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RESEARCH ARTICLE

An Approach to the Calculation of Parameters in BS-UAV Networks

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ABSTRACT Today, unmanned aerial vehicles (UAVs) are extensively employed in wireless communication systems due to their mobility and exceptional maneuverability. With the advantage of flying high to increase the line of sight (LOS) probability with ground user equipment (UE), many studies have demonstrated that using UAVs to replace ground base stations (BS) can reduce transmission power loss. However, most research results are still limited to simulations with implicit formulas. This paper provides a closed formula for calculating the communication power gain of a cell based on environmental parameters. To achieve this, we propose an approximately linear mathematical model that allows for determining the formula for the optimal elevation angle, thereby calculating the coverage area of the UAV-BS and communication power gain of the coverage area. Simulations show that the proposed formula can be applied over a wide range of environmental parameters, and the quantitative results enable rapid cell planning for communication designers.

INDEX TERMS UAV, BS, BS-UAV, channel model, power gain, communication.

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) also known as drones or remotely piloted aircraft, boast numerous applications owing to their exceptional mobility and cost-effectiveness [1]. In contemporary wireless communication, the quantity of mobile users has experienced substantial growth. Concurrently, in tandem with this increase, user demands have also undergone significant evolution. To accommodate this increase, the system designers have to deploy a large number of base stations (BSs) for serving user equipment (UE) with varying demands. So installing more BSs is forced. In this context, the base stations mounted on unmanned aerial vehicles (UAVs) have garnered substantial interest from wireless system designers [2]. In densely populated regions, UAV-based base stations (UAV-BSs) facilitate the offloading of terrestrial base stations. Additionally, they can offer wireless connectivity in disaster or war zones [3].

Wireless communication systems integrating UAVs exhibit several distinctions from traditional wireless communication systems. There are two distinct characteristics of UAV-BS compared to BS on the ground that are easily noticeable. Firstly, the position of the UAV-based base station (UAV-BS) is in three dimensions (3D), compared with the two-dimensional (2D) position of a fixed base station on the ground. Determining the UAV-BS location also requires consideration of factors such as geographical details, user location, channel characteristics, details of the air-to-ground link, battery constraints, and the duration of the UAV hovering, among others. UAV placement determines the covered area and QoS(quality of service) criteria for UAVs directly. Unlike 2D in traditional wireless communication networks, determining the placement of UAV-based base stations (UAV-BS) poses a significant challenge. Second, the UAV-BS moves while the BS on the ground is fixed. So in the traditional communication system, path loss solely depends on the user's location; In contrast, both the user and the BS are mobile in the context of UAV-assisted BS so the air-to-ground path between the user and the UAV depends on the user's location and the location of the UAV [4]. To fully leverage the capabilities of UAVs, it is crucial to harness and control their three-dimensional mobility. One of the important factors of UAV mobility is the altitude at which it operates within the cellular network [5]. Moreover,

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the altitude of UAV-BS enables ground users (GUEs) to be easily distinguishable at different altitudes and elevation angles measured concerning the UAV. This capability aids UAVs in efficiently executing massive multi-input multi-output (MIMO), 3D network MIMO, and millimeter-wave communications. Additionally, line-of-sight (LOS) paths in UAV-to-ground links ensure effective beamforming in both azimuth and elevation domains [6], [7]. In this domain, primary research directions center around air-to-ground modeling, the optimal deployment of UAV-BSs, such as trajectory optimization for UAVs [8], [9], [10], optimizing UAV's velocity [11], cellular network planning involving UAVs, resource management, interference mitigation, collision avoidance, and minimizing latency in communication between user devices and UAVs [2].

So far, there has been a lot of research focused on altitude optimization of UAV-BSs. Huang et al. formulate an optimization problem to minimize the total system latency by designing the optimal flying altitude of a UAV and the optimal task allocation ratio in a UAV-assisted MEC uplink maritime communication system [12]. In a different approach, Azari et al. provided approximate expressions for the optimum height of the UAV to maximize coverage area, specifically in the case of Rician fading [13]. A novel formula for the optimal altitude of cellularly connected UAV networks, which is separated into three regions corresponding to three integral operations in the coverage probability expression, was introduced by Shahbazi and Renzo [5]. Additionally, Zhang et al. proposed another expression for both the optimal flying altitude and the optimal number of UAVs based on minimizing the overall UAV power while meeting user rate requirements [14]. The coverage area and communication quality are directly impacted by altitude and elevation angle. However, the common point of the above expressions is that the optimal height (or elevation angle) of UAV are not calculated directly from environmental parameters but is hidden together in a formula. The optimal results must then be performed through simulation based on the support of computers.

In this study, we consider an air-to-ground communication network where a UAV provides wireless access to several ground UE, which are uniformly distributed in the cell. By studying the threshold path loss of the cell, our main proposition includes:

i) The linear approximate mathematical model to directly calculate the optimal elevation angle of UAV according to environmental parameters

ii) The approximate closed-form expressions for the total power gain are provided when utilizing a UAV as a mobile base station, instead of employing a fixed base station.

The results of this research help system designers enable rapid cell planning. The remainder of this paper is organized as the following: in Section II, we define the system model and problem formulation. In Section III, we provide the methodology for obtaining the optimum optimal elevation angle. Followed by Section IV is the Simulation and discussion. Section V shows the formula for UAV altitude, and power gain of the cell, final Section VI concludes with important notes and remarks.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. SYSTEM MODEL

We consider the system model as shown in Figure 1. It comprises a UAV functioning as a mobile base station at a height h above the ground. The UAV effectively covers a cell with a radius of R. The ground-based receivers (UE) in the cell are positioned under a uniform distribution. When the UE is at the cell edge, it views the UAV at the smallest angle with the greatest transmission power loss.

B. PROBLEM FORMULATION

Firstly, use the formula to calculate the Line-of-Sight (LOS) probability between the UAV and the ground-based User Equipment (UE). It is presented in [15]:

$$P(LoS,\theta) = \frac{1}{1 + a\exp\left(-b[\theta - a]\right)}. \tag{1}$$

where: a and b are environment-dependent parameters. θ represents the angle between UE - UAV and a distance R from the cell center (in degrees)

Secondly, according to Friis' law, the LOS and NLOS path loss are calculated using the following formulas:

$$PL_{LoS} = 20\log d + 20\log f + 20\log\frac{4\pi}{c} + \eta_{LoS}. \tag{2}$$

$$\mathrm{PL}_{NLoS} = \underbrace{20\log d + 20\log f + 20\log\frac{4\pi}{c}}_{FSPL} + \eta_{NLoS}. \tag{3}$$

where: c is speed of light; f: carrier frequency; d: distance between UAV and ground-UE η_{LoS} and ξ_{NLoS} are shadow fading obeys Gaussian distribution with zero mean and standard deviation of σ (σ depends on the environment).

Combine with the formula:

$$P(NLoS,\theta) = 1 - P(LoS,\theta). \tag{4}$$

The PLmax can be calculated as (PLmax achieved When UE is at the cell edge):

$$\begin{aligned} PL_{max} = &\frac{A}{1 + a\exp(-b(\arctan(\frac{h}{R}) - a)})\\ &+ 10\log(h^2 + R^2) + B. \end{aligned} \tag{5}$$

In this:

$$A = \eta_{LoS} - \eta_{NLoS}. \tag{6}$$

$$B = 20\log f + 20\log(\frac{4\pi}{c}) + \eta_{NLoS}. \tag{7}$$

On the other hand:

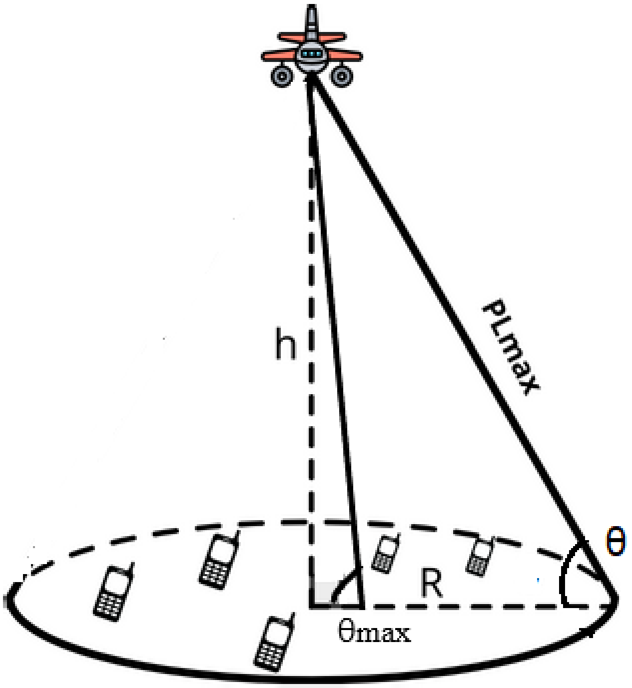

FIGURE 1. System model.

$h^2 + R^2 = d^2 = (\frac{R}{\cos\theta})^2$ and $\theta = \arctan(\frac{h}{R})$ The expression (5) can be rewritten as:

$$PL_{max} = \frac{A}{1 + a\exp(-b(\theta - a))} + 20\log(\frac{R}{\cos(\pi\frac{\theta}{180})}) + B. \tag{8}$$

With PL_{max} being the established value, the θ optimal can be determined by solving equation: $\frac{\partial R}{\partial \theta} = 0$, resulting in the following [15]:

$$0 = \frac{pi}{9\ln 10}\tan(\theta\frac{pi}{180}) + \frac{abA\exp(-b(\theta - a))}{(1 + a\exp(-b(\theta - a)))^2}. \tag{9}$$

The equation (9) can be solved with the help of a computer. However, the numerical root of an equation does not reveal the relationship between the optimal angle and the environmental parameters. Meanwhile, the provided optimal angle closure formula can facilitate the rapid calculation of UAV-based telecommunications network planning problems.

III. PROPOSED MODEL

To avoid the traditional Taylor series expansion method when solving complex higher-order equations, in this section, we proposed a linear approximate model for simply solving the equation (9). Firstly, equation (9) is converted into the following system of 2 equations:

$$\begin{cases} y1 = \dfrac{abA\exp(-b(\theta - a))}{(1 + a\exp(-b(\theta - a)))^2} \\ y2 = \dfrac{pi}{9\ln 10}\tan(\theta\dfrac{pi}{180}) \end{cases} \tag{10}$$

The root of equation (9) is found when y1 = y2. For simplicity, the formulas for y1 and y2 are depicted in the graph shown in Figure 2. Investigate two functions y1(θ) and y2(θ) we have the following observations and proposals:

- y2 is linear for angles $\theta < 55^0$. In the case where θ is the elevation angle of the UAV, then the $\theta_{op} < 55^0$ for most transmission environments.

- y1 is bell-shaped. The right flank can be approximated linearly by a straight line y1' connecting the top of the bell (where the first derivative is zero) with the inflection point on the right flank of the bell (where the second derivative is zero).

- When the steep slope of the bell is small, the exact solution of (y1,y2) approximates the solution of the linear model (y1', y2'). However, when the steep slope of the bell is large, the solution of the linear model is significantly different from the exact solution (y1, y2). Therefore, an additional correction proportional to this slope is needed.

From this, we derive the following results:

Theorem 1: The solution θ of equation (9) approximate is:

$$\theta = \frac{\frac{-bA}{4} - (a + \frac{1}{b}lna - 1.58\ Ab^2)0.0726b^2A}{-0.0726b^2A + 0.0027}. \tag{11}$$

Proof: From (10), The exact solution of θ can be considered as the intersection of two curves (Fig. 2)

$$y1(\theta) = \frac{abA\exp(-b(\theta - a))}{(1 + a\exp(-b(\theta - a)))^2}. \tag{12}$$

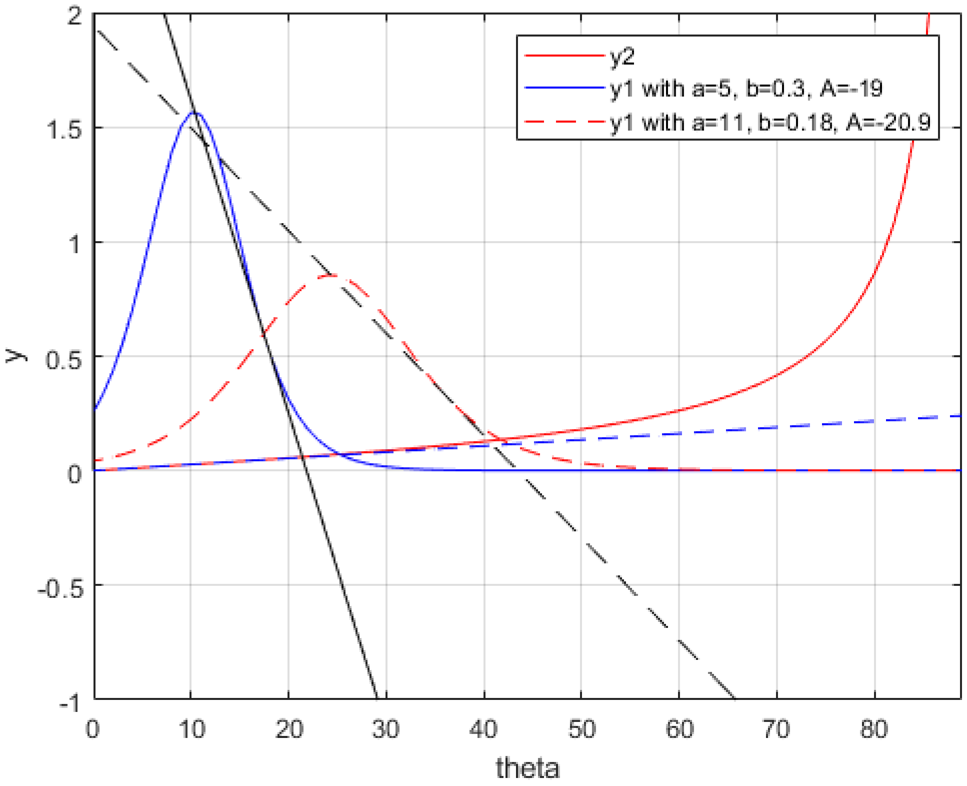

FIGURE 2. The graph of y1(θ) and y2(θ).

and

$$y2(\theta) = \frac{pi}{9\ln 10}\tan(\theta\frac{pi}{180}). \tag{13}$$

In range $\theta < 55^0$, the value $\frac{\theta\pi}{180}$ is small so

$$\tan(\theta\frac{pi}{180}) \approx \theta\frac{pi}{180} \Longrightarrow y2(\theta) \approx \frac{\pi^2}{9(\ln 10)180}\theta. \tag{14}$$

That means y2(θ) is approximately linear.

The y1(θ) is bell-shaped, and the bell's slope is approximately the straight line connecting its vertex and inflection point. The vertex and inflection point of y1(θ) are the points where the first and second derivatives of y1(θ) are zero.

Set: $X = \sqrt{a\exp(-b(\theta - a))}$ with $0 < X < \infty$

$$\longrightarrow \theta = a - \frac{1}{b}Ln(\frac{X^2}{a}). \tag{15}$$

We have:

$$\begin{aligned} y1(\theta) &= \frac{abA\exp(-b(\theta - a))}{(1 + a\exp(-b(\theta - a)))^2} \\ &= f(X) = \frac{-bA}{(X + X^{-}1)^2}. \end{aligned} \tag{16}$$

At the vertex, we can write:

$$\begin{aligned} \frac{\partial f(X)}{\partial X} &= \frac{-2bA(1 - X^{-2})}{\left(X + X^{-1}\right)^3} \\ &= 0 \longrightarrow X = 1; f(X = 1) = \frac{-bA}{4}. \end{aligned}$$

The coordinates of the vertex point are:

$$(a + \frac{1}{b}lna; \frac{-bA}{4}).$$

At inflection point:

$$\begin{aligned} \frac{\partial^2 f(X)}{\partial X^2} &= \frac{-4bAX^{-3}}{\left(X + X^{-1}\right)^3} + \frac{6bA(1 - X^{-2})^2}{\left(X + X^{-1}\right)^4} = 0. \\ &\longleftrightarrow X^{-4} - 8X^{-2} + 3 = 0X_{1,2}^{-2} = 4 \pm \sqrt{13}. \end{aligned} \tag{17}$$

Use (15), the coordinates of the inflection point are:

$$(a - \frac{1}{b}ln(\frac{0.3626^2}{a}); 0.1027bA).$$

From the coordinates of the vertex and the inflection point, we build the equation of the straight line through the 2 points. In addition, since the slope of y1 depends on the value of b^2A, we adjust y1 by shifting to the right an amount of the slope ratio. Based on empirical selection, this value is $1.58Ab^2$. The

TABLE 1. The optimal and approximate elevation angle of a UAV.

Environment	a	b	η_{LoS}	η_{NLoS}	θ_{op}	θ_{app}	Error	Error (%)
Dense Urban	15	0.16	1.6	23	49.36	50.87	-1.50	3%
Urban	11	0.18	1	20	41.71	41.90	-0.18	0.40%
High-rise Urban	5	0.3	2.3	34	26.42	26.07	0.35	1.30%
Suburban	5	0.3	0.1	21	25.03	24.37	0.66	2.80%

approximate θ is the solution of the system of equations.

$$\begin{cases} y1' = \frac{-bA}{4} + 0.0726b^2A(\theta - (a + \frac{1}{b}\ln a) + 1.58Ab^2) \\ y2 = \theta(\frac{\pi^2}{9(\ln 10)\cdot 180}) \end{cases} \tag{18}$$

When y1'=y2 we have:

$$\theta_{app} = \frac{\frac{-bA}{4} - (a + \frac{1}{b}lna - 1.58Ab^2)0.0726b^2A}{-0.0726b^2A + 0.0027}. \tag{19}$$

IV. NUMERICAL RESULTS

In this section, we compare the results obtained from the approximate model proposed above with those from computer simulations described in research [15], [16] at a frequency equal 2000MHz with the corresponding environmental parameters (a, b, A) are Dense Urban (0.5, 300, 20), Urban (0.3, 500, 15), High-rise Urban (0.5, 300, 50), and Suburban (0.1, 750, 8). The results are shown in Table 1.

The numerical results indicate that our approximate mathematical model for deriving the closed-form expression of the optimal elevation angle yields approximate results consistent with those from research [15], [16] (with an error of less than 3%). Based on this expression, we introduce two other additional closed-form expressions and prove their correctness for calculating the coverage radius of UAVs and the power gain of the cell when utilizing it as a mobile BS station.

V. COMMUNICATION POWER GAIN

Theorem 2: when Pmax is given, the cell radius can be calculated as follows:

$$R = 10^{\frac{\bar{PL}}{20}} \cos(\pi \frac{\theta_{app}}{180}). \tag{20}$$

where:

$$\bar{PL} = PL_{max} - (\frac{A}{1 + a\exp(-b(\theta_{app} - a)} + B). \tag{21}$$

Proof: From (8) we have:

$$\begin{aligned} \bar{PL} &= 20\log(\frac{R}{\cos(\pi\frac{\theta_{app}}{180}))} \\ &= PL_{max} - (\frac{A}{(a + a\exp(-b(\theta_{app} - a)))} + B). \end{aligned} \tag{22}$$

By substituting the results from expression (11), we can directly calculate R (the cell radius) using the path loss threshold (PL) and the environmental parameters a, b, and A.

The above problem is based on the maximum capacity of the UAV's power. The UAV's power must exceed the sum of PLmax and the threshold power of the UE ground receiver (assuming the threshold power is the same for all UEs). If this condition is met, a larger PLmax will result in a greater coverage radius for the UAV.

When cell planning, the R is usually predetermined according to traffic density, not PLmax. Then the optimal height of the UAV is also easily calculated by

$$h = R\tan(\theta_{app}). \tag{23}$$

Theorem 3: With the assumption that the UE distributions are uniformly distributed, and when using a UAV replacing ground Base Station at the optimal height, the communication total power gain in a cell of radius R is determined by the following expression:

$$G_{PL} = I_1 + I_2. \tag{24}$$

In this:

$$I_1 = \pi R^2|A|(1 - \frac{1}{1 + a\exp(ba)}). \tag{25}$$

$$I_2 = \frac{20\pi R^2}{ln10}(\frac{1}{2\cos\theta_{app}} - \frac{\tan\theta_{app}}{2}ln(\frac{1 + \frac{1}{\cos\theta_{app}}}{\tan\theta_{app}}) - 1). \tag{26}$$

Proof: Consider a UE placed at a distance r from the cell center and look at UAV with θ elevation angle, from (8) the power loss between UAV and UE link is calculated by:

$$\begin{aligned} PL_{UAV} &= \frac{A}{1 + a\exp(-b(\theta - a))} + 20\log(R) \\ &\quad - 20\log\cos(\theta\frac{\pi}{180}) + B. \end{aligned} \tag{27}$$

The power loss of link between BS and UE also follows the probabilistic LOS model but not the Rayleigh model. That means with the high of BS = 0, the power loss can be calculated by:

$$PL_{BS} = \frac{A}{(1 + a\exp(ba))} + 20\log(R) + B. \tag{28}$$

The power gain for this UE when replacing ground BS with UAV is:

$$\begin{aligned} G_{PL} &= PL_{BS} - PL_{UAV} \\ &= \frac{A}{1 + a\exp(ba)} - \frac{A}{1 + a\exp(-b(\theta - a))} \\ &\quad + 20\log\cos(\theta\frac{\pi}{180}). \end{aligned} \tag{29}$$

Because $A = \xi_{LoS} - \xi_{NLoS} < 0$ In addition, when the UE is located in a circle of radius R, the UAV height $h = R\tan\theta_{op}$, and the angle θ are always satisfied $90^0 > \theta > \theta_{op}$. we have:

$$\begin{aligned} &P(LOS, 90^0) > P(LOS, \theta) > P(LOS, \theta_{op}). \\ &= \frac{1}{(1 + a\exp(-b(\theta_{op} - a)))} \approx 1. \end{aligned} \tag{30}$$

So:

$$PL_{BS} - PL_{UAV} = |A|(1 - \frac{1}{(1 + a\exp(ba))} + 20\log\cos(\theta\frac{\pi}{180}). \tag{31}$$

On the other hand:

$$0 < \cos\theta\frac{\pi}{180} < 1$$

Using the first-order approximation in the Taylor expansion of the function ln(cos()):

$$\frac{20}{\ln 10}ln(cos\theta\frac{\pi}{180} - 1 + 1) = \frac{20}{\ln 10}(\cos\theta\frac{\pi}{180} - 1). \tag{32}$$

Set ρ_{UE} is a cell area, the power gain can be calculated by:

$$\begin{aligned} G_{PL} &= \int_0^{2\pi}\int_0^R \rho_{ue}(PL_{BS} - PL_{UAV})rdrd\varphi \\ &= \rho_{ue}\pi R^2|A|(1 - \frac{1}{1 + a\exp(ba)}) + I. \end{aligned} \tag{33}$$

In this:

$$I = \frac{20}{ln10}\int_0^{2\pi}\int_0^R \rho_{ue}\left((\cos\left(\theta\frac{pi}{180}\right) - 1\right)rdrd\varphi. \tag{34}$$

In addition:

$$cos\theta\frac{pi}{180} = \frac{r}{\sqrt{r^2 + h^2}}. \tag{35}$$

$$\begin{aligned} \Longrightarrow I = &\frac{40\pi}{ln10}\int_0^R \rho_{ue}\left(\frac{r}{\sqrt{r^2 + h^2}}\right)rdr \\ &- \frac{20}{ln10}\int_0^{2\pi}\int_0^R \rho_{ue}rdrd\varphi. \end{aligned} \tag{36}$$

According to the following formula:

$$\begin{aligned} \left(\frac{r}{\sqrt{r^2 + h^2}}\right)rdr &= \frac{1}{2}rd\left(\sqrt{r^2 + h^2}\right) \\ &= \frac{1}{2}\left(d\left(r\sqrt{r^2 + h^2}\right) - \sqrt{r^2 + h^2}dr\right). \end{aligned} \tag{37}$$

We have:

$$\begin{aligned} I = &\frac{20\rho_{ue}\pi}{ln10}\left[r\sqrt{r^2 + h^2}\right]_0^R \\ &- \frac{20\pi}{ln10}\left[\frac{r}{2}\sqrt{r^2 + h^2} + \frac{h^2}{2}ln\left(r + \sqrt{r^2 + h^2}\right)\right]_0^R \\ &- \frac{20\rho_{ue}\pi R^2}{ln10} = \frac{20\rho_{ue}\pi}{ln10}\left(\frac{R}{2}\sqrt{R^2 + h^2}\right. \\ &\left.- \frac{h^2}{2}ln\left(\frac{R + \sqrt{R^2 + h^2}}{h}\right) - R^2\right). \end{aligned} \tag{38}$$

Substituting expression (24) into (38) we have:

$$\begin{aligned} I = &\frac{20\rho_{ue}\pi R^2}{ln10}[\frac{1}{2cos\left(\theta_{OP}\frac{pi}{180}\right)} \\ &- \frac{tan^2\left(\theta_{OP}\frac{pi}{180}\right)}{2}ln\left(\frac{1 + \frac{1}{cos\left(\theta_{OP}\frac{pi}{180}\right)}}{tan\left(\theta_{OP}\frac{pi}{180}\right)}\right) - 1]. \end{aligned} \tag{39}$$

TABLE 2. The power gain of BS-UAV.

Environment	a	b	η_{LoS}	η_{NLoS}	θ_{app}	Power Gain (dB)
Dense Urban	15	0.16	1.6	23	50.87	14.59 N
Urban	11	0.18	1	20	41.90	12.55 N
High-rise Urban	5	0.3	2.3	34	26.06	24.97 N
Suburban	5	0.3	0.1	21	24.37	14.72 N

By substituting θ from expression (19) and assuming that uniformly distributed UEs have orthogonal connections with UAVs, we can calculate the total power gain of the entire cell when a UAV replaces the ground BS base station as follows:

$$G_{PL} = \rho_{ue}\pi R^2\,|A|\left(1 - \frac{1}{1 + a\exp(ba)}\right) + I. \tag{40}$$

Set N is the number of active UE in the cell. So (40) can be rewritten following:

$$\begin{aligned} G_{PL} = N\{&|A|\left(1 - \frac{1}{1 + a\exp(ba)}\right) \\ &+ \frac{20}{ln10}[\frac{1}{2cos\left(\theta_{app}\frac{pi}{180}\right)} \\ &- \frac{tan^2\left(\theta_{app}\frac{pi}{180}\right)}{2}ln\left(\frac{1 + \frac{1}{cos\left(\theta_{app}\frac{pi}{180}\right)}}{tan\left(\theta_{app}\frac{pi}{180}\right)}\right) - 1]\}. \end{aligned} \tag{41}$$

Formula (41) shows that the power gain for the entire cell, when replacing the ground BS with a UAV, is a function of the environmental parameters a,b, A. It is also proportional to the number of UEs in the cell. Table 2 shows the relationship between the number of users and the power gain of BS-UAV in different communication environments.

The results in Table 2 indicate that the power gain when replacing a BS with a UAV varies between urban and suburban areas, with the gain being higher when the value of A is greater. This is characteristic of environments with a significant difference between η_{LoS} and η_{NLoS}, such as high-rise urban areas.

VI. CONCLUSION

In this paper, we proposed an approximate mathematical model for determining the optimal angle between the UAV height h and the coverage radius R based on environmental parameters. The numerical results validate the model's reliability. Using the closed-form expression of the optimal angle, we derive formulas for the cell radius and communication power gain directly from environmental parameters when employing a UAV as a mobile BS. Although, UAVs are mobile airborne devices, so it is necessary to consider mechanical energy costs. Our proposed formulas do not yet address these mechanical energy costs. However, calculating the communication power gain independently is crucial for telecommunications system designers. Closed-form formulas allow designers to quickly calculate and evaluate the effectiveness of wireless transmission parameters in different transmission environments. In future work, we will study the total power requirements of the UAV, including both mechanical energy and communication power. Additionally, we will expand our research to consider different distributions of users within a cell.

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