)$$

where $\alpha = \eta_{LoS} - \eta_{NLoS}$ and $\beta = 20\log_{10}(\frac{4\pi f_c}{c}) + \eta_{NLoS}$.

For simplicity, we assume that the operating UAV-BS uses a fixed power P^{transmit} to transmit signals, and the power received by UE u_m is $P^{\text{receive}}_{m,t} = P^{\text{transmit}} - L_{h_{i,t},r_{i,m,t}}$. In the considered scenario, we assume that the allowable path loss (ψ) is predefined by the cellular operator. According to [12], we can find the optimal elevation angle (θ_{opt}) of the UAV-BS by solving the following partial differential equation, $\frac{\partial r}{\partial h} = \frac{\partial r}{\partial \theta}\frac{\partial \theta}{\partial h} = 0$. With the optimal elevation angle (θ_{opt}) and the allowable path loss (ψ), the allowable Euclidean distance between a UAV-BS and its covered UE $(d_{\max})$ can be obtained from (1). Thus, the maximum altitude and the maximum coverage radius of the UAV-BS are $h_{\max} = d_{\max}\sin\theta_{\text{opt}}$ and $r_{\max} = d_{\max}\cos\theta_{\text{opt}}$, respectively.

III. Outage Probability Minimization Problem

Considering the UAV-BS replacement scenario using a straightforward approach in Fig. 3, two UAV-BSs U_1 and U_2 fly at the same altitude and provide the identical coverage size with the radius r. The size of hotspot area, $|T_A| = \pi r_A^2$, is equal to the coverage of U_1

in this scenario. The replacement procedure will be triggered when the horizontal distance between two UAV-BSs meets the given distance constraint $d_{U_1,U_2} = \overline{U_1U_2}$. In this straightforward replacement scenario, U_1 is leaving the hotspot area with a fixed speed v and U_2 is going to the horizontal location of U_1 with the same speed and direction. It is clear that only the UE in the *Street of Coverage* [13] [14] region can seamlessly hands over its association to the new UAV-BS. Conversely, the separated shaded regions do not be covered by U_1 and U_2 simultaneously during the entire replacement process. It means that the UEs in shaded regions will not be covered by any one UAV for a certain time period, so we denote these separated shaded regions as unguaranteed regions.

Consider the triangle $\triangle U_1BC$, we can obtain the angle $\angle BU_1C = \frac{\angle AU_1C}{2} = \sin^{-1}(\frac{d_{U_1,U_2}}{2r})$ and the angle $\angle AU_1C = 2\angle BU_1C$. Then, we can calculate the size of sector $\triangledown AU_1C = \frac{\pi r^2 \angle AU_1C}{360}$. Since $\overline{AC} = \overline{U_1U_2} = d_{U_1,U_2} = 2r\sin(\frac{\angle AU_1C}{2})$ and $\overline{BU_1} = r\cos(\frac{\angle AU_1C}{2})$, the size of triangle $\triangle AU_1C$ can be obtained by $\triangle AU_1C = \frac{\overline{AC}\times\overline{BU_1}}{2} = \frac{1}{2}d_{U_1,U_2}r\cos(\frac{\angle AU_1C}{2}) = \frac{1}{2}r^2\sin\angle AU_1C$. Then, the size of the shaded area can be derived by

$$\begin{aligned}\mathcal{A}_{\text{outage}} &= 2\times(\triangledown AU_1C - \triangle AU_1C)\\ &= r^2\times\left(\frac{\pi\angle AU_1C}{180} - \sin\angle AU_1C\right).\end{aligned}$$

Finally, the outage probability of the replacement approach is

$$\begin{aligned}\mathrm{P}_{\text{outage}}(T_A) &= \frac{\mathcal{A}_{\text{outage}}}{|T_A|}\times 100\%\\ &= \left(\frac{\angle AU_1C}{180} - \frac{\sin\angle AU_1C}{\pi}\right)\times 100\%. \end{aligned}\tag{2}$$

However, for the above straightforward replacement approach, $P_{\text{outage}} = 0$ is impossible to be achieved since $P_{\text{outage}} = 0$ holds only if $\theta = 0$ and $d_{U_1,U_2} = 0$. In practice, the collision of two UAV-BSs will occur if $d_{U_1,U_2} = 0$. Hence, the objective of this work is to minimize outage probability during UAV-BS replacement procedure within the allowable constraint, $h_{\min} \leq h_{i,t} \leq h_{\max}$, where $i \in \{1,2\}$. In this letter, we only consider the case of $r_A < r_{\max}$, where r_A is the radius of the hotspot area and $r_{\max}$ is the maximum radius provided by a UAV-BS.

With the above assumptions, the OFRP problem under consideration can be formulated as an Outage Probability Minimization Problem (OPMP), which can be defined as

$$\min_{U_{i,t},\forall i} \ \mathrm{P}_{\text{outage}}(T_A) = \frac{1}{M}\sum_{m=1}^{M}\Delta_m \tag{P1}$$

$$s.t.\ \ \Delta_m = \begin{cases}1, & \text{if } \sum_{t=1}^{T}\delta_{m,t} > 0\\ 0, & \text{otherwise}\end{cases} \tag{3}$$

$$\delta_{m,t} = \begin{cases}1, & \text{if } r_{1,m,t} > r_{1,t} \wedge r_{2,m,t} > r_{2,t}\\ 0, & \text{otherwise}\end{cases} \tag{4}$$

$$h_{\min} \leq h_{i,t} \leq h_{\max}, \forall i \tag{5}$$

$$r_{\min} \leq r_{i,t} \leq r_{\max}, \forall i \tag{6}$$

where $U_{i,t} = (x_{i,t}, y_{i,t}, h_{i,t})$ is the 3D coordinates of UAV-BS U_i; $i \in \{1,2\}$, M is the number of UEs; Δ_m is a function used to indicate UE u_m has been interrupted during the time period of the UAV-BS replacement, T; and $\delta_{m,t}$ is a binary variable to indicate a UE is whether out of U_1's coverage $r_{1,m,t}$ and U_2's coverage, $r_{2,m,t}$, at time t.

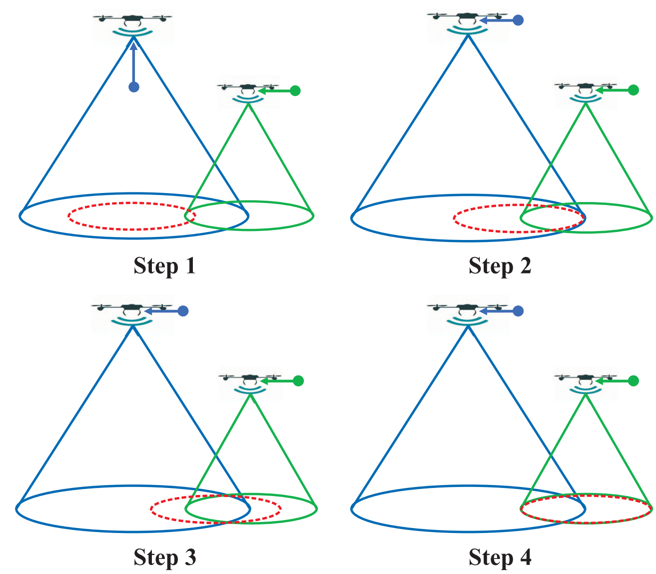

Fig. 4. The steps of OFRA, where the red dash circle is the target hotspot area, the blue circle is the coverage of the leaving UAV-BS, the green circle is the coverage of the upcoming fully charged UAV-BS, and the blue (green) arrows with dots represent the movement of each UAV-BS from the previous position to the current position.

IV. The Proposed 3-Dimensional Outage-Free UAV-BS Replacement Approach

In this section, we present the procedure of the proposed 3-Dimensional Outage-Free Replacement Approach (3D-OFRA), for provisioning reliable communications to the hotspot UEs. The proposed model aims to achieve zero outage coverage during the UAV-BS replacement procedure. Fig. 4 depicts the steps of proposed replacement approach and Algorithm 1 shows the proposed procedure. The detailed explanations are addressed below.

A. The Proposed Procedure of 3D-OFRA

The required input information includes $(T_A, \psi, h_{\min}, v)$, where T_A is the target hotspot area, ψ is the predefined allowable path loss, $h_{\min}$ is the minimum altitude of a UAV-BS redefined by local laws, and v is the fixed horizontal flying speed of a UAV-BS. The controllable parameters includes $U_{1,t}$ and $U_{2,t}$, which are the coordinates of two UAV-BSs. The output of this algorithm is the outage probability of T_A. At the first step, the system gets following important constraints, $h_{\max}$, $r_{\max}$, and $r_{\min}$, by the operations from lines 1 and 3. With $h_{\max}$, the system increases the altitude of UAV-BS U_1 until $h_{1,t=1} = h_{\max}$ at line 4. Since the maximum altitude $h_{\max}$ is derived by (1) with the given allowable path loss, the communication outage of all the UEs in T_A will not occur. The operation at line 5 flies the fully charged UAV-BS U_2 with a predefined speed v to the T_A. UAV-BS U_2 will fly at the appropriate altitude based on the radius of given hotspot area, r_A. At the second step, when $d_{U_1,U_2} = d^{\text{upperbound}}_{U_1,U_2}$, UAV-BS U_1 starts leaving T_A with the same speed v as UAV-BS U_2 coming. Such an operation is executed at line 6 of Algorithm 1. After the second step, both U_1 and U_2 simultaneously move with the same speed and direction until U_2 cover the whole hotspot area T_A as shown in step 4 of Fig. 4. During the time period of the UAV-BS replacement, all the UEs, covered by U_1 and U_2 at the same time, hand over their associations to U_2. The operation of step 3 is executed at line 7. After U_2 covers the whole T_A at step 4, the system keeps U_1 leaving T_A with the speed v for charging

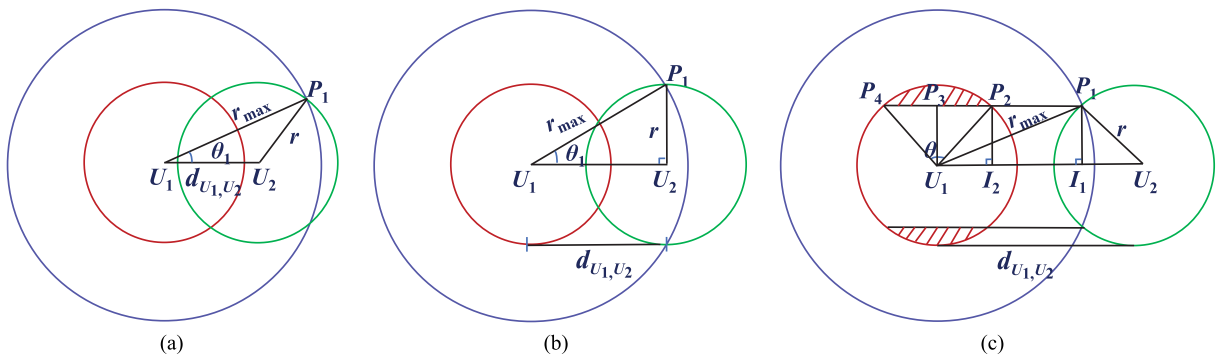

Fig. 5. The outage probabilities of different cases: (a) $d_{U_1,U_2} < \sqrt{r_{\max}^2 - r_A^2}$; (b) $d_{U_1,U_2} = \sqrt{r_{\max}^2 - r_A^2}$; and (c) $d_{U_1,U_2} > \sqrt{r_{\max}^2 - r_A^2}$, where U_1 and U_2 represent the horizontal locations of two UAV-BSs, respectively.

Algorithm 1: The Procedure of 3D-OFRA.

Input: T_A, ψ, $h_{\min}$, v, $U_{1,t}$ and $U_{2,t}$
Output: $\mathrm{P}_{\text{outage}}(T_A)$
1: Use (1) with the given ψ to derive $d_{\max}$;
2: Solve the partial differential equation $\partial r/\partial\theta = 0$ of (1) with ψ and then get θ_{opt};
3: Obtain $h_{\max} = d_{\max}\sin\theta_{\text{opt}}$, $r_{\max} = d_{\max}\cos\theta_{\text{opt}}$, and $r_{\min} = h_{\min}\cot\theta_{\text{opt}}$;
/*Step 1 $(t=1)$*/
4: UAV-BS U_1 increases $h_{1,t=1}$ of itself until $h_{1,t=1} = h_{\max}$;
5: UAV-BS U_2 starts moving to the coordinates of T_A, (x_A, y_A), with a given fixed speed v, and altitude of U_2 is $h_{2,t=1} = r_A\tan\theta_{\text{opt}}$;
/*Step 2 $(t=2)$*/
6: When $d_{U_1,U_2} = d_{U_1,U_2}^{\text{upperbound}}$, UAV-BS U_1 starts leaving T_A with the same speed v;
/*Steps 3 and 4 $(t=3)$*/
7: The UEs, simultaneously covered by T_A, U_1, and U_2, hand over the associations to U_2;
/*Steps 4 $(t=4)$*/
8: After U_2 covers the whole area of T_A, U_1 keeps leaving T_A with the speed v for charging/replacing the battery;
9: Calculate $\mathrm{P}_{\text{outage}}(T_A)$ during the time period of above operations;
10: **return** $\mathrm{P}_{\text{outage}}(T_A)$;

its battery at line 8. The system monitors and calculates the average outage probability $\mathrm{P}_{\text{outage}}(T_A)$ during the time period of executing the above operations at line 9. Finally, the system outputs the obtained $\mathrm{P}_{\text{outage}}(T_A)$ at line 10.

B. Outage Probability Analysis

The key issue is how to determine the appropriate horizontal distance d_{U_1,U_2} (at line 6) so as to achieve $\mathrm{P}_{\text{outage}}(T_A) = 0$ during the entire replacement process. According to our design, UAV-BS U_1 will increase the altitude of itself to $h_{\max}$ to provide the maximum allowable coverage radius $r_{\max}$ and wait for the upcoming fully charged UAV-BS U_2. Since each UAV-BS can move with a fixed horizontal speed, the horizontal distance d_{U_1,U_2} between U_1 and U_2 will be a constant while both UAV-BSs moves simultaneously. Fig. 5(a) and Fig. 5(b) show that the outage probability is zero ($\mathrm{P}_{\text{outage}}(T_A) = 0$) during the entire replacement procedure if $d_{U_1,U_2} \le \sqrt{r_{\max}^2 - r_A^2}$. The reason is that all the UEs in T_A are always covered by U_1 or U_2 until finishing the UAV-BS replacement. Outage only occurs under the case of $d_{U_1,U_2} > \sqrt{r_{\max}^2 - r_A^2}$ as shown in Fig. 5(c). Hence, the upper bound of the horizontal distance between U_1 and U_2 for guaranteeing zero outage probability is

$$d_{U_1,U_2}^{\text{upperbound}} = \sqrt{r_{\max}^2 - r_A^2}. \tag{7}$$

By observing the scenario depicted in Fig. 5(c), we can formulate the outage probability of the case $d_{U_1,U_2} > \sqrt{r_{\max}^2 - r_A^2}$. Note that $r_2 = r_A$ in this case. First, by law of cosines, we can calculate

$$\angle P_1U_1U_2 = \cos^{-1}\left(\frac{r_{\max}^2 + d_{U_1,U_2}^2 - r_A^2}{2\cdot r_{\max}\cdot d_{U_1,U_2}}\right).$$

Because $\angle P_1U_1I_1 = \angle P_1U_1U_2$, we can obtain $\overline{P_2I_2} = \overline{P_1I_1} = r_{\max}\cdot \sin\angle P_1U_1I_1$. Second, we can get $\angle P_2U_1I_2 = \sin^{-1}(\frac{\overline{P_2I_2}}{r_A})$ and $\angle P_2U_1P_4 = 180 - 2\angle P_2U_1I_2$. Then, the size of the shaded area can be derived by

$$\begin{aligned}\mathcal{A}_{\text{outage}} &= 2\times(\diamond P_2U_1P_4 - \triangle P_2U_1P_4)\\ &= r_A^2\times\left(\frac{\pi\angle P_2U_1P_4}{180} - \sin\angle P_2U_1P_4\right).\end{aligned}$$

Finally, the outage probability of the proposed 3D-OFRA can expressed as (8).

$$\mathrm{P}_{\text{outage}}(T_A) = \begin{cases}\left(\dfrac{\angle P_2U_1P_4}{180} - \dfrac{\sin\angle P_2U_1P_4}{\pi}\right)\\ \times 100\%, \text{if } d_{U_1,U_2} > d_{U_1,U_2}^{\text{upperbound}}\\ 0, \qquad\qquad \text{otherwise}\end{cases} \tag{8}$$

C. Complexity Analysis

The proposed 3D-OFRA is based on some analytical models. For instance, the maximum altitude of the UAV-BS is determined by the air-to-ground channel model discussed in [12] and the outage probability is derived by (8). A mathematical computation only costs $\mathcal{O}(1)$ complexity and the procedure of 3D-OFRA takes T seconds, so the time complexity of 3D-OFRA is $\mathcal{O}(T)$. To validate the correctness of (8), some simulations are needed to observe the performance gap between the simulation results and the analysis results. The simulation based 3D-OFRA is implemented to solve problem (P1) directly and the program needs to use (3) and (4) to check all the UEs are covered by any UAV-BS or not at each time step. So the time complexity will be

$\mathcal{O}(MT)$, where M is the number of UEs in the system. Furthermore, if we consider interference issue and use *Signal-to-Interference-Plus-Noise Ratio* (SINR) threshold as the condition in (4), calculating the SINR of a UE needs to derive the sum of interference from other UEs and such a computation costs $\mathcal{O}(M^2)$ at each step. Hence, the time complexity of 3D-OFRA with the consideration of interference becomes $\mathcal{O}(M^2T)$.

D. Design Discussion

In this subsection, we summarize the benefits of 3D-OFRA's design as follows:

1) Seamless Handover: In the proposed 3D-OFRA, we only allow U_1 to increase its altitude and U_2 flies at a relatively low altitude during the replacement procedure. Such a design makes it easy for a UE to receive stronger signals from the new UAV-BS U_2 and then the UE will hands its association over to U_2.
2) Collision Avoidance: Since two UAV-BSs fly at different altitudes and follow the suggested horizontal distance condition, the proposed 3D-OFRA can obviously avoid UAV-BS collisions.
3) Low Complexity: According to our analysis in the previous subsection, time complexity of the proposed 3D-OFRA is very low, $\mathcal{O}(T)$, mainly depends on the replacement time. If we design the solution from the perspective of resource allocation, interference and power control schemes need to be considered, and cause at least $\mathcal{O}(M^2T)$ complexity.
4) Less Implementation Cost: For cellular operators, the proposed 3D-OFRA is simple and easy to implement, and the UAV-BS used does not need to be equipped with expensive payload hardware, including computing units, antennas, and power amplifiers.

V. Numerical Results

We consider the urban scenario and the environmental parameters are $(a, b, \eta_{\text{LoS}}, \eta_{\text{NLoS}}) = (9.61, 0.16, 1, 20)$ given by [12]. We assume that the used spectrum frequency is $f_c = 2.4$ (GHz), the maximum allowable path-loss of the received signals UAV-BS to the UE link is $\psi = 119$ (dB), and the transmit power of a UAV is $P^{\text{transmit}} = 20$ (dBm). We conduct several simulations to verify the performance of the proposed model and compare our approach with the conventional/straightforward replacement method. The simulations are implemented in MATLAB R2019a and the program will observe the performance of comparison approaches per second.

We first observe how the horizontal distance between two UAV-BSs, d_{U_1,U_2}, affects the outage probability. In Fig. 6, we use (7) and (8) to show the outage probability of the proposed 3D-OFRA while varying the radius of hotspot area, $r_A = [1, 200]$, and the distance between two UAV-BSs, $d_{U_1,U_2} = [1, 350]$. The red line indicates the suggested/optimal values of d_{U_1,U_2} that guarantee zero outage probability to the users in the target area T_A with different radius r_A.

Second, we consider the case of $r_A = 100$ (m). In Fig. 7, the conventional replacement approach based on our analytical model, denoted as Conventional (Analytical) using black-dashed line, shows that the average outage probability increases as d_{U_1,U_2} increases. The conventional approach can achieve zero outage probability only if $d_{U_1,U_2} = 0$. However, in practice, the UAV-BS collision will occur if two UAV-BSs fly at the same altitude using the conventional replacement approach. In the proposed 3D-OFRA, we can derive the optimal (or upper-bound/maximum) horizontal distance d_{U_1,U_2} by (7). In Fig. 7, the analytical model of 3D-OFRA, denoted as 3D-OFRA (Analytical) using red-dashed line, indicates that 3D-OFRA can guarantee the zero outage probability until $d_{U_1,U_2} > d^{\text{upperbound}}_{U_1,U_2} = 175$ (m). Conversely,

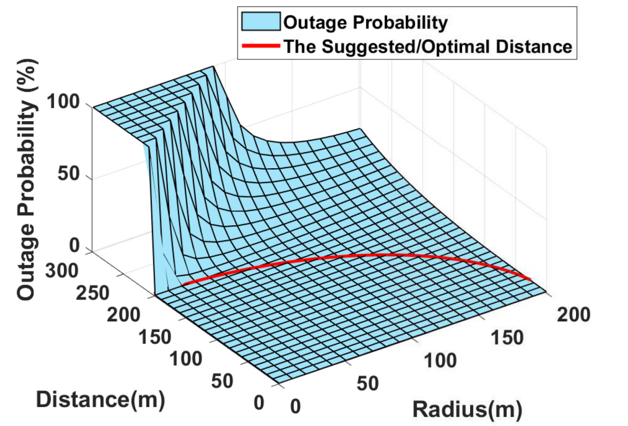

Fig. 6. The performance of the proposed replacement approach in terms of outage probability by (8) while varying the radius of hotspot area, r_A, and the horizontal distance between two UAV-BSs, d_{U_1,U_2}.

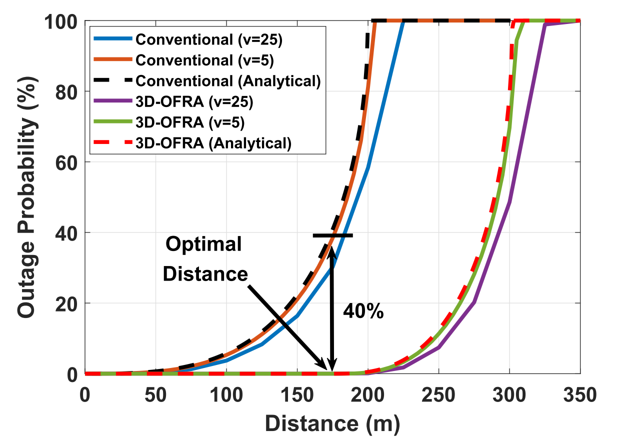

Fig. 7. The outage probabilities of different cases $d_{U_1,U_2} \in [1, 350]$ when $r_A = 100$.

the conventional straightforward approach leads about 40% of outage probability of UEs when $d_{U_1,U_2} = 175$ (m).

We also conduct some simulations with Monte Carlo method to observe the performance of conventional approach and the proposed 3D-OFRA in terms of outage probability. We uniformly spread 1,000 UEs in T_A and execute the simulation 10,000 runs to get the average result. For validating the correctness of our proposed analytical model in 3D-OFRA, we then simulate both conventional approach and 3D-OFRA with two different flying speeds $v \in \{5, 25\}$ (m/s) of UAV-BS. According to the result in Fig. 7, we find that the high-speed replacement method leads to a small outage probability while the low-speed replacement method will have the performance results close to the proposed analytical model. However, it does not means that the high-speed replacement has a better performance. The reason is that a lot of outage events cannot be well-observed in the considered discrete-time observing/simulation system, especially for the high-speed replacement approaches.

In practice, the interference from different UAV-BSs will make both conventional approach and 3D-OFRA have a worse outage performance than the analytical result. Although we do not consider interference in the proposed 3D-OFRA, the effect of interference can be solved by applying a simple fractional power control scheme. For example, the leaving UAV-BS uses less transmit power than the new UAV-BS.

VI. Conclusion

In this work, we proposed a new UAV-BS replacement approach for providing reliable communications coverage to service the users in the hotspot. The proposed 3-Dimensional Outage-Free Replacement Approach (3D-OFRA) utilizes the altitude of a UAV-BS to provide a larger coverage with the allowable path loss for the hotspot users. In this way, the users in the hotspot area can always be covered by at least one UAV-BS before the UAV-BS replacement is finished. Compared to the straightforward approach, the simulation results validate that the proposed approach not only can avoid the UAV-BS collision but also can effectively provide reliable communications with zero outage probability. An interesting work that be extended from the work is the design of collaborative replacement for a group of UAV-BSs while considering joint energy efficiency and trajectory optimization.

References

[1] A. Fotouhi *et al.*, "Survey on UAV cellular communications: Practical aspects, standardization advancements, regulation, and security challenges," *IEEE Commun. Surv. Tut.*, vol. 21, no. 4, pp. 3417–3442, Oct.–Dec. 2019.

[2] L. D. P. Pugliese, F. Guerriero, D. Zorbas, and T. Razafindralambo, "Modelling the mobile target covering problem using flying drones," *Optim. Lett.*, vol. 10, no. 5, pp. 1021–1052, Jun. 2016.

[3] C.-C. Lai, C.-T. Chen, and L.-C. Wang, "On-demand density-aware UAV base station 3D placement for arbitrarily distributed users with guaranteed data rates," *IEEE Wireless Commun. Lett.*, vol. 8, no. 3, pp. 913–916, Jun. 2019.

[4] X. Jiang, Z. Yang, N. Zhao, Y. Chen, Z. Ding, and X. Wang, "Resource allocation and trajectory optimization for UAV-enabled multi-user covert communications," *IEEE Trans. Veh. Technol.*, vol. 70, no. 2, pp. 1989–1994, Feb. 2021.

[5] J. Lu *et al.*, "UAV-enabled uplink non-orthogonal multiple access system: Joint deployment and power control," *IEEE Trans. Veh. Technol.*, vol. 69, no. 9, pp. 10 090–10 102, Sep. 2020.

[6] C.-C. Lai, L.-C. Wang, and Z. Han, "The coverage overlapping problem of serving arbitrary crowds in 3D drone cellular networks," *IEEE Trans. Mobile Computing*, to be published, doi: 10.1109/TMC.2020.3019106.

[7] L.-C. Wang, Y.-S. Chao, S.-H. Cheng, and Z. Han, "An integrated affinity propagation and machine learning approach for interference management in drone base stations," *IEEE Trans. Cogn. Commun. Netw.*, vol. 6, no. 1, pp. 83–94, Mar. 2020.

[8] F. Tang, Z. M. Fadlullah, N. Kato, F. Ono, and R. Miura, "AC-POCA: Anticoordination game based partially overlapping channels assignment in combined UAV and D2D-based networks," *IEEE Trans. Veh. Technol.*, vol. 67, no. 2, pp. 1672–1683, Feb. 2018.

[9] D. Takaishi, Y. Kawamoto, H. Nishiyama, N. Kato, F. Ono, and R. Miura, "Virtual cell based resource allocation for efficient frequency utilization in unmanned aircraft systems," *IEEE Trans. Veh. Technol.*, vol. 67, no. 4, pp. 3495–3504, Apr. 2018.

[10] V. Sanchez-Aguero, F. Valera, I. Vidal, C. Tipantuña, and X. Hesselbach, "Energy-aware management in multi-UAV deployments: Modelling and strategies," *Sensors*, vol. 20, no. 10, May 2020, Art. no. 2791.

[11] A. N. Patra, P. A. Regis, and S. Sengupta, "Dynamic self-reconfiguration of unmanned aerial vehicles to serve overloaded hotspot cells," *Comput. Elect. Eng.*, vol. 75, pp. 77–89, May 2019.

[12] A. Al-Hourani, S. Kandeepan, and S. Lardner, "Optimal LAP altitude for maximum coverage," *IEEE Wireless Commun. Lett.*, vol. 3, no. 6, pp. 569–572, Dec. 2014.

[13] A. Schoen and M. H. Ullock, "Optimum polar satellite networks for continuous earth coverage," *AIAA J.*, vol. 1, pp. 69–72, 1963.

[14] B. Yang, Y. Wu, X. Chu, and G. Song, "Seamless handover in software-defined satellite networking," *IEEE Commun. Lett.*, vol. 20, no. 9, pp. 1768–1771, Sep. 2016.