UAV Base Station Site Selection Based on Spiral Algorithm in Complex Environment

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Abstract. The Wireless broadband communication system is the wireless communication hub and the main means of communication under the background of actual combat. In complex environments such as terrain impact and external interference strikes, the on-board base station of wireless broadband communication system may not work properly. As an air base station, UAV ensures the continuity and reliability of communication. Aiming at the problem of UAV base station location in complex environment, this paper proposes a UAV base station location method based on spiral algorithm. Firstly, this paper establishes the air-to-ground propagation model based on the characteristics of the actual geographical environment. Secondly, the coverage capability of the UAV base station is obtained by link budget and the optimal height analysis of the UAV. Finally, the location planning of the UAV base station is completed by the spiral algorithm. The simulation results show that the spiral algorithm needs fewer UAV base stations than the k-means algorithm, which can reduce the cost of the network. The method proposed in this paper can select the appropriate site for the base station of the UAV under the complex environment.

1. Introduction

The wireless broadband communication system is one of the main methods of current battlefield communication. In the actual combat process, the wireless broadband communication system will encounter complex situations such as deployment in mountainous areas and destruction by the enemy. The ground base stations cannot meet the communication guarantee tasks, and the system makes full use of the UAV’s own characteristics of rapid deployment, flexible maneuverability and high probability of line-of-sight communication. UAVs carrying communication equipment lift off as an air base station to provide services for ground terminals, which can effectively solve the problem that ground base stations cannot guarantee communication. At present, how to deploy UAV base stations quickly and efficiently so as to provide troops with reliable and uninterrupted communication support is a key issue that must be resolved.

The wireless communication method is adopted between the air base station and the ground terminal of the wireless broadband communication system. Due to the diversity of application environments and scenarios of wireless broadband communication systems, there are differences in the coverage of air base stations and ground base stations. Most of the radio wave propagation models currently used in wireless communication are empirical models, which are mainly based on statistical analysis of the law of radio wave propagation obtained from the measured data between ground base stations and terminals [1]. UAV base stations are generally more than a few hundred meters above the ground, and sometimes reach several kilometers. Therefore, traditional empirical models are not
suitable for scenarios where UAV base stations and ground terminals communicate. Air-to-ground channel analysis is required, and a radio wave propagation model in an air-to-ground scenario should be established. Hourani A [2] proposed a statistical propagation model to predict the path loss of aerial platforms and ground terminals based on the characteristics of urban environments. Different propagation groups have different propagation characteristics. Qixing Feng [3,4] proposed a prediction model for the possibility of line-of-sight propagation of space-to-ground radio propagation based on a certain elevation angle. Jaroslav Holis [5] proposed line-of-sight and non-line-of-sight propagation models, and verified their rationality through simulation experiments. Sithamparanathan Kandeepan [6] proposed a statistical air-to-ground propagation model based on the different probability of occurrence of different propagation. Although there are many researches on air-to-ground propagation models, there is still a lot of room for improvement in the research of complex environments. Based on the characteristics of wireless signal propagation in complex environments, this paper establishes a probability propagation consisting of line-of-sight propagation and non-line-of-sight propagation model. The modeling of the radio wave propagation model is a necessary work for the site selection of the base station, and the accuracy of the model directly determines the rationality of the site selection of the base station. On the basis of completing channel modeling, it is also necessary to study the specific content of site planning. In recent years, there are many ways to solve the problem of base station location planning. Nadir Adam [7] modeled the UAV base station location problem as a non-convex optimization problem, and used SES algorithm and SMWA algorithm to solve the problem. Mohamed Alzenad [8] modeled the UAV base station location problem as a circle placement problem, and used an exhaustive algorithm to solve the problem. Alzenad M [9] modeled the UAV base station location problem as a recursive problem, and used a recursive divide-and-conquer algorithm to solve the problem. R. IremBor-Yalıniz [10] modeled the UAV base station location problem as a quadratic constrained mixed integer nonlinear programming problem, and used a mixed integer linear programming algorithm to solve the problem. Wang Hua [11] used the cyclic k-means algorithm to solve the problem of UAV aerial base station deployment planning. Wang Chao [12] modeled the UAV deployment problem as a mathematical optimization problem, and used a strong evolutionary genetic algorithm to solve the problem. For the base station site selection problem, researchers use different algorithms to solve the problem. In this paper, the spiral algorithm is used to solve the UAV base station site selection problem.

This paper mainly studies the complex environment encountered in the deployment of wireless broadband communication system. When the ground base station cannot provide services, the UAV base station can be selected for site selection planning. So as to realize uninterrupted communication and meet the requirements of smooth communication. First, the air-to-ground propagation model is obtained through electromagnetic theory analysis and optimization model. Then, UAV coverage analysis is conducted through link budget and coverage radius. Finally, the spiral algorithm is used to plan the location of the UAV base station. The communication support unit can deploy UAV base stations based on the results of the site selection plan, which can shorten the combat preparation time.
2. Modeling of Radio Wave Propagation Model

Currently, the most used models of the wireless communication channel models are empirical models, which are based on actual test data and perform statistical analysis to obtain the laws that exist in the propagation process. When the wireless broadband communication system is deployed in a complex geographic environment such as mountainous areas, or in a harsh environment where the enemy's equipment is damaged, and the ground base station cannot provide services, the UAV carries the base station to provide services. Due to the different environments through which wireless signals propagate, their propagation characteristics will be different. In general, during the propagation of wireless signals, there is line-of-sight propagation and non-line-of-sight propagation. In the process of wireless signal propagation, the relevant communication data is calculated through calculation. However, because the non-line-of-sight propagation cannot be specifically calculated, this paper will include the line-of-sight propagation and the non-propagation distance propagation model as the air-to-ground propagation model, this model is shown in figure 1. This paper combining the characteristics of the actual geographic information environment, the model refers to the modeling method of Sithamparanathan Kandeepan [6], and obtains the probability of line-of-sight propagation through parameters such as the ratio of mountain to regional area, the average number of mountains, and the Rayleigh probability density function:

\[
P(LoS) = \prod_{m=0}^{m} \left[ 1 - \exp \left( -\frac{\left( H_{TX} - \left( n + \frac{1}{2} \right) (H_{TX} - H_{RX})/(m+1) \right)^2}{2\gamma^2} \right) \right]
\]  

(1)

In the above formula:

The parameter \( \alpha \) is the ratio of the mountain area to the total area of the area (dimensionless).

The parameter \( \beta \) is the average number of mountains per unit area (block/km\(^2\)).

The Parameter \( \gamma \) is the parameter that determines the scale of mountain height distribution according to the Rayleigh probability density function.

Since the line-of-sight transmission probability of the UAV base station has nothing to do with the frequency parameters of the communication system, the model modeling can be applied to base stations and terminals with any deployment height. Probability formula \( m = \text{floor}(R\sqrt{\alpha\beta} - 1) \), \( H_{TX} \) is the height of the transmitter, \( H_{RX} \) is the height of the receiver, and \( R \) is the distance between the UAV base station's vertical projection and the ground terminal on the horizontal ground. The UAV coverage radius is closely related to the transmitter height, receiver height and other parameters, so the following formula can be obtained through construction:
Since there is a certain relationship between $\theta$ and $H$, so the line-of-sight transmission probability equation is transformed into the $P(\text{LoS}, \theta)$ equation, which can be simplified to the Sigmoid function. The simplified function expression is as follows:

$$P(\text{LoS}, \theta) = \frac{1}{1 + a \exp \left( \frac{180 - \theta}{\pi} - a \right)}$$

(3)

In the formula (3), $a$ and $b$ are the parameters of the Sigmoid function, and $\theta$ is the radian angle, which represents the elevation angle between the ground terminal and the UAV base station. From formula (3), the non-line-of-sight transmission probability formula can be obtained:

$$P(\text{NLoS}, \theta) = 1 - P(\text{LoS}, \theta)$$

(4)

The parameters of reference [13] are used for simulation experiments. The specific simulation parameters are shown in table 1. The relationship between the line-of-sight propagation probability and the elevation angle from the ground terminal to the UAV base station is shown in figure 2:

| Geographical environment | Fitting parameters $(a,b, \eta_{\text{LoS}}, \eta_{\text{NLoS}})$ |
|--------------------------|-------------------------------------------------------------|
| suburbs                  | $(4.88,0.43,0.1,20)$                                       |
| city                     | $(9.61,0.28,1,21)$                                         |
| Dense city               | $(12.08,0.16,1.6,23)$                                      |
| High-rise city           | $(27.23,0.13,2.3,34)$                                      |

Figure 2. The relationship between line-of-sight propagation probability and elevation angle.

The simulation results can be analyzed: 1. Comparing the four curves, it is found that the line-of-sight propagation probability of wireless signals in open areas is greater than that in areas with obstacles. 2. Under the same elevation angle, the higher the building, the more obstacles, and the smaller the probability of distance propagation. 3. In different environments, there is an optimal elevation angle between the ground terminal and the UAV base station. At this time, the probability of
line-of-sight propagation is the greatest. For example, the optimal elevation angle in the suburbs is about 20 degrees. 4. When the elevation angle is greater than or equal to the optimal elevation angle, the line-of-sight propagation probability will no longer change. In summary, the deployment of UAV base stations is preferred in open areas and try to avoid high-rise buildings. Based on this deployment strategy, the line-of-sight propagation probability between UAV base stations and terminals will be improved to a certain extent.

3. Analysis of UAV Base Station Coverage Capability

The coverage capability of UAV base stations is restricted by link loss and flight altitude. The coverage of a UAV is shown in figure 3. In order to maximize the coverage of UAV base stations, link budget and optimal height analysis are required. The link budget is divided into uplink and downlink budgets. Generally, the uplink with a larger budget value is used for link budget.

![UAV base station coverage](image)

**Figure 3.** UAV base station coverage.

3.1. Link Budget

The model needs to be adapted to the complex and changeable actual geographic environment, it is necessary to consider both line-of-sight propagation and non-line-of-sight propagation. Therefore, the link loss of air-to-ground propagation is expressed as:

\[ PL_{\xi} = FSPL + \eta_{\xi} \]  

(5)

Among them, FSPL refers to the free space path loss between the UAV base station and the ground terminal. \( \xi \) is the propagation group, \( \eta_{\xi} \) is the additional loss added by the propagation group. When communicating between the UAV base station and the ground terminal, the FSPL loss can be calculated according to the Flynns transmission equation for the propagation loss link:

\[ L(D) = 20\log\left(\frac{4\pi D f}{c}\right) \]  

(6)

Where\( D \) is the distance between the UAV base station and the ground terminal, and \( \lambda \) is the wavelength.

Combining formulas (5) and (6), the path loss of space-to-ground propagation in line-of-sight and non-line-of-sight conditions can be obtained as \( PL_{LOS} \) and \( PL_{NLOS} \) respectively:

\[ PL_{LOS} = 20\log_{10}\left(\frac{4\pi D f}{c}\right) + \eta_{LOS} \]  

(7)

\[ PL_{NLOS} = 20\log_{10}\left(\frac{4\pi D f}{c}\right) + \eta_{NLOS} \]  

(8)
\( \eta_{\text{LoS}}, \eta_{\text{NLoS}} \) are the additional loss of line-of-sight propagation and non-line-of-sight propagation respectively. The specific loss value is determined by environmental parameters, \( c \) is the speed of light, \( f \) is the frequency, and \( D \) is the distance between the UAV base station and the ground terminal. Since the actual propagation process of wireless signals is very complicated, it is impossible to determine whether it is line-of-sight or non-line-of-sight propagation. Therefore, the average path loss is used to represent the path propagation loss between the UAV base station and the ground terminal, and the average path loss can be expressed as:

\[
PL = P(\text{LoS}) \times PL_{\text{LoS}} + P(\text{NLoS}) \times PL_{\text{NLoS}}
\]

After simplifying the joint formulas (3), (4), (7), (8), (9), the maximum path loss is obtained:

\[
PL_{\text{max}} = \frac{H_{\text{LoS}} - H_{\text{NLoS}} + 10\log\left(H^2 + R^2\right) + 20\log\left(\frac{4\pi}{c}\right) + \eta_{\text{NLoS}}}{1 + a \exp\left(-b \left[\arctan\left(\frac{H}{R}\right) - a\right]\right)}
\]

### 3.2. Analysis of the Best Flight Altitude

The analysis of the UAV base station coverage capability is actually an analysis of the best altitude for UAV flight. It can be seen from formula (10) that in a specific environment, the path loss of the UAV base station and ground terminal in flight is a fixed value. According to the air-to-ground propagation model obtained by modeling, if the transmission power of the UAV base station is \( P_T \), the received power of the ground terminal is:

\[
P_R = P_T - PL + G_T + G_R - L_c
\]

\( G_T \) is the UAV base station antenna gain, \( G_R \) is the ground terminal antenna gain, and \( L_c \) is the transmission feeder loss.

When the ratio of the received power to the noise power at a certain point in the UAV base station coverage area is less than the signal-to-noise ratio threshold, the communication signal is submerged in noise at this time, that is, normal communication cannot be performed. Therefore, the coverage area of the UAV base station should meet \( \frac{P_R}{N} \geq \phi_{\text{TH}} \), which \( N \) is the noise power and \( \phi_{\text{TH}}(dB) \) is the signal-to-noise ratio threshold. When the parameters are fixed, the average path loss at the same elevation angle is the same, so the UAV base station coverage area is the area of a circle with a radius of \( R \).

Assuming that the edge of the UAV base station coverage just meets the maximum path loss, the path loss from the ground terminal to the UAV base station in the coverage area is less than or equal to \( PL_{\text{max}} \), and the simultaneous formulas (10) and (11) can be obtained:

\[
PL_{\text{max}} = P_T + G_T + G_R - L_c - \phi_{\text{TH}} - N = \frac{\mu_{\text{LoS}} - \mu_{\text{NLoS}}}{1 + a \exp\left(-b \left[\arctan\left(\frac{H}{R}\right) - a\right]\right)} + 20\log_{10}\left(\frac{R}{\cos \theta}\right) + 20\log_{10}\left(\frac{4\pi f}{c}\right) + \mu_{\text{NLoS}}
\]

The parameters \( P_T, G_T, G_R, \phi_{\text{TH}}, L_c \) and \( N \) in the above formula in the critical equation are constants. Because \( \tan \theta = \frac{H}{R} \), the radius of the maximum coverage of the UAV can be obtained by solving the
optimal flying height of the UAV base station.

The simulation parameters in Reference [13] are simulated for different geographical environments. The specific simulation parameters are shown in table 2. Under the condition of fixed transmission power, there is a certain relationship between the height of the UAV base station and the maximum coverage radius. The specific relationship is shown in figure 4.

**Table 2. Simulation parameters.**

| Parameter | Value     |
|-----------|-----------|
| $f$       | 2000MHz   |
| $P_T$     | 1W        |
| $G_T$     | 11dBi     |
| $G_R$     | 0dBi      |
| $\phi_{TH}$ | 10dB    |
| $L_c$     | 1.5dB     |
| $N$       | -100dBm   |

**Figure 4.** Relationship between base station height and coverage radius in different environments.

The simulation results can be analyzed: 1. When the UAV base station is on the ground, as the complexity of the environment increases, the coverage radius of the UAV decreases. 2. Comparing the four curves, it is found that the more high-rise buildings, the greater the impact of the deployment of aircraft base stations, the largest coverage radius of the suburban environment. 3. Each curve has a maximum value, indicating that the UAV base station has the best flight altitude in each environment. 4. Comparing the four curves, it is found that the environment in the deployment area is greater complex, the smaller the base station coverage radius. 5. In the figure 4, when the UAV base station flying height exceeds 1800 meters, it will not be able to communicate with the ground terminal, which means that when the UAV base station flying height exceeds a certain height, it will not be able to communicate with the ground terminal. 6. When it is necessary to cover the radius of 1000 meters, the flying height of the UAV increases as the complexity of the environment increases. In summary, when the UAV base station is deployed at the optimal height, the coverage of the base station is the largest. Based on this deployment strategy, the effectiveness of the base station deployment is improved.
4. **UAV Base Station Site Selection Based on Spiral Algorithm**

4.1. **Algorithm Flow**

The UAV base station site selection based on the spiral algorithm is mainly divided into three parts. The first part is to classify and number the ground base station. The second part is to adjust the location of the UAV base station to ensure that the UAV covers the most ground terminal. The third part is to determine whether the ground terminal is fully covered. If it is fully covered, the algorithm outputs the number and location of base stations. Otherwise, repeat the second part.

Step 1: Input all the ground terminal positions, the algorithm divide them into boundary terminals and internal terminals through iterative calculation, find the boundary terminals through iterative calculation, and number the ground terminals in a counterclockwise direction, that is, the number connected by the dotted line is the ground terminal of A1-A11 (as shown in figure 5), the terminal inside the dashed line is a non-boundary terminal.

Step 2: The algorithm randomly select a border terminal (A4), and place a UAV base station with a certain flying height above A4. The UAV base station flying height is the best flying height obtained through simulation experiments. Adjust the position of the UAV base station, make it cover more border terminals, and cover the three border terminals of A3, A4, and A5. Finally, the UAV base station adjusts its position to cover more internal base stations. At this time, the UAV base station covers A3, A4, A5, A12, the final location of UAV base station deployment is determined as F1, as shown in figure 6. In the process of adjusting the position of the UAV base station, the boundary terminal has priority over the internal base station to be selected by the UAV base station. The UAV base station covers at least one boundary terminal. The ground terminal exceeding the boundary terminal 2R is not considered, that is, the same boundary terminal cannot be covered by two UAV base stations. During the deployment of UAV base stations, it is necessary to cover as many ground terminals as possible within the area, but each ground terminal must be covered by at least one UAV base station.

![Figure 5. Process diagram of UAV base station site selection.](image_url)

Step 3: Determine whether the UAV base station completely covers the terminal on the ground. If it is fully covered, output the location coordinates and quantity of the UAV base station. If there are uncovered ground terminals, update the uncovered base station area boundary. Select the first ground terminal that is not covered by the UAV base station in the counterclockwise direction before updating the boundary as the next boundary terminal, and then repeat step 2 until all ground terminals are covered by the UAV base station.

4.2. **Simulation Experiment**

Experimental parameter setting: Assuming in a complex mountainous region, there are 200 ground terminals, the UAV base station has a flying height of 300 meters, and the coverage radius is 1500 meters. The path loss between the UAV base station and the ground terminal is 100dB and the
frequency is 2000MHz. This experiment does not consider the interference between UAV base stations. The experimental results are shown in figure 6. The green circle represents the coverage of a single UAV base station, and the red line connects the location of the UAV base station from the outside to the inside counterclockwise. It can be seen from figure 6 that 13 UAVs need to be deployed. The specific location of the base station is shown in table 3.

![Figure 6. Layout plan of UAV base station.](attachment:figure6.png)

**Table 3. Location of UAV base station.**

| Base station serial number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---------------------------|---|---|---|---|---|---|---|---|---|----|----|----|----|
| Abscissa (km)             | 2.7 | 17.0 | 20.0 | 16.2 | 6.5 | 2.5 | 3.0 | 7.5 | 14.7 | 16.0 | 13.7 | 9.5 | 10.5 |
| Ordinate (km)             | 4.1 | 2.5 | 10.5 | 17.9 | 20.0 | 16.8 | 10.5 | 5.0 | 5.1 | 8.0 | 15.0 | 15.5 | 10.5 |

**4.3. Comparative Analysis**

In order to test the performance of the algorithm, compare this algorithm with the k-means algorithm. The k-means algorithm is a clustering algorithm for unsupervised learning. The algorithm is simple in principle, the coding process is not complicated, the algorithm logic is clear, and it is easy to converge. It is often used for site planning problems. This paper conducts simulation experiments on these two algorithms in the same environment. Network planning range: 20km*20km. 100 and 200 ground terminals are randomly placed in the network planning area, with a propagation loss of 100dB and a frequency of 2000MHz. The simulation results are shown in table 4.

**Table 4. Simulation results of different algorithms.**

| Number of terminals | 100   | 200   |
|---------------------|-------|-------|
| Covering radius (m) |       |       |
| Spiral algorithm    | 1200  | 1350  |
|                     | 1500  | 1650  |
|                     | 1200  | 1350  |
|                     | 1500  | 1650  |
| k-means             | 22    | 16    |
|                     | 14    | 10    |
|                     | 14    | 10    |
|                     | 14    | 10    |

Analyzing the simulation results, we can get: 1. With the same number of ground terminals and the same coverage radius, the k-means algorithm requires more UAV base stations than the site selection results of this algorithm. 2. When the coverage radius of the two algorithms increase, the number of UAVs required will decrease. 3. Under the same experimental conditions, with the increase of ground terminals, the number of UAV base stations required will also increase. 4. When the deployment
height is the optimal height (1650 meters), there is no the number of man-machine base stations is the least. 5. As the UAV base station slowly drops from the optimal height, the simulation results show that the k-means algorithm needs to deploy more UAV base stations than this algorithm. 6. For changes in coverage radius, the k-means algorithm is more sensitive than this algorithm. In summary, this algorithm is superior to the k-means algorithm in terms of effectiveness and practicability.

5. Conclusion
UAV base station network planning can effectively improve the communication guarantee capability of wireless broadband communication systems in complex environments. In this paper, the air to ground propagation model is established, and the spiral algorithm is used to complete the site planning of UAV base station. When the ground base station cannot work, this method ensures uninterrupted communication support. First of all, for the ground experience propagation model can not be applied to the content of this paper, this paper establishes the air-to-ground propagation model. Then, for the characteristics of the ground terminal service of the UAV base station, the maximum coverage of the UAV base station is obtained by link budget analysis, line-of-sight propagation probability analysis, optimal height analysis and other methods. Finally, the location of the UAV base station is completed by using a spiral algorithm. In order to test the performance of our algorithm, our algorithm is compared with the k-means algorithm. It is concluded that our algorithm can reduce the cost of network. The practicability and effectiveness of our algorithm are proved. However, our method still has some deficiencies in considering communication factors. For example, this paper does not consider the interference between UAVs in the process of UAV network planning. The next study will be more in-depth research in this aspect.

References
[1] Data P 2003 Prediction methods required for the design of terrestrial broadband millimetric radio access systems operating in a frequency range of about 20-50 ghz Draft New Reco. ITU-R P.[DOC. 3/47], Working Party K 3
[2] Al-Hourani A, Kandeepan S and Jamalipour A 2014 Modeling air-to-ground path loss for low altitude platforms in urban environments 2014 IEEE global communications conference (IEEE) pp 2898-2904
[3] Feng Q, Tameh E K and Nix A R WLCp2-06: Modelling the likelihood of line-of-sight for air-to-ground radio propagation in urban environments IEEE Globecom 2006 (IEEE) pp 1-5
[4] Feng Q, McGeehan J, Tameh E and Nix A 2006 Path Loss Models for Air-to-Ground Radio Channels in Urban environments IEEE VTC 6 pp 2901–2905
[5] Holis J and Pechac P 2008 Elevation dependent shadowing model for mobile communications via high altitude platforms in built-up areas IEEE Transactions on Antennas and Propagation 56(4): 1078-1084
[6] Kandeepan S, Hourani A and Lardner S 2014 Optimal LAP Altitude for Maximum Coverage IEEE Wireless Communication Letters 3(6):569-572
[7] Adam N, Tapparello C and Heinzelman W et al. Placement optimization of multiple uav base stations 2021 2021 IEEE Wireless Communications and Networking Conference (WCNC). IEEE pp 1-7
[8] DoAlzenad M, El-Keyi A and Yanikomeroglu H 2017 3-D placement of an unmanned aerial vehicle base station for maximum coverage of users with different QoS requirements IEEE Wireless Communications Letters 7(1): 38-41
[9] Zhao H, Wang H and Wu W et al. 2018 Deployment algorithms for UAV airborne networks toward on-demand coverage IEEE Journal on Selected Areas in Communications 36(9): 2015-2031
[10] Bor-Yaliniz R I, El-Keyi A and Yanikomeroglu H 2016 Efficient 3-D placement of an aerial base station in next generation cellular networks 2016 IEEE international conference on communications (ICC) IEEE pp 1-5

[11] Wang H 2020 Research on coverage deployment method of UAV aerial base station Xi'an University of Technology

[12] Wang C 2019 Research on UAV base station deployment and location update Xidian University

[13] Peng Z N 2017 Research and Practice on Key Technologies of Wireless Network planning—Research and Practice on UAV Base Station Network Planning Beijing University of Posts and Telecommunications