



Beam Illumination and Resource Allocation for Multi-beam Satellite Systems

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Abstract. Multi-beam satellite communication systems have received considerable attentions in recent years. By generating multiple beams at the transmitting satellites, the coverage areas can be enlarged and the transmission capacity can be improved. In this paper, we study beam illumination and resource allocation problem in multi-beam satellite communication systems. Jointly considering the revenue received from successful packet transmission and the energy consumption required for packet transmission, we define a system utility function and formulate joint user grouping, beam illumination, and time-frequency resource allocation problem as a constrained utility function maximization problem. Since beam illumination and time-frequency resource allocation problems are of different time and regional scales, this paper proposes a two-stage resource allocation algorithm. On relatively large temporal scale, we propose an offline user grouping algorithm and a group-oriented beam illumination scheme. Then based on the obtained user grouping and beam assignment strategy, an online resource scheduling algorithm is proposed, which schedules time and frequency resources for individual users. Numerical results verify the effectiveness of the proposed algorithm.

Keywords: Multi-beam satellite systems · Resource allocation · Two-stage resource allocation algorithm

1 Introduction

With the rapid development of mobile Internet applications, the exponential growth of data traffic brings huge challenges to terrestrial cellular networks. Benefited from their wide coverage, high throughput and low cost, satellite communication systems are expected to act as an efficient complementary to the terrestrial systems and offer high-performance data transmission services to the terrestrial users [1]. To further enhance the transmission performance of satellite communications, multiple beams (multi-beam) satellite systems can be exploited. Specifically, by generating multiple satellite beams and allowing individual beams to provide services for different areas, the coverage area of

the satellites can be enlarged and system throughput is expected to increase significantly [2].

In multi-beam satellite communication systems, the diverse user service requirements and time-varying channel characteristics pose challenges to the resource management schemes. In [3], the problem of user grouping was investigated for a multiuser multi-beam satellite system where each user group is illuminated by one individual satellite beam, and a sum-rate maximization-based user grouping algorithm was proposed. The beam scheduling and time-frequency resource allocation issue was considered for multi-beam satellite systems in [4–6]. Reference [4] proposed a sub-channel allocation scheme which maximizes the throughput of the satellite communication system. Reference [5] studied the wavelength and time slot allocation issue in satellite optical networks, and proposed an elastic resource allocation algorithm to reduce the communication blocking rate. An optimal power control and subchannel allocation scheme was proposed to maximize the total data rate and the number of accessing users [6].

Aiming to reduce inter-beam interference in multi-beam satellite systems, [7] proposed a heuristic beam shut off algorithm to minimize the number of active beams. Joint beam illumination and resource allocation problem was investigated for low-orbit satellites in [8]. The authors proposed a hybrid multi-beamforming-based low-power channel allocation method so as to minimize the number of handovers. Reference [9] studied the joint resource allocation problem and formulated the problem of frequency selection, beam allocation and power allocation as a sum-rate maximization model.

In this paper, we investigate the problem of user grouping and resource allocation for multi-beam satellite communication systems. Considering different time scales of user grouping and time-frequency resource scheduling, we first propose an offline user grouping algorithm. Given user grouping strategy, a beam illumination strategy is designed for user groups, then an intra-group time-frequency resource allocation strategy is proposed for ground users (GUs) inside individual user groups.

2 System Model

In this paper, we consider a satellite communication system consisting of a multi-beam low orbit satellite (LEO) satellite and multiple GUs, where the LEO satellite is equipped with an onboard transceiver thus is capable of transmitting data packets to GUs via service links. In order to improve data transmission capacity, the satellite supports a number of spot beams with each beam covering certain GUs. Let K denote the number of spot beams, and r denote the coverage radius of each beam. The total bandwidth of the satellite is divided into F sub-channels, and the sub-channels are full-frequency multiplexed among beams. Let B represent the bandwidth of each sub-channel. Denote user n as GU_n and (x_n, y_n) as the coordinate of GU_n , $1 \leq n \leq N$.

For convenience, system time T is divided into consecutive equal-length time slots, and the time slot length is τ . Without loss of generality, we assume that

the channel characteristics of the links from the satellite to the GUs may change over time, however, they remain unchanged in each time slot. The system model considered in this paper is shown in Fig. 1.

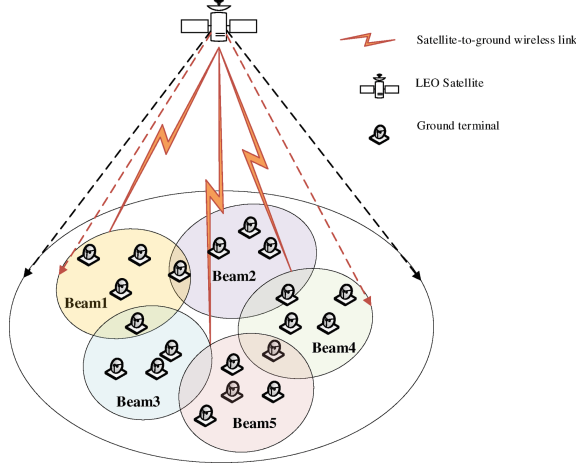


Fig. 1. System Model

2.1 Mission Executing Scenario

Let q_n denote the service characteristics of GU_n , which can be described as: $q_n = \langle s_n, w_n, T_n^{\max} \rangle$, where s_n represents the size of the data packets of GU_n , and w_n denotes the service weight of the data packets of GU_n . Note that w_n indicates the relative importance and urgency of the service of GU_n . T_n^{\max} denotes the transmission deadline of the packets of GU_n . Specifically, the data packets of GU_n should be transmitted before T_n^{\max} , otherwise, the packets will be dropped.

Let $h_{t,n,f}$ represent the channel gain of the service link from the satellite to GU_n in time slot t on sub-channel f , which can be modelled as $h_{t,n,f} = g^t g_n^r L_{t,n,f}$, where $g^t = \frac{2\pi - (2\pi - \theta)\delta}{\theta}$, is the transmit antenna gain of satellite beams, θ is the antenna beam width, $\delta \ll 1$ is a constant, g_n^r is the receive antenna gain of GU_n and $L_{t,n,f}$ represents the free space loss of the link from the satellite to GU_n in time slot t on sub-channel f , which can be expressed as $L_{t,n,f} = \left(\frac{c}{4\pi d_{t,n} \xi_f} \right)^2$, where c represents the speed of light, $d_{t,n}$ is the distance between the satellite and GU_n in time slot t , and ξ_f is the carrier frequency of sub-channel f .

3 Proposed Offline User Grouping Algorithm

To enable efficient data transmission from the satellite to the GUs in the considered satellite system, each GU should be illuminated by one satellite beam

and specific time-frequency resources should be assigned to the GU. However, it should be noted that beam illumination and time-frequency resource allocation are of different time and region scales. Specifically, on account of the given beam width of satellite beams and geographical aggregation of GUs, one beam may illuminate a number of GUs over certain time duration, whereas for an individual GU, unique time-frequency resources should be allocated to avoid intra-beam interference.

In this work, to address the different resource management granularities in the multi-beam satellite system, we propose a two-stage resource management algorithm. In particular, over a relatively large time scale and wide region scale, we divide GUs into different user groups and then propose an offline beam-oriented user grouping algorithm which allows each user group being illuminated by an individual beam. Based on the obtained user grouping strategy, we then present an online resource scheduling algorithm which assigns beam and time slot scheduling resources to any individual GUs in small time scale. In this section, the proposed offline user grouping algorithm is discussed.

3.1 The Basic Idea of the Proposed Grouping Algorithm

Since one user group is illuminated by an individual satellite beam, in an attempt to utilize the beam resources in an efficient manner, the number of user groups should be highly limited under the constraint of beam coverage area. Aiming to achieve a tradeoff between the number of groups and the characteristics of user aggregation, we assign high priority to boundary users and propose a heuristic priority-based grouping algorithm.

Given the geographical distribution of the GUs, we form a minimum convex hull containing all the GUs. For convenience, we refer the GUs located at the boundary of the convex hull as boundary users and the remaining users as the internal users. The basic idea of the proposed algorithm is that starting from one boundary user, the neighboring boundary users are grouped, then by moving the circle covering all the grouped users using minimum enclosing circle method, as many internal users are grouped as possible. The procedure repeats until all the users are grouped.

3.2 Algorithm Description

The steps of the proposed user grouping algorithm are summarized as follows.

- a) Initialization: Let Φ_m be the set of GUs in the m -th user group, and Φ_m^c be the m -th candidate user group. Set $m = 1$, $\Phi_m = \Phi_m^c = \emptyset$, where \emptyset denotes the empty set.
- b) Determine boundary users and internal users: Create a convex hull containing all the users, determine the boundary users and internal users of the hull. Let the sets of boundary users and internal users be \mathbb{N}_b and \mathbb{N}_{in} , respectively.

- c) Evaluate the distance degree of GUs: Let $d_{n,n'}$ represent the distance between GU_n and $\text{GU}_{n'}$, $1 \leq n \neq n' \leq N$. Let ρ_n denote the distance degree of GU_n , which is defined as the sum of the distances between GU_n and all other GUs, i.e., $\rho_n = \sum_{n'=1, n' \neq n}^N d_{n,n'}$.
- d) Select the ungrouped boundary user with the highest distance degree: Among all the ungrouped boundary users, i.e., $\text{GU}_n \in \mathbb{N}_b$, select the one with the highest distance degree, i.e., if $\rho_{n_0} = \max\{\rho_1, \dots, \rho_N\}$, then GU_{n_0} is selected to initiate user grouping, update the set of the m -th group and the boundary set as $\Phi_m = \Phi_m \cup \{\text{GU}_{n_0}\}$ and $\mathbb{N}_b = \mathbb{N}_b / \{\text{GU}_{n_0}\}$.
- e) Determine the GUs of the m -th user group: Collect the boundary users whose distance with GU_{n_0} is less than or equal to r into the m -th user group, i.e., $\forall \text{GU}_n \in \mathbb{N}_b$, check if $d_{n_0,n} \leq r$, if yes, then put GU_n into the m -th user group. Update the set of Φ_m as $\Phi_m = \Phi_m \cup \{\text{GU}_n\}$. Remove GU_n from the set of boundary users, i.e., $\mathbb{N}_b = \mathbb{N}_b / \{\text{GU}_n\}$. Denote C_m as the circle with the center being GU_{n_0} and the radius being r .
- f) Determine the m -th candidate user set: If there exist boundary users whose distance with GU_{n_0} is greater than r and less than or equal to $2r$, then put these users into the m -th candidate user set. That is, if $\forall \text{GU}_n \in \mathbb{N}_b$ and $r < d_{n_0,n} \leq 2r$, then put GU_n into the m -th candidate user set. Update the candidate user set as $\Phi_m^c = \Phi_m^c \cup \{\text{GU}_n\}$.
- g) Move C_m to cover as many candidate users as possible: Under the condition that all the GUs in Φ_m are covered by C_m , move the center of C_m to cover as many candidate users as possible by applying the minimum enclosing circle algorithm (discussed in next subsection). Update the corresponding sets. In particular, if $\text{GU}_{n_1} \in \mathbb{N}_b \cap \Phi_m^c$ and GU_{n_1} is covered by C_m , then put GU_{n_1} into the m -th user group, i.e., $\Phi_m = \Phi_m \cup \{\text{GU}_{n_1}\}$, remove GU_{n_1} from the sets of boundary users and candidate users, i.e., $\mathbb{N}_b = \mathbb{N}_b / \{\text{GU}_{n_1}\}$, $\Phi_m^c = \Phi_m^c / \{\text{GU}_{n_1}\}$. Let $\overline{\text{GU}}_m$ denote the virtual center user of the m -th user group, and (\bar{x}_m, \bar{y}_m) denote the location of $\overline{\text{GU}}_m$.
- h) Put the internal users covered by C_m into the m -th user group: Calculate the distance between internal user $\text{GU}_{n_1} \in \mathbb{N}_{\text{in}}$ and $\overline{\text{GU}}_m$, denoted by $\bar{d}_{n_1,m}$. If $\bar{d}_{n_1,m} \leq r$, then put GU_{n_1} into the m -th user group, update the m -th user set, i.e., $\Phi_m = \Phi_m \cup \{\text{GU}_{n_1}\}$, remove GU_{n_1} from the set of internal users, i.e., $\mathbb{N}_{\text{in}} = \mathbb{N}_{\text{in}} / \{\text{GU}_{n_1}\}$.
- i) Evaluate the termination of the algorithm: If all the users are grouped, that is, $\mathbb{N}_b = \mathbb{N}_{\text{in}} = \emptyset$, the algorithm terminates, otherwise, let $m = m + 1$, return to Step d).

3.3 The Minimum Enclosing Circle Method-Based Group Position Update Algorithm

In this work, the minimum enclosing circle algorithm is applied to determine the optimal positions of individual groups.

The main idea of the minimum enclosing circle method is that given existing users, a circle with a minimum radius is determined which covers all the exist-

ing users. The procedure of the minimum enclosing circle method-based group position update algorithm is summarized as below.

- a) Select two users in Φ_m : Give the set Φ_m , which consists of the boundary users with the distance from GU_{n_0} being less than or equal to r , two users of the farthest distance are selected and denoted as GU_{n_1} and GU_{n_2} , respectively.
- b) Form an initial circle: Draw a circle with the diameter being the line connecting the two points GU_{n_1} and GU_{n_2} . If the circle covers all the GUs, put all the ungrouped GUs in Φ_m , update user sets and the algorithm completes, otherwise, move to Step c).
- c) Select an ungrouped GU: From the candidate user set Φ_m^c , select one GU which is located outside the circle. That is, if $\text{GU}_{n_3} \in \Phi_m^c$ and $\bar{d}_{m_0, n_3} > r$, then GU_{n_3} is selected. Remove GU_{n_3} from Φ_m^c , i.e., $\Phi_m^c = \Phi_m^c / \text{GU}_{n_3}$.
- d) Determine the minimum circle covering three GUs: Based on the three GUs, form the minimum circle. If the radius of the circle is less than or equal to r , and the circle covers all the GUs in Φ_m , then put GU_{n_3} in Φ_m , set $\Phi_m = \Phi_m \cup \text{GU}_{n_3}$, otherwise, check if $\Phi_m^c = \emptyset$, if yes, the algorithm terminates, else, move to Step c).

4 Resource Allocation Problem Formulation

In this section, given the obtained user grouping strategy, system utility function is defined which jointly considers the reward received for transmitting data packets and the consumed energy of the satellite. Then, a constrained resource allocation optimization problem is formulated to maximize system utility.

4.1 System Utility Function Formulation

Considering the overall utility of all the GUs in the system, we define system utility function U as

$$U = \sum_{n=1}^N U_n \quad (1)$$

where U_n represents the utility function of GU_n , which can be modeled as the difference between reward and cost for transmitting data packets from the satellite to GU_n , i.e.,

$$U_n = \lambda_1 \eta_n - \lambda_2 \tilde{E}_n \quad (2)$$

where λ_1 and λ_2 are weighting factors, η_n represents the reward that the satellite earns from transmitting the data packets of GU_n . Without loss of generality, it is assume that only if the data packets are received before the predefined deadline, the satellite is rewarded certain payment, hence, the reward function η_n can be

modeled as $\eta_n = w_n \alpha_n$, where α_n represents the packet drop identifier, which is given by

$$\alpha_n = 1_{\{T_n \leq \lceil \frac{T_n^{\max}}{\tau} \rceil\}} \quad (3)$$

where $1_{\{x\}}$ is an indicator function. If a logical variable x is true, $1_{\{x\}} = 1$; otherwise, $1_{\{x\}} = 0$, T_n is the time slot that the data transmission of GU_n is completed. It can be shown that in order to transit all the data packets of GU_n , T_n should meet the following constraints.

$$\text{C1: } \sum_{t=1}^{T_n-1} \sum_{m=1}^M \sum_{k=1}^K \sum_{f=1}^F z_{t,m,k} x_{t,n,m,f} R_{t,n,m,f} \tau < s_n \quad (4)$$

$$\text{C2: } \sum_{t=1}^{T_n} \sum_{m=1}^M \sum_{k=1}^K \sum_{f=1}^F z_{t,m,k} x_{t,n,m,f} R_{t,n,m,f} \tau \geq s_n \quad (5)$$

where $z_{t,k,m} \in \{0, 1\}$ is the beam illumination variable of user groups, i.e., $z_{t,k,m} = 1$, if user group m is illuminated by satellite beam k at time slot t , otherwise, $z_{t,k,m} = 0$, $x_{t,n,m,f}$ denotes the time-frequency allocation variable of GUs, $x_{t,n,m,f} = 1$, if sub-channel f is assigned to GU_n in user group m at time slot t , otherwise, $x_{t,n,m,f} = 0$, $1 \leq t \leq T$, $1 \leq n \leq N$, $1 \leq m \leq M$, $1 \leq f \leq F$, $R_{t,n,m,f}$ denotes the achievable data rate of GU_n in user group m when receiving data from the satellite on sub-channel f in time slot t . $R_{t,n,m,f}$ can be expressed as

$$R_{t,n,m,f} = B \log\left(1 + \frac{x_{t,n,m,f} p g_n^t L_{t,n,f}}{N_0 B}\right) \quad (6)$$

where p represents the transmit power of satellite beams and N_0 is the power spectral density of additive white Gaussian noise (AWGN).

\tilde{E}_n in (3) is the normalized energy consumption of the satellite when transmitting the data packets of GU_n , which is defined as

$$\tilde{E}_n = \frac{E_n^{\max} - E_n}{E_n^{\max} - E_n^{\min}} \quad (7)$$

where $E_n^{\max} = \max_n \{E_n\}$, $E_n^{\min} = \min_n \{E_n\}$, and E_n represents the energy consumption of the satellite when transmitting data packets to GU_n , which can be computed as

$$E_n = \sum_{t=1}^{T_n} \sum_{m=1}^M \sum_{k=1}^K \sum_{f=1}^F z_{t,m,k} x_{t,n,m,f} p \tau \quad (8)$$

4.2 Optimization Problem Formulation

Aiming to maximize the system utility function under the constraints, we formulate the beam illumination and resource allocation problem of the considered multibeam satellite system as follows

$$\begin{aligned}
 & \max_{x_{t,n,m,f}, z_{t,m,k}} U \\
 & \text{s.t.} \quad \text{C1, C2} \\
 & \quad \text{C3: } \sum_{m=1}^M y_{n,m} \leq 1 \\
 & \quad \text{C4: } \sum_{k=1}^K z_{t,m,k} \leq 1 \\
 & \quad \text{C5: } \sum_{m=1}^M \sum_{f=1}^F x_{t,n,m,f} \leq 1 \\
 & \quad \text{C6: } \sum_{m=1}^M \sum_{GU_n \in \Phi_m} \sum_{f=1}^F x_{t,n,m,f} \leq \min\{F, \left\lfloor \frac{p_b}{p} \right\rfloor\} \\
 & \quad \text{C7: } x_{t,n,m,f} \mathbb{1}_{\{z_{t,m,k}=0\}} = 0 \\
 & \quad \text{C8: } R_{t,n,m,f} \geq x_{t,n,m,f} R_n^{\min}
 \end{aligned} \tag{9}$$

where C1 and C2 are the data packet transmission time constraints, C3 indicates that a user can only be associated with one user group, C4 represents that a user group can only be associated with one beam, C5 is the sub-channel association constraint. C6 is the maximum transmit power constraint of the satellite, where p_b is the maximum transmit power of a single satellite beam. C7 describes the coupling constraint between beam illumination and sub-channel allocation. C8 is the minimum transmission rate constraint, where R_n^{\min} is the minimum data rate requirement of GU_n .

The formulated problem involves joint optimization of beam illumination and time-frequency resource allocation, which is difficult to solve conveniently due to the tight coupling of these problems. Considering the different granularities of beam illumination and resource allocation, we split the original optimization problem into two sub-problems, i.e., beam illumination sub-problem and time-frequency resource scheduling sub-problem, and design user group-oriented beam illumination algorithm and GU-oriented time-frequency resource scheduling algorithm, respectively.

5 User Group-Oriented Beam Illumination

Considering the fact that the distance between the satellite and the GUs is much longer than that between two GUs inside one user group, we ignore the variation of the link transmission performance of the GUs in one user group, employ virtual users to represent individual user groups and design a proportional fairness-based beam illumination strategy.

5.1 Service Model of Virtual Users

According to the user grouping algorithm discussed in Sect. 4, the virtual user of user group m is denoted by $\overline{\text{GU}}_m$, which is located in the center of the group. Given user grouping strategy $y_{n,m}^*$, the weighted aggregation traffic of $\overline{\text{GU}}_m$, denoted by \bar{S}_m , can be computed as

$$\bar{S}_m = \sum_{n=1}^N y_{n,m}^* w_n s_n \quad (10)$$

To characterize the diverse transmission deadline requirements of the GUs in user groups, we denote \bar{T}_m as the maximum deadline of the GUs in user group m , which is computed as $\bar{T}_m = \max\{T_n^{\max}\}, \forall \text{GU}_n \in \Phi_m$.

6 Number of Beam-Slot Elements Allocated for User Groups

It can be understood in a straightforward manner that if one user group is of higher aggregate traffic requirement, a larger amount of beam and time slot resources should be assigned. To describe the beam illumination status of user groups, we introduce the concept of beam-slot element for convenience. Specifically, in the case that in one time slot, a satellite beam is assigned to illuminate one user group, we refer that one beam-slot element is allocated to the user group.

Let $N_0 = KT$ denote the total number of beam-slot elements and ϵ_m denote the number of beam-slot elements allocated to user group m . Applying proportional fairness scheme, we obtain

$$\frac{\epsilon_1}{\bar{S}_1} \approx \frac{\epsilon_2}{\bar{S}_2} \approx \dots \approx \frac{\epsilon_m}{\bar{S}_M} \quad (11)$$

Under the constraint $\sum_{m=1}^M \epsilon_m = N_0$, we may solve the above equation and obtain $\epsilon_m, 1 \leq m \leq M$. ϵ_m represents the number of beam-slot elements which should be assigned to user group m , however, the specific beam-slot scheduling strategy still should be determined. To this end, we examine the transmission performance of user groups in different time slots. According to the definitions of utility function specified in (5) and (6), under the circumstance that the transmission deadline constraint is satisfied, maximizing the utility function is equivalent to minimizing the energy consumption of the satellite beams. Furthermore, as the transmit power is a given constant, when multiple transmission slots are required, minimizing the energy consumption is equivalent to assigning GUs to the time slots with the highest data rate, so as to reduce the overall time slots. As a consequence, we may assign satellite beams to user groups in the time slots when higher data rate is achieved.

6.1 Beam Illumination Sub-problem Formulation

Let \bar{U}_m denote the aggregate utility function of user group m , suppose $\bar{G}\bar{U}_m$ is assigned satellite beam k at time slot t . For simplicity, it is assumed that the transmission performance of $\bar{G}\bar{U}_m$ on different sub-channels is similar, and the difference is negligible. Denote \bar{R}_m as the transmission data rate of $\bar{G}\bar{U}_m$ in time slot t when a satellite beam is assigned, we obtain

$$\bar{R}_{t,m,f} = B \log\left(1 + \frac{pg^t g_n^r \bar{L}_{t,m,f}}{N_0 B}\right) \quad (12)$$

where $\bar{L}_{t,m,f}$ is the path loss from the satellite to $\bar{G}\bar{U}_m$.

To characterize the beam-slot scheduling strategy, we further apply resource virtualization scheme, and virtualize user group m into ϵ_m virtual groups with each virtual group being assigned one beam-slot element. Accordingly, the beam illumination sub-problem can be formulated as

$$\begin{aligned} \max_{\bar{z}_{t,m,a_m,k}} \quad & \sum_{t=1}^T \sum_{m=1}^M \sum_{k=1}^K R_{t,m,k} \\ \text{s.t.} \quad & \sum_{t=1}^T \sum_{k=1}^K \bar{z}_{t,m,a_m,k} \leq 1 \\ & \sum_{m=1}^M \sum_{a_m=1}^{\epsilon_m} \bar{z}_{t,m,a_m,k} \leq 1 \\ & \bar{z}_{t,m,a_m,k} \mathbf{1}_{\{t > \bar{T}_m\}} = 0 \end{aligned} \quad (13)$$

The above formulated optimization problem can be regarded as a one-to-one matching problem which maps beam-slot element (t, k) to virtual user group (m, a_m) . To solve the problem, we first map the optimization problem into a weighted complete bipartite graph with bipartite division $G^0 = (V_1, V_2, E, W)$, where V_1 and V_2 are the set of vertices, $V_1 = \{(m, a_m)\}$ denotes the set of virtual groups, where (m, a_m) represents the virtual group a_m in user group m , $V_2 = \{(t, k)\}$ represents the set of beam-slot elements, $E = \{e(v_1, v_2)\}$ denotes the set of edges which connect vertex $v_1 \in V_1$ to another vertex $v_2 \in V_2$, $W = \{w(v_1, v_2)\}$ is the set of edge weights, $\{w(v_1, v_2)\}$ denotes the weight of the edge $e(v_1, v_2) \in E$. If $v_1 = \{(m, a_m)\}$, $v_2 = \{(t, k)\}$, then $w(v_1, v_2) = R_{t,m,k}$. Applying Kuhn-Munkres algorithm, we are able to solve the optimization problem and obtain the beam illumination strategy for the virtual groups, denoted by $\bar{z}_{t,m,a_m,k}^*$. Denote $z_{t,m,k}^*$ as the beam illumination strategy of user groups, we obtain that if $\bar{z}_{t,m,a_m,k}^* = 1$, then $z_{t,m,k}^* = 1$.

7 Intra-group Time-Frequency Resource Assignment Algorithm

Based on the obtained user grouping and beam illumination strategy $y_{n,m}^*$ and $z_{t,m,k}^*$, we now assign time-frequency resources to the individual GUs.

7.1 Sub-problem Formulation

Suppose $z_{t_0, m_0, k}^* = 1$, i.e., at time slot t_0 , user group m_0 is assigned a satellite beam. As there are F sub-channels offered by each satellite beam, the sub-channel resources should be allocated to GUs in group m_0 . Let \bar{U}_{m_0} denote the utility of the GUs in user group m_0 , we obtain

$$\bar{U}_{m_0} = \sum_{\text{GU}_n \in \Phi_{m_0}} \lambda_1 \eta_n - \sum_{t=1}^T \sum_{k=1}^K \sum_{f=1}^F \lambda_2 z_{t, m_0, k}^* x_{t, n, m_0, f} p \tau \quad (14)$$

For user group m_0 , the time-frequency resource assignment sub-problem can be formulated as follows

$$\begin{aligned} \min \quad & \bar{U}_m \\ \text{s.t.} \quad & \text{C1, C2, C6} - \text{C8} \end{aligned} \quad (15)$$

Solving the above problem involves the time-frequency resource allocation over multiple slots. Obviously, the preceding resource allocation strategy will affect the successive solution as well as the total number of resource elements. Therefore, it is difficult to solve by using optimization tools. To tackle this problem, we present a priority-based resource allocation strategy. Specifically, stressing the importance of service weight and transmission deadline of GUs, we assign priority to GUs in user group m_0 , then rank the GUs in descending order. Starting from the GU with the highest priority, the optimal time-frequency resource allocation strategy is designed. Updating the available resources, and assigning resources to the GU with the second highest priority. The procedure continues until all the GUs in the group are assigned resources or no available resources left.

7.2 Assigning Priority for GUs

To jointly consider user service weight and transmission deadline, we propose a two-level prioritizing scheme. Firstly, examining the service weight of GUs in Φ_{m_0} and assigning higher priority to the GUs with higher service weight. Let ξ_n denote the priority of GU_n . For $\text{GU}_{n_1} \in \Phi_{m_0}$ and $\text{GU}_{n_2} \in \Phi_{m_0}$, if $w_{n_1} > w_{n_2}$, we assign $\xi_{n_1} > \xi_{n_2}$, otherwise, set $\xi_{n_1} < \xi_{n_2}$. In the case that $w_{n_1} = w_{n_2}$, we then evaluate the transmission deadline of the two GUs, if $T_{n_1}^{\max} < T_{n_2}^{\max}$, we set $\xi_{n_1} > \xi_{n_2}$.

In this section, we compare the priorities of GUs in Φ_{m_0} , assign resources to the GU with the highest priority. Suppose GU_{n_0} is of the highest priority, we then design time-frequency resource allocation strategy for GU_{n_0} . To this end, we first evaluate the transmission performance of GU_{n_0} in various time-frequency elements and successively assign GU_{n_0} the resource elements which offer the highest performance, until all the data packets of GU_{n_0} can be transmitted. In order to complete the data transmission of GU_{n_0} before the given deadline $T_{n_0}^{\max}$, only the time slots earlier than $\lceil T_{n_0}^{\max} / \tau \rceil$ can be allocated.

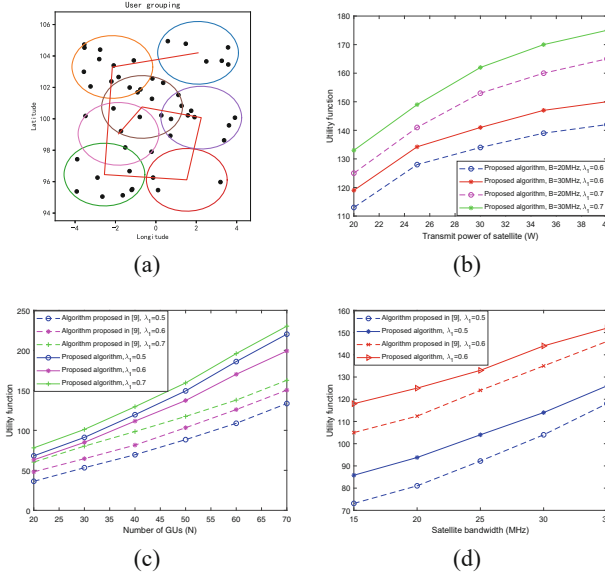


Fig. 2. (a) An example of user grouping results. (b) Utility function versus the transmit power of satellite. (c) Utility function versus the number of GUs. (d) Utility function versus satellite bandwidth.

The detail steps of the proposed time-frequency allocation algorithm can be summarized as follows:

- a) Initialization: Given the set of GUs in user group m_0 , Φ_{m_0} , user priority ξ_n , set $l = 1$.
- b) Select the GU with the highest priority in Φ_{m_0} : Suppose $n_l = \operatorname{argmax} \xi_n$, $\forall \text{GU}_n \in \Phi_{m_0}$, assign time-frequency resource to GU_{n_l} .
- c) Evaluate the transmission performance of GU_{n_l} on various sub-channels: Under the assumption $z_{t_i, m_0, k}^* = 1$, $1 \leq i \leq i'$, where $i' = \lceil \epsilon_{m_0} / K \rceil$, we evaluate the transmission performance of GU_{n_l} on various sub-channels in time slot t_i . Assume that $R_{t_i, n_l, m_0, f_i^*} \geq \dots \geq R_{t_i, n_l, m_0, f_F^*}$, i.e., in time slot t_i , among all the sub-channels, sub-channel f_i^* yields the locally optimal performance.
- d) Examine the transmission performance of GU_{n_l} over different time slots: Compare the locally optimal performance of GU_{n_l} over time slot t_i , suppose $R_{t_1, n_l, m_0, f_1^*} \geq R_{t_2, n_l, m_0, f_i^*} \geq \dots \geq R_{t_{i'}, n_l, m_0, f_{i'}^*}$.
- e) Assign the locally optimal time-frequency resource element to GU_{n_l} : We assign time-frequency resource element (t_1, f_1^*) to GU_{n_l} , set $x_{t_1, n_l, m_0, f_1^*}^* = 1$, update the available resources by removing the element (t_1, f_1^*) , then check whether there are still data packets of GU_{n_l} which need to be transmitted, i.e., whether $R_{t_1, n_l, m_0, f_1^*} \tau < s_{n_l}$, if yes, assign the remaining optimal resource element to GU_{n_l} , repeat the process, until all the data packets of GU_{n_l} are

- transmitted, update the set of Φ_{m_0} , i.e., $\Phi_{m_0} = \Phi_{m_0}/\text{GU}_{n_l}$, otherwise, check whether there are still GUs in Φ_{m_l} .
- f) Check algorithm terminates: If $\Phi_{m_0} = \emptyset$, then the algorithm terminates, otherwise, $l = l + 1$, return to Step b).

It should be noted that for certain GUs, the data packets may not be transmitted completely before the transmission deadline. In this case, we do not assign any resources to the GUs and assign the corresponding packet drop identifiers as 0. For instance, if for GU_n , the available resources are insufficient for transmitting s_n , i.e., $\sum_{i=1}^{i'} R_{t_i, n, m_0, f_i^*} \tau < s_n$, where the resource elements (t_i, f_i^*) are the remaining available resources for offering data transmission service of GU_n , then we set $\alpha_n = 0$ and $x_{t, n, m_0, f} = 0, \forall t, f$.

7.3 Mission Scheduling Strategy

It should be mentioned that the proposed mission assignment algorithm is capable of allocating various missions to individual UAVs, however, the exact mission execution time is still unknown. This can be tackled in a simple way by integrating the obtained trajectory planing strategy with mission assignment strategy. In particular, we may start from one specific MA, for instance, the MA located in the boundary region of the overall MAs, examine all the UAVs arrival at the MA, compute the UAV arrival time, and determine the time slots for executing missions. The procedure repeats until the scheduling strategy is determined for all the missions in MAs. Accordingly, the association strategy between MAs and UAVs, denoted by $\alpha_{n, m, t}^*$, the mission schedule strategy, denoted by $\beta_{n, m, k, t}^*$ and mission partition strategy, i.e., $\eta_{n, m, k, t}^*$ can be obtained.

8 Simulation Results

In this section, we examine the performance of the proposed algorithm. In the simulation, set the system bandwidth B as 20MHz, the carrier frequency ξ_f as 20 GHz, and noise spectral density N_0 as 3×10^8 m/s. The number of beams K is set to 4, the user receive antenna gain g_n^r is 15 dB and the maximum transmit power p_b is 43 dB.

Figure 2(a) plots an example of user grouping results which is obtained from our proposed heuristic user grouping algorithm. In Fig. 2, the circles represent different user groups and the red polyline connects the center of groups. As can be seen from Fig. 2(a), all the GUs are clustered into groups with equal coverage ranges determine by the width of satellite beams.

In Fig. 2(b), we show the utility function versus the transmit power of the satellite. It can be seen from the figure, as the transmit power increases, the utility function also increases. This is because the increase in transmit power results in the increase of the data transmission rate and the possibility of successful transmissions as well. Comparing the effects of transmission bandwidth and the weighting factor λ_1 on utility function, we can observe that as the transmission

bandwidth becomes larger, higher utility function can be obtained which is benefited from higher data rate. In addition, when the weighting factor λ_1 increases, the utility function also increases. The reason is that higher reward function is obtained from larger λ_1 .

Figure 2(c) depicts the utility function versus the number of GUs. In the figure, we compare the performance of the algorithm proposed in this paper with the one proposed in [9]. In [9], a time-frequency resource allocation algorithm was proposed to maximize user transmission rate. It can be seen from the figure that as the number of GUs increases, the utility functions obtained from both algorithms increase accordingly. Comparing the performance obtained from our proposed algorithm and the one proposed in [9], we can observe that our proposed algorithm offers higher utility function. The reason is that while data transmission rate was considered in [9], the authors failed to examine the successful transmission of data packets, thus may result in relatively high packet loss rate, and low utility function in turn.

Figure 2(d) depicts utility function versus satellite bandwidth. In the figure, we also compare the performance of the algorithm proposed in this paper with the one proposed in [9]. As can be seen from the figure, the utility function increases as the bandwidth increases. This is because the increase in bandwidth leads to higher data transmission rate, resulting in less packet loss and higher utility. It can also be seen that the utility function of the algorithm proposed in [9] is lower than that of the algorithm proposed in this paper. Comparing the utility functions corresponding to different values of λ_1 , we can observe that the increase of the weighting factor λ_1 offers higher utility function.

9 Conclusions

In this paper, we have studied the problem of beam illumination and resource allocation for multibeam satellite communication systems. An large scale offline user grouping algorithm and a group-oriented beam illumination scheme have been proposed. Then, an online time-frequency resource allocation algorithm has been designed. Numerical results demonstrate the our proposed algorithms offered better performance than existing algorithm.

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