Research on Beam Interference Optimization Strategy of LEO Constellation

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Abstract. The LEO constellation is a near earth polar orbit satellite constellation, which will cause a large number of beam overlap in the high latitude during the motion, and frequency multiplexing is usually used in LEO constellation to improve the efficiency of system resource use. All these factors will cause the interference between beams. The frequency interference of the whole constellation can be reduced to a large extent by closing the beam strategy of partial overlapping points, but due to the high speed movement of the satellite beams, it is still unable to guarantee the full period of the whole constellation without interference or interference below the threshold value. The dynamic adjustment strategy of the beam resource designed in this paper is based on the periodic closing strategy, using the sub-band division and frequency dynamic allocation technology, so as to better realize the global beam frequency resource allocation and interference optimization.

Keywords: LEO constellation · Interference · Beam on/off · Optimization strategy

1 Introduction

With the diversification and rapid increase of LEO satellite constellations, there are many kinds of interference between LEO satellite constellations and GSO satellite constellations. Potter, Bob researched how traditional carrier monitoring, ground system monitor and control (M&C) and data analytic products can be utilized by LEO operators to monitor the performance of their complete satellite network, drilling down to ground systems, satellite performance, beam pointing and power usage to minimize interference with GEO satellites [1]. Braun, Christophe and others have shown that many satellite operators are planning to deploy NGSO systems in Ku, Ka, and V bands. The coexistence of satellites between systems will face new challenges, because the heterogeneity of the constellation leads to increased interference levels and complex interactions. The existing spectrum adjustment may not be enough to ensure that GSO is protected from NGSO interference [2]. As the satellite advances from the equator to the polar regions, certain coverage areas will overlap to a certain extent, which may cause severe inter-beam interference (IBI) [3]. The implementation of any LEO satellite system's high-throughput satellite system will cause a conflict between the radio

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spectrum of the fixed-satellite service and the satellite broadcasting service (Ku, Ka, Q/V band) [4].

Aiming at the interference problem: for the interference mitigation technology between GEO and NGEO systems, Sharma et al. proposed an adaptive power control technology suitable for uplink and downlink to reduce interference [5]. Mendoza et al. proposed a RF interference analysis method for dynamic satellite constellation simulation based on the inter-satellite link (ISL) of LEO satellites, analyzed and designed reasonable ISL parameters, and reached the conclusion that the spectrum of LEO and GSO network coexisted [6]. Su, Yongtao adopted a shutdown strategy when LEO satellite caused interference to GSO satellite communication. If the closed LEO satellite provided service for covered users, the progressive pitching method and coverage expansion method were adopted [7]. Garcia et al. proposed a method of measuring interference on the large-scale LEO satellite communication constellation system by SINR [8]. Leyva-Mayorga et al. proposed a dynamic ISL resource allocation method based on the non-interference environment [9]. Based on interference analysis, Li, R. et al. proposed an adaptive beam power control method, which attempted to maximize the throughput of LEO satellite [10]. Saiko, V. et al. proposed a multipath signal processing method to improve the interference immunity of inter-satellite communication link [11].

When the satellites in the LEO constellation motion from low latitude to high latitude, the distance between the satellites in adjacent orbits decreases gradually, causing a considerable number of beams to fall into the coverage of other satellites completely or partially, leading to the waste of some beam resources and the problem of co-frequency interference.

Because of the LEO satellite constellation system available frequency resources are limited, even in the case of static allocation without interference, with the movement of the satellites, the beams of different satellites will appear adjacent, overlapping, and covering interference. Therefore, the problem of beam interference suppression under the whole constellation is a prominent problem that must be solved in constellation system.

Beam frequency resource allocation result quality in the whole constellation is closely related with the beams interference, the beam of resource dynamic adjustment strategy designed in this paper is distributed by track, reduce the overlapping interference with beam in contiguous or overlapping area of the beam basis on closing overlapping beam, using beam resource dynamic adjustment strategy, the global users of frequency assignment problem attribute to a sub-band distribution problem which greatly simplifies the whole constellation frequency assignment problem and the analysis of the whole constellation interference, by optimizing the number of sub-bands and adjusting the period to achieve a certain balance between beam capacity and interference, at the same time, it takes into account the problems of less sub-band division, less interference, and less adjustment frequency. While suppressing beam interference, it also achieves better constellation beam frequency resource allocation, which not only supports the dynamic allocation of local beam frequency resource, but also reduces the interference factors between beams in the satellite constellation to the greatest extent.

2 Periodic Beam Closing Strategy

2.1 Beam on/off Policy

In order to solve the interference problem caused by the overlapping of satellite beams at high latitudes, the beam on/off strategy in this paper realizes the global single repeating cover on the premise of seamless global beam coverage, and reduces the number and frequency of satellite beam on/off control in the whole constellation.

The simulated LEO constellation has 6 orbital planes, each of which has 9 satellites, and each satellite has 52 spot beams (as shown in Fig. 2), Fig. 1 shows the beam coverage of the LEO constellation, their relative position to the satellite is fixed. The satellites moving relative to each other on both sides of the seam area are interlaced about every 5 min 40 s, and the satellites in the non-reversing slit area are interlaced about every 53 min. For all beams, the on/off state will have the same period as the satellite's orbit periodicity (about 107 min).

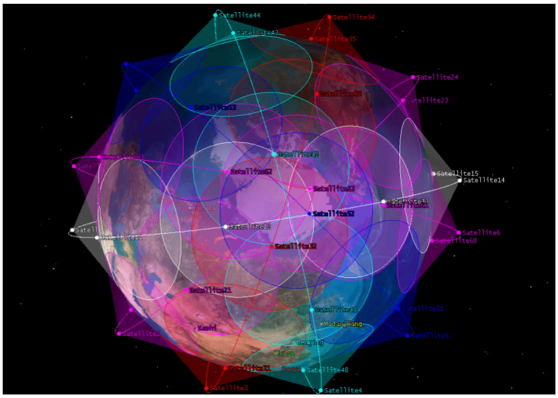

Fig. 1. Satellite beam coverage as seen from above the North Pole (10° elevation)

Periodic beam on/off processing is considered for the main lobe based on the optimized beam pattern. The strategy (flowchart shown in Fig. 3) gives priority to the beam on/off control of odd orbital plane (1, 3, 5 orbital plane). The first step is to complete the beam single cover decision for all beams on the first orbital plane. When the satellite in the third orbital plane overlaps with the satellite in the first orbital plane near the poles, turn off the satellite beam in the third orbital plane which falls completely into the first orbital plane. Similarly, when the satellite in the fifth orbital plane overlaps with the satellite in the first or third orbital plane near the poles, turn off the satellite beam in the fifth orbital plane which falls completely into the first or third orbital plane. After completing the beam assignment to the odd orbital planes (as shown in Fig. 4), the even orbital planes (2, 4, 6 orbital planes) are used as supplementary orbital planes for beam allocation, and the allocation method is the same as that of odd orbital planes.

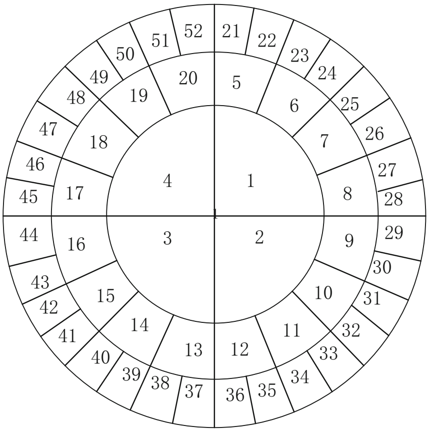

Fig. 2. Schematic diagram of point beam

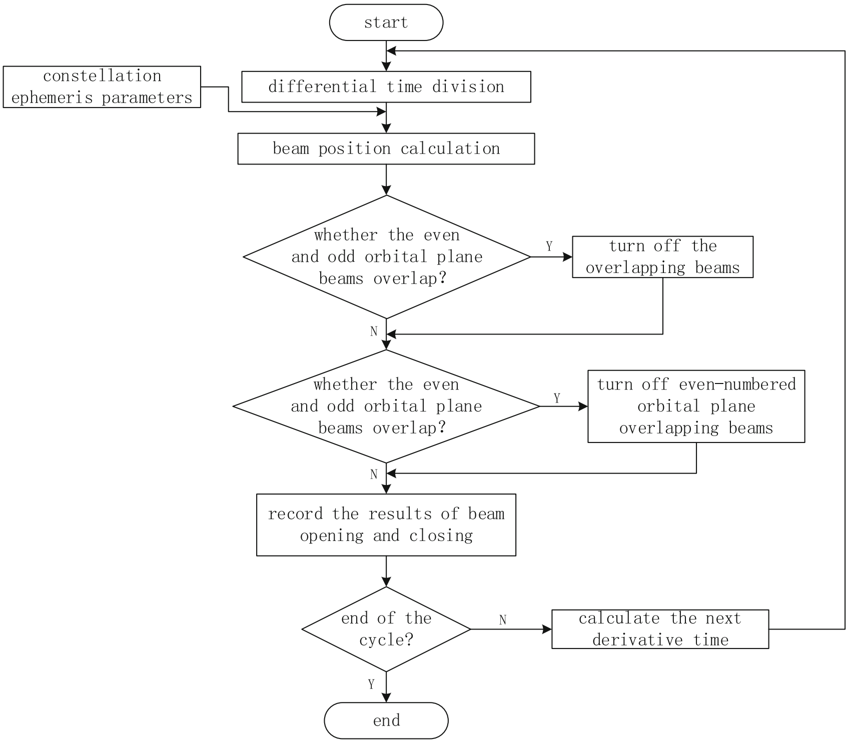

Fig. 3. The planning process of periodic beam-opening and closing

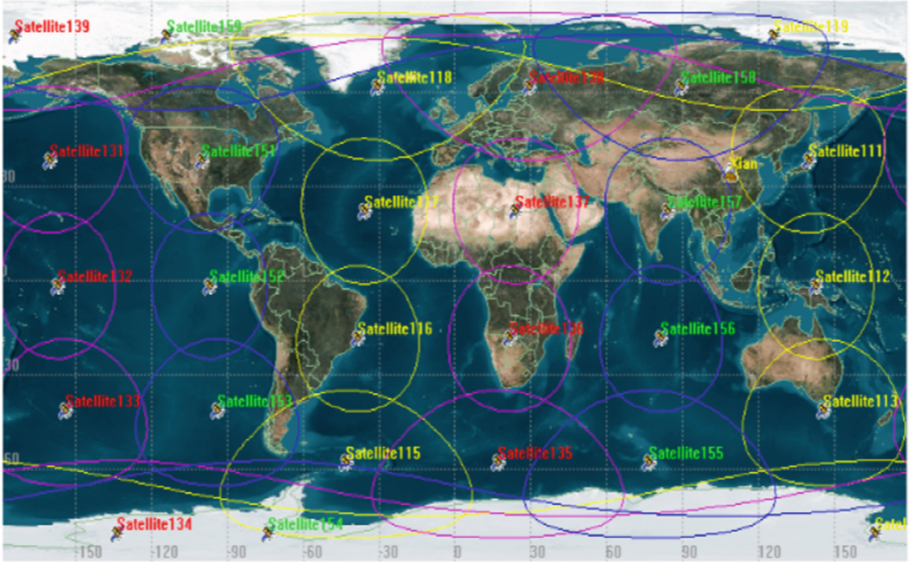

Fig. 4. Schematic diagram of satellite coverage on the main orbital plane

2.2 Simulation Results and Analysis

Since the beams of odd orbiting satellite has been able to realize the complete coverage of the region above 60° north and south latitude, when the even orbiting satellite moves into that area, it can completely close all the beams of the corresponding satellite.

The simulation of the whole constellation by using the periodic on/off strategy of the beam, and the results of the change of the on/off state of all beams with time in 12 h are as follows. The abscissa represents time, the ordinate represents the beam number of the satellite, and the red line represents the beam opening state during this period.

The following is the time sequence diagram of the first satellite in each orbital plane (Figs. 5, 7, 8, 9 and 10):

The simulation results are analyzed as follows:

1. The beam state has a periodicity of about 107 min, satellites in the same orbit have similar beam states and have a certain phase difference.
2. Except for the first and sixth orbital planes, the beams of all odd orbital planes also have a certain similarity (there are differences in individual beams). The beam states of the corresponding satellites in different orbits (such as satellite 1 in 1 orbit and satellite 1 in 5 orbit) are basically the same except for individual satellites. This rule also applies to even orbital.
3. Because the beam is preferentially allocated to the first orbital surface, the beam remains open throughout the entire process, but the 6th orbit satellite beam turns on/off more frequently than other even orbital planes due to the seam.

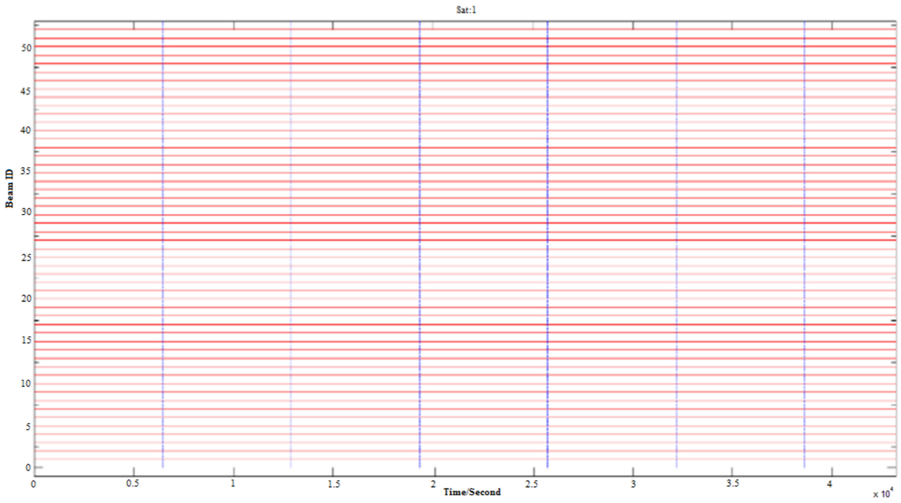

Fig. 5. Beam status of satellite 1 in 1 orbit

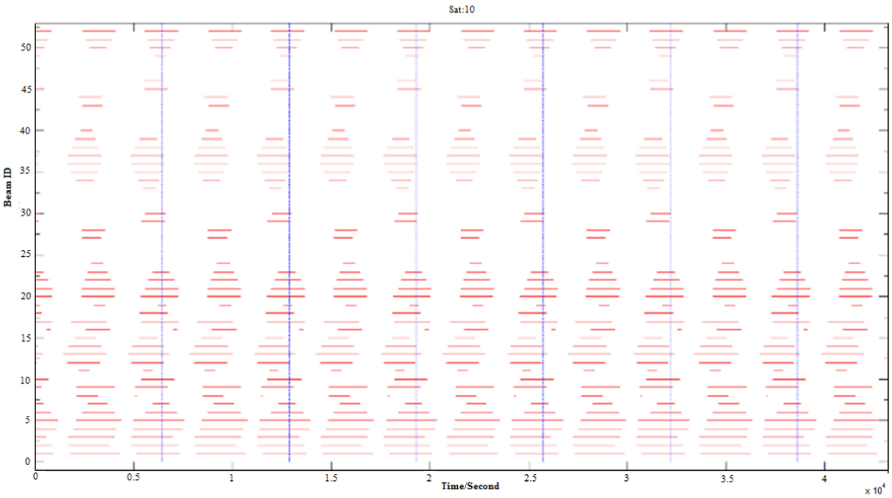

Fig. 6. Beam status of satellite 10 in 2 orbit

4. Satellite beams on odd orbital take more than 50% longer to turn on than even orbital, and many of which never turn on during the entire cycle.
5. The number of open beams varies steadily with time and remains between 1530 and 1590.
6. The first orbital remains open during the full cycle, and the beam opening time of the other odd orbital is also significantly longer than that of the even orbital. In order to maintain the normal operation of the satellites in the whole constellation

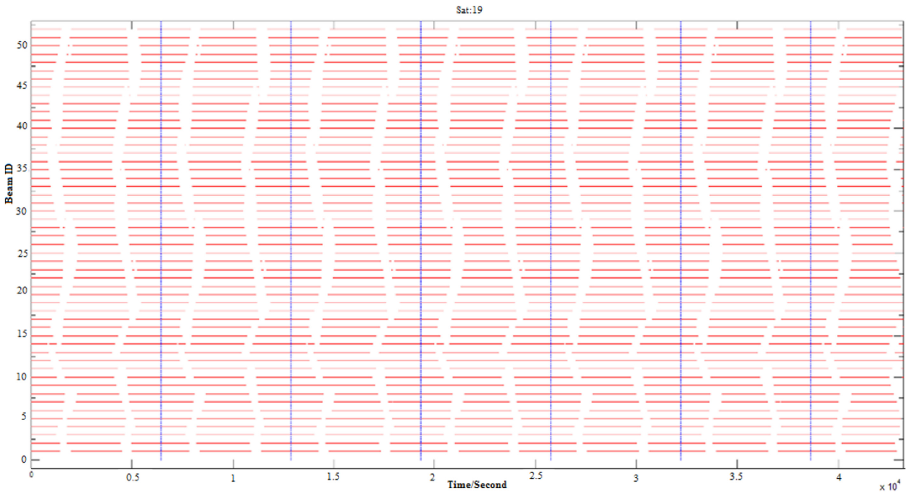

Fig. 7. Beam status of satellite 19 in 3 orbit

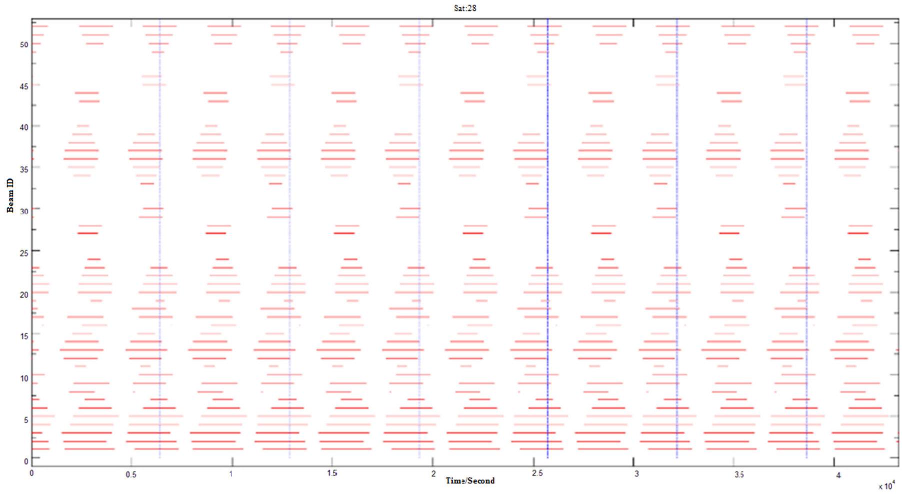

Fig. 8. Beam status of satellite 28 in 4 orbit

and avoid the long-term operation of the satellites in a certain orbital plane, we can rotate in each orbital plane in a certain period to balance the burden.

7. Dynamic frequency allocation prevents the beams on both sides of the seam from interference, thereby solving the problem of frequent opening and closing of the sixth orbit beam.

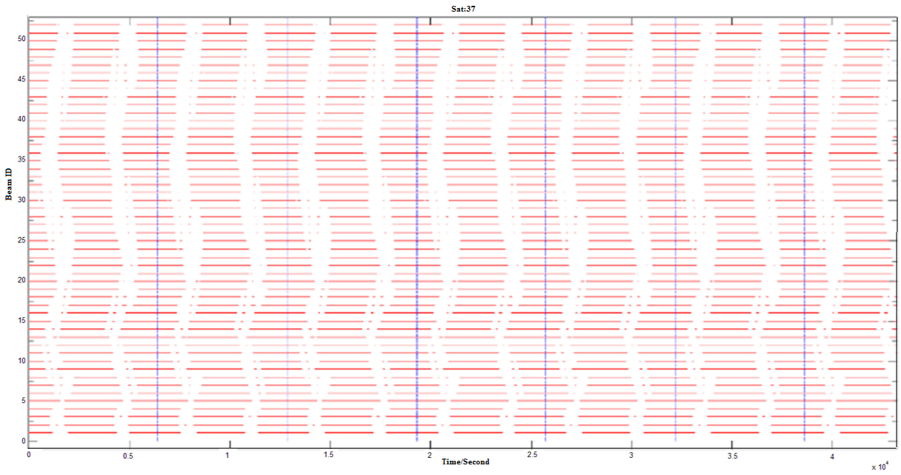

Fig. 9. Beam status of satellite 37 in 5 orbit

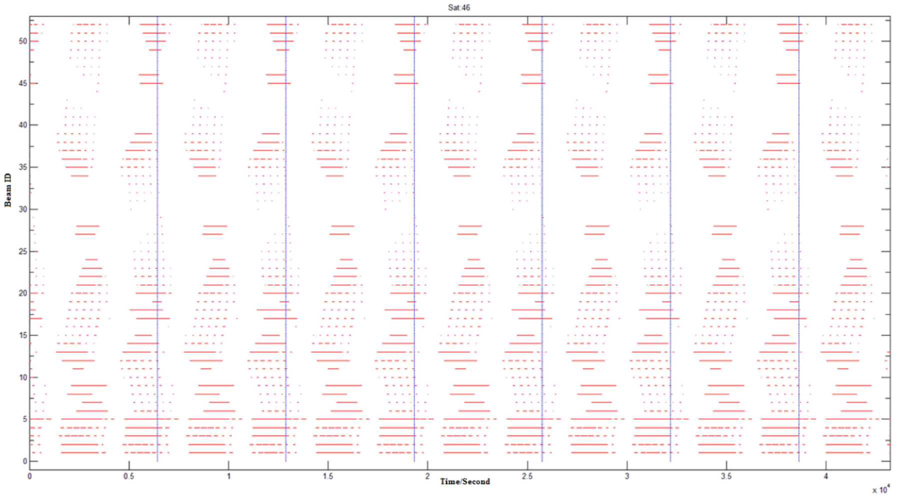

Fig. 10. Beam status of satellite 46 in 6 orbit

3 Dynamic Adjustment Strategy of Beam Resources

The periodic on/off strategy of spot beam greatly reduces the interference problem of the whole constellation, but it does not consider the interference problem of the cross area. In order to improve resource utilization, frequency multiplexing is usually adopted to divide the user's bandwidth into several sub-bands and allocate them to different beams. The more sub-bands are divided, the greater the choice of frequency reusability and the smaller the interference, but the less the number of carriers available to users under a single beam; the less the sub-bands are divided, the more serious the inter beam interference in the constellation. Due to the relative motion of satellites, it is difficult to ensure that the initial allocated non-interference sub-bands remain non-interference in the whole process. If the allocated sub-bands of satellite point beam are not adjusted dynamically during the operation cycle of the constellation, the difficulty of initial sub-band allocation and the probability of interference will be increased.

In order to take into account the number of sub-band divisions and interference, the constellation operating period can be divided into several equally spaced time slices. In each time slice, the sub-band allocation of each point beam in the constellation remains unchanged. Prioritize the allocation result of the previous time slice as the initial value of the next time slice and perform interference detection. If there is interference, re-adjust and allocate the beam sub-bands in the interference area. In the case of a fixed time slice, by repeatedly iterating the beam frequency allocation scheme, which can obtain a better beam frequency allocation scheme within the time slice.

3.1 Frequency Dynamic Allocation Strategy

Initial Allocation

In order to simplify the process, first simulate an initial frequency allocation plan, and use the result of the initial frequency allocation as input for iterative calculations. The allocation result is the same for all 54 satellites. The initial frequency allocation generation process is as follows (Fig. 11):

First, assign a frequency point to the i-th beam, and calculate whether the beam will produce interference exceeding the threshold with other beams. In order not to affect the communication quality, the beam interference threshold is set to -12dB, if it exceeds threshold, judge whether other available frequency points also produce interference exceeding the threshold; if it still exceeds, it indicates that there is a problem in the frequency point allocation of the first i-1 beam, firstly, reallocate the frequency point of the i-1 beam, and so on the interference generated by the beam is within the threshold.

Assign a frequency point to the i-th beam, and calculate whether this beam will cause interference with other beams that exceeds the threshold; if it exceeds, then determine in turn whether other frequency points available for allocation also cause interference that exceeds the threshold; if it still exceeds, it means that there is a problem in the frequency allocation of the i-1 beam. Then the frequency points of the i-1th beam are re-allocated, until the interference generated by all beams is within the threshold.

Interference calculation is to calculate the interference value of the i-th beam to other beams. The calculation process is as follows (Fig. 12):

By simulating the influence factors of the interference pattern of each point beam of the satellite, the interference values of other beams under the same satellite for each beam are calculated. Through the above iterative method, a sub-band and carrier allocation strategy lower than the interference threshold value (−12dB) is assigned to each beam (Figs. 13, 14 and 15).

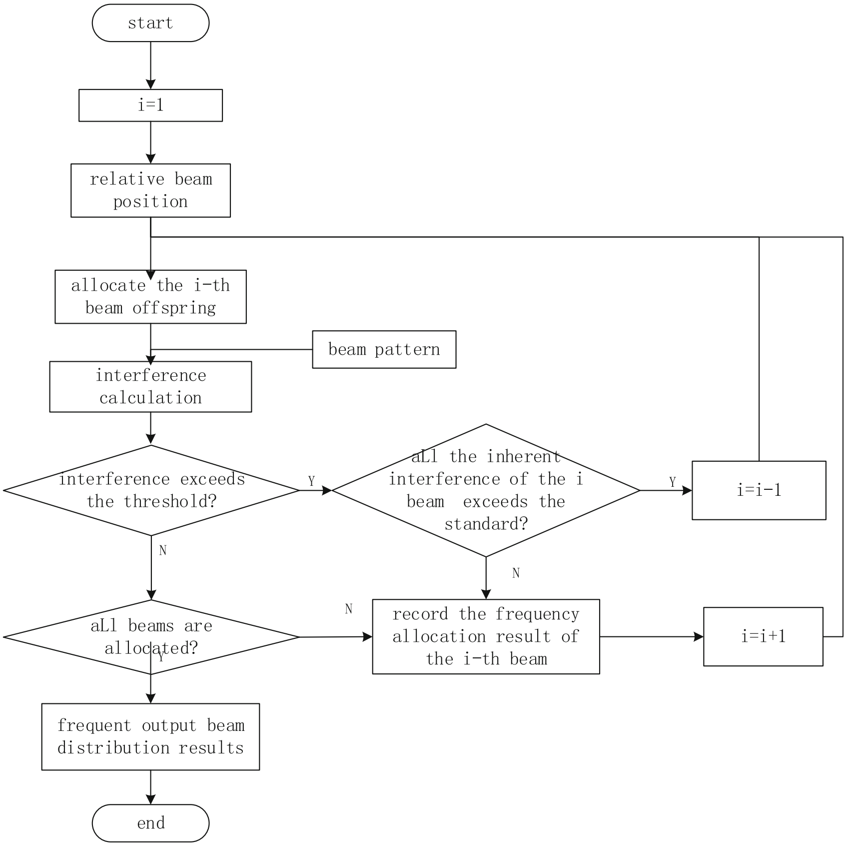

Fig. 11. Initial frequency allocation process

If the number of access terminals under a certain beam exceeds the number of users that can be carried by the initial sub-band during the actual system operation, the operation control system will then separately increase the available sub-bands or carriers for the satellite beam. The premise of allocating sub-bands or carriers is that the allocated carriers will not cause interference to other users and will not be interfered by the same carriers in other beams.

We randomly simulate 780 user terminals under a single satellite, and the terminals are randomly distributed in each spot beam; the L-band 7M user bandwidth is divided into 12 sub-bands, and each sub-band is divided into 15 carriers. The simulation results are shown in Fig. 6. In the figure, the black number represents the beam number, the red number represents the sub-band number obtained through allocation of the beam, and the two red numbers indicate that the beam has obtained additional sub-bands allocated by the system on the basis of the existing initial sub-bands (Fig. 16).

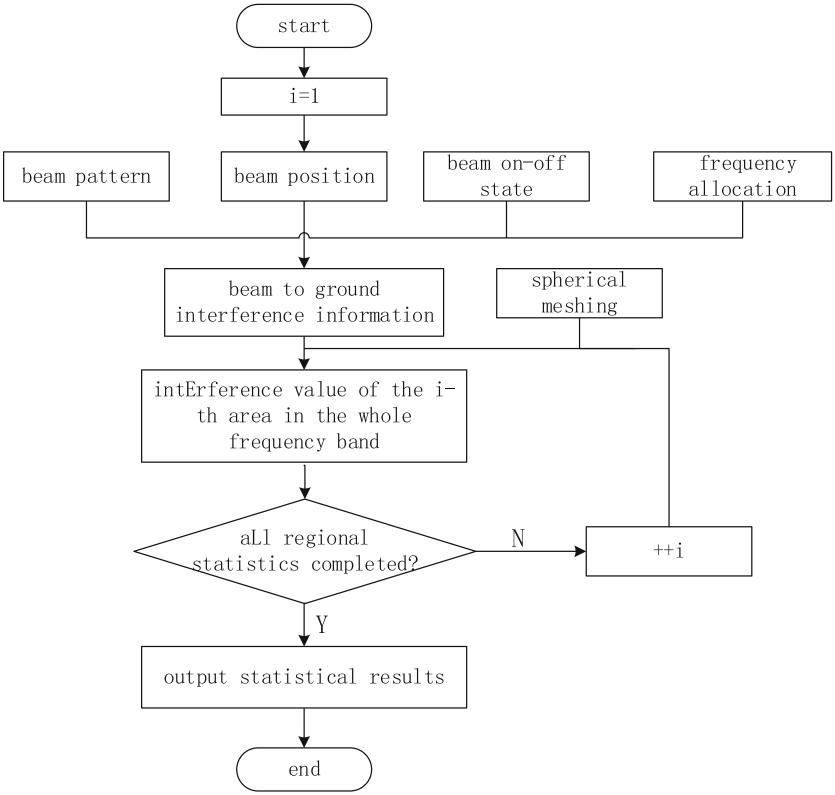

Fig. 12. Interference calculation process

Dynamic Allocation

According to the beam periodic closing strategy, the beam opening and closing have the same periodicity (about 107 min) as the constellation operation, and the beam frequency allocation scheme only needs to consider one cycle, which can greatly reduce the amount of calculation.

Divide a satellite's operating cycle into a number of differential times with a length of ΔT. The satellite state, the beam on/off state within a differential time and the frequency allocated to it are regarded as fixed. The earth's surface is evenly divided into 10560 sampling points, and a constellation operating cycle is divided according to the time slice length ΔT, assuming that M is the number of global subbands, and N is the number of time slices.

According to the current time and ephemeris parameters, the real-time position of the constellation satellites can be obtained. Since the beam position is fixed relative to the satellite, the position of all beams can be calculated from the position of the satellite. Beam pattern is obtained from satellite antenna data, and the on/off state of the beam can be obtained from the periodic closing strategy. In this paper, the method of gridding the earth's surface is adopted, and the spherical surface is divided into several

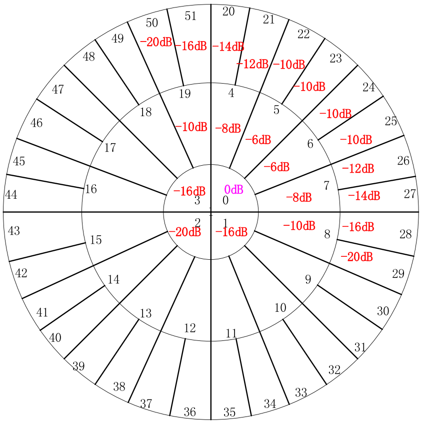

Fig. 13. Pattern interference influence factor of inner spot beam

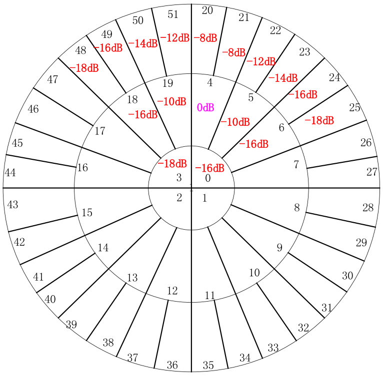

Fig. 14. Pattern interference influence factor of mid-level spot beam

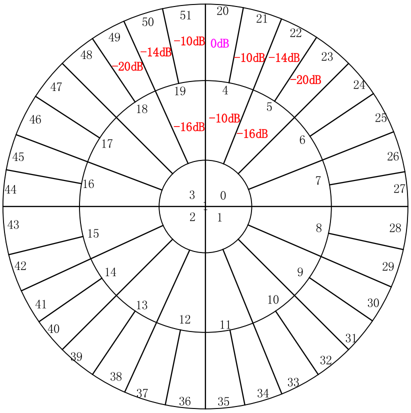

Fig. 15. Pattern interference influence factor of outer spot beam

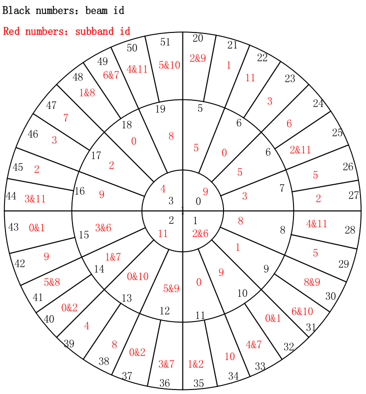

Fig. 16. Schematic diagram of sub-band allocation

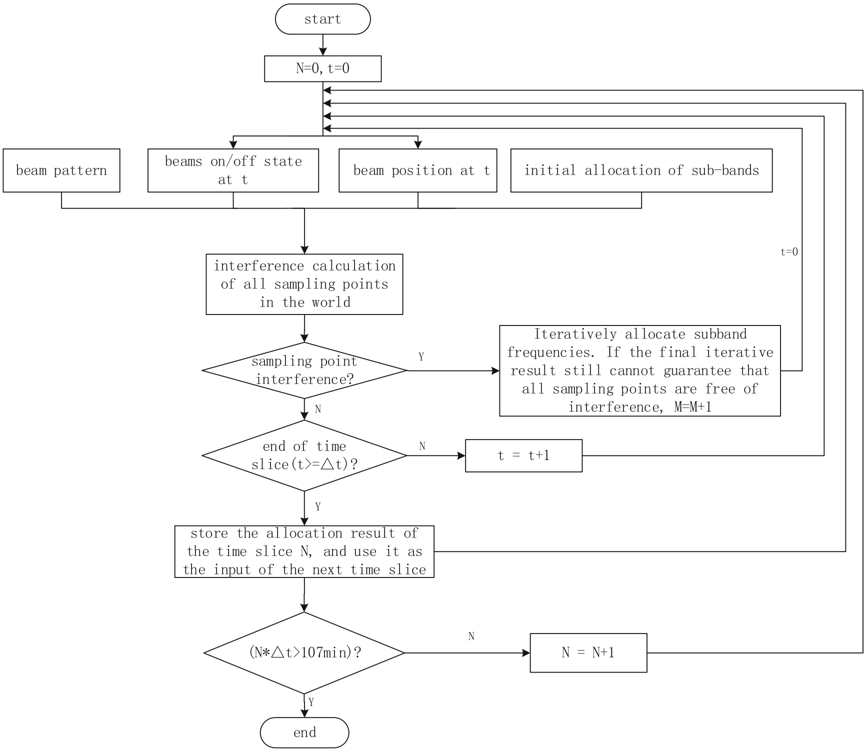

Fig. 17. Constellation frequency resource optimization allocation processing flow

cells. This way, while ensuring considerable calculation accuracy, numerical solutions can be used instead of analytical solutions, which greatly reduces the amount of calculation.

In the process of frequency allocation, the interference values of all regions in the world can be calculated by combining the beam position, the beam on/off state and the beam pattern. If the interference in a location region exceeds the threshold value, the beam allocation state is reprogrammed. After many iterations, the frequency allocation of the whole constellation beam in [T0, T0 + ΔT] can be obtained, and the results are used as the input for the iterative calculation of the beam sub-band of [T0 + ΔT, T0 + 2ΔT], until a broadcast frequency allocation scheme can be obtained without interference in the whole constellation period. There is no situation of being in two or more beams and allocating the same beam sub-bands at any place at any time in the world. During the iteration process, the beams of the same frequency band do not overlap, and the iteration period is the entire constellation period, the flowchart is as follows (Fig. 17):

Set the time slice length ΔT, and iteratively change the frequency of the sub-bands through the algorithm processing flow. If after all the frequencies are iterated, all sampling points cannot be satisfied without interference, the number of sub-bands needs to be re-divided, and then the iterative calculation is performed again until meet the algorithm termination condition for global beam interference-free.

3.2 Simulation Results and Analysis

Set different time slice lengths ΔT and the number of sub-bands M, and perform simulation according to the above procedure. Under the constraint of full constellation without interference, the relationship between the selection of time slice length and the required number of sub-bands is shown in the following table (Table 1).

Table 1. The relationship between the selection of time slice length and the number of interference-free sub-bands

Time slice length (ΔT)	The number of sub-bands that satisfy the interference-free (M)
6 min	21
5 min	16
4 min	12

The simulation results show that when the set time slice length is longer, more sub-bands need to be set to meet global interference-free. When the number of sub-bands is set less, beam frequency adjustments are more frequent, after comprehensively considering the beam capacity and the dynamic adjustment period, this scheme selects that the beam frequency dynamic adjustment duration in the constellation is 4 min, and the frequency allocation of the global interference-free beam can be satisfied by the division of 12 sub-bands.

Based on the above-mentioned dynamic adjustment strategy, this paper performs beam control and dynamic allocation of frequency resources for 54 LEO satellites. The simulation results before and after the optimization of the beam and resource show that the optimized beam can satisfy the global single repeat cover. At the same time, the overlapping coverage is greatly reduced, and the frequency of adjacent and intersecting beams is not repeated, which not only reduces the waste of beam resources, but also satisfies the interference suppression results of the beams (Figs. 18 and 19).

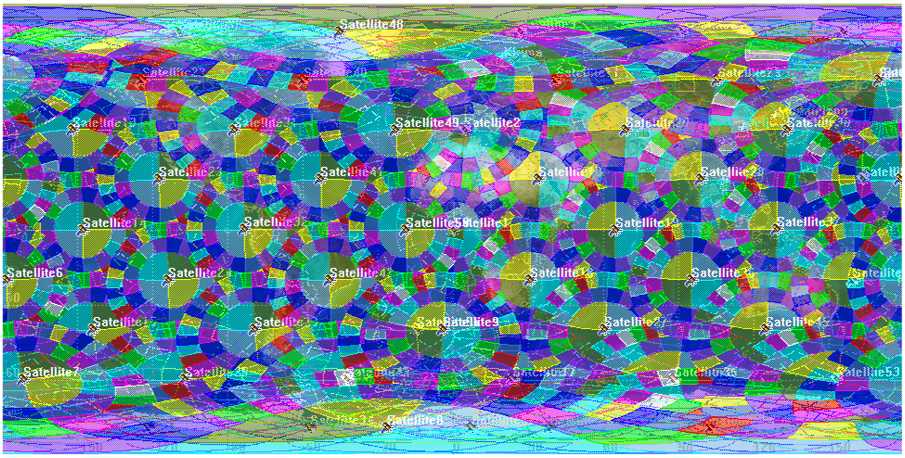

Fig. 18. Global beam coverage map before dynamic adjustment of beam resources.

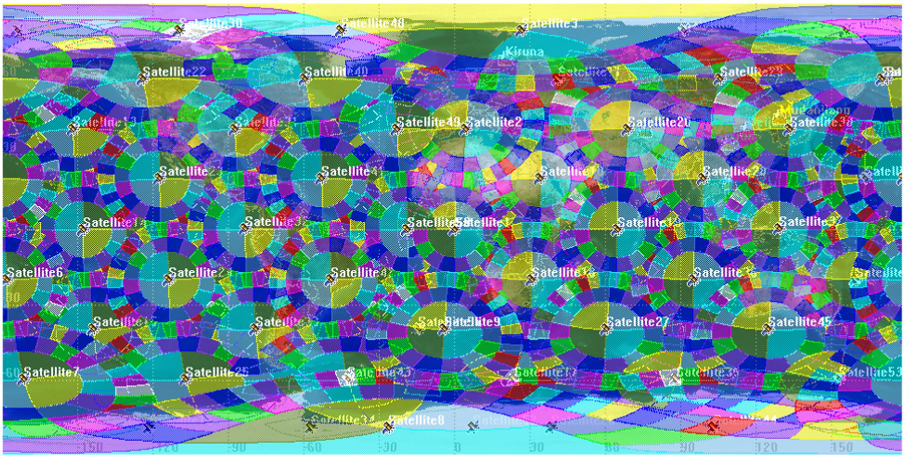

Fig. 19. Global beam coverage map after dynamic adjustment of beam resources.

The simulation results are analyzed as follows:

1. Due to the relative movement of the satellite and the ground, the coverage time of a single beam can be up to 3–4 min. When performing global beam frequency allocation (including broadcast and user carriers), it is not necessary to use a fixed frequency allocation scheme for each satellite beam, otherwise will greatly increase the difficulty of frequency allocation and the occurrence of interference.

2. Through reasonable sub-band division and the setting of the dynamic beam frequency adjustment duration, a better allocation of global beam frequency resources can be achieved and no interference or below the interference threshold can be achieved.
3. There are two types of constellation operation: large period and small period. The large period of constellation operation is 6397 s (106 min and 37 s), and the small period of constellation operation is 6397/9 s (about 11 min and 50 s). Regardless of the rotation of the earth and the number of satellites, only from the constellation's own beam sub-band allocation, if it can ensure that the allocated beam sub-bands within a small period of 11 min and 50 s (approximately 3 4-min time slices) are free of global interference. Then it can be guaranteed that there will be no interference in the entire constellation operating cycle.
4. Implementation process of non-interference frequency resource allocation: first calculate the sub-band allocation of each beam in the time slice (which can be converted into the corresponding latitude interval) of each satellite in the world within a small period of time. When a satellite arriving from the same orbital plane moves to the corresponding latitude interval, it uses the results of the beam sub-band or frequency assigned by the satellite in front of it under the condition that there is no interference in the interval.

4 Conclusion

The periodic beam closing strategy designed in this paper ensure the global coverage and suppress interference between beams by closing overlapping beams. A beam sub-band division and frequency dynamic allocation is proposed on the basis of periodic beam closing strategy, in this way, the interference between beams is avoided and the constraint condition of global coverage without interference is met. On the basis of the research in this article, we will continue to optimize the interference for the movable beam and beam hopping of the mega-constellation in the future.

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