Regional LEO Satellite Constellation Design Based on User Requirements

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***Abstract*—In the traditional satellite constellation design, it is hard to find a suitable method to evaluate the user requirements precisely and the existing algorithms result in a high computing cost. In this paper, a method of designing and optimizing the regional satellite constellation is proposed. The user requirements are represented by the the number of users, which is established based on communication markets and population distribution. The design of satellite constellations is a multi-objective problem, which can be solved through the proposed non-dominated sorting genetic algorithm with elitist strategy. By constructing a satellite constellation for the target area, the effectiveness of the method has been verified. The simulation results show that compared with OneWeb constellation, the proposed constellation design method can effectively meet the user requirements with lower satellite cost.**

I. Introduction

Satellite networks are composed of one or several satellites, exclusive earth stations and inter-satellite links (ISLs) [1]. The network has advantages in wide area coverage, emergency communication and high throughput capacity, which can fully compensate for the shortage of ground communication system.

Satellites are the basic components of a satellite constellation. According to the difference of orbital altitude that is defined as the distance between satellites and earth, those nodes are segmented into geosynchronous orbit (GEO) satellites, medium earth orbit (MEO) or low earth orbit (LEO). The orbit height of GEO satellites have a precise altitude of 35786km. The MEO satellites have orbits with an altitude from 10000 to 20000km. And the orbit height of LEO satellites are generally from 500 to 2000km. GEO satellites are relatively geostationary because of the same rate as rotation speed of earth, therefore those nodes are capable of providing continuous communication service to the same users. The coverage area of a single satellite is large for the high orbit, therefore three satellites can offer communication service for the whole world. Furthermore, compared to other altitude orbits satellites, GEO satellites are characterized by poor resolution, long time delay to transmit data and expensive launch costs. More seriously, the fixed orbits lead to the emergency of communication blackout in the north and south poles. By contrast, low earth orbit satellites take advantage of high resolution, low emission cost, short propagation delay. However, a single LEO satellite coverages small area and offers poor communication service, so it's significant to use multiple satellites to form a constellation. As a result, LEO satellite communication constellations have attracted the attention of the world because it can overcome weaknesses of the GEO satellites.

Nowadays, the existing LEO satellite constellations are mostly aim to serve global communication markets like Iridium and OneWeb system. They usually include many satellites, which means a heavy financial burden for small countries and regions. It's impossible for those groups to afford large and expensive constellation systems now, even in the future. On the contrary, they have the power to build their own systems to fulfill individual requirements for small coverage regions. Therefore, the constellation design for regional coverage has become present and future trends.

Satellite constellation design is a complicated process to achieve precise satellite and orbit parameters such as type of service, number of satellites, minimal elevation angle, orbit height, etc [3]. In the process of constellation design and optimization, there are great number of variables causing high computational complexity. Therefore, it's necessary to adopt a basic constellation model (such as polar constellation model and Walker constellation model) to reduce the dimension of solution space. Many satellite constellation design methods have been proposed, and most of them mainly focus on satellite coverage. Reference [4] has designed a three layer satellite communication architecture and reference [5] has proposed a satellite constellation, which was across two satellite orbits, and a basic constellation models for regional satellite constellation design has been proposed in [6]. However, the goal of those constellation design and optimization is coverage optimization rather than the user requirements, which makes that the constellation design is incompatible with the actual requirements. Reference [7] has proposed a user requirement model and capacity metrics, but the system model is aimed at unmanned aerial vehicle constellations.

In this paper, the main contribution is a method of regional constellation design which aims to use the minimum number of satellites to achieve user requirements. The user requirements on the target region is evaluated based on the communication markets and population density. A system model is build concerning the user requirements, overlay weight, minimal elevation angle, and orbit height. Finally, the optimization algorithm is achieving in MATLAB, and a connection to STK is established to compute constellation performance. The remainder of this paper is organized as follows.

II. Regional constellation model

In the process of the satellite constellation design, it's significant to compare the users who are willing to subscribe to the satellite network and the capacity of the users served by the satellite networks. For meeting the requirements of the user, the capacity of the constellation should be greater than the real users. Therefore the user requirement model and the constellation capacity metrics are established in this section, and the satellite downlink is the main scene of the satellite constellation design.

A. Basic constellation model

Satellite constellations are composed of a number of satellites according to a certain configuration, and those satellites cooperate to achieve tasks about coverage performance and communication service. Satellites are the core parts of the constellation, therefore the process of constellation design is to determine the satellite and constellation orbit parameters. A satellite has six parameters consisting of orbit inclination i, the right ascension of ascending node Ω, the argument of perigee w, the semimajor axis a, eccentricity e, and the true anomaly v [8]. Among them, the position of the orbit plane is determined by i and Ω. The direction of the orbit is decided by w. The size and shape of the orbit are determined by a and e. And the position of the satellite at a certain time in the orbit is determined by v.

LEO satellite constellation is intended to offer a great service to the target area. The precondition for providing services is to cover the target area, for a single satellite, coverage capacity is one of the main standards, and the situation of a single satellite coverage is shown in Figure 1. Wherein R is the symbol of earth's radius, h represents orbit height, φ is the minimum elevation that is significant to establish links between satellites and the ground users, and ω is a half of geocentric angle of a satellite covered area.

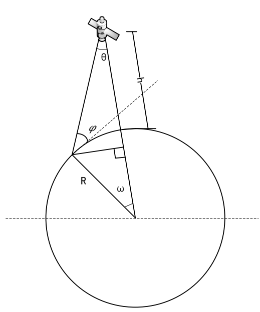

Fig. 1. The coverage of a single satellite.

The formula to calculate θ is

$$\theta = \arcsin(\frac{R}{R+h}\cos\varphi). \tag{1}$$

According to the spherical surface area formula, a single satellite coverage S can be noted by

$$S = 2\pi R^2[1-\sin(\varphi+\theta)]. \tag{2}$$

The coverage of the whole satellite constellation is complicated concerning the overlaps between satellites, so the concept of the constellation coverage ratio is given. The formula to calculate ρ can be expressed as

$$\rho = \frac{S_{net}}{S_{tar}}, \tag{3}$$

where S_{net} denotes the covered area and S_{tar} represents the target area, respectively. Because of the complicated computing process and many related variables, STK is usually used to calculate the performance of the satellites [9]. It is easy to get precise numeric results without tedious calculation process with the tool.

In the process of designing constellations which have many satellites, it should consider the satellite parameters and ensure the geometric configuration of the constellation. The parameters about the constellation design are number of orbit planes N_P, number of satellites per orbit plane N_{sat}, altitude of orbit h, inclination of orbit θ, relative spacing between satellites in adjacent orbit planes [10]. There are basic constellation models belonging to the symmetric constellation like polar orbit and Walker orbit to reducing the computational complexity. In symmetric constellation, satellite orbit plane distributes homogeneously and has the same number of satellites on each track. In polar orbit constellation, the orbital inclination is above 90 degrees and all of the satellites can pass through north and south poles in each circle [11]. However, in Walker orbit constellation, the orbit inclination is usually from 40 degrees to 60 degrees and it provides poor coverage performance to the poles [12]. Both of the satellite configuration possess distinguishing features applying to different situations. The satellites in Walker constellation enable uniform distribution while the satellites of the polar orbit tend to the two poles of the earth leading to poor coverage over the middle or lower latitude areas. The deign of constellation is divided into the global constellation design and the regional constellation design. For the sake of providing communication globally, many countries and regions are incapable of developing gateway stations around the world, so it's necessary to deploy the inter-satellite links to make up for the lack of earth stations. In polar orbit, the position among the satellites is stationary which make sure the stability of the links. In contrast, the position of the satellites in the Walker constellation is changeable providing a bad situation for the developing of ISL. However, the development of ground stations is beyond the regional constellations' concern. Consequently, the polar orbit is usually the basic configuration for global coverage while the Walker orbit is chosen to offer communication for the region, so the Walker orbit is superior to polar orbit in the regional constellation design.

B. User requirement model

User requirements are one of the major criterion for the establishment of communication networks. When the constellation design combines user requirements, it can bring better user service and economic performance. However, in other constellation design process, they usually consider satellite coverage performance instead of user requirements, which leads to resource waste and economic loss. In this section, a user requirements model is proposed based on communication markets and population distribution.

The user requirement model generates a map of users who are willing to subscribes to the satellite networks. It will be combined with the capacity model to estimated the number of users. The total size of the users depend on the communication market size, population distribution, and national income of regions etc. The global population distribution is available from the Center for international Earth Science Information(CIESIN) and the digitized population map is with 1° longitude by 1° latitude resolution, as show in Fig. 2

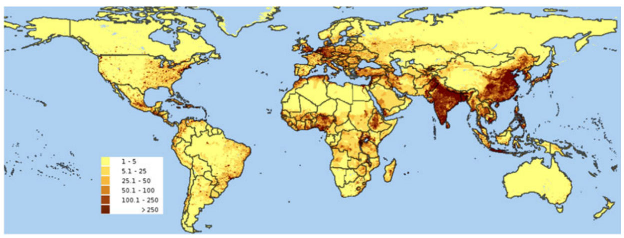

Fig. 2. The population distribution in 2016.

The function of the normalized population distribution density can be represented by

$$\sum_{grid=1}^{N_g} D(grid) = 1, \tag{4}$$

where N_g denotes the number of the grid points, $D(grid)$ is the population distribution density, which contains the number of potential users in the each earth grid.

Therefore, the requirement map can be written as

$$DM(grid) = f_{sat} M_{number} D(grid), \tag{5}$$

where M_{number} denotes the total communication users which is primarily served by terrestrial communication networks. f_{sat} represents the scale factor of the satellite network users, which may changes during the development of the satellite communication networks.

C. Capacity model

The interference from other satellites is calculated by

$$I = \sum_{j \in N and j \neq i} P_{sat,j} G_{sat,j} G_j (\frac{\lambda}{4\pi d_j})^2, \tag{6}$$

where $P_{sat,j}$ denotes the transmitted power from the jth interfering satellite to the terminal, $G_{sat,j}$ represents the gains of the jth interfering satellite antennas, G_j is the receive gains of the terminal antenna for the jth interfering satellite, the last part indicates the free space path loss from the jth interfering satellite to the terminal.

The capacity model is used to measure the number of users served by the system. In the satellite communication system, the capacity will introduced by the ratio of satellite transmitting power to the user receiving power. By the analysis above ,the single-user downlink capacity of the satellite to the requirement map grid can be calculated as follows. The satellite capacity C_{sat} which is determined by the downlink transmitting power, various losses, gain of the user antenna, system noise temperature, required SNR, required rate, can be found by

$$Csat = \frac{P_{sat} G_{sat} G L_f L_M - I}{SNRkTR_{user}}, \tag{7}$$

where L_M is the rain loss plus link margin, and R_{user} is the individual terminal data rate. SNR notes the signal-to-noise ratio, and k is boltzmann constant. P_{sat} represents the transmitting power of the satellite which connects to the user, G_{sat} is the antenna gain, G is the user gain, L_f is path loss. C_{total} which represents the sum of served users in the satellite communication network, can be expressed by

$$C_{total} = N_P N_{sat} C_{sat}. \tag{8}$$

The combination of user requirements and capacity model form the optimization constraints of the constellation design. The constellation designed in this way are more appropriate to the user's requirements.

III. Optimization System and Algorithm

Satellite constellation design is a complicated process to achieve precise satellite and orbit parameters. In this section, sorting genetic algorithm with elitist strategy(NSGA-II) is applied to solve the constellation design and optimization problem.

A. Optimization model

In the LEO satellite constellation, there are a large number of parameters affect the system performance. More importantly, in this paper,the user requirements become a novelty constraint condition besides conventional constrained. The method of the regional constellation design aims to use the minimum number of satellites to achieve user requirements, therefore the combinatorial optimization model is represented as

$$\min(N_p * N_{sat}) \tag{9}$$

subject to the following constraints:

$$C_{total} \geq \sum_{grid=1}^{N_g} DM(grid), \tag{10}$$

$$S_{net}/S_{tar} \geq \rho_0 (\rho_0 = 1), \tag{11}$$

$$N_{P\max} \geq N_P \geq N_{P\min}, \tag{12}$$

$$N_{sat\max} \geq N_{sat} \geq N_{sat\min}, \tag{13}$$

$$\varphi_{\max} \geq \varphi \geq \varphi_{\min}, \tag{14}$$

$$h_{\max} \geq h \geq h_{\min}, \tag{15}$$

$$\theta_{\max} \geq \theta \geq \theta_{\min}, \tag{16}$$

where C_{total} denotes the sum of served users in the satellite communication network, the second half of the inequality is the user numbers of the target area. ρ_0 denotes the required coverage ratio in the second constraints. The final five constraints place upper and lower bounds on each of the design vector variables whose values are based on special mission. In order to achieve better economic benefits, the number of satellites and orbit height need to be controlled in a limited range. The orbit height of LEO satellites is usually less than 2000km. The Walker constellation is the basic constellation, so the orbit inclination is from 40 degrees to 60 degrees. The minimum communication elevation angle play an important role in satellite communication system [13]. The aim of the method is to design a regional constellation which minimizes the number of satellites under the condition of meeting user requirements and coverage requirements of the target area.

B. Solution

NSGA-II is one of the most popular multi-objective genetic algorithms at present [14]. It reduces the complexity of the non-dominated sorting genetic algorithm and it has the advantages of fast running speed and good convergence. Therefore, it has become a good solution for satellite constellation optimization problems.

The NSGA-II algorithm is modified so that it can address the satellite constellation design problem [15]. The proposed method has the following six major steps.

1) Initialize the population set and generate chromosome coding. The chromosome for each solution x is

$$x = [N_P/N_{sat}/\varphi/h/\omega]. \tag{17}$$

Binary coding is used for the chromosome coding, the number of coding bits are set to be[5/5/21/9/8]. The encoding length depends on the range and accuracy of each influence factor.

2) Non-Dominated sort. By using fast non-dominated sorting method will improve computational speed complexity. The initialized population is sorted based on non-domination, it utilize the information about the set that an individual dominate and the number of individuals that dominated the individual.

3) Crowding distance. It takes place of the sharing function to maintain population diversity and improve the robustness of the algorithm. The individuals are selected based on rank and crowding distance, so all the individuals in the population are assigned a crowding distance value. The basic idea behind the crowing distance is finding the Euclidian distance between each individual in a front based on optimization target including the number of satellites, the capacity of the satellite constellation and the coverage ratio.

4) Selection. The selection is carried out using a crowded-comparison-operator, nondomination rank and local level crowding distance for each individual are calculated. If the non-domination rank of two random individuals is different, the individual is selected with high non-domination rank, on the other hand, if the non-domination rank of two random individuals is the same, the individual with greater crowding distance is selected.

5) Genetic operators. Real-coded GA's use simulated binary crossover operator for crossover and polynomial mutation. It includes simulated binary crossover and polynomial mutation. Simulated binary crossover simulates the binary crossover observed in nature, and polynomial mutation is used for genetic variation of chromosomes.

6) Recombination and selection. The offspring population is combined with the current generation population and selection is performed to set the individuals of the next generation.Since all the previous and current best individuals are added in the population, elitism is ensured. Population is now sorted based on non-domination. The new generation is filled by each front subsequently until the population size exceeds the current population size. And hence the process repeats to generate the subsequent generations.

With the preceding analysis and method, the final satellite constellation design will be acquired.

IV. Simulation and Results

In order to validate the effectiveness of the proposed regional constellation design method, a simulation experiment is performed. China is the target region to design the LEO satellite constellation. In this section, constellation configuration and performance analysis are completed by STK. Several basic parameters for NSGA-II are set in Table I.

TABLE I
BASIC PARAMETERS FOR NSGA-II

Algorithm paremeters	Value/Mode
Population Size	50
Maximum Generation	100
Crossover Probability	0.8
Mutation Probability	0.3
Coding Bit Length	48
Encoded Mode	Binary Code
Selection Strategy	Tournament

In the process of using genetic algorithms for performance optimization, satellite parameters like transmitting power and data rate to estimate the user requirements are also important. Those constant vectors are shown in Table II.

TABLE II
CONSTANT VECTOR

Parameter	Symbol	Value/Mode
Individual User Terminal Data Rate	R_0	1.544Mbps
Downlink Frequency	f	40GHz
User Terminal Antenna Gain	G_r	41dB
User Terminal System Noise Temperature	T	$135K$
Signal-To-Noise Ratio Require	SNR	4.8dB
Rain + Link Margin	L	-5dB

According to the user requirements, the user rate is set to 1.544Mbps, and the antenna gain of user terminal is assumed to 0 dB. On the other hand, the system noise temperature of the user terminal is 135K and the 40 GHz band is considered in the simulations. Because the coverage performance of a single satellite is great, therefore the target area surface is covered using a grid of 3 degrees multiplied 3 degrees. With those conditions, the final optimized regional LEO satellite constellation is proposed. In the following part, the proposed constellation is compared with the OneWeb constellation.

A. The framework of satellite constellation

The goal of the regional satellite constellation design and optimization is to build a constellation which uses the minimum number of satellites to meet the requirements of the regional users. The existing constellations offer global service which mean enormous manpower, materials and satellite resource. However, some small countries and regions cannot afford the heaven financial burden. The proposed regional satellite constellation design method provides a balance between cost and performance. Through the comparison between the new regional constellation and the existing global constellation, it shows the new regional constellation gets great performance with less satellites.

The OneWeb is the representative of the global constellation.OneWeb consists of 648 satellites including 18 orbit planes and 36 satellites in each orbit plane. The satellite orbit altitude is 1200km, which belongs to the LEO satellite constellation facing to the global service. In addition, the minimum communication elevation of the constellation is 50 degrees [16]. Because the communication of the satellites is based on ground gateway station or inter-satellite links, so the design of global constellation should take the deployment of the two infrastructure into account. However, few countries have the capacity to build the stations all over the world, therefore the communication between satellites depends on inter-satellite links. Finally, the base constellation configuration is polar orbit for the stability of inter-satellite links.

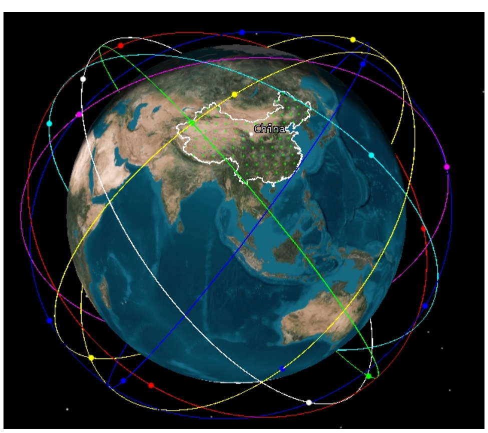

Fig. 3. The regional constellation.

On the contrary, the proposed regional satellite constellation is based on Walker orbit because the ground gateway station is deployed in the target region without the issues of territorial authority. The inter-satellite links can be supplemented to the ground stations, therefore Walker constellation is the basic constellation in the design of regional constellation, which have better coverage performance compared with polar orbit. According to the result of NSGA-II, the proposed regional constellation is shown as Fig. 3. The regional constellation consists of 27 satellites including 9 orbit planes and 3 satellites in each orbit plane. The satellite orbit altitude is 1650km, which belongs to the LEO satellite constellation facing to the regional service. In addition, the minimum communication elevation of the constellation is 30 degrees.

B. Simulation analysis

For the task of regional coverage, the number of the regional constellation is great less compared with OneWeb constellation. The simulation results about coverage and elevation indicate the regional constellation can meet the user requirements of the target area. The coverage and communication elevation of the satellite constellation is the important system performance. The proposed regional constellation compares with OneWeb constellation from the two aspects in the following section.

1) Comparison of coverage

Satellites are capable for wide range of coverage, therefore coverage is an significant criteria for constellations. China is the target area of the constellation design method, therefore the coverage performance of this target conuntry is obtained by STK. The coverage of OneWeb is shown as Fig. 4 and the coverage of the regional constellation is shown as Fig. 5. The coverage weight of the target area is 4 in OneWeb. However, the coverage weight is same in the whole target area. While the coverage weight of the target area is more than 1 but less than 2 in the regional constellation. The proposed constellation can cover the whole area and the coverage performance is better in crowded area than sparsely populated area. For the perspective of coverage performance, the proposed constellation take full account of the user requirements.

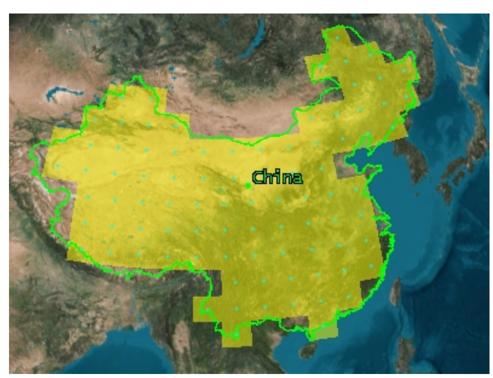

Fig. 4. The coverage of OneWeb.

2) Comparison of communication elevation

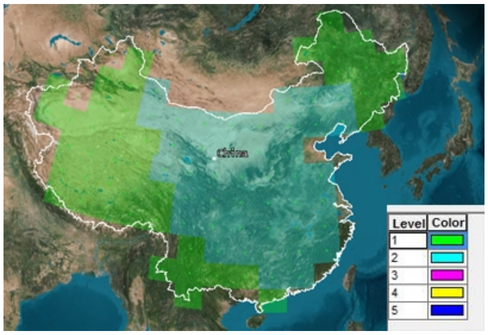

Fig. 5. The coverage of the regional constellation.

In the satellite constellation, due to blocking and multipath effects, electron flow attenuation, atmospheric absorption and flashing have bad impact on satellite-user downlink. The influence is mainly based on the distance of the link path through the atmosphere. However, the distance is depend on the orbit altitude and the communication elevation. With the increase of the elevation, the communication is improved. The communication elevation of the grid is shown as Fig. 6. According to the communication elevation, the proposed constellation is worse than OneWeb, but it can meet the communication requirement. From the aspect of cost, the regional constellation can meet the requirements of communication in a more economical way.

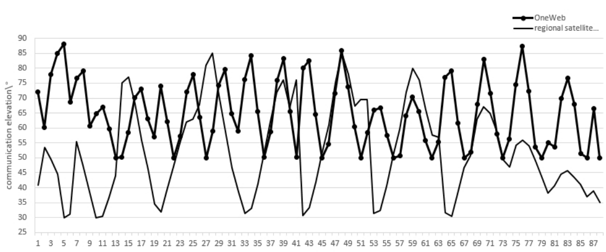

Fig. 6. The comparison of the communication elevation.

The proposed regional constellation meet the user requirements with less satellite compared with OneWeb constellation. The coverage performance of the regional constellation is better than OneWeb constellation because of considering of the distribution of users. And the regional constellation can meet the communication needs of users with less satellites compared with OneWeb constellation. The goal of the proposed constellation design method is find the balance between the system cost and performance, and the simulation results indicate the effectiveness of the scheme.

V. Conclusion

In this paper, a method of the regional satellite constellation design is proposed. For meeting the user requirements and reducing the design cost of the system, the regional constellation is tight coupling with the number of users, which depends on communication markets and population distribution. By constructing a satellite constellation for the target area, the effectiveness of the method has been verified. The simulation results indicate that the constellation gets good performance with fewer satellites compared with OneWeb constellation.

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References

[1] S. Xu, X. W. Wang, and M. Huang, "Software-defined next-generation satellite networks: Architecture, challenges, and solutions," *IEEE Access*, vol. 6, pp. 4027-4041, Jan. 2018.
[2] W. Ban, K. Yu, and X. H. Zhang, "GEO-satellite-based reflectometry for soil moisture estimation: Signal modeling and algorithm development," *IEEE Trans. Geosci. Remote Sens.*, vol. 56, no. 3, pp. 1829-1838, Mar. 2018.
[3] M. Anedda, A. Meloni, and M. Murroni, "64-APSK constellation and mapping optimization for satellite broadcasting using genetic algorithms," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 1-9, Mar. 2016.
[4] I. F. Akyildiz, E. Ekici, and M. D. Bender, "MLSR: A novel routing algorithm for multilayered satellite IP networks," *IEEE/ACM Trans. Netw.*, vol. 10, no. 3, pp. 411-424, Aug. 2002.
[5] H. Nishiyama, Y. Tada, N. Kato, and *et al.*, "Toward optimized traffic distribution for efficient network capacity utilization in two-layered satellite networks," *IEEE Trans. Veh. Technol.*, vol. 62, no. 3, pp. 1303-1313, Nov. 2013.
[6] F. S. Marzano, D. Cimini, A. Memmo, and *et al.*, "Flower constellation of millimeter-wave radiometers for tropospheric monitoring at pseudogeostationary scale," *IEEE Trans. Geosci. Remote Sens.*, vol. 47, no. 9, pp. 3107-3122, Sep. 2009.
[7] F. Dong, H. Han, X. Gong, and *et al.*, "A constellation design methodology based on QoS and user demand in high-altitude platform broadband networks, " *IEEE Trans. Multimedia.*, vol. 18, no. 12, pp. 2384-2397, Dec. 2016.
[8] S. F. Meng, J. S. Shu, Q. Yang, and *et al.*, "Analysis of detection capabilities of LEO reconnaissance satellite constellation based on coverage performance, " *J. Syst. Eng. Electron.*, vol. 29, no. 1, pp. 98-104, Mar. 2018.
[9] P. D. Kessler, B. D. Killough, S. Gowda, and *et al.*, "CEOS visualization environment (COVE) tool for intercalibration of satellite instruments, " *IEEE Trans. Geosci. Remote Sens.*, vol. 51, no. 3, pp. 1081-1087, Mar. 2013.
[10] X. Wang, J. Li, T. Wang, and *et al.*, "Satellite constellation design with genetic algorithms based on system performance, " *J. Syst. Eng. Electron.*, vol. 27, no. 2, pp. 379-385, Apr. 2016.
[11] X. Chen, G. Dai, G. Reinelt, and *et al.*, "A semi-analytical method for periodic earth coverage satellites optimization, " *IEEE Commun. Lett.*, vol. 22, no. 3, pp. 534-537, Mar. 2018.
[12] R. Radhakrishnan, W. W. Edmonson, F. Afghah, and *et al.*, "Survey of inter-satellite communication for small satellite systems: Physical layer to network layer view, " *IEEE Commun. Surveys Tuts.*, vol. 18, no. 4, pp. 2442-2473, May. 2016.
[13] X. D. Zhong, H. Yin, Y. He, and *et al.*, "Joint downlink power and time-slot allocation for distributed satellite cluster network based on pareto optimization, " *IEEE Access*, vol. 5, pp. 25081-25096, Oct. 2017.
[14] Q. Liu and G. S. Jiao, "A pipe routing method considering vibration for aero-engine using kriging model and NSGA-II, " *IEEE Access*, vol. 6, pp. 6286-6292, Jan. 2018.
[15] G. F. Zhang, Z. Su, M. Li, and *et al.*, "Constraint handling in NSGA-II for solving optimal testing resource allocation problems, " *IEEE Trans. Rel.*, vol. 66, no. 4, pp. 1193-1212, Aug. 2017.
[16] Z. C. QU, G. X. Zhang, H. T. Cao, and *et al.*, "LEO satellite constellation for Internet of things, " *IEEE Access*, vol. 5, pp. 18391-18401, Aug. 2017.