Optimal Design of Shaped Multiple-Beam Antenna Based on Artificial Bee Colony Algorithm

Zhengxin Shi*, Xingang Zhang¹, Fei Yu¹ and Men Gao¹
1China Academy of Space Technology (Xi'an), Xi’an, Shaanxi, China
*Corresponding author’s e-mail: zhongzhuanjit504@cast504.com

Abstract. In order to maximize the multiple-beam performance in a specific service area, a new optimization design method of shaped single-aperture single-feed multiple-beam antenna was proposed. The contradiction between the layout of satellite platform and the performance of specific service area was solved by comprehensively optimizing the reflector and feed position. As the reflector surface and the feed position were taken as optimization variables, the objective function was constructed by the gain and XPD in the service area, and then the artificial bee colony algorithm was used for optimization, so as to obtain the optimal performance of the whole service area. Finally, an optimization design example was given, and the simulation results indicated the effectiveness of the optimization method.

1. Introduction

With the wide application of multiple-beam antenna in satellite communication[1-3], multiple-beam antenna for satellite communication requires a high level of overlapping beams and great beam isolation. Power allocation can be flexibly carried out between beams at various spots according to the change of communication capacity. However, the application of multiple-beam antennas is limited by the layout of satellite platform and the channel of communication system.

One of the most common forms of spaceborne multiple-beam antenna is the structure of parabolic reflector and a group of feed arrays. Multiple-beam antennas are divided into single-aperture multiple-beam and multi-aperture multiple-beam antennas in terms of aperture number[1-2]. The multi-aperture multiple-beam antennas have good performance in transmitting and receiving beams, but occupy more satellite platform resources. Although the aperture number of multi-feed and multi-beam antennas with feed arrays and beam-forming network is reduced to 2 pairs, its beamforming network is complex, the design cycle is long, and the machining precision requirements are higher.

Research institutes and universities at home and abroad have done a lot of research on how to use low-difficulty technology to achieve the optimal performance of multiple-beams[4-5], and got remarkable results. One of them is to solve the contradiction between overlapping gain and sidelobe level in traditional single-aperture single-feed multiple-beams by shaping the reflector. Shaping the reflector is to effectively broaden the beam under the condition that the sidelobe performance deteriorates little, thus improving the performance of beam margin gain.

The typical design idea is to determine the beam width according to the performance requirements, then arrange the beams with seamless coverage in the service area, and only optimize the reflector surface through optimization algorithms or commercial software, the last obtain the surface meeting the requirements of the beams performance. However, this method fails to achieve the combination of the optimal overall performance of the service area and the minimum number of beams, that is, when
the overall performance requirements of the service area are met, the number of beams is large. When
the number of beams is small, the service area does not achieve the optimal performance, and the
current commercial software does not have the function of optimizing the performance of the whole
area of multiple-beams.

This paper presents a new optimization design method based on the previous studies. This method
takes the reflector surface and feed position as optimization variables, calculates the far field by
physical optics method, and optimizes the overall gain performance and XPD performance in a
specific service area, so that the gain in the service area and the XPD performance in the area achieve
optimal performance.

This paper first introduces the parameter model and analysis method of antennas, then expounds
the artificial bee colony algorithm used in optimization, and finally gives an example of optimization
design and its analysis results.

2. Antenna Analysis Method

The antenna is a single offset parabolic reflector antenna structure, as shown in the figure below:

Zernike polynomial[6] is a basis function in the cyclotomic fields, which is linearly independent
and orthogonal in the continuous range inside the unit circle. In this paper, the Zernike function is used
to represent the reflector, which is shown in the following formula[6]:

\[
\begin{align*}
  x(t, \varphi) &= a \cos(\varphi) + H \\
  y(t, \varphi) &= a \sin(\varphi) \\
  z(t, \varphi) &= \sum_{n=0}^{\infty} \sum_{m=0}^{n} (C_{nm} \cos m \varphi + D_{nm} \sin m \varphi) F_n(t)
\end{align*}
\]

In the above formula, \( t \) and \( \varphi \) are the coordinates in the aperture projection coordinate system, \( C_{nm} \)
and \( D_{nm} \) are the expansion coefficients of the reflector, \( F_n(t) \) is the modified Jacobi polynomial.

In this paper, the performance of antenna is analyzed by physical optics method. When the feed is
at any position within the space, the angle between the phase center and any point \( M \) on the reflector is
\( \theta_c \). The coordinate of the far field point is \( (R, \theta, \varphi) \). The far-area radiation field of the reflector antenna
calculated by physical optics is[1]:

\[
E(\theta, \varphi) = -\frac{jk\eta}{4\pi R} \left( \vec{t} - RR \right) \int \frac{J(r) e^{ikr/R}}{r} ds'
\]

In the formula, \( k \) and \( \eta \) represent the wave number and the intrinsic impedance of free space
respectively, \( J(r) \) is the current density on the reflecting surface, \( \vec{t} \) represents the unit dyad, \( RR \)
represents dyad of \( R \) and parabolic integral surface is:
\[ ds' = \frac{4F^2 \sin \theta_i d\theta_i d\phi_i}{(1 + \cos \theta_i)^2 \cos(\theta_i/2)} \] (3)

### 3. Artificial Bee Colony Algorithm

Artificial Bee Colony (ABC) algorithm[7-8] is a global optimization algorithm based on swarm intelligence. The algorithm simulates the bee colony’s behavior of gathering honey. Bees carry out different activities according to their respective division of labor, and realize the sharing and exchanges of information among bee colony, so as to find the optimal solution of the problem. The algorithm has the advantages of few parameters, simple calculation and easy to implement.

Each cycle of artificial bee colony algorithm includes three steps. In the first step, employed bees look for food sources and estimate the amount of honey in food sources. In the second step, onlooker bees select a food source to collect honey according to the shared information of the employed bees, and determine the honey amount of the food source. In the third step, scout bees are identified to search for new food sources. Based on the optimization design process of multiple-beam antennas, the position information of all feeds in the focal plane \((x_i, y_i, \theta_i, \phi_i)\) and the coefficients of Zernike polynomials \(C_{mn}\), \(D_{mn}\) are taken as the optimization variable \(X\), the optimization goal is to optimize the performance such as gain (D) and polarization isolation (XPD) within the specified area, as shown in the following formula:

\[
\text{Fitness} = \min \left\{ \sum_{j=1}^{n} |D_j - D_0| \times m_j + \sum_{j=1}^{n} |XPD_j - XPD_0| \times n_j \right\} \quad \text{if} \ D_j \leq D_0, XPD_j \leq XPD_0
\] (4)

Among them, \(D_j\) and \(XPD_j\) are the gain and XPD value when the variable at the \((j)\)th sampling point is \(X\). \(D_0\) and \(XPD_0\) are target values of gain and XPD respectively. \(m_j\) and \(n_j\) are the weight coefficients of the corresponding gain and XPD respectively.

First of all, the honey source is initialized and nPop honey sources are defined. The number of honey sources is also the number of employed bees. Initialize the honey source:

\[
X_{p,q} = X_{q}^{\min} + \text{rand}(0,1)(X_{q}^{\max} - X_{q}^{\min})
\] (5)

In the above formula, \(X_{q}^{\max}\) and \(X_{q}^{\min}\) are the upper limit and the lower limit of the domain, and \(\text{rand}(0,1)\) represents a random number in the range from 0 to 1.

The second process is to update the new honey source. Once the employed bees find new and better honey sources in their corresponding honey sources, they will replace the old honey sources. The updating formula is:

\[
X_{p,q}^{\text{new}} = X_{p,q}^{\text{old}} + \alpha (X_{p,q}^{\text{old}} - X_{k,q}^{\text{old}}) \quad k \neq p
\] (6)

Among them, \(\alpha\) is a random number evenly distributed in the range of \([-1, 1]\), which determines the degree of disturbance.

The third process is to calculate the probability of onlooker bees following employed bees by fitness and roulette, and to update the honey sources.

The fourth process is to generate scout bees. Because the artificial bee colony algorithm is prone to local optimal solution, in order to find the global optimal solution, the scout bee process is set in the algorithm, and the scout bees generate new honey sources according to formula (5). In the scout bee process, if we observe that the counter value of all honey sources reaches \(\text{Limit}\), then the feasible solution should be conducted through scout bees.

### 4. Design Example

The goal of optimization design is to cover a designated service area seamlessly. The service area is an irregular area with a range of \(7^\circ \times 4.7^\circ\). For the working frequency of the antenna: the transmit frequency band is \(19.2\ \text{GHz} \sim 20.2\ \text{GHz}\) and the receive frequency band is \(29.0\ \text{GHz} \sim 30.0\ \text{GHz}\). Due
to the limitation of satellite layout and the requirements of system channels, the number of antenna apertures is 1, the projection aperture ≤ 2 m, the number of beams is no more than 18, and for the performance of the service area: gain ≥ 37.5 dB, XPD ≥ 25 dB. Its exact shape is shown in the blue area of Figure 2 below.

![Figure 2. Distribution of antenna observation stations.](image)

Before the optimization design, observation stations are set within the service area, as shown in the figure above. J= 847 observation stations with equal intervals are set in the service area shown in the figure and according to the requirements of gain and XPD, the setting is $D_0 = 37.5$, $XPD_0 = 25$. Considering the limitation of satellite platform layout and the requirement of maximizing the performance of the service area, the antenna aperture and offset distance are respectively 2.0 m and 1.9 m, and the focal distance is 3.1 m. According to the beam requirements, the total number of feeds is set as $i = 18$. The honey source nPop is set as 100, the number of onlooker bees is set to 60, and the maximum number of iterations is 1000. The artificial bee colony algorithm is used for optimization.

After optimization convergence, the optimized shaped reflector and the position information of 18 feeds are obtained. The nephogram of the surface variation of the shaped reflector to the standard paraboloid is shown in Figure 3 below. Its range of surface variation is between -3.0 mm and 5.3 mm. The whole surface gradually changes and transits through the structural processing of the reflector in proE software, and it belongs to the machinable surfaces.

![Figure 3. Nephogram of the Surface Variation of the Shaped Reflector to the Standard Paraboloid.](image)

| Feed Serial No. | Feed Position/mm | Feed Angle/deg |
|-----------------|------------------|----------------|
|                 | $x$              | $y$            | $z$ | Theta | Phi   |
| 1               | -134.68          | 149.55         | 0.00 | 4.03   | -47.99 |
| 2               | -164.20          | 85.12          | 0.00 | 3.71   | -27.40 |
| 3               | -188.80          | 18.66          | 0.00 | 3.80   | -5.65  |

The positions and directions of the optimized 18 feeds in the feed coordinate system are shown in the following table:

| Feed Serial No. | Feed Position/mm | Feed Angle/deg |
|-----------------|------------------|----------------|
|                 | $x$              | $y$            | $z$ | Theta | Phi   |
| 1               | -134.68          | 149.55         | 0.00 | 4.03   | -47.99 |
| 2               | -164.20          | 85.12          | 0.00 | 3.71   | -27.40 |
| 3               | -188.80          | 18.66          | 0.00 | 3.80   | -5.65  |
In order to verify the performance of the optimized service area, the optimized reflector surface and feed information are substituted into the commercial simulation software GRASP10 for simulation and recalculation, and the antenna gain pattern of the entire service area is obtained as shown in Figure 4 below:

![Antenna Far-field Gain Contour](image)

(a) Tx  (b) Rx

Figure 4. Antenna Far-field Gain Contour.

As can be seen from the figure above, the gain performance of the service area in the transmit frequency band and the receive frequency band is greater than 37.7 dB, which meets the design requirements. In order to facilitate statistics of XPD performance in the service area, the service area is divided into 18 regions based on the principle of maximum margin gain, as shown in Figure 5 below. The 18 regions correspond to 18 beams meeting the design requirement to cover the service area seamlessly.

![Beam Layout in Service Area](image)

Figure 5. Schematic Diagram of Beam Layout in Service Area.

Due to the large number of beams, the XPD contour map with all beams drawn on it cannot be well discriminated. Therefore, the following figure shows a typical XPD contour map of the antenna. From the figure 6, it can be seen that the XPD performance of the transmit frequency band and the receive frequency band corresponding to the beams is greater than 25.5 dB, which meets the design requirements.
From the above-mentioned results, it can be seen that the whole service area is covered by 18 beams seamlessly, and the gain and XPD performance of the service area are better than the performance requirements, thus verifying the effectiveness of the optimization of shaped multiple-beam antennas based on artificial bee colony algorithm in this paper.

5. Conclusions
In this paper, an optimization design method of multiple-beam antenna with optimal performance in service area based on artificial bee colony algorithm is provided. This method improves the gain and XPD performance of the whole service area by comprehensively optimizing the reflector surface and the position of the feed. In order to prove the effectiveness of the algorithm, a Ka-band dual-mode antenna is optimized and verified through the simulation of commercial software. The simulation results show the effectiveness of this optimization algorithm. This method can not only optimize the performance of the service area, but also shorten the design cycle, and can design the antenna beams according to the user’s demand distribution, which is of important guiding significance for practical engineering application.

References
[1] Lei Juan. Research on Satellite Multiple Beam Antenna. Xi’an: Xidian University. 2003.
[2] Ding Wei, Tao Xiao, Ye Wenxi. Advances in Research on Multi-beam Antenna Techniques for GEO High Throughput Satellites. 2019, 16(1): 62-69.
[3] Chen Xiuj, Wan Jixiang. Development Status and Proposals for Multi-beam Antennas of Communication Satellites. Space Electronic Technology. 2016, 13(2): 54-60.
[4] D.-W. Duan, Y. Rahmat-Samii. A generalized diffraction synthesis technique for high performance reflector antenna. IEEE Transactions on Antennas and Propagation, Vol. 43, No.1, pp. 27-39, 1995.
[5] Zhang Xingang, Xue Zhaoxuan. Optimized Design of Multi-beam Antenna Based on Real-coded Genetic Algorithm. Journal of Microwaves. 2018, 34(6): 58-61.
[6] Zhang Tengyue. Optimal Design of Multiple-beam Shaping for Spaceborne Reflector Antenna. Nanjing: Nanjing University of Science and Technology. 2018.
[7] GAO Yang, LI Xu, DONG Ming, LI He-peng. An enhanced artificial bee colony optimizer and its application to multi-level threshold image segmentation. Journal of Central South University. 2018, 25(1): 107-120.
[8] Wang Yanjiao, Xiao Jing. Optimization of Multi-objective Problems Based on Artificial Bee Colony Algorithm. Journal of Central South University (Science and Technology): 2015, 46(6): 2109-2117.
[9] Duan Yuhu. Design of Spaceborne Multi-beam Antennas. Journal of Spacecraft TT&C Technology. 2011, 30(1): 16-21.