Energy Efficient Placement of a Drone Base Station for Minimum Required Transmit Power

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***Abstract*—Drone base stations (DBSs) can provide wireless coverage on the ground. In this letter, we propose an energy efficient placement algorithm for a DBS that serves a set of ground users, using minimum required transmit power. We obtain the optimal drone position by decoupling the deployment problem in the horizontal and vertical dimensions. Simulations are performed for hotspot and non-hotspot scenarios to evaluate the performance of our proposed algorithm, and the results show significant reductions in transmit power of the DBS. Furthermore, the optimal drone altitude is proportional to the minimum horizontal distance of the edge users from the DBS, and the slope depends on the environment.**

***Index Terms*—Drone Base Station, Energy Efficient Optimization, Wireless coverage**

I. INTRODUCTION

Drone-assisted communication is an emerging technology in the field of next generation networks. With the development of drone technology, utilization of drones equipped with small base stations, known as drone base stations (DBSs), in wireless networks has attracted considerable attention [1] [2]. DBSs can assist the ground infrastructure to accomplish wireless coverage on the ground in a rapid manner [3] [4] [5]. However, due to the size and weight constraints of drones, the available on-board energy of drones, which is partly consumed in the DBSs, is practically finite [6]. Clearly, energy efficient placement of a DBS, minimizing the transmit power of the DBS for the purpose of power savings while achieving the desired objectives, is very important.

The work in [7] modeled the air to ground path loss for low altitude platforms (LAPs) and concluded that there exist two main propagation groups, denoted as group 1 (G1) and group 2 (G2) respectively, where G1 corresponds to receivers with a Line-of-Sight (LoS) connection between a LAP and a ground receiver, while G2 corresponds to receivers with a None-Line-of-Sight (NLoS) connection between a LAP and a ground receiver. Besides, the probabilities of LoS and NLoS connections were derived. The work in [8] evaluated the drone altitude that provides the maximum wireless coverage on the ground by setting a suitable maximum allowed path loss threshold. The authors in [9] considered that one of the limitations in DBSs deployment is the availability of reliable wireless backhaul link, and then they investigated how different types of wireless backhaul, offering various rates, would affect the number of served users under the premise of a constant transmit power of the DBS. The authors in [10] assumed that the DBS transmits at full power and found the optimal drone position, using the method of mixed integer nonlinear programming, for maximum number of covered users. The authors in [11] set the vertical position of the drone at the altitude providing maximal coverage, and optimized the horizontal position of the drone maximizing the number of covered users while using minimum transmit power.

In this letter, we propose an optimal DBS placement method to serve a set of ground users, using minimum required transmit power. We formulate the optimal drone position problem by decoupling the horizontal dimension from the vertical dimension. Simulation results show significant reductions in transmit power of the DBS for hotspot and non-hotspot scenarios. Moreover, our numerical results show the linear relationship between the optimal drone altitude and the minimum horizontal distance of the edge users from the DBS, and the slope is determined by the environment.

II. SYSTEM MODEL

DBSs are extremely helpful for various scenarios. In case of an extreme event, the ground base station may be of congestion due to an extensive temporal increase in the number of users. It is unfeasible from economical perspective to invest in the ground infrastructure for a relatively short time period. For this reason, a DBS can be used to act as an aerial access point to serve these temporary or unexpected users. Let (x_i, y_i) represent the location of the unserved user i in the set $\mathbb{C}$. Several models have been proposed for air to ground links. In this letter, we adopt the model proposed in [7]. The air to ground communication links are mainly LoS or NLoS links, and the probability of a LoS connection between user i and the DBS is given by [7]:

$$P_{LoS}(r_i, h) = c_0(\frac{180}{\pi}\tan^{-1}(\frac{h}{r_i}) - 15)^{d_0}, \tag{1}$$

where c_0 and d_0 are environmental constants and have been given in [7], h is the drone altitude, and r_i is the horizontal distance of user i from the DBS and equal to $\sqrt{(x_i - x_H)^2 + (y_i - y_H)^2}$, where (x_H, y_H) is the horizontal position of the DBS. The probability $P_{NLoS}(r_i, h)$ of an NLoS connection between user i and the DBS is $1 - P_{LoS}(r_i, h)$.

Additionally, in air to ground links, there exist two types of radio propagation modes, named as free space propagation

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and urban space propagation respectively. The free space propagation results in the free space path loss, which of user i can be calculated as $20\log(\frac{4\pi f_c d_i}{c})$, where f_c is the carrier frequency, d_i is the distance of user i from the DBS given by $\sqrt{r_i^2+h^2}$, and c is the speed of light, which is $3\times 10^8\ m/s$. The urban space propagation results in the additional path loss and depends on the corresponding connection between user i and the DBS. Let $\eta_{LoS}(r_i,h)$ and $\eta_{NLoS}(r_i,h)$ be the additional path losses for LoS or NLoS connection between user i and the DBS respectively, then the average path loss between user i and the DBS can be calculated as:

$$\begin{aligned} PL_A(r_i,h) = 20\log(\frac{4\pi f_c d_i}{c}) + P_{LoS}(r_i,h)\eta_{LoS}(r_i,h) \\ + P_{NLoS}(r_i,h)\eta_{NLoS}(r_i,h). \end{aligned} \tag{2}$$

The work in [7] concluded that $\eta_{LoS}(r_i,h)$ and $\eta_{NLoS}(r_i,h)$ obey different Gaussian distributions:

$$\begin{aligned} \eta_{LoS}(r_i,h) &\backsim (\mu_{LoS}, \sigma^2_{LoS}(r_i,h)) \\ \eta_{NLoS}(r_i,h) &\backsim (\mu_{NLoS}, \sigma^2_{NLoS}(r_i,h)), \end{aligned} \tag{3}$$

where the means μ_{LoS} and μ_{NLoS} are constants given by [7] and depend on the environment, and the standard deviations $\sigma_{LoS}(r_i,h)$ and $\sigma_{NLoS}(r_i,h)$ are functions of r_i and h, equal to $a_{LoS}\exp(-b_{LoS}\frac{180}{\pi}\tan^{-1}(\frac{h}{r_i}))$ and $a_{NLoS}\exp(-b_{NLoS}\frac{180}{\pi}\tan^{-1}(\frac{h}{r_i}))$ respectively. The parameters a_{LoS}, b_{LoS}, a_{NLoS} and b_{NLoS} are also enviromental constants given by [7].

Obviously, in order to calculate the average path loss between user i and the DBS, two explicit equations are needed to describe the additional path losses $\eta_{LoS}(r_i,h)$ and $\eta_{NLoS}(r_i,h)$. According to the characteristics of the Gaussian distribution, take $\eta_{LoS}(r_i,h)$ for example, we can get:

$$P\{|\eta_{LoS}(r_i,h) - \mu_{LoS}| \leq k\sigma_{LoS}(r_i,h)\} = 2\Phi(k) - 1, \tag{4}$$

where $\Phi(k)$ is the standard Gaussian distribution function of k. When k is assigned 3, $2\Phi(3)-1 \approx 0.997$, this means that $\eta_{LoS}(r_i,h)$ falls into the interval $[\mu_{LoS}-3\sigma_{LoS}(r_i,h), \mu_{LoS}+3\sigma_{LoS}(r_i,h)]$ with a probability of approximately 1. Then we define the following equation to give a quantitative description of $\eta_{LoS}(r_i,h)$:

$$\eta_{LoS}(r_i,h) = \mu_{LoS} + 3\sigma_{LoS}(r_i,h)(L_2 - L_1), \tag{5}$$

where L_1 and L_2, falling into the interval $[0,1]$, are regular factors and subject to $L_1 + L_2 = 1$. Correspondingly:

$$\eta_{NLoS}(r_i,h) = \mu_{NLoS} + 3\sigma_{NLoS}(r_i,h)(L_2 - L_1). \tag{6}$$

Clearly, substitute equations (1), (5) and (6) into equation (2), the average path loss between user i and the DBS is a function of the horizontal distance r_i of user i from the DBS and the drone altitude h. Let P_t be the transmit power of the DBS, then the received power $P_r(i)$ of user i can be calculated as $P_r(i) = P_t - PL_A(r_i,h)$. In order to guarantee the users' quality of service (QoS), we assume the users' received power must be greater than or equal to a threshold P_{th}. This means that $PL_A(r_i,h) \leq PL_{MAX}$, where PL_{MAX} is the maximum allowed average path loss that the covered users can tolerate. According to (2), Figure 1 shows the

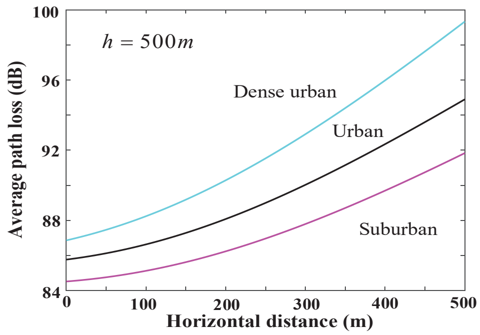

Fig. 1: Average path loss versus horizontal distance

average path loss versus the users' horizontal distance from the DBS with $h = 500\ m$ for suburban, urban and dense urban environments. As easily seen from Figure 1, for a particular environment and the given drone altitude, firstly, the users located at the same horizontal distance from the DBS share the same average path loss. Secondly, decreasing the users' horizontal distance from the DBS also decreases the average path loss. The above two conclusions imply that the wireless coverage region of the DBS is a circular disk with radius R defined as $R = r|_{PL_A(r,h)=PL_{MAX}}$. Moreover, the users with the same maximum horizontal distance from the DBS are known as edge users, experiencing the highest average path loss. Therefore, ensuring that these edge users' QoS exceeds the threshold guarantees that all other users also satisfy the QoS requirements.

Let r_e represent the horizontal distance of the edge users from the DBS, hence the transmit power P_t of the DBS can be described as $P_t = P_r(e) + PL_A(r_e,h)$, where $P_r(e)$ represents the received power of the edge users. Our objective is to find the minimum required transmit power P_m of the DBS and can be transformed as:

$$\begin{aligned} P_m = \min P_t &= \min(P_r(e) + PL_A(r_e,h)) \\ &= P_{th} + \min(PL_A(r_e,h)). \end{aligned} \tag{7}$$

Mathematically speaking, P_m only depends on r_e and h.

III. Energy Efficient Deployment Algorithm

Figure 2 illustrates the average path loss versus drone altitude for different horizontal distances of the edge users from the DBS. For a given horizontal distance of the edge

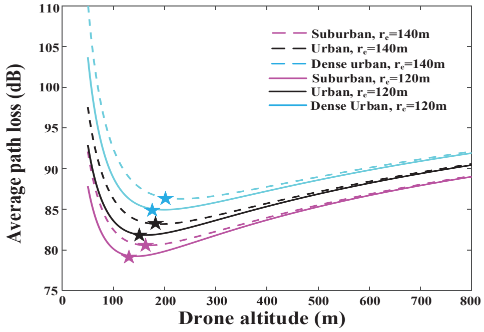

Fig. 2: Average path loss versus drone altitude

users from the DBS and a particular environment, there exists a point of minimum value, where y and x coordinates of the point represent the minimum average path loss of the edge users and the corresponding drone altitude respectively. Moreover, as the horizontal distance of the edge users from the DBS decreases, both the the minimum average path loss of the edge users and the corresponding drone altitude decrease. This leads us to decouple the optimal drone position in the horizontal and vertical dimensions. We firstly find the optimal horizontal position of the DBS, providing the minimum horizontal distance of the edge users from the DBS. In fact, for a given user distribution, this problem is a minimum coverage circle problem and can be formulated as:

$$\underset{x_H, y_H, r_e}{min} \; r_e$$

subject to:

$$\begin{aligned} &\sqrt{(x_i - x_H)^2 + (y_i - y_H)^2} \le r_e, \;\; \forall i \in \mathbb{C}, \\ &x_{lower} \le x_H \le x_{upper}, \\ &y_{lower} \le y_H \le y_{upper}, \end{aligned} \tag{8}$$

where subscripts $(\cdot)_{lower}$ and $(\cdot)_{upper}$ denote respectively the minimum and maximum allowed values for x_H and y_H. The problem (8) is a second order cone problem and can be solved using the software MATLAB/CVX. Let (x_*, y_*) and r_{min} be the optimal horizontal position of the DBS and the minimum horizontal distance of the edge users from the DBS respectively, then (x_*, y_*) and r_{min} can be obtained by solving the problem (8).

Figure 3 shows the drone altitude-wireless coverage radius curves with $PL_{MAX} = 100 \; dB$ for suburban, urban and dense urban environments. In Figure 3, take the dense urban environment for example, h_* is the drone altitude providing maximal coverage radius r_{max} [8]. h' and h'' are the drone altitudes providing the coverage radius r_{min}. For the DBS at our optimized horizontal position (x_*, y_*), if the drone altitude is h' or h'', the wireless coverage radius of the DBS is rightly equal to r_{min}. As a result, the average path loss of the edge users is rightly equal to the maximum allowed average path loss PL_{MAX} that the users can tolerate. If the drone altitude is lower than h' or higher than h'', the corresponding wireless coverage radius of the DBS is smaller than r_{min}, causing the edge users uncovered. As a result, the average path loss of the edge users exceeds the threshold PL_{MAX}. Thus for a given r_{min}, the placement problem in the vertical dimension can be formulated as:

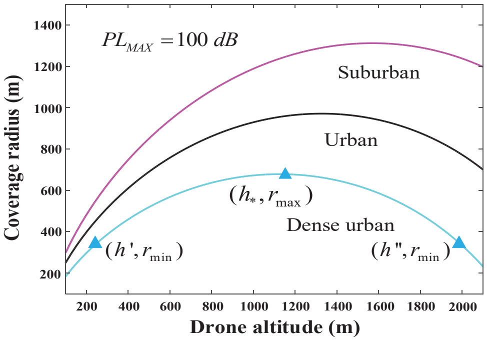

Fig. 3: Drone altitude versus coverage radius

$$\underset{h}{min} \; PL_A(r_{\min}, h)$$

subject to:

$$h' \le h \le h''. \tag{9}$$

The problem (9) can be solved using the software MATLAB. Let h_{opt} be the optimal drone altitude, and h_{opt} can be obtained by solving the problem (9). Thus we can obtain that $P_m = P_{th} + PL_A(r_{min}, h_{opt})$. Our proposed algorithm is given in Algorithm 1.

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Algorithm 1: Energy Efficient Placement $(x_*, y_*, h_{opt})$
Input: $(\mu_{LoS}, \mu_{NLoS})$ $(a_{LoS}, b_{LoS})$ $(a_{NLoS}, b_{NLoS})$ $P_{th}$
    $(L_1, L_2)$ $(x_i, y_i)$ $(x_{lower}, x_{upper})$ $(y_{lower}, y_{upper})$ $(c_0, d_0)$
    $f_c$ $PL_{MAX}$
Output: $(x_*, y_*, h_{opt})$
1. Obtain $(x_*, y_*)$ and $r_{\min}$ by solving the problem (8)
2. Obtain $h'$ and $h''$ by solving (2) with the given $PL_{MAX}$
3. Obtain $h_{opt}$ by solving the problem (9)
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IV. SIMULATION RESULTS

In this letter, we consider suburban, urban and dense urban environments. According to [7], the environmental parameters are provided in Table I.

TABLE I: ENVIRONMENTAL PARAMETERS

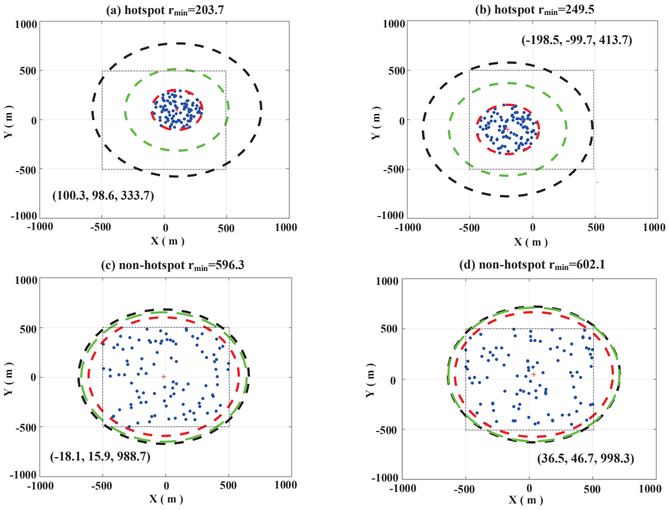
	Suburban	Urban	Dense urban
(μ_{LoS}, μ_{NLoS})	$(0, 18)$	$(0.6, 17)$	$(1, 20)$
(c_0, d_0)	$(0.77, 0.05)$	$(0.63, 0.09)$	$(0.37, 0.21)$
(a_{LoS}, b_{LoS})	$(11.53, 0.06)$	$(10.98, 0.05)$	$(9.64, 0.04)$
(a_{NLoS}, b_{NLoS})	$(26.53, 0.03)$	$(23.31, 0.03)$	$(30.83, 0.04)$

In our simulations, we consider a 1Km × 1Km area and two types of scenarios: the non-hotspot scenario with 100 ground users randomly distributed in the area and the hotspot scenario with 100 ground users randomly forming a hotspot cluster in the area. The simulation parameters are shown in Table II.

TABLE II: SIMULATION PARAMETERS

P_{th}	PL_{MAX}	f_c
$-70dBm$	$100dB$	$700M$
(L_1, L_2)	(x_{lower}, x_{upper})	(y_{lower}, y_{upper})
$(0, 1)$	$(-500m, 500m)$	$(-500m, 500m)$

For comparison, we assume a DBS is horizontally placed at our optimized position and vertically placed at the altitude providing maximum wireless coverage on the ground [8]. For the given dense urban environmental parameters, Figure 4 shows four possible deployments for hotspot and non-hotspot scenarios. Take the Figure 4(a) for example, the black circle represents the maximum wireless coverage area on the ground provided by [8]. The green circle, provided by our proposed algorithm, is the wireless coverage area on the ground with minimum required transmit power. The red circle represents the minimum coverage circle with radius $r_{\min} = 203.7 \; m$. The optimal horizontal position $(100.3, 98.6)$ and the minimum horizontal distance $r_{\min} = 203.7 \; m$ of the edge users from the DBS can be obtained by solving the problem (8). Then


(a) hotspot r_{min}=203.7

(b) hotspot r_{min}=249.5

(c) non-hotspot r_{min}=596.3

(d) non-hotspot r_{min}=602.1

Fig. 4: Four possible deployments with different $r_{\min}$

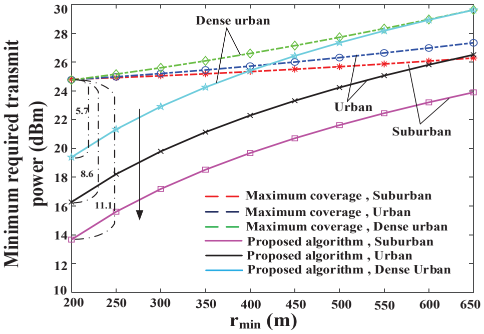


Fig. 5: Minimum required transmit power versus $r_{\min}$

the optimal drone altitude $h_{opt} = 333.7\ m$ can be obtained by solving the problem (9).

Figure 5 illustrates the minimum required transmit power versus $r_{\min}$ for suburban, urban and dense urban environments. In Figure 5, when $r_{\min} = 200\ m$, compared with the optimal placement for maximum coverage on the ground [8], our proposed algorithm has significant reductions of 5.7 dBm, 8.6 dBm and 11.1 dBm in minimum required transmit power for dense urban, urban and suburban environments respectively. Furthermore, as $r_{\min}$ decreases, which means the ground users locate in a more congested area, the minimum required transmit power also decreases for dense urban, urban and suburban environments respectively, which results in more significant power savings and is quite suitable for hotspot coverage. Moreover, power savings for the suburban environment outperform that for the urban and dense urban environments.

Figure 6 illustrates the optimal drone altitude versus $r_{\min}$ for suburban, urban and dense urban environments. Obviously, the optimal drone altitude is proportional to $r_{\min}$, and the slope is determined by the environment. The linear equations are presented in Figure 6. Therefore, once obtain the minimum horizontal distance $r_{\min}$ of the edge users from the DBS, solving these linear equations can be more simple to obtained the corresponding optimal drone altitude h_{opt}. The slopes are 1.197, 1.366 and 1.658 for dense urban, urban and suburban environments respectively. The slope in the suburban environment is lower than that in the other two environments, and

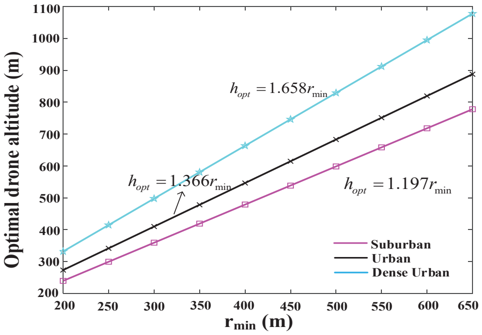


Fig. 6: Optimal drone altitude versus $r_{\min}$

this is because the ground users in the suburban environment have higher probability of LoS links.

V. CONCLUSION

In this letter, we have studied an energy efficient placement algorithm for a DBS that serves a set of ground users, using minimum required transmit power. We have found the optimal drone position by decoupling the DBS deployment problem in the horizontal and vertical dimensions. Simulation results have shown power savings for suburban, urban and dense urban environments. Furthermore, our numerical results show the linear relationship between the optimal drone altitude and the minimum horizontal distance of the edge users from the drone, which simplifies the calculation of the optimal drone altitude.

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