Beam Hopping Resource Allocation for Uneven Traffic Distribution in HTS System

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Abstract. Recently beam hopping technique is considered as a potential key technology in the next generation of high throughput satellite (HTS) systems for its flexible resource allocation. This paper is focused on the downlink resource allocation of beam hopping in the HTS System. Firstly, the user traffic model which varies in geography and time is built. Then with the proposed uneven traffic distribution model, the beam hopping time slot optimization algorithm is provided based on fairness objective function. Finally, the beam hopping pattern is designed to be combined with precoding to suppress co-channel interference. The simulation results show that compared with the traditional methods, the proposed algorithm can dynamically adjust the resource allocation with the change of the traffic requirements, and eliminate the co-channel interference of the beam as much as possible to meet the traffic requirements of each beam, thus improving the capacity of the satellite network.

Keywords: Traffic modeling · High-throughput satellite · Beam hopping · Resource allocation

1 Introduction

In the last few years, as a resource allocation method in high-throughput satellites (HTS), beam hopping (BH) technology has become a research hotspot in academia. The core concept of BH is to employ time-slicing method: not all beams are illuminated at the same time, only part of them are activated on demand. Compared to the traditional resource allocation methods, BH can flexibly allocate resources in dimensions of time, space, frequency, and power [1], which improves the system resource utilization [2].

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According to the objective function of the allocation algorithm and whether the co-channel interference (CCI) is considered, the existing resource allocation algorithms of the beam-hopping satellite system are divided into three categories: heuristic genetic algorithm, iterative algorithm and convex optimization algorithm. In order to meet the users' traffic demand, [3, 4] proposes the genetic algorithms for BH resource allocation. Focused on the influence of CCI of the beam-hopping satellite system, two iterative algorithms, minCCI and maxSIRN, was proposed to meet users' traffic demand [5, 6]. However, both the above-mentioned heuristic genetic algorithm and iterative algorithm have the problems of large amount of calculation and long calculation time, and are not suitable for scenarios where users' traffic demand changes dynamically. Although the convex optimization algorithm saves calculation time in resource allocation, it is not suitable for scenarios with severe CCI [7]. In addition, these previous researches lack the relatively real user traffic demand model.

In order to solve these problems, with the goal of service-driven and on-demand coverage, this paper is focused on the downlink resource allocation of beam hopping for uneven traffic distribution in the HTS system. Firstly, through grid division and comprehensive consideration of economic development and population density, the user traffic demand model which varies in geography and time is built. Secondly, based on the proposed uneven traffic model, a fair objective function is established and solved through integer programming method. Finally, the beam hopping pattern is designed to combing with precoding to suppress co-channel interference [8–12].

2 Beam Hopping Satellite System

The model of the beam-hopping system is illustrated in Fig. 1. This paper focuses on the forward link of HTS system, because the forward link is the main direction of traffic [13]. The forward link consists of the uplink between the gateway ground station and the satellite and the downlink between the satellite and the user terminals. The downlink adopts Time Division Multiplexing (TDM). According to the beam hopping time slot table, beam switched by the Hopping-beam Controller on satellite to meet the traffic demand of terminals.

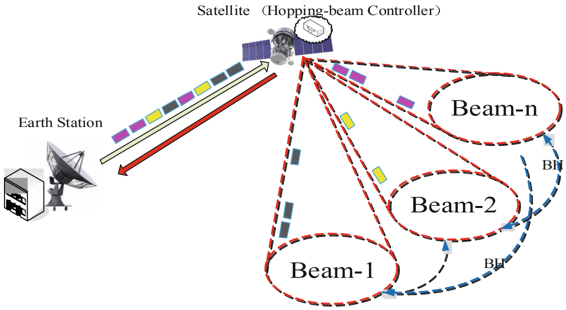

Fig. 1. Beam hopping system model

In order to accurately describe the beam-hopping satellite system, this paper assumes that the total power of the satellite is P_{tot}, the total bandwidth is B_{tot}, and the number of beams is N_B. Besides, constrained by the payload, the BH period is set to T_H, the time slot length is set to T_{slot}, the window length is defined by $N_t = T_H/T_{slot}$, and the maximum number of beams are illuminated simultaneously is N_{mat}^{st}. The beam-hopping time slot allocation model is illustrated in Fig. 2, different colors represent different beams, and the number of the same color represents the number of time slots allocated to the beam by the system.

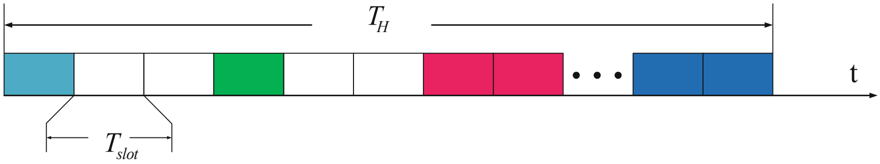

Fig. 2. Model of time slot allocation for beam-hopping

3 Traffic Demand Model

3.1 Spatial Model

Affected by factors such as economy and population density, the traffic demand of different regions is uneven. The region under the satellite coverage is divided into 559 grids, each gird has a longitude width of about 1.5° and latitude width of about 1.25°. The grid' distribution is illustrated in Fig. 3. For convenience, this paper takes China as the research object and builds its traffic demand model, but the method of building the traffic demand model is also applicable to other countries.

According to [14], the traffic intensity $\rho(j)$ inside the grid j is given by

$$\rho(j) = \lambda_1 T_m \sum_j n_{1j} + \lambda_2 T_m \sum_j n_{2j} \tag{1}$$

Where λ_1 is the mean call arrival rate per mobile subscriber (=0.01 call/hour), λ_2 is the mean call arrival rate per fixed user (=0.04 call/hour), and T_m is the average unencumbered call duration (=2 min). $n_{1,j}$ is the number of mobile subscribers in the grid j. $n_{2,j}$ is the number of fixed users in the grid j. It is assumed that the number of users in each province is evenly distributed, so the number of users in each grid can be calculated by the area ratio:

$$n_{i,j} = \frac{A_j}{S_k} N_{i,k} \text{ i = 1, 2} \tag{2}$$

Where, if $i = 1$, $N_{i,k}$ is the mobile subscribers in province k, if $i = 2$, $N_{i,k}$ is the fixed users in province k. A_j is the area of grid j. S_k is the area of province j, which got by

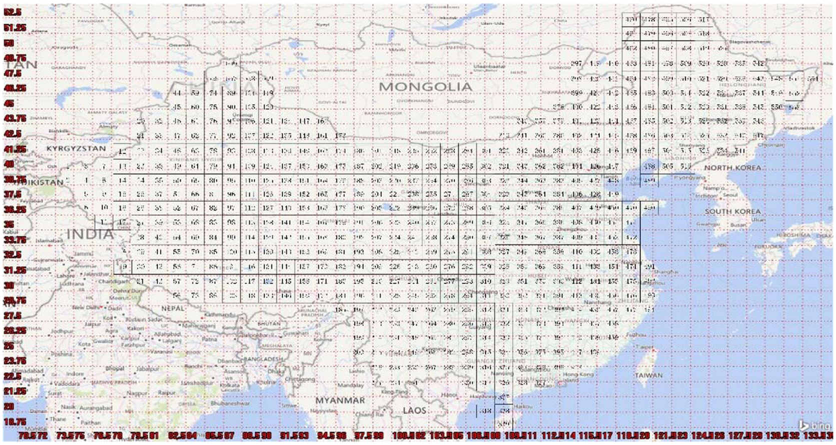

Fig. 3. Spatial traffic grid distribution

adding area of all grids belong to province k. $N_{i,k}$ and A_j are calculated by the following steps.

Calculation of the number of users:

$$N = GPM \times P_r \times T_p \tag{3}$$

Where GPM is the determination of the gross potential market, expressed in GDP (Gross Domestic Product), P_r is the popularity of satellite services, and T_p is the take-up rate of satellite services, expressed in population density. When estimating the number of users, this paper only considers GPM and T_p, GDP and population density are from [15].

Calculation of grid area:

$$\begin{aligned} A \approx l_m l_n &= R_E^2 \times \frac{\pi}{120} \times \frac{\pi}{144}\cos(\theta) \\ &= R_E^2 \times \frac{\pi^2}{17280} \times \cos(\theta) \end{aligned} \tag{4}$$

Where l_m is the length of each grid in the longitude direction, l_n is the length of each grid in the latitude direction, θ is the latitude of the center of each grid, and $R_E = 6378$ Km.

The spatial model is related to the position of the beams. The beams coverage and arrangement are illustrated in Fig. 4.

Fig. 4. Beam distribution

The peak traffic demand of each beam calculated by the following steps:

(1) Calculate the traffic demand intensity in each grid by formula (1);
(2) Calculate the coordinate of the beam;
(3) Calculate and sum the traffic demand intensity of all grids, which belong to the same beam;
(4) Repeat steps 1–4 for all beams in turns, the peak traffic demand intensity of all beams can be obtained.

This paper multiplies the peak traffic demand intensity with the PCM30/32 channel group rate (2.048 Mbps) to get the peak traffic demand (in Mbps) [16]. (Note that, if other services are considered, such as Internet services, multimedia services, the corresponding service rate should be chosen.)

After the above process, the spatial model of peak traffic demand is built. As illustrated in Fig. 5.

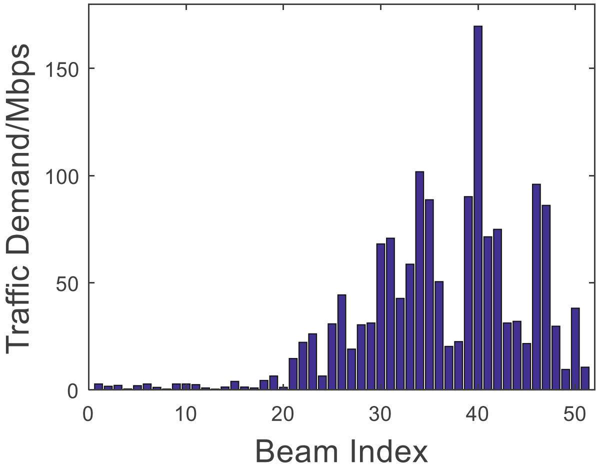

Fig. 5. Peak traffic demand of all beams

3.2 Time Varying Model

In order to analyze the change of traffic demand affected by time and describe the change of traffic demand within one day, a normalized time weighting factor was proposed. Within a day (24 h), according to people's daily habits, a time weighting factor was assigned to each period. This model is applied to all regions, as depicted in Fig. 6. The local time of each spot beam is obtained by GMT (Greenwich Mean Time).

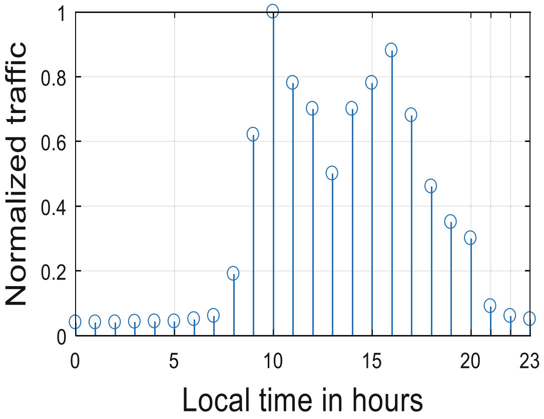

Fig. 6. Diurnal variation model

In order to study the traffic demand of beams in different geographic locations at different times, this paper assumes that China is divided into four time zones, namely A time zone (GMT + 9), B time zone (GMT + 8), and C time zone (GMT + 7) and D time zone (GMT + 6). According to the beam distribution and the international time zone division rules, beams No. 1 to No. 13 belong to time zone A, beams No. 14 to No. 27 belong to time zone B, beams No. 28 to No. 42 belong to time zone C, and beams No. 43 to No. 51 belong to time zone D. The beam in same time zone composes a cluster. (Please note that, in reality, all regions in China use the Eastern Eighth time as the standard time, the time zone assumption here used to study the relationship between time and traffic demand.). The method for calculating the traffic demand of a beam at different times is as follows:

The method for calculating the traffic demand of a beam at different times is as follows:

(1) Identify GMT time;
(2) Calculate the time weighting factor of the time zone to where the beam belongs;
(3) Multiply the peak traffic demand of the beam by the weighting factor.

Through the above steps, the change of the traffic demand of a beam in one day is built. Here, the change of traffic demand of beam No. 40 in one day are given, as illustrated in Fig. 7.

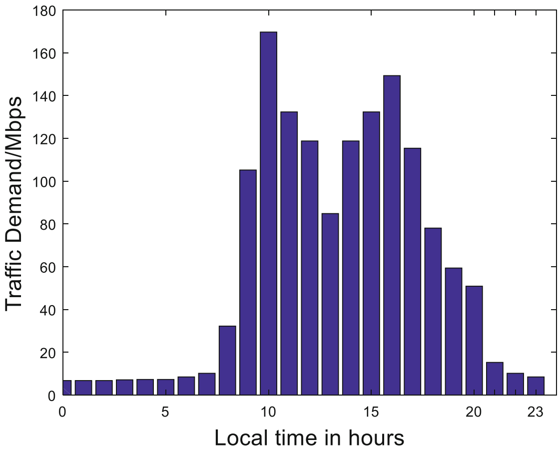

Fig. 7. Changes of traffic demand of beam No. 40 in one day

4 Beam Hopping Resource Allocation and Pattern Design

4.1 Resource Allocation by Beam Hopping

According to Sect. 3, the traffic demand model has the characteristics of time-varying and uneven distribution. Compared with the traditional resource allocation method, the beam-hopping technology can improve the resource utilization of the satellite system. According to the traffic demand of each beam and with the objective of maximizing the traffic offered to each beam, a method of allocating beam-hopping time slots is established. The specific method is as follows.

Firstly, according to the traffic demand of each beam, the fairness objective function is established to calculate the number of timeslots of each beam. As following:

$$\max \prod\nolimits_{k=1}^{N_B} \left(\frac{r_k}{d_k}\right) \tag{5}$$

$$\text{s.t. } \mathrm{r}_k \le d_k \tag{6}$$

$$\sum_{k=1}^{N_B} N_k \le N_{\max}^{st} N_t \tag{7}$$

$$N_k \ge 0, N_k \in \text{integer} \tag{8}$$

Where, N_k is the number of timeslots allocated to beam k. d_k is the traffic demand of beam k and r_k is the capacity allocated to beam k, which can be calculated by (9). The rest parameters can be got form Sect. 2.

$$r_k = \frac{N_k}{N_{slot} \times T_{slot}} B_{tot} \log_2(1 + SNR_k) \tag{9}$$

Secondly, we reform the objective function of Eq. (5) into a convex optimization problem by the logarithmic equivalent transformation:

$$\max \sum_{k=1}^{N_B} \ln\left(\frac{r_k}{d_k}\right) \tag{10}$$

Finally, the established optimization problem is an integer programming, therefore integer programming solution package of CVX is employed to obtain beam hopping time slot schedule matrix $\mathbf{T} = [\mathbf{T}_1, \mathbf{T}_2, \ldots \mathbf{T}_{N_B}]^T$ [17], where $\mathbf{T}_i = [n_{i1}, n_{i2}, \ldots n_{iN_t}]$, $\forall n_{ij} \in [0, 1]$. And $\mathrm{n}_{ij} = 1$ indicates that the beam i is allocated to the time slot j.

4.2 Beam Hopping Pattern Design

By arranging the illuminated order of each beam, the beam-hopping pattern can avoid partial interference between beams. However, for those inevitable interferences, it is necessary to introduce a new interference avoidance strategy. The specific measures are as follows:

Firstly, the time-slot allocation schedule of beam hopping is analyzed to search out the beams suffering serious co-frequency interference in the same time slot. Secondly, in the non-ideal channel, the MMSE precoding is used to suppress the co-frequency interference. According to [18], the non-ideal channel matrix is composed by the channel state information estimation matrix and the channel estimation error matrix, as shown in (11):

$$\mathrm{H} = \hat{\mathrm{H}} + \Delta H \tag{11}$$

Where $\hat{\mathrm{H}}$ is the channel estimation matrix and ΔH is the channel estimation error matrix. Each element in ΔH are assumed to be complex Gaussian, with zero mean and a variance of σ_{ε}^2. According to [19], the elements in $\hat{\mathrm{H}}$ is

$$\left[\overline{\mathrm{H}}\right]_{k,n} = \frac{G_T G_R B_{kn} e^{j\psi}}{4\pi\left(\frac{D_k}{\lambda}\right)^2} k = 1, \ldots N_B; n = 1, \ldots N_B \tag{12}$$

Where G_T is the antenna transmission gain, G_R is the antenna reception gain, B_{kn} is the gain factor of the co-channel interference of the user in the $n - th$ beam to the $k - th$ beam, ψ is the time-varying phase, D_k is the distance from the user in the $k - th$ beam to the satellite, λ is the wavelength.

According to the MMSE, the smaller the difference between the transmitted and received signals, the smaller the interference received by the users. According to this, the objective function and constraints are as follows:

$$\begin{gathered} \arg\min E\left[\left\|\hat{a} - a\right\|^2\right] \\ s.t. E\left[\|\mathrm{F}a\|^2\right] \leq P_T \end{gathered} \tag{13}$$

Where $\hat{a} = \mathrm{HFa} + \beta^{-1}\mathrm{n}$, $\beta = \sqrt{\frac{P_T}{E\left[\|\mathrm{F}a\|^2\right]}}$, For the optimization problem in (13), detailed theoretical derivation and calculation is given in[18], which is not calculated here. Finally, the precoding matrix expression as shown in (14):

$$\mathrm{F} = \hat{\mathrm{H}}\left(\hat{\mathrm{H}}\hat{\mathrm{H}} + K\sigma_{\varepsilon}^2\mathrm{I} + \xi\mathrm{I}\right)^{-1} \tag{14}$$

5 Simulation Results and Analysis

The simulation parameters in this paper are illustrated in Table 1. In addition, in order to better compare the experimental results, two indicators of traffic unsatisfied and traffic satisfaction are used. The two definitions are as follows:

traffic unsatisfied:

$$U_s = r_k - \min\{r_k, d_k\} \tag{15}$$

Table 1. Simulation parameters

Parameter	Value
Satellite longitude	105° east (GEO)
Satellite total on-board power	$P_{tot} = 200\text{W}$
Downlink carrier frequency	$f_{down} = 20$ GHz
Number of beams	$N_B = 51$
Maximum number of beams are illuminated simultaneously	$N_{max}^{st} = 4$
Total bandwidth	$B_{tot} = 200$ MHz
Duration of one time-slot	$T_{slot} = 1.4$ ms
Beam hopping period	$T_H = 512\text{T}_{slot}$
Transmit antenna gain	$G_T = 40\text{dBi}$
Receive antenna gain	$G_R = 50$ dBi
Variance of ΔH	$\sigma_\varepsilon^2 = 0.1$

traffic satisfaction:

$$\rho_j = \frac{\sum_{k=1}^{K} \overline{r_k}}{\sum_{k=1}^{K} d_k} \tag{16}$$

Where $\overline{r}_k = \min(r_k, d_k)$, r_k, d_k is the same as the definition in Sect. 4. This article compares four resource allocation algorithms: the Proposed Algorithm is the algorithm proposed in this paper, it cooperates all clusters for beam-hopping pattern design and uses precoding algorithms to suppress inter-beam interference. The Joint Cluster algorithm refers to the design of hopping beam pattern by spatial isolation and time isolation, which is employed in [11]. The Only BH refers to the design of hopping beam pattern by time isolation only, which is employed in [2]. The Uniform Timeslot algorithm refers to that system resources are evenly allocated.

As illustrated in Figs. 8 and 9, the Uniform Timeslot algorithm evenly divides the satellite's bandwidth and power to each spot beam, which cannot meet the high traffic demand of the beam. The Only BH algorithm avoids the intra-cluster interference through time isolation method, but it cannot avoid the inter-cluster interference. The Joint Cluster algorithm reduces some inter-cluster interference by increasing spatial isolation method. The Proposed Algorithm effectively suppresses intra-cluster interference and inter-cluster interference, making full use of on-board resources.

As illustrated in Figs. 10 and 11, when the traffic demand of beam No.40 is small, the beam needs fewer time slots and has less interference with other beams, therefore the traffic satisfaction of the four algorithms is close to 1. However, when the traffic demand of the beam is large, the Uniform Timeslot algorithm lacks flexibility to optimize the allocation of satellite resource. The Only BH algorithm can allocate more time

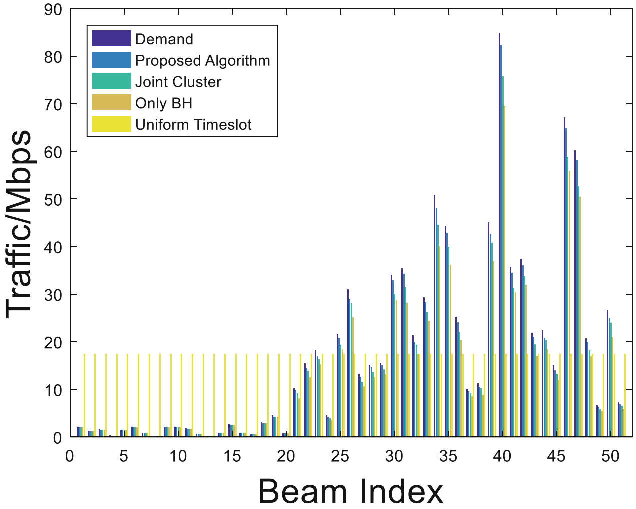

Fig. 8. System traffic at GMT = 6

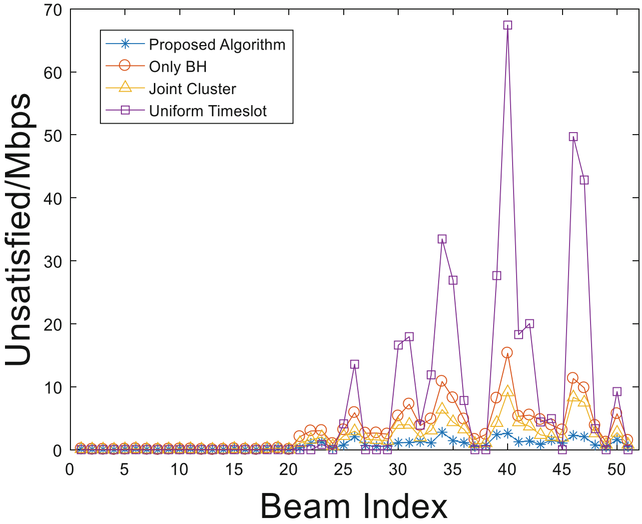

Fig. 9. System traffic unsatisfied at GMT = 6

slots to No. 40 as the traffic demand increases, but at the same time, it increases the interference between the No.40 beam and its neighboring beams. The Joint Cluster algorithm can reduce some interference of adjacent beams through the beam-hopping pattern design method. Compared with previous algorithms, the Proposed Algorithm has a better performance.

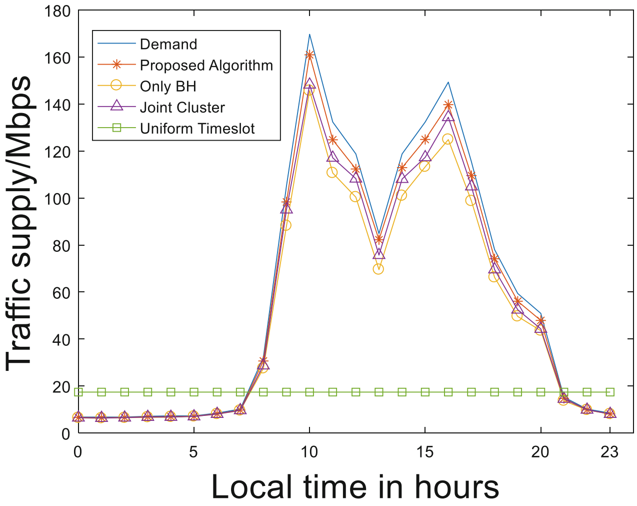

Fig. 10. System traffic supply for the 40th beam in a day

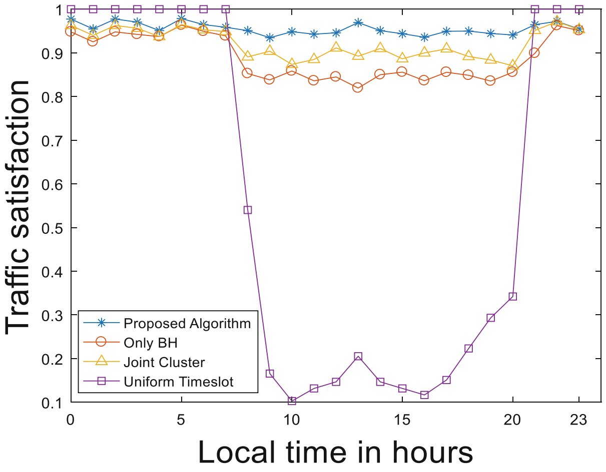

Fig. 11. System traffic satisfaction for the 40th beam in a day

6 Conclusion

In this paper, two kinds of traffic demand model, spatial model and time-varying model, are established, which make the beam hopping communication system more complete. To improve the efficiency of on-board resource utilization in HTS, beam hopping pattern is designed to combing with precoding to suppress co-channel interference. Simulation results clarify that the proposed algorithm can dynamically adjust the resource allocation with the change of the traffic requirements, and eliminate the co-frequency interference of the beam as much as possible.

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