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Deployment Optimization of Near Space Airships Based on MOEA/D with Local Search

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***Abstract*— The near space communication system is a burgeoning communication system. This system has many advantages over the satellite and terrestrial networks. Being built on the near space airships, the deployment of the airships has a significant impact on the performance of the system. Various factors should be taken into consideration to build such a system of which some objectives relate with each other and specific areas weight objectives differently. The evolutionary multiobjective optimization can fulfill the purpose to provide a series of choices of the deployment scheme. In this paper, a model of such a system is proposed and the deployment of airships is solved using the multiobjective evolutionary algorithm based on decomposition. Cases with different numbers of airships are tested and the Pareto fronts are obtained. In order to increase the density of the Pareto front, a local search method based on the positions of the airships is proposed. The experiment shows that the local search method can effectively increase the number of Pareto solutions obtained.**

I. Introduction

In recent years, the modern communication system is being challenged with increasing demands for large coverage, high-speed transmission, low price and rapid deployment which the current communication systems have many difficulties to deal with [1]. The satellite communication system (SCS) is expensive, low in speed and complicated to deploy, while the terrestrial wireless communication system (TWCS) is terrain dependent and unfit for remote areas. The near space communication system (NSCS) has emerged as a novel backbone communication system which shows immense advantages over SCS and TWCS.

The altitude of the near space is about 17km to 100km above the sea level which is higher than the commercial liner but lower than the orbit satellite including the stratosphere, mesosphere and part of thermosphere [2]. The atmosphere at this altitude has many special properties so that specific aircrafts like high altitude balloon, airship etc. are required [3]. Featured with advantages like long endurance, low price, rapid deployment etc., the NSCS has many advantages over other communication systems. Compared with the TWCS, the NSCS is able to cover large area with relatively less airships, while the TWCS has to build large quantities of base stations to offset the effect of the landscape on the transmission of the signal. The deployment of the TWCS is time-consuming while the NSCS can be deployed rapidly. The SCS is characterized with global coverage, but the cost is so high that it is mainly dedicated to special purposes and not suitable for personal use. The NSCS system can provide high speed network with reasonable price. With all the features above, the NSCS will establish a large market of civil use [4].

The advantages of the NSCS make it a powerful competitor in the territory of wireless communication. Except for the application on communication, the near space airship can also serve as the platform for remote sensing. The synthetic aperture radar (SAR) based on near space platform (NSP) combines both the advantages of SAR based on satellite and airplane [5] [6]. The NSP can be integrated with terrestrial cellular network, such as 4G or TDMA, to provide high quality mobile communication for large and remote area [7] [8]. The NSP can also serve as the platform for high speed broadband network [9] and earth observation [10].

Despite other technical details to build such a communication system, the deployment of the near space airships has a significant impact on the performance of the communication system. Many researches have been done in this respect [11–15], while none of them takes multiobjective into consideration. Specific situation weights objectives differently, e.g. large coverage is required for remote area while high speed network for urban area. As a result, the deployment problem is a multiobjective problem (MOP) and we need to obtain the Pareto Front (PF).

The multiobjective evolutionary algorithm based on decomposition (MOEA/D) decomposes the MOP into a series of single optimization problems with emphasis on different objectives, and multiple solutions are obtained by solving each of them [16]. In the experiment we applied the MOEA/D on the deployment problem and obtained a PF which is a little sparse. In order to increase the density of the PF, we improved the MOEA/D with a local search method based on the obtained PF and a better PF with more Pareto solutions was obtained.

The paper is arranged as follows. The structure and connection strategy of the near space communication system are described in section II. The modeling and objectives of the NSCS are talked in section III. The optimization procedure and the local search method are described in section IV. The results and analyses of the experiments are shown in section V and the conclusion comes the last.

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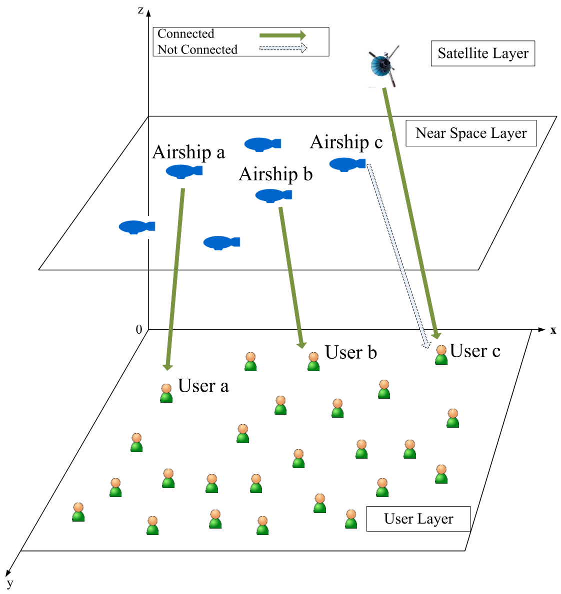

Fig. 1. Model of near space communication system

II. Near Space Communication System

The NSCS is featured with large coverage, low price and rapid deployment etc.. In order to make full use of the NSCS, the near space communication system could collaborate with the satellite network or terrestrial cellular network to form a heterogeneous communication system.

A heterogeneous NSCS is shown in Fig.1. This NSCS consists of three layers: the user layer, the near space layer and the satellite layer. The airships cooperate with the satellite to provide network connection for all the users.

A. User layer

The user layer simulates the terrestrial user distribution. The user layer is a plane area of $a \times b$ large consisting of two parts of users: the background users and the hot spot users with n users in total. The coordinates of user i is $(x^i_{usr}, y^i_{usr}, 0), i = 1, 2, \ldots, n$. The background users are uniformly distributed, which simulates the user distribution of general area. The user layer also contains l hot spots, which simulate the urban areas with dense users. The users in each hot spot obey Gaussian distribution with center at $(x^j_{hs}, y^j_{hs}, 0), j = 1, 2, \ldots, l$. The radius of each hot spot is r^j_{hs} which equals 3δ. δ is the standard variance of the standard Gaussian distribution. Users of each hot spot are generated by the Box-Muller method [17] shown in Fig.2. The radius of the circle on which the user A is to be generated is:

$$r'^j_{hs} = (\sqrt{-2 \ln u_1} \cdot \cos 2\pi u_2) \cdot \frac{1}{3} r^j_{hs} \quad (1)$$

where

$$u_1, u_2 \sim U(0, 1]$$

and then

$$r'^j_{hs} \sim N(0, (\frac{1}{3} r^j_{hs})^2) \quad (2)$$

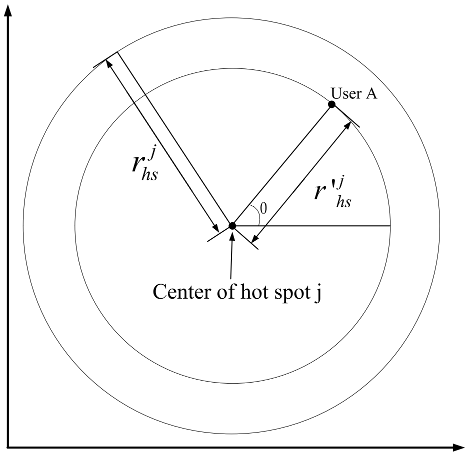

Fig. 2. Formation of hot spot user

the position of user A is:

$$\begin{cases} x^A_{usr} = r'^j_{hs} \cdot \cos\theta + x^j_{hs} \\ y^A_{usr} = r'^j_{hs} \cdot \sin\theta + y^j_{hs} \end{cases} \quad (3)$$

where

$$\theta \sim U[0, 2\pi]$$

Each user in the user layer will connect the airships to get higher performance-price ratio as long as being covered by the airships. When a certain user is not covered by any airships, the user would switch to the satellite to get access to the network even though the service is expensive and low in speed.

B. Near space layer

The near space layer contains m airships of which the altitude alt_{as} is the same and fixed. The position of each airship is:

$$X^j_{as} = (x^j_{as}, y^j_{as}, alt_{as}) \quad j = 1, 2, \ldots, m$$

$$subject\ to \quad \begin{cases} 0 \le x^j_{as} \le a \\ 0 \le y^j_{as} \le b \end{cases}$$

The coverage of each airship is cvg_{as}: the radius of the circle of which the center is the project point of the airship. The user i is covered by the airship j if:

$$dis_{ij} \le cvg_{as}$$

where

$$dis_{ij} = \sqrt{(x^i_{us} - x^j_{as})^2 + (y^i_{us} - y^j_{as})^2}$$

Each airship can provide network connection for the user under its coverage with channel capacity of chp_{as}, that is to say, if a user connects N airships, the channel capacity gained by the user is: $chp_{as} \times N$. The more airships a user connect, the faster the network speed.

C. Satellite layer

The satellite layer contains one satellite and mainly serves as the backup access point when some users are out of the reach of the airships. The satellite is able to connect any user wherever it is. As a result, the satellite improves the robustness of the heterogeneous communication system. The satellite is settled at $(x_{st}, y_{st}, alt_{st})$. When the users connect the satellite, each of them will gain a channel capacity of chp_{st}.

III. Multiobjective Optimization Model for Deployment of The Airships

In order to optimize the deployment of the airships, many aspects should be taken into consideration such as:

- The number of the airships: the airships are always limited, which is directly related to the cost of the system.
- The coverage of the system: to cover as large area as possible with limited airships.
- The network speed: which is directly related to the total capacity gained by the users.

Assuming that the number of the airships is settled, all of the concerns come down to two aspects. On one hand, the airships tend to spread as much to cover larger area (the background area) as possible, on the other hand, the airships also tend to gather around the urban areas (the hot spot areas) to provide high-speed network for the dense users. As a result, two objectives are proposed to reflect these two tendencies.

A. The first objective

The total distance between the users and the NSCS reflects the coverage of the NSCS. When the user $i, i = 1 \dots n$ under the coverage of the near space airships, the distance dis_i is the smallest one by which the user is away from the airships:

$$dis_i = \min_{1 \le j \le m} \{ \sqrt{(x_{usr}^i - x_{as}^j)^2 + (y_{usr}^i - y_{as}^j)^2 + alt_{as}^2} \} \tag{4}$$

If the user has to connect the satellite and then the distance is:

$$dis_i = \sqrt{(x_{usr}^i - x_{st})^2 + (y_{usr}^i - y_{st})^2 + alt_{st}^2} \tag{5}$$

and then the total distance is:

$$d = \sum_{i=1}^{n} dis_i \tag{6}$$

According to the discussion above, the total distance d will be smaller with more equally distributed airships rather than concentrated ones. We convert the minimization of d into a maximization problem and obtain the first objective:

$$Maximize \quad D = -\sum_{i=1}^{n} dis_i \tag{7}$$

B. The second objective

The total channel capacity obtained by all the users reflects the network speed, the larger the total channel capacity, the faster the network speed. The total capacity gained by user i through airships is:

$$chp_{us}^i = \sum_{j=1}^{m} chp_{as} \cdot ua_{ij} \tag{8}$$

where

$$ua_{ij} = \begin{cases} 0 & dis_{ij} > cvg_{as} \\ 1 & dis_{ij} \le cvg_{as} \end{cases}$$

When user i is not covered by any airship, the user will gain capacity through the satellite:

$$chp_{us}^i = chp_{st} \cdot us_i \tag{9}$$

where

$$us_i = \begin{cases} 1 & \sum_{j=1}^{m} ua_{ij} = 0 \\ 0 & otherwise \end{cases}$$

from (8) and (9), the total capacity obtained by all the users is:

$$C = \sum_{i=1}^{n} chp_{us}^i$$

and we obtain the second objective:

$$Maximize \quad C = \sum_{i=1}^{n} chp_{us}^i \tag{10}$$

From the discussion above, the deployment problem of the near space airships is the MOP:

$$\begin{aligned} &Maximize \quad F(X_{as}^1, \dots, X_{as}^m) = \{D, C\} \\ &subject\ to \quad \begin{cases} 0 \le x_{as}^j \le a \\ 0 \le y_{as}^j \le b \end{cases} \end{aligned} \tag{11}$$

IV. Implementation of MOEA/D for The Proposed Problem

A. Representation of individual

In our experiment, the individual is real-coded as shown in Fig.3. Due to the fact that the altitude of the airships is settled, the third coordinate of the position is omitted.

Airship 1		Airship 2		...
x_1	y_1	x_2	y_2	

Fig. 3. Code scheme of the individuals

Algorithm 1 The optimization of deployment

Input
- population size P and neighborhood size N
- number of iteration: T. number of objectives:Q
- other parameters

Initialization
- randomly generate $\lambda_i, i = 1, \ldots, P$ for all subproblems, and generate set $S_i = \{X_{i_1}, X_{i_2}, \ldots, X_{i_N}\}$ containing N neighbors of subproblem i.
- randomly generate the population POP and calculate the objective vectors $FV(X_i)$.
- find the boundaries $B = \{\{b^j_{max}, b^j_{min}\}, j = 1, \ldots, Q\}$ of the values of each objectives and calculate the normalized objective vector $FV_{norm}(X_i)$.
- calculate the $f_{pbi}(X_i|\lambda_i)$.
- set EP=$\emptyset$.

for $t = 1$ to T **do**
  for $i = 1$ to P **do**
    Reproduction: randomly select two individuals from S_i and generate a new individual X_{new} by SBX crossover and non-uniform mutation.
    Repair:
    if any airship of X_{new} is out of area **then**
      abandon X_{new}, set $i = i-1$ and skip all the steps of this inner iteration blow.
    end if
    Update B: update B according to X_{new}.
    Update POP:
    for $l = 1, \ldots, P$ **do**
      update $FV_{norm}(X_l)$ and $f_{pbi}(X_l|\lambda_l)$ according to B
    end for
    Update Neighbors: for all $X_{i_k} \in S_i, k = 1, \ldots, N$
    if $f_{pbi}(X_{i_k}|\lambda_{i_k}) > f_{pbi}(X_{new}|\lambda_{i_k})$ **then**
      set $X_{i_k} = X_{new}$ and update all the objective values of X_{i_k}
    end if
    Update EP: if X_{new} is not dominated by any solutions in EP, then add X_{new} to EP and omit the solutions in EP dominated by X_{new}
  end for
end for
Output: EP.

B. Procedure of optimization

The procedure of the optimization is Algorithm 1. After generating the λ, the distance between any two weight vectors is calculated using the Euclidean distance. For the comparability between different objectives, the boundary set B is maintained and all the objective values are normalized to the interval of [0 1]. The normalized objective vector FV_{norm} of each individual is calculated. The f_{pbi} of each individual is calculated using the FV_{norm} and each individual contains three kinds of objective values: FV, FV_{norm} and f_{pbi}. Each element of reference point Z^* is set to 1 and does not need to be updated. During each iteration, because of the appearance of new individuals, B is updated, and so do FV_{norm} and f_{pbi}.

The airships of X_{new} generated by crossover and mutation might be out of the boundary of the area. Those new individuals are abandoned and $i = i - 1$.

1) Crossover: The simulated binary crossover (SBX) [18] operator is applied in the reproduction. Given two parents:

$$X_1 = (x_{11}, x_{12}, \ldots, x_{1j}, \ldots, x_{1n})$$
$$X_2 = (x_{21}, x_{22}, \ldots, x_{2j}, \ldots, x_{2n})$$

the offsprings are generated as:

$$\begin{aligned} \tilde{x}_{1j} &= 0.5[(1+\gamma_j)x_{1j} + (1-\gamma_j)x_{2j}] \\ \tilde{x}_{2j} &= 0.5[(1-\gamma_j)x_{1j} + (1+\gamma_j)x_{2j}] \end{aligned} \tag{12}$$

where

$$\gamma_j = \begin{cases} (2r_j)^{\frac{1}{\eta+1}} & if\ r_j \le 0.5 \\ (\frac{1}{2(1-r_j)})^{\frac{1}{\eta+1}} & otherwise \end{cases}$$
$$r_j \sim U(0,1)$$

the $\eta > 0$ is the distribution factor and it is suggested that $\eta = 1$. Each call for the SBX produces two offsprings and the one with best $f_{pbi}(X|\lambda_i)$ is selected.

2) Mutation: Non-uniform mutation is applied on the completion of crossover. The offspring of X_1 is as follows:

$$\begin{cases} \tilde{x}_{1j} = x_{1j} + (UL - x_{1j}) \cdot r \cdot (1 - \frac{t}{T})^b & a > 0.5 \\ \tilde{x}_{1j} = x_{1j} - (x_{1j} - LL) \cdot r \cdot (1 - \frac{t}{T})^b & a \le 0.5 \end{cases} \tag{13}$$

where

$$r, a \sim U[0,1]$$

and b is the degree of non-uniformity, which is suggested to be 1. The t is the current iteration of total T iterations. The UL and LL are the upper limit and lower limit of the corresponding coordinate respectively.

C. Local search

There will not be enough nondominated solutions on the PF by simply using MOEA/D. In order to increase the density of the PF, we proposed a local search based on the obtained PF. Take 4 airships case for example, in Fig. 4 we notice that two adjacent points, saying A and B, on the PF have the similar deployment of airships. As the airships of solution A approach those of solution B step by step, we expect more nondominated solutions would be obtained between A and B. The more intensive the search, the more nondominated solutions we would obtain. The search process is shown in Fig. 5 and Fig. 6. The positions of airships of two solutions are:

$$\begin{aligned} A &= \{Airship_i|(x_{Ai}, y_{Ai}, alt_{as}), i = 1, \ldots, 4\} \\ B &= \{Airship_i|(x_{Bi}, y_{Bi}, alt_{as}), i = 1, \ldots, 4\} \end{aligned} \tag{14}$$

In order to move the airships of solution A to the airships of solution B, the airships of both solutions need to pair up first.

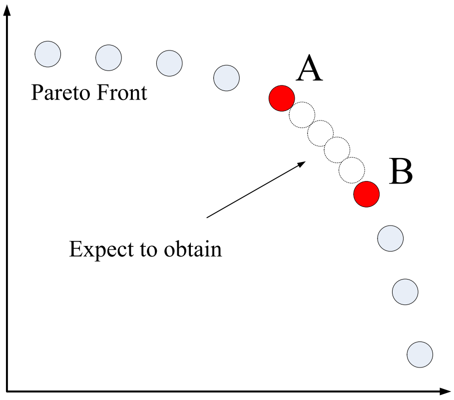

Fig. 4. Adjacent nondominated solutions

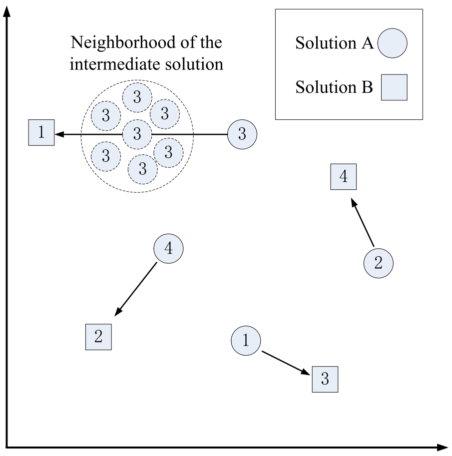

Fig. 5. Local search based on Pareto Front

For the search process from A to B, each airship of B finds the nearest airship in A and pairs up. The paired airship of A cannot be selected by other airships of B any more. Then each airship i of A gets paired up with airship of B with index p_i. The airship i of A moves to airship p_i of B and searches N_{ls} intermediate positions. All the airships of A take the similar action at the same time. The $j, j = 1, 2, \dots, N_{ls}$ intermediate solution is:

$$\begin{cases} x_{ji} = x_{Ai} + sx_i \cdot j \\ y_{ji} = y_{Ai} + sy_i \cdot j \end{cases} \tag{15}$$

where

$$i = 1, 2, 3, 4$$

$$j = 1, 2, \dots, N_{ls}$$

$$sx_i = \frac{x_{Bp_i} - x_{Ai}}{N_{ls} + 1}$$

$$sy_i = \frac{y_{Bp_i} - y_{Ai}}{N_{ls} + 1}$$

The algorithm above searches solutions along the line between A and B, which ignores the neighborhood of the intermediate solutions. In order to increase the effectiveness, the local search process will search the neighborhood of each intermediate position. In Fig. 6, as airship 3 of solution A moving to airship 1 of solution B, it will stop at each intermediate position j and search its neighborhood. The number of neighborhood solutions to be searched is N_{ns}. Based on the current position j, the neighborhood solution is:

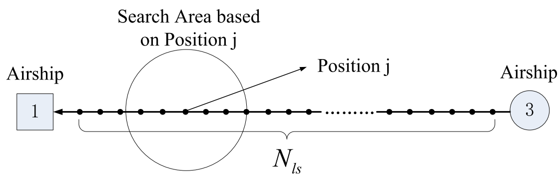

Fig. 6. Local search on the neighborhood of the intermediate solution

$$\begin{cases} x_{kji} = x_{ji} + \gamma_1 \cdot \beta \cdot a \\ y_{kji} = y_{ji} + \gamma_2 \cdot \beta \cdot b \end{cases} \tag{16}$$

where

$$\begin{cases} i = 1, 2, 3, 4 \\ j = 1, 2, \dots, N_{ls} \\ k = 1, 2, \dots, N_{ns} \\ \gamma_1 = \begin{cases} 1 & m > 0.5 \\ -1 & m \le 0.5 \end{cases} \\ \gamma_2 = \begin{cases} 1 & n > 0.5 \\ -1 & n \le 0.5 \end{cases} \\ m, n \sim U(0, 1) \end{cases}$$

β is the search factor. a and b are the length and the width of the user area respectively. The process of local search is shown in Algorithm 2.

Algorithm 2 Procedure of local search

Require: Pareto Front is obtained

Initialization:set new solution set of local search: $L = \emptyset$.
for $j = 1$ to N_{ls} **do**
  for $i = 1$ to 4 **do**
    calculate the position of airship i of step j: (x_{ji}, y_{ji}).
  end for
  obtain intermediate solution X_{new}
  add X_{new} to L.
  for $k = 1$ to N_{ns} **do**
    for $i = 1$ to 4 **do**
      calculate the position of airship i of neighbor solution k: (x_{kji}, y_{kji}).
    end for
    obtain intermediate solution X_{new}
    add X_{new} to L.
  end for
end for
calculate the FV of each solution in L.
Update: update EP according to L.

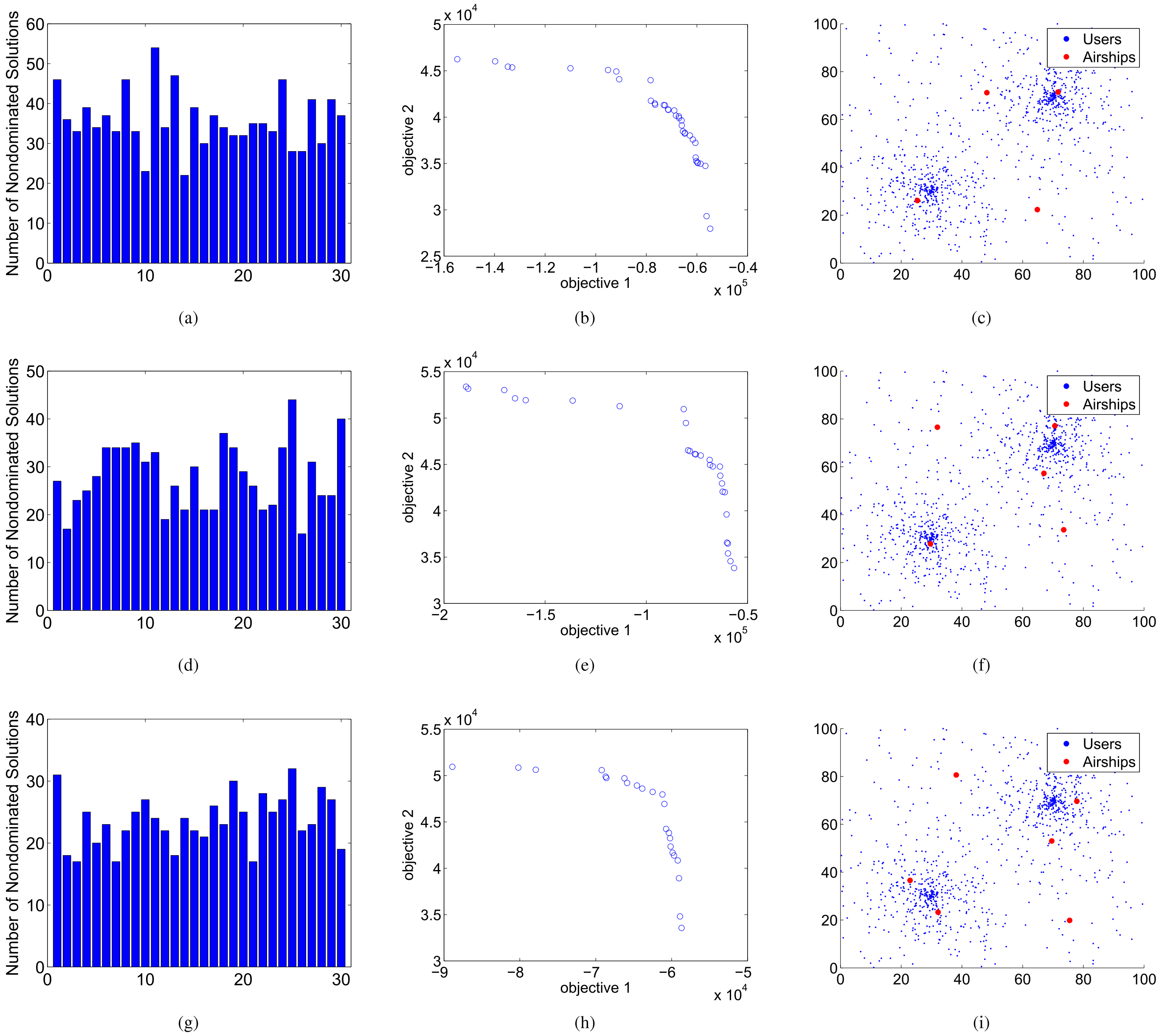

Fig. 7. Experiment results of 4, 5 and 6 airships.The numbers of nondominated solutions of 4,5 and 6 airships case are shown in (a), (d) and (g) respectively. (b), (e) and (h) are the PFs equaling to the average number of nondominated solutions of each case. (c), (f) and (i) are the deployments of the airships of moderate solutions selected from PF of each case.

V. Experiments

A. Parameter settings

1) Parameters of NSCS: In our experiment, the area is 100×100 large. The user layer contains 200 background users and 2 hot spots each of which has 400 users. The position of two hot spot is $(30, 30, 0)$ and $(70, 70, 0)$ respectively. The altitude of airships is 50. The channel capacity for each user provided by each airship is $chp_{as} = 20$ and $chp_{st} = 20$ by the satellite. The position of the satellite is $(50, 50, 300)$. Two objectives talked above in section III-A and section III-B are applied. In order to test the validity of the model, cases of 4, 5 and 6 airships are tested. For comparability, all the cases have the similar coverage ratio, that is, the total area covered by the airships without overlap is approximately the same in all cases. As a result, the coverage of the 4 airships case is $cvg_{as} = 30$, $cvg_{as} = 27$ for 5 airships case and $cvg_{as} = 25$ for 6 airships case.

2) Parameters of MOEA/D: For all the cases described above, the settings of MOEA/D are the same. The number of subproblem is 200, and 20 neighbors are selected for each of them. The penalty factor of PBI is 8. As for the crossover and mutation operator, the parameters are $\eta = 1$ and $b = 1$ respectively. The probability of crossover is 0.9 and 0.05 of mutation. The number of iteration is 2500 for all the cases. Each case is repeated 30 times separately.

B. Experiment results

After 30 runs of each case, the result is shown in Fig. 7. The average number of nondominated solutions of each case in 30 runs is shown in Table I.

TABLE I
AVERAGE NUMBER OF NONDOMINATED SOLUTIONS

Number of Airship	Number of Nondominated Solutions
4	35.8
5	28
6	23

TABLE II
AVERAGE NUMBER OF NONDOMINATED SOLUTIONS WITH LOCAL SEARCH

Number of Airship	Number of Nondominated Solutions
4	35.8
4+	55.8
5	28
5+	40.3
6	23
6+	35.6

C. Experiment results with improvement

From the results above, it is clear that we have obtained a series of nondominated solutions, that is, the approximation of the Pareto front. A moderate solution which strikes a balance between two objectives tracks two hot spots well: several airships are in the hot spot areas and the others cover the remote area. According to the PF and the number of nondominated solutions, we notice that the PF of each case without local search is sparse so that there are not enough solutions on the PF for the decision maker to chose from.

In the improved experiment, we have $\beta = 0.2$. The average number of nondominated solutions is shown in Table II. The result is shown in Fig. 8, The items of 4+, 5+, and 6+ are experiment results with local search method.

From Fig.8 and Table II, it is clear that the MOEA/D with the local search can obtain more solutions than the one without local search. The effect of the local search is a little unstable that in the run 21 of 4 airships case the MOEA/D with local search can obtain almost 3 times more solutions than the original one, but in the run 22 and 23 the results are almost the same. From the PF of 4 airships case, some parts of the PF is still sparse but some part has evenly distributed solutions. For different cases, the PFs of 5 and 6 airships cases are more evenly distributed than the 4 airships case.

VI. Conclusion

The near space communication system has many advantages over the satellite and terrestrial communication systems. The deployment of the airships has a significant impact on the performance of the NSCS. The application of MODA/D with local search on the NSCS can provide a series of nondominated solutions of deployment for decision maker to choose from.

This paper proposed a model with two objectives, which reflect the demands of the near space communication system for dispersal and centralization. As a multiobjective problem, various areas weight objectives differently. In our experiment, the cases of 4, 5 and 6 airships are tested and the application of MOEA/D with the PBI method has obtained the Pareto front. In order to increase the number of nondominated solutions, a local search method is proposed based on the positions of airships of two adjacent Pareto solutions. With the local search, more Pareto solutions were obtained and the PFs are denser.

This model could be expanded easily. The other objectives which might make the airships more disperse or more centralized have the similar effect with either of the two objectives. As a result, the model could be applied in different situations with various combinations of objectives.

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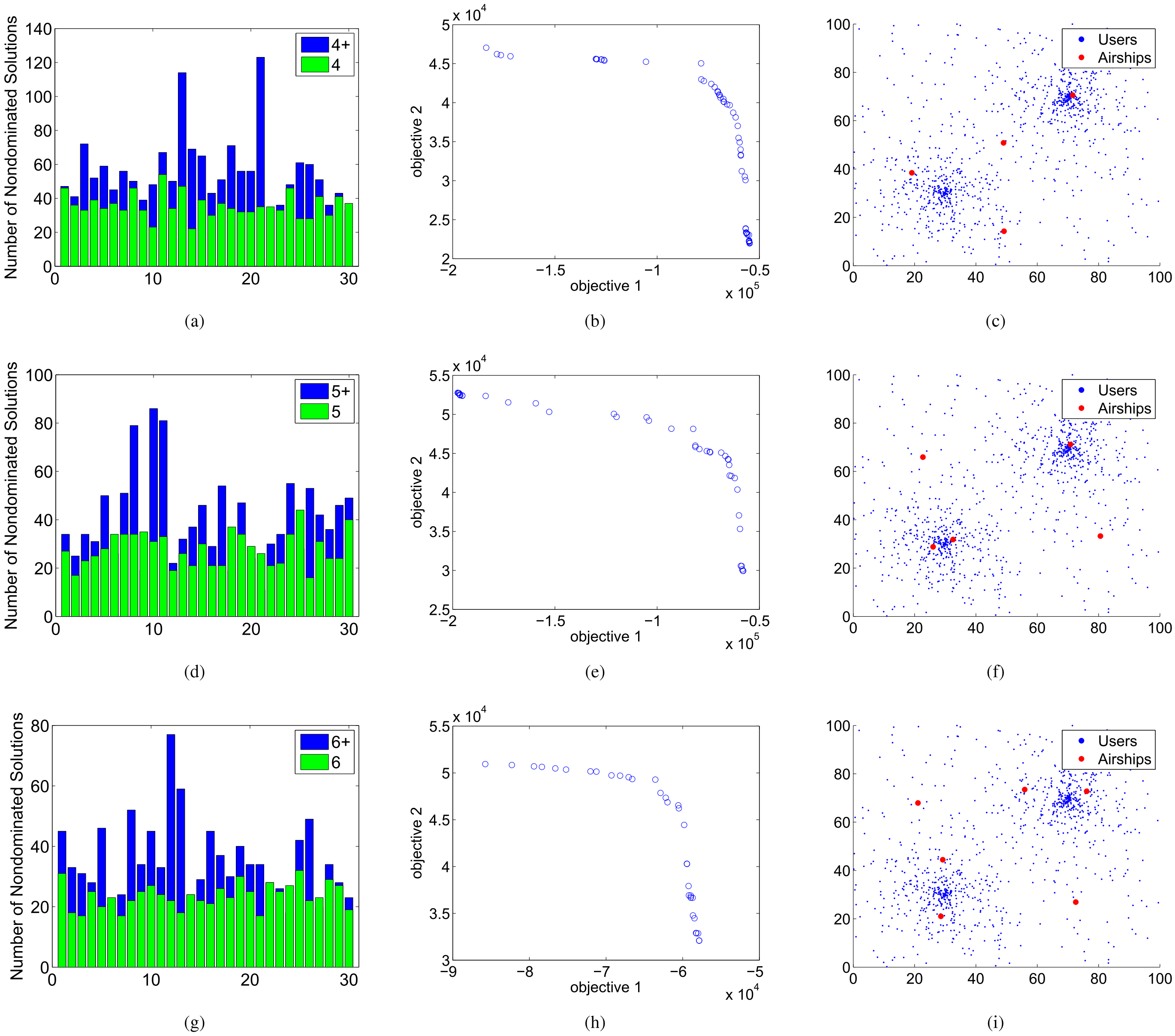

Fig. 8. Experiment results with local search. (a), (d) and (g) are the numbers of nondominated solutions of 4, 5 and 6 airship cases with and without local search respectively. (b), (e) and (h) are PFs equaling the average number of nondominated solutions of each case. (c), (f) and (i) are the deployments of moderate solutions from PF of each case.

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