A Beam Hopping Algorithm Based on Multi-objective Optimization in LEO Satellite Systems

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Abstract. The limited onboard beam resources bring great challenges to low earth orbit (LEO) satellite communication systems. In addition, there are lots of difficulties in satisfying the nonuniform traffic requirements. At present, multi-beam satellite systems have the ability to solve the problem through utilizing beam hopping (BH) technology, which increases the system throughput by effectively scheduling beam resources. This paper proposes a BH algorithm based on multi-objective optimization, which takes into account metrics including traffic distribution, frequency multiplexing distance, time slot allocation and so on when designing BH patterns. Simulation results illustrate that the proposed algorithm performs well in throughput and average delay.

Keywords: Satellite Communication · Beam Hopping · Resource Allocation

1 Introduction

Low earth orbit (LEO) satellite communication systems are becoming more and more important in the 6th generation (6G) [1]. Due to the characteristic of seamless coverage and low construction cost, a number of commercial companies have constructed their own LEO constellations, such as SpaceX, OneWeb and so on [2]. However, the nonuniformity spatial and temporal distributions of traffic requirements cause challenges to make full use of the limited onboard resources [3]. On this condition, beam hopping (BH) technology has been proposed to effectively utilize the resources by time division multiplexing. Therefore, it is necessary to optimize the BH technology in LEO multibeam satellite (MBS) communication systems [4].

Reference [5] proposed a BH scheme based on genetic algorithm to improve the capacity of LEO systems, and simulation results illustrate the superior performance when comparing to systems without BH. Similarly, reference [6] and [7] also reveal the advantages of applying the BH technology to LEO systems. In addition, cochannel interference (CCI) could be suppressed to a certain extent by certain BH schemes. More specifically, reference [8] combined BH with precoding technology to mitigate

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CCI caused by too short cochannel multiplexing distance. And frequency reuse scheme was considered in [9] when applying BH technology, however, although CCI could be eliminated through spatial isolation, the overall capacity of the system decreased because of lower resource utilization rate. A joint optimization of spectrum and power resources BH strategy was proposed in [10], and this scheme could not only increase the system throughput, but also satisfy the traffic demands of users as much as possible.

Currently, the resource allocation of LEO systems is almost based on terrestrial traffic requests, where the single-objective optimization of a certain resource will be carried out. However, an effective BH scheme should allocate multidimensional resources at the same time, which means it is necessary to consider various optimization objectives and constraints when designing BH algorithms. Therefore, this paper proposes a beam hopping algorithm based on multi objective optimization (MOBH) for LEO satellite systems, in which communication resources are divided into three dimensions including time, frequency, and beam. And the performances on throughput ratio and average delay are analyzed at the end of this article.

The rest of this paper is organized as follows. Section 2 describes the system model of LEO satellite systems with BH. Section 3 formulates the BH optimization problem and elaborates the solutions. The performance evaluation is presented in Sect. 4. Section 5 presents the conclusions.

2 System Model

This section presents a LEO satellite communication scenario with beam hopping and describes the traffic distribution statistics.

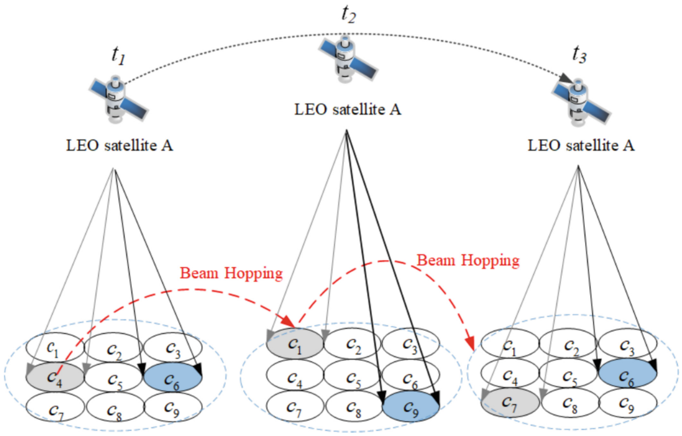

Fig. 1. LEO beam hopping satellite communication scenario

2.1 System Scenario

The system scenario is shown in Fig. 1, where every user can get service by accessing the nearest satellite. The LEO satellite can generate $L_{\max}$ beams simultaneously and allocate them to the user region which is divided into N cells. Assuming that b_i and c_i represent beam i and cell i respectively, and user j in c_i is defined as u_{ij}.

2.2 Traffic Distribution

The nonuniform traffic distribution characteristic of the proposed communication scenario is mainly caused by the random location distribution of users. Denoting the coordinate of u_{ij} is represented as a vector (x_{ij}, y_{ij}), and assuming it follows the two dimension normal distribution, then the probability density function can be expressed as follows.

$$f(x_{ij}, y_{ij}) = \frac{1}{2\pi\sigma_1\sigma_2}\exp\left\{-\frac{1}{2}\left[\frac{(x_{ij}-\mu_1)^2}{\sigma_1^2}+\frac{(y_{ij}-\mu_2)^2}{\sigma_2^2}\right]\right\} \tag{1}$$

where μ_1 and μ_2 represent expectation while σ_1 and σ_2 stand for variance.

The traffic demands of u_{ij} and c_i can be expressed as R_{ij} and R_i respectively, and both of them are functions of (x_{ij}, y_{ij}). We define T_i as the total throughput that c_i can obtain from the system, and it is related to the bandwidth W and transmission power P of the LEO satellite.

3 MOBH Algorithm

3.1 Frequency Multiplexing Distance Calculation

To improve spectral efficiency, full frequency reuse strategy should be applied in the proposed system. However, when beams owning the same frequency provide service for nearby cells, it is obvious that significant interference will be generated. Therefore, frequency multiplexing distance should be controlled properly to improve the signal to interference plus noise (SINR). The cochannel interference between LEO satellite beams is shown in Fig. 2.

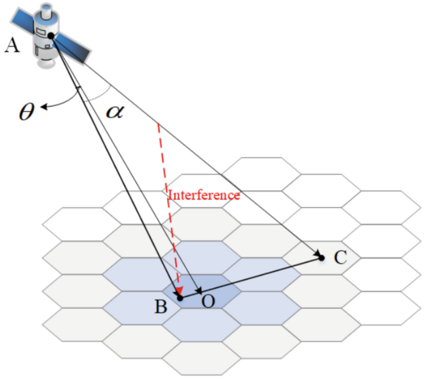

Fig. 2. Co-channel interference between LEO satellite beams

The antenna gain of the satellite is expressed as

$$G = G_0\left[\frac{J_1(\mu)}{2\mu} + 36\frac{J_3(\mu)}{\mu^3}\right]^2 \tag{2}$$

where $\mu = 2.07123\sin\theta/\sin(\theta_{3dB})$, and θ is the angle between AB and AO. θ_{3dB} is the half beam angle. G_0 represents the maximum gain when the off axis angle is zero. $J_1(\mu)$ and $J_3(\mu)$ are the first order Bessel function and the third order Bessel function respectively. Considering the interference from beam C, SINR of users located in cell O is derived as

$$\gamma_O = \frac{EIRP_{\mathrm{t}}G_{\mathrm{t}}(\alpha)G_{\mathrm{r}}(0)(\lambda/4\pi r)^2}{N + EIRP_{\mathrm{t}}G_{\mathrm{t}}(\theta)G_{\mathrm{r}}(0)(\lambda/4\pi r)^2} \tag{3}$$

where γ_O represents the maximum SINR of users in cell O and $EIRP_{\mathrm{t}}$ is the equivlent isotropically radiated power of the satellite. $G_{\mathrm{t}}(\alpha)$ and $G_{\mathrm{t}}(\theta)$ is the useful antenna gain and interference antenna gain respectively. Simulation can be executed according to the parameters given in table 1.

Table 1. Antenna parameters of the LEO satellite

Parameters	Notation	Value
Beam radius of satellite	r	12 km
Height of satellite	H	550 km
Antenna efficiency	η	0.55
Half beam angle	θ_{3dB}	3.5°
Antenna aperture	D	0.1 m

The relationship between SINR and multiplexing distance are shown in Fig. 3.

Figure 3 illustrates that with the increase of multiplexing distance, SINR shows an upward trend. When the distance goes up to $3r$, SINR reaches a plateau and maintains the same level at 21 dB, which is close to SNR. Therefore, the distance between two different beams should be larger than $3r$ during the same time slot.

3.2 Time Slot Allocation

By allocating time slots to different beams of the satellite, traffic requirements of users should be satisfied as much as possible. The optimization problem is proposed as follow.

$$\begin{aligned} &P_1: \min \sum_{i=1}^{N} |R_i - T_i|^2 \\ &s.t.\ C_1: T_i \le R_i \\ &C_2: \sum_{i=1}^{N} M_i \le L_{\max} Z \\ &C_3: M_i \ge 0 \end{aligned} \tag{4}$$

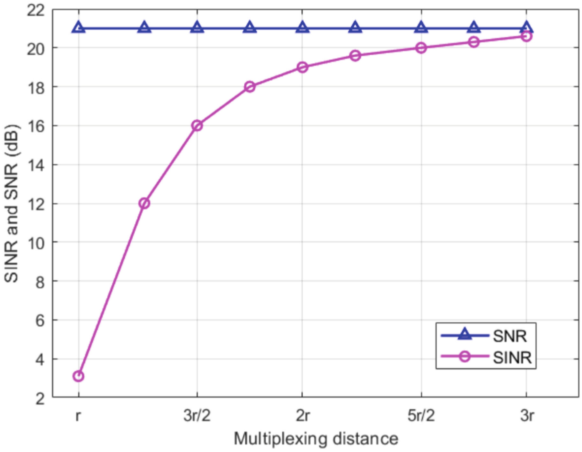

Fig. 3. Evaluation on frequency multiplexing distance

where M_i represents the number of time slots allocated to c_i, and $L_{\max}$ is the max numbers that beams are able to operate simultaneously in a single time slot. Z is the amount of time slots during a beam hopping period. The relationship between T_i and Z is $T_i = M_i \times \frac{W \times \eta_i}{L_{\max} \times Z}$, where η_i represents spectrum efficiency.

The goal of the optimization object P_1 is to satisfy the traffic needs and maximize the system throughput. C_1 is the constraint that communication resources are not able to be allocated to users whose traffic requirements are satisfied. C_2 represents that the number of beams working in the same time slots should be less than Z.

Actually, P_1 a convex optimization problem, which can be solved by leading in antithetic variables $\lambda_1, \lambda_2, \lambda_3$. According to Karush-Kuhn-Tucker (KKT) conditions, the Lagrangian function of this problem is expressed as

$$L(M_i, \lambda_1, \lambda_2, \lambda_3) = \sum_{i=1}^{N} |R_i - T_i|^2 + \lambda_1 (\sum_{i=1}^{N} M_i - L_{\max} Z) + \lambda_2 (T_i - R_i) + \lambda_3 M_i \quad (5)$$

Obviously, traffic allocation T_i and traffic request R_i cannot always be equal, so Eq. 5 should satisfy the following boundary conditions.

$$\lambda_2 = \lambda_3 = 0 \quad (6)$$

$$\sum_{i=1}^{m \times n} M_i - L_{\max} Z = 0 \quad (7)$$

Then, after taking the derivative of the Lagrangian function, we can get

$$\frac{\partial L(M_i)}{\partial M_i} = 2N_i \left(\frac{W \eta_i}{L_{\max} Z} \right)^2 - 2R_i \cdot \frac{W \eta_i}{L_{\max} Z} + \lambda_1 = 0 \quad (8)$$

By solving Eq. 8, M_i is expressed as

$$M_i = R_i \times \left(\frac{L_{\max}Z}{W\eta_i}\right) - \frac{\lambda_1}{2}\left(\frac{L_{\max}Z}{W\eta_i}\right)^2 \tag{9}$$

Substituting the inequality boundary conditions, we can obtain

$$\lambda_1 = \frac{2}{N}\left(\frac{\sum_{i=1}^{m\times n} R_i W\eta_i - W^2\eta_i^2}{L_{\max}Z}\right) \tag{10}$$

$$M_i = \frac{L_{\max}Z}{W\eta_i}(R_i - \frac{1}{N}\sum_{i=1}^{N} R_i) + \frac{L_{\max}Z}{N} \tag{11}$$

3.3 Beam Hopping Pattern Design

During a beam hopping period, according to traffic distribution, cells are divided into hot spot areas and common areas. The beam hopping pattern design strategy should follow three criteria. Firstly, pre-allocation. A time slot is reserved for all cells even if there are no service demands. Secondly, priority allocation to high traffic regions. According to the number of time slots calculated by the previous sections, the cells which require more services are assigned slots in advance. Thirdly, interference avoidance. Frequency multiplexing distance must be satisfied when designing beam hopping patterns, and interference can be avoided by spatial isolation. A detailed description of designing beam hopping pattern is illustrated in Algorithm 1.

Algorithm 1: Beam Hopping Pattern Design

```
Input: The traffic demands matrix $R$, the total throughput $T$, the frequency multiplexing distance $d_{th}$.
Initialize: The allocated throughput matrix $A = \min\{R, T\}$.
For $t = 0, 1, \cdots, Z$ do
    $\alpha_t \Leftarrow$ vectorize$\{A(x, y, t)\}$.
    Sort the traffic request matrix: $index \Leftarrow \arg\max_S(\alpha_t)$.
    For $i = 0, 1, \cdots, S$ do
        If $d > d_{th}$ then
            $E\left(\left[\frac{index[i]}{N}\right], index[i] \quad \left[\frac{index[i]}{N}\right] M, t\right) \quad 1$.
        End If
    End For
End For
Output: Beam hopping pattern matrix $B$.
```

4 Performance Evaluation

In this section, simulation experiments are presented to evaluate the performance of MOBH. Table 2 summarizes the simulation parameters.

Table 2. Simulation Parameters

Parameters	Notation	Value
Total capacity of a satellite	T_{sum}	1 Gbps
Capacity of every beam	T_{beam}	100 Mbps
Length of a single time slot	t_s	10 ms
The number of beams in a slot	$L_{\max}$	10
The number of cells	N	37
Packet size	P_s	100 kb

In this paper, three different BH schemes are compared with MOBH. First, the fixed beam hopping (F-BH), which allocates a fixed number of time slots to each cell. Second, the random beam hopping (R-BH), which means that each satellite selects cells for service at each time slot randomly. The last one is the genetic algorithm beam hopping (GA-BH) [11], where every satellite calculates its own beam hopping pattern through a greedy strategy.

4.1 Throughput Ratio

Throughput ratio [12] is proposed to measure the utilization rate of the total capacity of a satellite, which has the form as

$$\eta = \frac{\sum\limits_{i=1}^{N} T_i}{T_{sum}} \tag{12}$$

where η represents throughput ratio, and the total throughput provided by a satellite equals $\sum\limits_{i=1}^{N} T_i$. The capacity of a satellite is T_{sum}.

The value of η is between 0 and 1, which is an intuitive reflection of the system throughput performance. When η equals 1, the satellite resource utilization reaches the maximum. Figure 4 describes the throughput ratio performance in detail.

Figure 4 reveals that with the increase of traffic requirements, for F-BH and R-BH, the throughput ratio shows an upward trend in the beginning, and then remains stable at about 50% and 60% respectively. For GA-BH and MOBH, the throughput ratio rises significantly at first and fluctuates around 90% in the end. When the value of traffic demands is less than 400 Mbps, the four BH schemes perform similarly. While when total user demands are larger than 600 Mbps, the performance of MOBH is ahead of the other three algorithms, especially when the requirements are more than 800Mbps. Although GA-BH takes the second place whose performance is close to MOBH, there is still a gap between 5% and 10%.

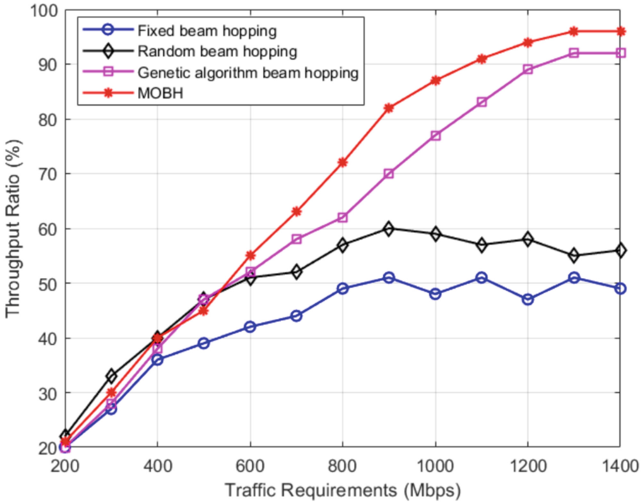

Fig. 4. The performance of throughput ratio among different BH schemes

4.2 Average Delay

In addition to throughput ratio, the performance of average delay is also important in beam hopping systems. The total delay is mainly composed of transmission delay, data processing delay and queuing delay. And we only consider the queuing delay in this paper because it is the most major metric. The average delay is defined as the mean value of the queuing delay, and the performance is shown in Fig. 5.

The graph illustrates that the average delay of R-BH stays constant at 550 ms and GA-BH hovers around 300ms. Both F-BH and MOBH show an upward trend but the former is more dramatically. When the traffic requirements less than 700Mbps, MOBH performs better than GA-BH and R-BH but worse than F-BH. However, it can be clearly seen in this figure that the average delay of F-BH increases to more than 800ms when traffic demands are heavy. Therefore, MOBH performs well in both low and high traffic requirements.

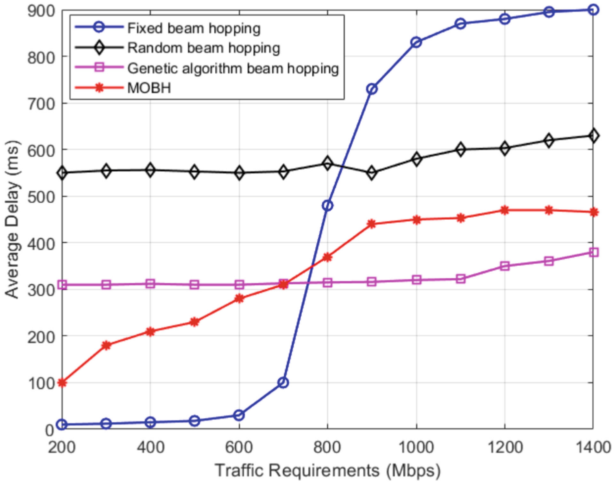

Fig. 5. The performance of average delay among different BH schemes

5 Conclusions

This study set out to find an effective resource allocation scheme for LEO multibeam satellite systems, and the MOBH algorithm is proposed to satisfy the nonuniformly distributed business requirements. At first, a beam hopping application scenario is established and the corresponding traffic distribution characteristic is expressed. Next, an optimization problem is proposed to maximize the traffic demands rate as much as possible. When designing the BH pattern, we take into account not only the cochannel interference caused by full frequency reuse, but also the dynamic equilibrium relationship between system throughput and user satisfaction. Finally, simulation results verifies that the proposed algorithm has excellent performance in terms of throughput ratio and average delay.

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