Opportunistic Resource Scheduling for Multibeam Satellite Communications

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***Abstract*—The demand for satellite communication is increasing to provide connectivity in areas without terrestrial network coverage. Specifically, multibeam low-Earth orbit (LEO) satellite communication is emerging as a key solution to providing high-capacity, wide-area coverage to remote regions such as oceans, mountains, and deserts. In this paper, an opportunistic resource scheduling scheme is analyzed to efficiently utilize LEO satellite resources. An opportunistic resource scheduling algorithm is proposed that optimally allocates and schedules based on the time-varying channel conditions of each user. Moreover, the proposed algorithm is designed to maximize total average capacity while satisfying the minimum capacity requirement for each user, thereby ensuring user-specific quality of service (QoS). An algorithm utilizing a Lagrangian dual approach was developed to find the optimal beam allocation. The simulation results demonstrate that the proposed algorithm achieves capacity convergence while satisfying the QoS requirements of all users.**

***Index Terms*—Multibeam low-Earth orbit satellite, opportunistic resource scheduling.**

I. Introduction

The integration of satellite and terrestrial wireless systems is gaining considerable attention as a critical technology for future wireless communication. The satellite-terrestrial integrated network has attracted attention for achieving high spectral efficiency and exploiting the advantages of terrestrial and satellite networks [1]. In particular, multibeam low-Earth orbit (LEO) satellite communication is considered a highly promising solution for the B5G and 6G eras, as it can provide high-capacity transmissions and expand network coverage to remote locations [2]. In such LEO systems, the user locations and channel conditions are inherently time-varying. This dynamic environment necessitates the application of opportunistic scheduling schemes that allocate resources based on instantaneous channel states. Therefore, we propose an opportunistic resource scheduling algorithm that allocates and schedules the satellite's multiple beams to users based on the time-varying channel conditions while satisfying the quality of service (QoS) requirements and ensuring fairness for each user [3]. The proposed algorithm is operated without requiring prior knowledge of the system state, and its optimality is guaranteed as the scheduling time approaches infinity. To demonstrate our proposed scheme, we conducted simulations based on the LEO satellite system. This paper is organized as follows. Section II details the system model for the multibeam LEO satellite communication environment. Section III, we proposed an opportunistic resource scheduling problem and present a dual-based algorithmic approach to solve the formulated problem. In Section IV, we analyze the simulation results to assess the performance of our proposed algorithm. The paper concludes in Section V, where we also discuss directions for future work.

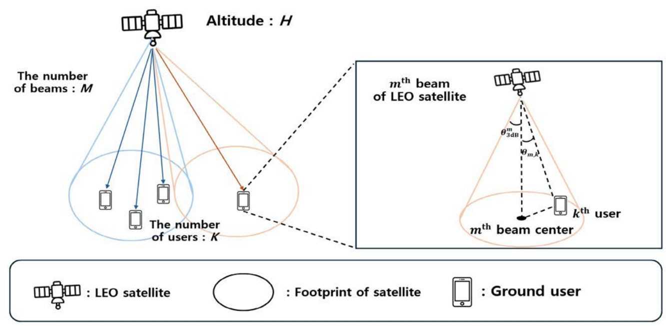

Fig. 1. LEO satellite communication system transmitting M multibeam to K users

II. System Model

We consider a multibeam LEO satellite communication system transmitting M multibeam to K users, as shown in Fig. 1. Provided that the system operates under a quasi-static channel assumption, the channel conditions are considered static within a single time slot, but they vary over time. We detail the channel loss model, including path loss and shadow fading. The total channel loss between satellite u and user k is defined as follows [4]:

$$L_k^{\text{total}}[\text{dB}] = L_k^{\text{pl}}[\text{dB}] + L_k^{\text{sd}}[\text{dB}], \tag{1}$$

where $L_k^{\text{pl}}[\text{dB}]$ represents the path loss term, which is defined as follows:

$$L_k^{\text{pl}}[\text{dB}] = 32.45 + 20\log_{10}(f_{\text{freq}}) + 20\log_{10}(d_{u,k}). \tag{2}$$

Additionally, $L_k^{\text{sd}}[\text{dB}]$ is the effect of shadow fading on the user k, that follows a log-normal distribution in (1). The parameter f_{freq} represents the carrier frequency in GHz, and $d_{u,k}$ denotes the distance between the satellite u and the user k. To obtain the distance $d_{u,k}$ between satellite u and user k, we first define $d_{u,o}$ as the distance from the satellite u to the beam center

o, and $d_{k,o}$ as the distance from the user k to the center of the beam m. Consequently, the distance $d_{u,k}$ is expressed as follows:

$$d_{u,o} = \sqrt{(r_{\mathrm{E}} \sin\theta_e)^2 + H^2 + 2Hr_{\mathrm{E}}\sin\theta_e} - r_{\mathrm{E}}\sin\theta_e, \quad (3)$$

$$d_{k,o} = \sqrt{x_k^2 + y_k^2}, \quad (4)$$

$$d_{u,k} = \sqrt{d_{u,o}^2 + d_{k,o}^2 - 2d_{u,o}d_{k,o}\cos\theta_e}, \quad (5)$$

where r_{E} is Earth radius and θ_e is the elevation angle of the LEO satellite. The angle between the beam m and user k, denoted as $\theta_{m,k}$, is obtained as follows:

$$\theta_{m,k} = \cos^{-1}\left(\frac{v_m \cdot v_k}{\|v_m\|\|v_k\|}\right), \quad (6)$$

where $v_m = (x_m + d_{u,o}\cos\theta_e, y_m, -d_{u,o}\sin\theta_e)$ and $v_k = (x_k + d_{u,o}\cos\theta_e, y_k, -d_{u,o}\sin\theta_e)$ are used to describe the positions of the center of beam m and the location of user k with respect to the satellite, respectively. And $G_{m,k}$ represents the beam pattern gain from the beam m to user k, which is defined as follows:

$$G_{m,k} = \zeta_u \left(\frac{J_1(b_{m,k})}{2b_{m,k}} + \frac{36J_3(b_{m,k})}{b_{m,k}^3}\right)^2. \quad (7)$$

In equation (7), $J_n(\cdot)$ represents the th order Bessel function of the first kind. Also, ζ_u denotes the maximum antenna gain of the satellite, which is expressed as follows:

$$\zeta_u = \eta \left(\frac{70\pi}{\theta_{3\mathrm{dB}}^m}\right)^2, \quad (8)$$

where η is the antenna efficiency. In addition, $b_{m,k}$ is normalized off-axis angle that quantifies the angular displacement of user k from the boresight of beam m. It is given by

$$b_{m,k} = 2.07123\left(\frac{\sin\theta_{m,k}}{\sin\theta_{3\mathrm{dB}}^m}\right). \quad (9)$$

In (9), $\theta_{3\mathrm{dB}}^m$ is the 3dB beamwidth angle, at which the beam's power is reduced to half of its maximum. Based on (1) and (7), the channel gain for user k corresponding to beam m can be derived as

$$g_{m,k} = \frac{\zeta_k}{L_k^{\mathrm{total}}} G_{m,k}, \quad (10)$$

where ζ_k represents the antenna gain of user k. Therefore, the signal-to-interference-plus-noise ratio (SINR) is expressed as follows:

$$\gamma_{m,k}^s = \frac{\tilde{g}_{m,k}P}{\sum_{i\in M\setminus\{m\}} \tilde{g}_{i,k}P + 1}. \quad (11)$$

In (11), P is the transmit power per beam, which is fixed as $P = P_{\text{total}}/M$, with P_{total} being the total transmit power of the satellite. $\tilde{g}_{m,k}$ is calculated as $g_{m,k}/\sigma^2$, which represents the normalized channel gain for each user. Therefore, the capacity of user k receiving a signal from the satellite beam m can be expressed as follows:

$$R_{m,k}^s = B\log_2(1 + \gamma_{m,k}^s), \quad (12)$$

where B denotes the bandwidth per beam. Based on the system model and the capacity defined in (12), we can formulate the opportunistic resource scheduling problem. In Section III, we first formulate the optimization problem, followed by the derivation of an algorithm to achieve its optimal solution.

III. Optimality of Resource Scheduling

Based on the system model established in the preceding section, we formulate the optimization problem for opportunistic resource scheduling. The optimization problem is formulated to maximize the total average capacity, while ensuring that the QoS requirements of all users are satisfied. Using a Lagrangian dual approach, we then develop an algorithm to determine the optimal solution and handle the problem's non-convexity. The problem is formulated as follows:

$$\text{(P)} \quad \max_{a_{m,k}^s} \sum_{s\in S}\pi^s \sum_{m\in M}\sum_{k\in K} a_{m,k}^s R_{m,k}^s, \quad (13)$$

$$\text{s.t.} \quad \sum_{s\in S}\pi^s \sum_{m\in M} a_{m,k}^s R_{m,k}^s \geq R_{\min}, \quad \forall k \in K, \quad (14)$$

$$a_{m,k}^s = \{0,1\}, \quad \sum_{k\in K} a_{m,k}^s \leq 1. \quad (15)$$

However, due to the integer-valued variables $a_{m,k}^s$, the original formulation is a mixed-integer program, which is usually hard to solve. Therefore, to address this non-convex nature, we relax the integer-valued assignment variables $a_{m,k}^s$ into continuous-valued variables $\bar{a}_{m,k}^s$, and reformulate the problem with a new objective function and constraints as follows [5]:

$$\text{(P}'\text{)} \quad \max_{\bar{a}_{m,k}^s} \sum_{s\in S}\pi^s \sum_{m\in M}\sum_{k\in K} \bar{a}_{m,k}^s R_{m,k}^s, \quad (16)$$

$$\text{s.t.} \quad \sum_{s\in S}\pi^s \sum_{m\in M} \bar{a}_{m,k}^s R_{m,k}^s \geq R_{\min}, \quad \forall k \in K, \quad (17)$$

$$0 \leq \bar{a}_{m,k}^s \leq 1, \quad \sum_{k\in K} \bar{a}_{m,k}^s \leq 1. \quad (18)$$

Since the objective function and constraints in problem (P′) are continuous, problem (P′) can be solved using Lagrangian duality. Therefore, to define the dual problem of (P′), the Lagrangian function is given as follows:

$$\begin{aligned}\mathcal{L}(\bar{a}_{m,k}^s, \lambda_k, \mu_m^s) = &\sum_{s\in S}\pi^s \sum_{m\in M}\sum_{k\in K} \bar{a}_{m,k}^s R_{m,k}^s \\ &+ \sum_{k\in K}\lambda_k\left(\sum_{s\in S}\pi^s\sum_{m\in M}\bar{a}_{m,k}^s R_{m,k}^s - R_{\min}\right) \\ &+ \sum_{s\in S}\sum_{m\in M}\mu_m^s\left(1 - \sum_{k\in K}\bar{a}_{m,k}^s\right). \quad (19)\end{aligned}$$

Based on the Lagrangian function, the dual problem can now be formulated. The purpose of this dual problem is to find the optimal set of Lagrange multipliers that minimizes the dual

Algorithm 1 Resource Scheduling Algorithm

Initialize: $\lambda_k(0) = 0$, $\mu_m^s(0) = 0$, time slot $t = 0$
for each time slot t
  $\alpha(t) = 1/t$
  for each state s and user k
    $a_{m,k}^s(t) = \begin{cases} 1 & \text{if } k = \arg\max_{k' \in K} \{R_{m,k'}^s(t)(1 + \lambda_{k'}(t)) - \mu_m^s(t)\} \\ 0 & \text{otherwise} \end{cases}$
  end
  for each user k
    $\lambda_k(t+1) = [\lambda_k(t) - \alpha(t)(\sum_{m \in M} a_{m,k}^s(t) R_{m,k}^s(t) - R_{\min})]^+$
  end
  for each state s and beam m
    $\mu_m^s(t+1) = [\mu_m^s(t) - \alpha(t)(1 - \sum_{k \in K} a_{m,k}^s(t))]^+$
  end
end
Output: Beam allocation $a_{m,k}^s(t)$ for each state s, beam m, and user k

function, which is itself the maximum value of the Lagrangian. Then, the dual problem of (P′) is expressed as follows [6]:

$$\text{(D)} \qquad \min_{\lambda_k \geq 0, \mu_m^s \geq 0} F(\lambda_k, \mu_m^s), \tag{20}$$

where

$$F(\lambda_k, \mu_m^s) = \max_{\bar{a}_{m,k}^s} \mathcal{L}(\bar{a}_{m,k}^s, \lambda_k, \mu_m^s). \tag{21}$$

To solve the problem in (21), the Lagrangian function in (19) is reformulated as follows:

$$L(\bar{a}_{m,k}^s, \lambda_k, \mu_m^s) = \sum_{s \in S} \pi^s L_s(\bar{a}_{m,k}^s, \lambda_k, \mu_m^s) - \sum_{k \in K} \lambda_k R_{\min}, \tag{22}$$

where

$$\begin{aligned} L_s(\bar{a}_{m,k}^s, \lambda_k, \mu_m^s) = & \sum_{m \in M} \sum_{k \in K} \bar{a}_{m,k}^s R_{m,k}^s \\ & + \sum_{k \in K} \lambda_k \left(\sum_{m \in M} \bar{a}_{m,k}^s R_{m,k}^s \right) \\ & + \sum_{m \in M} \mu_m^s \left(1 - \sum_{k \in K} \bar{a}_{m,k}^s \right). \end{aligned} \tag{23}$$

Therefore, we can perform the maximization in (21) by separately maximizing $L_s(\bar{a}_{m,k}^s, \lambda_k, \mu_m^s)$ in (23) for each s. which is expressed as the following sub-problem for each s:

$$(\text{D}_s) \qquad \max_{\bar{a}_{m,k}^s} L_s(\bar{a}_{m,k}^s, \lambda_k, \mu_m^s). \tag{24}$$

The problem (D_s) can be solved without knowledge of the state distribution π^s. Therefore, we can solve the problem in (21) without knowledge of the state distribution π^s. The following proposition demonstrates that even with the continuous relaxation of the assignment variable, the optimal solution for the subproblem is a binary one [7].

Remark: Given the Lagrangian multipliers λ_k and μ_m^s, the optimal solution for the assignment variable $\bar{a}_{m,k}^s$ is an integer value.

TABLE I
SIMULATION PARAMETERS

Parameter	**Value**
Earth radius (r_{E})	6,371 km
Satellite altitude (H)	600 km
Carrier frequency (f_{freq})	2 GHz
Antenna efficiency of satellite (η)	0.5
Total satellite transmit power (P_{total})	43 dBm
Beam bandwidth (B)	10 MHz
Noise power (σ^2)	-104 dBm
Ground user antenna gain (ζ_k)	15 dB
Minimum requirement (R_{min})	6 Mbps, 10 Mbps
The number of beams (M)	3
The number of users (K)	7

Proof: The objective function of (D_s) can be expanded as follows:

$$(\text{D}'_s) \max_{\bar{a}_{m,k}^s} \sum_{m \in M} \sum_{k \in K} \bar{a}_{m,k}^s ((1 + \lambda_k) R_{m,k}^s - \mu_m^s) + \sum_{m \in M} \mu_m^s. \tag{25}$$

Problem (D'_s) is an affine function of variables $\bar{a}_{m,k}^s$. For notational simplicity, we define the scheduling metric $U_{m,k}^s$ as follows:

$$U_{m,k}^s \triangleq (1 + \lambda_k) R_{m,k}^s - \mu_m^s \tag{26}$$

To maximize this affine objective function, the optimal strategy is to assign the beam to the user with the maximum positive scheduling metric, since any assignment with a non-positive metric would not increase the objective value. Then we can achieve the optimal solution as follows:

$$a_{m,k}^s = \begin{cases} 1 & \text{if } k = \text{argmax}_{k' \in K : U_{m,k'}^s > 0} U_{m,k'}^s \\ 0 & \text{otherwise.} \end{cases} \tag{27}$$

The dual problem (D) is always convex and thus can be solved using a subgradient method. For problems of this nature, as the number of states $S \to \infty$, the duality gap approaches zero, ensuring that the solution to the dual problem converges to the optimal solution of the primal problem [7]. Therefore, a stochastic subgradient algorithm that iteratively updates the dual variables over time slots is carried out as follows [8]:

$$\lambda_k(t+1) = \left[\lambda_k(t) - \alpha(t) \left(\textstyle\sum_{m \in M} a_{m,k}^s(t) R_{m,k}^s(t) - R_{\min} \right) \right]^+. \tag{28}$$

$$\mu_m^s(t+1) = \left[\mu_m^s(t) - \alpha(t) \left(1 - \textstyle\sum_{k \in K} a_{m,k}^s(t) \right) \right]^+. \tag{29}$$

As given in equations (28) and (29), the convergence of the proposed algorithm depends on the step size $\alpha(t)$. Therefore, the proposed algorithm converges to its optimal performance as scheduling time progresses [9]. Algorithm 1 provides the detailed procedure for the proposed algorithm.

IV. SIMULATION RESULTS

In this paper, we model a multibeam LEO satellite communication environment and assume a quasi-static channel, as described in Section II. For simplicity and to establish a practical baseline, our simulations assume the same minimum

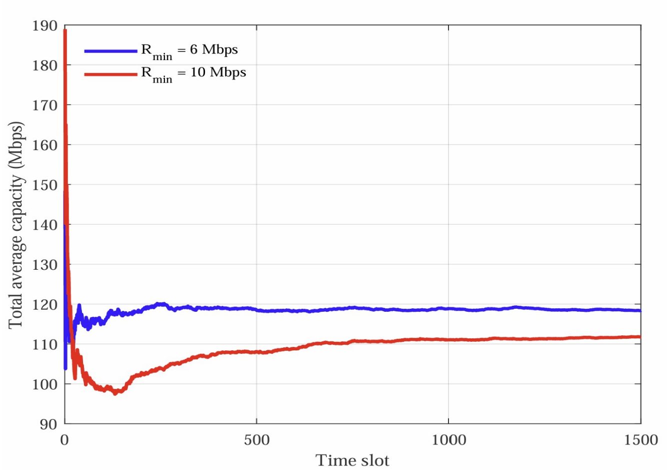

Fig. 2. Convergence of total average capacity of all users

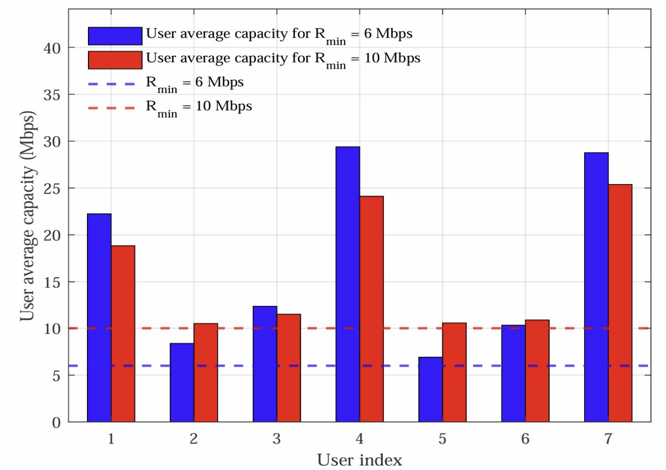

Fig. 3. Average capacity per user according to resource scheduling algorithm

rate requirement ($R_{\min}$) for all users and power allocations across all beams. Table 1 provides a detailed list of these assumptions and other key system parameters.

Fig. 2 shows the total average capacity of all users over time slots, where it can be noted that the total average capacity converges to a certain value as time progresses. Fig. 2 also shows that when $R_{\min}$ is higher, the total average capacity is lower, and it also takes longer for the system to converge. This demonstrates a trade-off between user fairness and overall system efficiency. To satisfy a higher QoS requirement for all users, the proposed algorithm allocates more time slots to users with poor channel conditions.

Fig. 3 illustrates the user average capacity for two distinct scenarios where $R_{\min}$ is set to 6 Mbps and 10 Mbps, respectively. The results show the average capacity for each user k over time slots, demonstrating that the minimum required capacity is guaranteed for each user while satisfying their individual QoS requirements. Thus, the convergence of the proposed opportunistic scheduling scheme is demonstrated via simulations, and its convergence to the optimal solution is confirmed through theoretical analysis.

V. Conclusion

Efficiently managing time-varying channel conditions and user QoS requirements in LEO satellite systems is critical for maximizing system performance. In this paper, we tackle this issue by proposing an opportunistic resource scheduling scheme for multibeam LEO satellite systems. Our proposed algorithm utilizes a Lagrangian dual approach to optimally allocate and schedule the satellite's multiple beams based on time-varying channel conditions. This approach not only maximizes the total average capacity but also guarantees the minimum QoS requirements for each user, demonstrating its ability to effectively control the trade-off between system efficiency and user fairness. Our simulation results show that the proposed algorithm effectively converges to a stable total average capacity while satisfying the individual QoS requirements for all users. A key finding is that a higher $R_{\min}$ results in a decrease in the total average capacity, which confirms that the algorithm quantitatively manages the trade-off between system performance and user fairness. However this work is based on a simplified assumption of fixed beam power. For future work, we intend to address this limitation by considering dynamic beam power allocation to verify the algorithm's practical scalability. We also plan to explore multicast precoding as a strategy to effectively handle the inter-beam interference (IBI), a key challenge in multibeam systems.

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