Resource Allocation of Uplink for Multibeam Satellite Based on MF-TDMA

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Abstract. In this article, Flexible Joint Time Slot and Power Allocation (FTPA) algorithm considering interference is used for system resources allocation. Combined with the actual situation of satellite communication, the demand supply variance minimization is used as the objective function to analyze and solve the resource allocation problem reasonably. The Lagrangian dual and sub-gradient algorithm are used to replace the traditional method to improve the problem, and the optimal system allocation under the current situation is obtained. Compared with classical algorithm, FTPA guarantees the maximum capacity of the system and the fairness between beams.

Keywords: Resource Allocation; MF-TDMA; FTPA.

1. Introduction

Satellite communication network has been widely used in the fields of communication, radio and television, aviation, maritime affairs and mobile after half a century of development. The government provides services for the citizens, enterprises need to meet the needs of a variety of multimedia users, consumers are eager to enjoy a fast and smooth Internet experience, this shows that people are increasingly relying on satellite communications. Therefore, multi-beam satellites with the advantages of beamspace isolation and frequency multiplexing are gradually emerging in the field of communication.

In communication of multi-beam satellite, the commonly used allocation strategies include fixed allocation and on-demand allocation. The allocation result of fixed allocation strategies remains the same when determined. This allocation method reduces the complexity of the system. But it causes great waste of resources. And it cannot adapt to the dynamic changes of business demand in the actual system. Therefore, dynamic resource allocation has become the focus of research.

The article [1] proposed an algorithm for joint allocation of power and carrier resources. Compared with the classical fixed algorithm, the utilization of spectrum and the satisfaction of communication have been improved. But the problem of maximizing system capacity is not considered. [2] proposed a joint power and time slot resource allocation algorithm in satellite communication system. But the main focus is on energy efficiency. A Lagrangian multiplier method is proposed in article [3] to allocate the power of the system. The algorithm improves the power utilization of the satellite. But it does not consider the issue of system capacity. [4] proposed golden section methods and sub-gradient iteration. In this way, the channel capacity can be maximized and the variance of bandwidth utilization can be minimized. A scheme about satellite downlink power and beam allocation based on demand and channel conditions is proposed in [6]. In this scheme, the objective function of first order, second order and third order difference between supply and demand is compared. The second order objective
A function is considered to be a good compromise between throughput maximization and fairness. A capacity calculation model based on the satellite link budget equation is established in [9]. But it only optimizes the power resource.

In fact, power and time-frequency resources are mutually complementary and interdependent. The joint design can increase the capacity of satellite system and reduce the payload. Despite the need for more information exchange and joint control, the prospect remains tantalizing. Without joint allocation of resources, it is difficult to guarantee the fairness between beams, particularly when the channel conditions are poor. In addition, the interference of the satellite system is also increasing. These studies have not considered the interference between beams, which is a problem that cannot be ignored.

Therefore, this paper proposes Flexible Joint Time Slot and Power Allocation (FTPA) algorithm which considering interference between beams and the current channel conditions. The problem was formulated and an appropriate mathematical model was established. The Lagrangian dual and sub-gradient iteration algorithm are used to replace the traditional method to solve the problem. The optimal system allocation under the current situation is obtained. It ensures the maximum capacity of the system and the fairness between the beams.

2. System Model of Multibeam Satellite

Satellite communication has two links, uplink and downlink. Uplink, also known as forward link, refers to the process of network control center-satellite-terminal. Downlink, also known as reverse link, refers to the process of terminal-satellite-network control center. This article uses the multi-beam satellite uplink of the MF-TDMA (Multi-frequency Time Division Multiple Access) system as the background to allocate satellite communication resources.

In actual satellite communication, one beam interference mainly comes from other same frequency beams. In order to reduce the same frequency interference, there are two forms of frequency use: partial frequency multiplexing and full frequency multiplexing. The full frequency is mostly used in the beam hopping system. Only part of the beam is in the working state in each time slot. In order to reduce the interference of the same frequency, the beam is multiplexed by spatial reuse. The nearest beam is multiplexed by time isolation. When partial frequency multiplexing, the total bandwidth of the system is divided into several equal size segments. Each beam can only use the allocated frequency and bandwidth. In order to reduce the same frequency interference, this paper uses three-color beam multiplexing. The nearest beam uses different frequencies to realize frequency multiplexing through space.

Considering the interference of interbeam due to frequency multiplexing, a multi-beam satellite communication system model can be established, which consists of a multi-beam satellite, a network control center, N beams and satellite terminals. The satellite multi-beam communications system is shown in figure 1.

![Figure 1. Multi-beam satellite system model.](image-url)
This article uses the MF-TDMA system used more commonly in satellite uplink communications as a background to allocate resources. For the purpose of reducing the complexity of the problem, the carrier bandwidth is assumed to be fixed.

Assuming $p_{\text{total}}$ is the total power value of the satellite communications system, $\hat{U}_i$ is the communication service demand of the beam $i$, $U_i$ is the actual channel capacity allocated for the beam $i$, $p_i$ is the actual power value assigned to of the beam $i$, $N_o$ is the power spectral density of all beams noise in communication transmission, $\alpha_i^2$ is the attenuation factor of the link of the channel where of the beam $i$ is located. Moreover, it is necessary to consider that the beam $i$ is affected by side-lobe $k$, and the link attenuation factor is $\alpha_k^2$, $h_{ik}$ represents the interference coefficient caused by the beam $k$ to the beam $i$, its formula is $h_{ik} = \frac{\alpha_k^2}{\alpha_i^2}$.

Accordingly, the signal-to-noise ratio of the beam $i$ can be expressed as:

$$SINR_i = \frac{\alpha_i^2 p_i}{N_o B + \sum_{k \neq i} h_{ik} p_k}$$  

(1)

Then the expression of the resource allocated by the system to the beam $i$ is:

$$U_i = T_i^* B^* \log_2(1 + SINR_i)$$  

(2)

Considering the fair allocation of resources, the second order differential objective function is used as its optimization problem, which is shown as follows:

$$\min_{h_i, l_i} \sum_{i=1}^{N} |U_i - \hat{U}_i|^2$$  

(3)

subject to:

$$U_i - \hat{U}_i \leq 0$$  

(4)

$$\sum_{i=1}^{N} p_i \leq p_{\text{total}}$$  

(5)

$$\sum_{i=1}^{N} T_i \leq T_{\text{total}}$$  

(6)

Formula (3)-(6) describes the objective function and its constraints of minimizing the variance of demand supply. The objective function formula(3) requires the minimum demand supply variance of the beam. The constraint condition formula(4) indicates that the resources allocated by the system to the beam should be as close as possible to the actual demand, but not larger than the beam demand, so as to ensure that the distribution is fair and the resources are not wasted. The constraint condition formula(5) indicates that the sum of power resources of all beams can not exceed the total power resources of the system. The constraint condition formula(6) indicates that the sum of slots for all beams can not exceed the total number of slots for the system.

3. Algorithm Description

The Lagrangian dual and sub-gradient iteration algorithm are used to solve the above problems, and the original optimization problem is modeled by introducing a non-negative dual variable $m$ and $l$ and $\sigma_i$. The Lagrange function is defined as:
The problem can be solved in three steps:

Step 1: getting the time slot allocation result of each point beam. The power of each beam is set as a certain value, and the partial derivative of the time slot \( T_i \) is obtained from the above equation (7):

\[
\frac{\partial L}{\partial T_i} = [2(\hat{U}_i - U_i) + \sigma_i][-B \cdot \log_2(1 + \text{SINR})] + m
\]

Setting the partial derivative of equation (8) to 0, the following equation can be obtained.

\[
T_i = \frac{(2\hat{U}_i - \sigma_i)(W_i \log_2(1 + \text{SINR})) - m}{2W_i \log_2(1 + \text{SINR})^2}
\]

Through the above equation (9), the time slot value allocated by the system can be obtained. The time slot should be a non-negative value, if its value is less than 0, we set it to 0 and set the power value of the corresponding beam to 0.

Step 2: getting the power distribution results of each point beam. The calculated time slot values of each beam are substituted into equation (7), and then the partial derivative of power \( p_i \) of equation (7) is obtained as follows:

\[
\frac{\partial L}{\partial p_i} = \left[ 2\left(\hat{U}_i - U_i\right) + \sigma_i \right] - \frac{T_i B \cdot \alpha_i^2 \left[ W_i N_0 + \sum_{k=1, k \neq i}^{N} p_k h_{ik} - p_i h_{ii} \right]}{2 \left(1 + \text{SINR}\right) \left[ W_i N_0 + \sum_{k=1, k \neq i}^{N} p_k h_{ik} \right]^2}
\]

Let the partial derivative of equation (9) be 0, the following equation can be obtained.

\[
(\hat{U}_i - U_i) \frac{2W_i T_i}{\ln 2} \left[ \frac{1}{W_i N_0 + \sum_{k=1, k \neq i}^{N} p_k h_{ik} + \alpha_i^2 p_i} - \frac{1}{W_i N_0 + \sum_{k=1, k \neq i}^{N} p_k h_{ik} + \alpha_i^2 p_i} \right] = l
\]

Through the above formula (11), the power value allocated by the system can be obtained. Since the power should be a non-negative value, if the value is less than 0, set it to 0 and set the time slot value of the corresponding beam to 0.

Step 3: updating dual variables iterative. The \( m \) update operator can be expressed as equation (12), the update operator \( l \) can be expressed as equation (13), the update operator \( \sigma \) can be expressed as equation (14).

\[
m^{n+1} = m^n - \Delta_m \left( T_{\text{total}} - \sum_{i=1}^{N} T_{i}^{\text{opt}} \right)^+ \]

\[
l^{n+1} = l^n - \Delta_l \left( p_{\text{total}} - \sum_{i=1}^{N} P_{i}^{\text{opt}} \right)^+ \]

\[
\sigma_i^{n+1} = \left[ \sigma_i^n - \Delta^{\sigma} (\hat{U}_i - U_i) \right]^+ \]
The update step size of the parameter $T^i$, $p^i$, and $U^i$ are $\Delta m^i$, $\Delta l^i$ and $\Delta n^i$.

The algorithm flow is shown as follows:

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Step1: determine the values of non-negative dual variables $m^i$, $l^i$ and $\sigma_i$, set the initial power value of each point beam;
Step2: use formula (9) to get the time slot value of each point beam;
Step3: use formula (11) to get the power value of each point beam;
Step4: use formula (12), formula(13) and formula(14) to update the nonnegative dual variables $m^i$, $l^i$ and $\sigma_i$ iteratively, if the conditions are satisfied at the same time, then the algorithm terminates, otherwise it jumps to the Step 2 for operation.
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4. Simulation and Results Analysis

4.1. Parameter Settings

The proposed FTPA algorithm considering interbeam interference is simulated and compared with the traditional FTA( flexible time slot allocation) and FPA( flexible power allocation) performance. The simulation was carried out using Matlab R2018a environment. Parameter settings required for simulation are set: the relevant parameters of the multi-beam satellite system are given in table 1. Assuming that the normalized noise spectral density coefficient $N_0/\alpha^2$ of each beam is $[0.2, 0.25, 0.3, 0.35, 0.4, 0.2, 0.2, 0.2, 0.2, 0.2] \times 10^6$. Considering the uneven operational requirements between satellite uplink beams, assume that the operational demand for each point beam is $[80, 90, 110, 110, 110, 130, 140, 150, 160, 170] Mbit/s$.

The interference coefficient between beams are as follows:

$$h_{ik} = \begin{cases} 
0.3, |k-i|=1; |k-i+N|=1 \\
0.2, |k-i|=2; |k-i+N|=2 \\
0.1, |k-i|=3; |k-i+N|=3 \\
0, others 
\end{cases}$$

(15)

Table 1. Parameters of a multi-beam satellite system.

| parameter                  | value   |
|---------------------------|---------|
| Satellite altitude $h$    | 36000km |
| beam radius $R$           | 97.5km  |
| Number of beams           | 10      |
| Total system power        | 200W    |
| Bandwidth of each beam    | 50MHz   |
| Maximum number of iterations | 5000 |
4.2. Algorithm Evaluation Parameters
Total system capacity $U_{\text{total}}$: the sum of the actual capacity of each beam is defined as:

$$U_{\text{total}} = \sum_{i=1}^{K} U_i$$  \hfill (16)

Error between beam demand and actual distribution capacity $e_i$: the capacity allocated to each beam by the system and the actual demand for that beam are made second-order difference, which is defined as:

$$e_i = \left( U_i - \hat{U}_i \right)^2$$  \hfill (17)

4.3. Analysis of Results
It can be seen from figure 3 that the channel capacity obtained by the beam is not only related to the demand of the beam but also to the current channel environment of the beam. Through the comparison of beam 3, beam 4 and beam 5, it can be found that when the service requirements of the beams are the same but the channel environments are different, the three algorithms assign higher channel capacity to the beams with better channel environments. When the channel environment of the beams are the same, but the service demands are different, the three algorithms will allocate the larger channel capacity to the beam with the larger service demand.

**Figure 3.** Channel capacity obtained by each point beam under three distribution modes.

Comparing the three algorithms, the beam allocation capacity of the proposed algorithm is higher for the beam with better channel conditions and higher service demand than the other two algorithms. In other words, under the proposed algorithm, the beam with lower service demand can obtain smaller capacity, the beam with higher service demand can obtain larger capacity similarly. It is more in line with the real situation of the communication.

The total system amount of each algorithm is calculated as equation (16). Total channel capacity of different algorithms are shown in figure 4. Compared with the two traditional algorithms, FTPA improves the total capacity of the system to a certain extent.
Error between beam demand and actual distribution capacity of each algorithm is calculated as equation (17). Figure 5 shows the error value between the demand for each beam and the allocation of the system under different algorithms. It can be seen that because the channel condition of beam 5 is poor, FTPA allocates less resources for it during allocation. Therefore, the error value is relatively large. For most other beams, the error value of the FTPA is smaller than that of the traditional two algorithms, which improves the fairness of system resource allocation to a certain extent.

Figure 5. Error values between beam demand and actual distribution capacity under different algorithms.

Figure 6 shows the accumulated error values of the three algorithms. We can get the following conclusion: the cumulative error value of FTPA is smaller than the other two algorithms, which proves that the algorithm makes the resource allocation of the system more balanced and reasonable.
5. Conclusion

Aiming at the resource allocation problem of multi-beam satellite communication system, this paper proposes the FTPA algorithm considering interference and considering the channel environment of the beam. Using the total capacity of the system and the fairness of communication as the basis of evaluation, FTPA is compared with the classical distribution algorithms. It is shown that FTPA improves the total capacity of the system and the fairness between the beams to a certain extent, and the utilization ratio of resources is higher and the performance is better.

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