An Optimal Model and Solution of Deployment of Airships for High Altitude Platforms

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***Abstract*—In future communication system, the demand for high capacity is a challenging problem for wireless services, especially for delivery of the 'last mile'. A potential solution is offered by the high altitude platforms (HAPs), which can utilize the best character and tradeoff of both satellite and terrestrial networks. Since the performance of the HAPs depends on the structure of network, how to deploy the nodes of airships for HAPs is increasingly important. In this paper, an optimal model of deployment of airships for HAPs is constructed and solved based on genetic algorithm. First, a heterogeneous system including terrestrial layer, HAP layer and GEO layer is given. Then, an optimal model with objective function of maximum entropy and minimum delay is established to optimize the deployment of airships for HAPs. Finally, a modified genetic algorithm (GA) is employed to optimize the objective function and get the optimal solution to the model. Simulation results show that the established objective function and the solution based on GA can reach the goal of on-demand deployment of airship for HAPs.**

***Index Terms*—High altitude platform; Network structure; Node deployment; Genetic algorithm.**

I. Introduction

With the development of modern communication system, the demand for high capacity has gained much more attentions. Thus, the wireless solutions are becoming increasing important, which can provide a variety of services without reliance on a fixed infrastructure and solve the 'last mile' problem, i.e. delivery directly to a customer's premises. High altitude platforms (HAPs) operating in the stratosphere at altitude between 17 and 22km offer a potential solution, which may be aeroplanes or airships and may be manned or unmanned[1][2][3]. Comparing with terrestrial infrastructure, they cover large areas in line-sight propagation condition. In addition, they have advantages over satellites, such as low cost, lower propagation delays, incremental deployment, and etc. Hence, HAPs can combine the advantages of both terrestrial networks and satellite networks to offer high-capacity services, which has wide application in the fields of broadcasting, multicast, rural sensing, pollution monitoring, traffic monitoring and control, disaster recue and navigation for military.

Recently, it is well known that some projects of HAPs have been studied by many countries, for example, the HeliNet and CAPANINA projects of the European Union [4], Sky Station and SkyTower projects in the US[5], SkyNet project in Japan[6], ETRI in Korea[7]. For these projects, on the one hand, a single HAP platform is studied, which mainly focuses on communication links establishment, array optimization, channel model, and system capacity[8][9][10][11][12][13]. On the other hand, new scenarios that take advantage of integrated satellite-HAP system are proposed, which are utilized to improve system performance [14][15]. However, there are few works for the deployment of HAPs. Ha Yoog Song [16] only presents a method based on *K*-mean clustering for placement of multiple HAPs, but exiting several problems regarding the clustering results.

In this paper, a satellite-HAPs-terrestrial system is given, and an optimal model of deployment of airships for HAPs is established, obtaining the on-demand deployment based on the objectives of maximum entropy and minimum delay. In addition, the genetic algorithm is utilized to optimize the model. Finally, the simulation results show the effectiveness of the proposed model and solution.

The rest of this paper is organized as follows. The satellite-HAPs-terrestrial network system is presented in Section II. The optimal model of deployment of airships is proposed in Section III. The genetic algorithm is introduced to optimize the objective of deployment of airships in Section IV. Experimental results and analysis are given in Section V. The final section is conclusion and future work.

II. Satellite-HAP-Terrestrial Network System

A heterogeneous communication network system is shown in Fig. 1, which consists of three layers, i.e., terrestrial layer, HAP layer and GEO layer. The three-layer network can provide users on the ground with full connection by airships or a satellite.

A. Terrestrial Layer

In order to measure the sparse level of users on the ground, the grid structure is utilized in terrestrial layer. In Fig. 1, the region of $a \times b$ area is divided into $k_0 \times l_0$ square grids, thus achieving two advantages: on the one hand, the index of the grid can substitute for indexes of all users to describe the feature of the area; on the other hand, it is easy to determine the number and position of users in the grid.

Considering the decreasing tendency of users from the urban to rural areas, we assume the distribution of users obeying Gaussian distribution. Let $\rho(r_k)$ denote the distribution of users for the hot spot k, that is

$$\rho(r_k) = \frac{M}{\sqrt{2\pi}\sigma} e^{-\frac{r_k^2}{2\sigma^2}} \tag{1}$$

where r_k is the distance between the center of the hot spot k and users, M is a constant, σ is the standard deviation.

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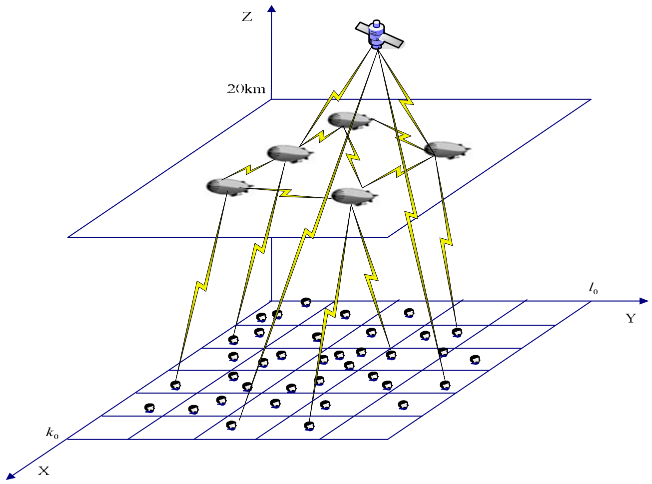


Fig. 1. A satellite-HAPs-terrestrial network system

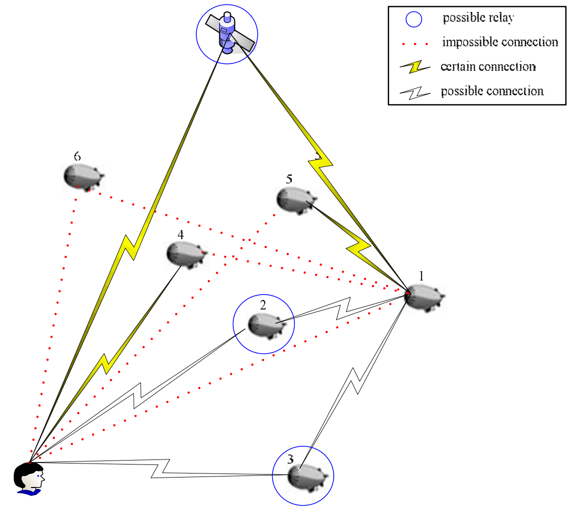


Fig. 2. The assumption of one-hop relay

B. HAP Layer

Although the height range of stratospheric is typically between 10 and 50 km, the altitude of 20km is thought as the optimal position for the deployment of airships due to the show wind speed and stable environment. In addition, Ad hoc network structure is employed as the connection of airships in stratosphere.

C. GEO Layer

Because of the large range that satellite covers, we assume that the satellite can connect to all users and airships. And there is only one satellite whose space position is defined as (x_0, y_0, z_0) in GEO layer.

D. Satellite-HAPs-Terrestrial network

In the satellite-HAPs-terrestrial network, one-hop relay is assumed, that is to say, when one user is not covered by one airship, the satellite or one of other airships is utilized as one relay to connect the user and the airship. In addition, if there are other airships used as the relay, selecting the minimum relay distance is considered; otherwise selecting the satellite is assumed. Thus all the users are connected by HAPs in the heterogeneous network. The assumption of one-hop relay is shown in Fig. 2. It is noticed that the satellite, airship 2 or airship 3 may be utilized as one relay to connect airship 1 and the user. On the one hand, if there are airship2 and airship 3, airship 2 will be selected due to the assumption of the minimum relay distance. On the other hand, the satellite is selected when airship 2 and airship 3 are not employed as the relay.

III. DEPLOYMENT OPTIMIZATION OF AIRSHIPS IN HAP

A. Problem Formulation

In the satellite-HAP-Terrestrial network, we focus on the problem of how to optimize the deployment of airships so that the system can provide users with fair connections. Given the distribution of users and satellite, space positions of airships are optimized based on criterions of maximum entropy and minimum delay, which is a typical multi-objective optimization problem with constrains.

B. Objective Function Modeling

In order to obtain the deployment of airships based on entropy, the performance of power coverage of one airship is first considered. We define that the average distance between airship i and the square area (k,l) is $\overline{r_{ikl}}$, which is given by

$$\overline{r_{ikl}} = \frac{1}{\sum_{q=1}^{n_{kl}} hu_{iklq}} \sum_{q=1}^{n_{kl}} hu_{iklq} r_{iklq} \tag{2}$$

where n_{kl} is the number of users in the (k,l) square area, r_{iklq} is the distance between airship i and user $(x_{klq}, y_{klq}, 0)$, which is defined as

$$r_{iklq} = \sqrt{(m_i - x_{klq})^2 + (n_i - y_{klq})^2 + 20^2} \tag{3}$$

where $(m_i, n_i, 20)$ is the position of airship i, $(x_{klq}, y_{klq}, 0)$ is the position of the q user in the square area (k,l), and hu_{iklq} is defined as the 0-1 indicator variable of the connection between airship i and user $(x_{klq}, y_{klq}, 0)$, that is

$$hu_{iklq} = \begin{cases} 1 & r_{iklq} \le R_0 \\ 0 & r_{iklq} > R_0 \end{cases} \tag{4}$$

where R_0 is the maximum distance that airships can cover users.

From Eq. (2), we obtain P_{kl} that is defined as the average coverage power of every user in the cell (k,l), i.e.,

$$P_{kl} = \frac{\sum_{i=1}^{N} \frac{P_0}{\overline{r_{ikl}}^{\alpha}}}{n_{kl}} \tag{5}$$

where P_0 is the power attenuation of the unite length of the airship, α is the attenuation factor, N is the number of airships.

The concept of entropy known from Shannon's information theory is utilized as an objective of on-demand deployment of airships. Let H denote the entropy of the average coverage power of every user in $k_0 \times l_0$ cells, that is

$$H=-\sum_{k=1}^{k_0}\sum_{l=1}^{l_0}\eta_{kl}\log_2\eta_{kl} \tag{6}$$

where η_{kl} is given by

$$\eta_{kl}=\frac{P_{kl}}{\sum_{k=1}^{k_0}\sum_{l=1}^{l_0}P_{kl}} \tag{7}$$

Thus the objective of on-demand deployment of airships is formulated as

$$\max\ H \tag{9}$$

When H is theoretical maximum, we have

$$\eta_{kl}=\frac{1}{k_0\times l_0} \tag{10}$$

Thus P_{kl} is a constant, which means that the average coverage power of every user in $k_0\times l_0$ cells is equal. From Eq. (5), it is noticed that that the larger n_{kl}, the larger $\sum_{i=1}^{N}\frac{P_0}{r_{ikl}^{\ \alpha}}$, that is to say, the larger the number of users in the (k,l) square area, the larger the coverage power of all the airships in the (k,l) square area. Therefore, on-demand deployment of airships is attained.

For the purpose of measuring the total delay, we define the available distance between airship i and user $(x_{klq},y_{klq},0)$ is d_{iklq}, which is given by

$$d_{iklq}=hu_{iklq}\cdot r_{iklq}+(1-hu_{iklq})\cdot w_{iklq} \tag{11}$$

where w_{iklq} is the relay distance by other airships or satellite, which is expressed by

$$w_{iklq}=H_{iklq}+S_{iklq} \tag{12}$$

where H_{iklq} is the minimal distance between airship i and user $(x_{klq},y_{klq},0)$, relayed by other airships, that is

$$H_{iklq}=\min_{j\in\{1\cdots i-1,i+1\cdots N\}} hh_{ij}\cdot hu_{jklq}\cdot(h_{ij}+r_{jklq}) \tag{13}$$

where h_{ij} is the distance between airship i and airship j, which is given by

$$h_{ij}=\sqrt{(m_i-m_j)^2+(n_i-n_j)^2} \tag{14}$$

and hh_{ij} is the 0-1 indicator variable of the connection between airship i and airship j, that is

$$hh_{ij}=\begin{cases}1 & h_{ij}\le h_0\\ 0 & h_{ij}>h_0\end{cases} \tag{15}$$

where h_0 is the maximum distance that one airship can communicate with other airships, and S_{iklq} is the distance between airship i and user $(x_{klq},y_{klq},0)$, relayed by satellite, that is

$$S_{iklq}=\delta(\sum_{j=1}^{N}hh_{ij}\cdot hu_{jklq})\cdot(sh_i+su_{ikq}) \tag{16}$$

where sh_i is the distance between airship i and the satellite, which is expressed by

$$sh_i=\sqrt{(m_i-x_0)^2+(n_i-y_0)^2+(20-z_0)^2} \tag{17}$$

and su_{ikq} is the distance between the satellite and user $(x_{klq},y_{klq},0)$, we have

$$su_{ikq}=\sqrt{(x_0-x_{klq})^2+(y_0-y_{klq})^2+{z_0}^2} \tag{18}$$

and $\delta(\sum_{j=1}^{N}hh_{ij}\cdot hu_{jklq})$ is the 0-1 indicator variable whether the airship i can select the satellite to relay, given by,

$$\delta(\sum_{j=1}^{N}hh_{ij}\cdot hu_{jklq})=\begin{cases}1 & \text{when } \sum_{j=1}^{N}hh_{ij}\cdot hu_{jklq}=0\\ 0 & \text{when } \sum_{j=1}^{N}hh_{ij}\cdot hu_{jklq}\ne 0\end{cases} \tag{19}$$

For $\sum_{j=1}^{N}hh_{ij}\cdot hu_{jklq}=0$, $\delta(\sum_{j=1}^{N}hh_{ij}\cdot hu_{jklq})=1$ means that airship i cannot connect user $(x_{klq},y_{klq},0)$ by other airships so that airship i connects the user $(x_{klq},y_{klq},0)$ only by satellite; and for $\sum_{j=1}^{N}hh_{ij}\cdot hu_{jklq}\ne 0$, $\delta(\sum_{j=1}^{N}hh_{ij}\cdot hu_{jklq})=0$ means that the airship i can connect the user $(x_{klq},y_{klq},0)$ by other airships.

Consequently, d_{iklq} is expressed as the available distance between the airship i and user $(x_{klq},y_{klq},0)$, relayed by other airships, satellite.

With the distance between airships, the satellite and the user long, the delay is utilized as an important factor for the deployment of airships. We only consider the propagation delay and define that the total propagation delay between airships and users is T, we have

$$T=\sum_{i=1}^{N}\sum_{k=1}^{k_0}\sum_{l=1}^{l_0}\sum_{q=1}^{n_{kl}}\frac{d_{iklq}}{c} \tag{20}$$

where c is the speed of light.

Thus, the objective of the total delay is

$$\min\ T \tag{21}$$

In addition, we have the following space constraint for airships.

$$st.\begin{cases}h_{ij}\ge h_{\min} & i=1\cdots\cdots N-1,\ i<j\le N\\ 0\le m_i\le a & i=1\cdots\cdots N\\ 0\le n_i\le b & i=1\cdots\cdots N\end{cases} \tag{22}$$

where $h_{\min}$ is the minimal safe distance between two airships.

Hence the deployment of airships based on the maximum entropy and the total minimal delay is described as a multi-objective optimization problem with constrain, which is formulated as

$$\max \quad H = -\sum_{k=1}^{k_0}\sum_{l=1}^{l_0}\eta_{kl}\log_2 \eta_{kl}$$

$$\min \quad T = \sum_{i=1}^{N}\sum_{k=1}^{k_0}\sum_{l=1}^{l_0}\sum_{q=1}^{n_{kl}}\frac{d_{iklq}}{c}$$

$$st.\begin{cases} \eta_{kl} = \dfrac{P_{kl}}{\sum_{k=1}^{k_0}\sum_{l=1}^{l_0} P_{kl}} \\ d_{iklq} = hu_{iklq}\cdot r_{iklq} + (1-hu_{iklq})\cdot w_{iklq} \\ w_{iklq} = H_{iklq} + S_{iklq} \\ h_{ij} \ge h_{\min} \qquad i = 1\cdots\cdots N-1,\ i<j\le N \\ 0 \le m_i \le a \qquad i = 1\cdots\cdots N \\ 0 \le n_i \le b \qquad i = 1\cdots\cdots N \end{cases}$$

IV. OPTIMIZATION OF THE DEPLOYMENT OF AIRSHIPS BASED ON GENETIC ALGORITHM FOR

The deployment of airships in stratosphere is formulated as the multi-objective optimization problem with constrains. In classical optimization theory, the optimization problem with constrain is transformed into the one without constrain by the Lagrange multiplier method, thus solved by the gradient descent or other iterative algorithms. However, it is difficult to obtain the global optimization solution to the complicated nonlinear optimal problem with constrains. For this end, the genetic algorithm (GA), as a global-heuristic search and optimization technique, is employed to solve the problem.

In genetic algorithms, first of all, the solution to the problem is encoded as the form of the chromosome, such as the string of binary numbers or real numbers. In addition, the generation of the population of the chromosomes is iteratively generated by genetic operators, for example, crossover and mutation. The population of the chromosomes with larger fitness value is selected as the next generation. Also, it is not stopped until the termination condition is met. Hence the population in genetic algorithms is evolved toward the direction of the global optimization solution [17]. In the model, the population of the chromosomes is employed as the candidate solution to the deployment of airships that is the space position of the airships in stratosphere, and the fitness function is used as the optimization objection of the deployment of the airships.

The genetic operations utilized in the model are given as follows.

A. *Encoding of the solution*

In this approach, the real-number encoding is employed as the encoding of the solution, which has the advantage of the computing cost without decoding, high encoding precision and large range of numbers. The space position of the airship i is encoded as

$$m_i = a + (b-a)\times rand(1, M) \tag{23}$$

$$n_i = a + (b-a)\times rand(1, M) \tag{24}$$

where M is the number of the population.

B. *Fitness function*

In genetic algorithms, the quality of the solution is evaluated by the fitness function of the population. The higher the fitness of the population is, the better the solution to the fitness. Thus the probability of the selection of the population with the higher fitness is larger. Because the deployment of airships is the multi-objective optimization problem with constrains, it should be first transformed into a single-objective one. Then constrains of the objective should be removed by certain penalty strategies. Thus the fitness can be computed. The process is expressed by

$$F = H - \lambda T - L \tag{25}$$

$$L = \begin{cases} L_1 & h_{ij} < h_{\min} \\ 0 & h_{ij} \ge h_{\min} \end{cases} \tag{26}$$

where λ is the scaling factor, L_1 is the penalty constant.

C. *Selection*

The selection operator utilized here is based on spinning the roulette wheel, whose basic principal is that the probability of the selection is determined by the proportionality of the fitness of the population. The elite strategy by which the largest fitness of populations is directly copied to next generation is also employed in selection process. The probability of the selection is expressed by

$$p_i = \frac{F_i}{\sum_{i=1}^{M} F_i} \tag{27}$$

D. *Crossover*

The linear crossover operator is used, which means that two new populations are generated by the convex combination of the old two populations. The crossover process is given by

$$m_i^{\text{new}} = \beta\cdot m_i^{\text{old}} + (1-\beta)\cdot m_j^{\text{old}} \tag{28}$$

$$m_j^{\text{new}} = (1-\beta)\cdot m_i^{\text{old}} + \beta\cdot m_j^{\text{old}} \tag{29}$$

where m_i^{old} and m_j^{old} are denoted as old population i and population j respectively, m_i^{new} and m_j^{new} are denoted as new population i and population j respectively, and β is the crossover factor.

E. *Mutation*

To obtain the high accuracy and tuning capability, the no-uniform mutation is employed. The mutation is expressed by

$$m_i^{new} = \begin{cases} m_i^{old} + (b - m_i^{old})\cdot r\cdot(1-\dfrac{t}{G})^b & p_i > 0.5 \\ m_i^{old} - (m_i^{old} - a)\cdot r\cdot(1-\dfrac{t}{G})^b & p_i \le 0.5 \end{cases} \tag{30}$$

where r and p_i are random values between 0 and 1 respectively, and t is the current generation number, G is the maximum generation number, b is the parameter of the no-uniform degree.

Finally, the parameter solution to this problem is generated. The process of genetic algorithms is shown in Fig. 3.

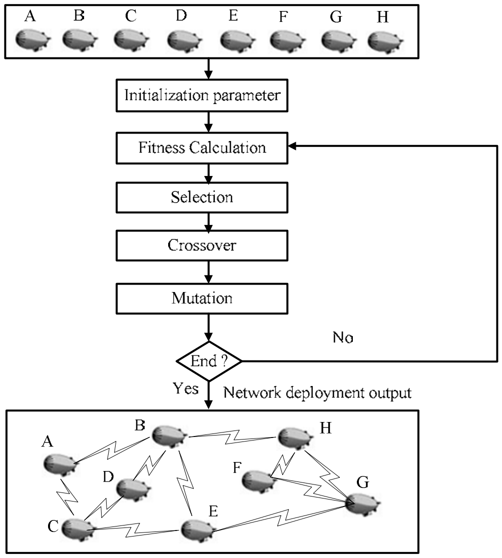


Fig. 3. The process of genetic algorithms.

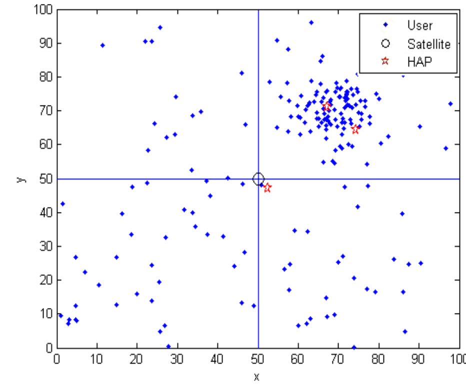
V. EXPERIMENTAL RESULTS AND ANALYSIS

In this section, we conduct simulation experiment to illustrate the effectiveness of the proposed deployment of airships scheme. In experiment, we have considered a field of area of 100km * 100km, which is uniformly divided into 2*2 grids. The satellite located at a point (50km, 50km, 36000km). On the one hand, 100 uniformly distributed users are generated in the field; on the other hand, 100 Gaussian distributed users are generated with its mean of space position at the point (70km, 70km) and of variance 5km, which is utilized to measure the on-demand performance. We assume that the attenuation factor α is 2, the maximum distance that airships can cover users R_0 is 70km, the maximum distance that airships can communicate with other airships h_0 is also 70km and the minimal safe distance between two airships $h_{\min}$ is 3km.

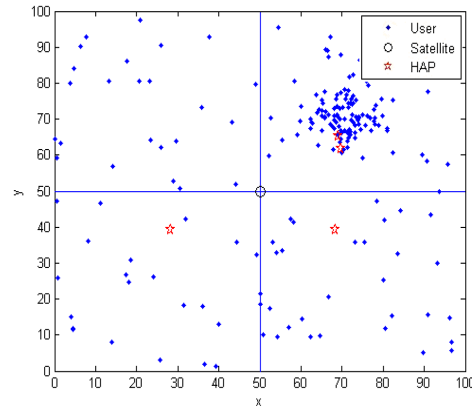
In GA, the optimal solution depends upon these values. We have tried different values of the population size, mutation probability and crossover probability to find the best solution. The best result obtained is given as follow: the number of the population M is 61, the mutation probability is 0.8, crossover probability is 0.08, and the maximum generation G is 200. The scaling factor λ is 0.01, and the penalty constant L_1 is 1.

Fig. 4 shows the deployment of different numbers of airships under given distribution of users and satellite. In Fig. 4(a), it is noticed that the positions of two airships are approximately (70km, 70km, 20km), which achieves the purpose for the demand of users following by Gaussian distribution; On the other hand, another airship is approximately at the point (50km, 50km, 20km), which may fairly cover other areas. Simultaneously, Fig. 4(b-d) show similar laws.

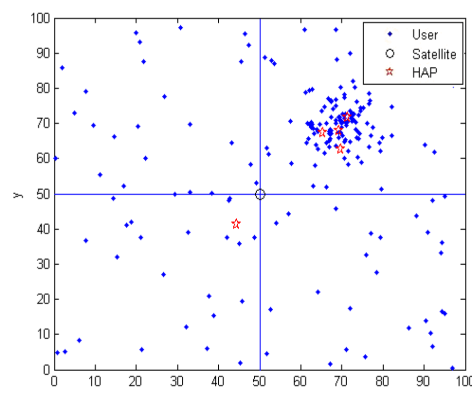
Fig. 5 shows coverage power rates of four grid areas for the cases that λ =0 and λ =0.01. For λ =0, the deployment of airships only considers the objective of entropy that obtains fair coverage power for every user, and thus any coverage power rate η_{kl} is approximately 0.25. On the other hand, for λ =0.01, a multi-objective based on the entropy and minimum delay can



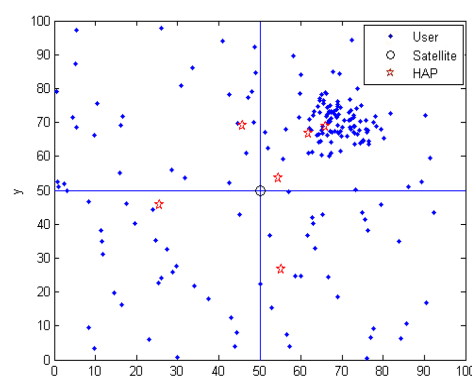
(a). The deployment of three airships.



(b). The deployment of four airships.



(c). The deployment of five airships.



(d). The deployment of six airships.
Fig. 4. The deployment of different numbers of airships

obtain a trade-off solution of deployment of airships, which may have small delay rather than identical coverage power rate.

Fig. 6 shows the evolution of best fitness for the cases that $\lambda=0$ and $\lambda=0.01$. For $\lambda=0$, the convergence rate is high. When the generation is 45, the best fitness converges to 1.994, which is approximately a global optimal solution. On the other hand, for $\lambda=0.01$, when the generation is 45, the best fitness of the multi-objective based on the entropy and minimum delay can converge to 1.969, thus achieving a trade-off solution of deployment of airships.

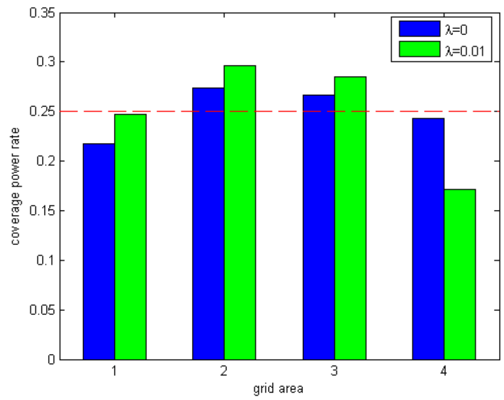


Fig. 5. The coverage power rate of grid areas.

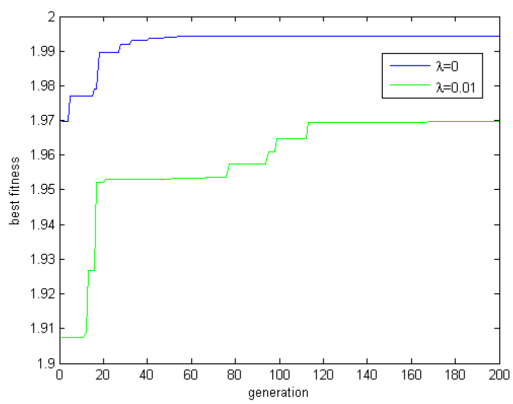


Fig. 6. The evolution of best fitness.

VI. CONCLUSION AND FUTURE WORKS

In this paper, we present a satellite-HAPs-terrestrial system that is different from traditional heterogeneous systems. In addition, an optimal model to achieve on-demand deployment of airships for HAPs with the objective of maximum entropy and minimum delay is proposed. Then a modified genetic algorithm is utilized to optimize the model. Simulation results indicate that the method based on maximum entropy and minimum delay can achieve a good result for deployment of airships in HAPs.

In the future, the effect of the base stations over deployment of airships can be considered. Moreover, the number of airships could be employed as an objective to minimize the cost of deployment of airships.

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