Dynamic Cooperative Spectrum Sharing in a Multi-Beam LEO-GEO Co-Existing Satellite System

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***Abstract*—Among the existing satellite types, Low Earth Orbit (LEO) satellites provide short round-trip delays and are becoming increasingly important. Due to its low orbital profile, the LEO satellites can provide high-speed, low-latency and no dead zone network services for ground users. However, as the number of satellites continues to increase, frequency bands as non-renewable resources will seriously restrict the future development of the Space-Earth integration network. In this paper, a flexible spectrum sharing and cooperative service method is proposed to address the co-linear interference issue caused by LEO satellites while passing through the coverage area of the GEO beam and allows the LEO satellites to provide services for multiple LEO ground users. In our proposed scheme, through continuous power allocation optimization, we ensure that the service of LEO satellites will not reduce the service quality of the GEO beam. At by taking full advantage of the cooperation between LEO satellites, the quality of their service can be significantly improved. Simulation results show that our proposed scheme converges quickly, the transmission efficiency and the stability of the system can all be guaranteed.**

***Index Terms*—LEO-GEO co-existing satellite system, cooperative spectrum sharing, Lyapunov drift analysis.**

I. INTRODUCTION

SATELLITE systems have drawn special attention in the past 20 years due to their ability to provide global coverage and support a wide range of services. Among the existing satellite types, Low Earth Orbit (LEO) satellites provide short round-trip delays and are becoming increasingly important. LEO satellites typically operating at the altitude of 500-1500 km [2], the launch cost is relatively low compared with GEO satellites, which makes the LEO satellite constellation network more likely to achieve global coverage. For example, companies like SpaceX, OneWeb and LeoSat all announced their giant constellation satellite network plan [3]. Due to its low orbital profile, the LEO satellites can provide high-speed, low-latency, and no dead zone network services for ground users [4].

However, as the number of satellites continues to increase, frequency bands as non-renewable resources will seriously restrict the future development of the Space-Earth integration network [5]. Especially in a LEO-GEO coexisting satellite system, the scarcity of frequency band resources will force different satellite constellations work in the same frequency band and wisely share spectrum resources [6]–[8]. Therefore, how to allocate and share spectrum resources among different satellite constellations, especially those operating on different orbital planes, will be an urgent issue in the design of future satellite systems. As the number of satellites and ground users increases, it will become more and more common for multiple satellites in different orbits to cover the same ground area. If the problem of spectrum sharing between satellites cannot be properly resolved, mutual interference between them will seriously affect the stability of space-to-ground transmission, and thus affect the availability of the entire space network.

In this paper, we focus on designing the cooperative spectrum sharing method for LEO-GEO co-existing systems. Specifically, we consider a practical scenario where multiple LEO ground users are located within the coverage of a GEO satellite beam, which are served by multiple LEO satellites of the same constellation cooperatively. Based on the Article 22.2 of the *ITU Regulations for Ka-band Satellite Network* [9], Non-geostationary-satellite systems shall not cause unacceptable interference to geostationary-satellite networks. Thus, we assume that in this scenario, the GEO satellite is considered as primary user and the LEO satellites are secondary users, which indicates that the LEO satellites can only provide services under the premise that GEO satellite service quality can be guaranteed.

As a solution, a flexible spectrum sharing and cooperative communication method is proposed to address the co-linear interference issue caused by LEO satellites while passing through the coverage area of the GEO beam, and allows the LEO satellites to provide services for multiple LEO ground users. Specifically, we propose to divide the ground users into

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several independent sets and pairing them with LEO satellite beams. In this way, multiple LEO spot beams can cooperatively serve a certain group of users and the inter-group interference can be effectively eliminated, which greatly improves the service quality of the LEO system. Moreover, since the LEO system is the secondary user, besides the efficiency, service fairness is another issue. Thus, we take both the data queue backlog and the current transmission rate of ground users into consideration and allocate more time slots to users with long queues and low transmission rates, which can greatly reduce the service latency and improves the stability of the system. Simulation results show that our proposed scheme converges quickly, the transmission efficiency and the stability of the system can all be guaranteed. As an extension of our previous work [1], we enriched the theoretical analysis by adding the system stability analysis based on the Lyapunov drift theory and obtained the theoretical stability condition of our proposed method. We provide a detailed literature analysis on the existing interference cancellation and spectrum sharing methods, which can help readers to understand better the background of this problem. At the same time, we also added simulation results to make our work more solid, including interference analysis and system stability analysis.

The main contributions of this paper are listed as follows:

- We propose a flexible spectrum sharing method for a challenging multiple LEO satellite scenario, which attempts to optimise the throughput of LEO satellites under the premise that the quality of service (QoS) of GEO satellite should be guaranteed. By jointly considering the satellite beam power allocation and the ground users scheduling in an unified framework, the problem is modelled as a mixed integer nonlinear programming (MINLP) problem, which is difficult to solve in polynomial time.
- By adopting the relaxation and approximation schemes, this intractable NP-hard optimization problem is divided into three consecutive polynomial level sub-problems, which significantly reduces the complexity, making the proposed scheme suitable for the dynamic satellite networks.
- Using the time proportional allocation algorithm, we take the data queue backlog and the current transmission rate of LEO ground users into consideration, and allocate more time slots to users with longer queues or lower transmission rates, which improves the system stability and the service fairness.

The rest of this paper is organized as follows. Some related work are introduced and analysed in Section II. We introduce the system model and formulate the cooperative spectrum sharing problem in Section III and IV respectively, and some relaxation and approximation schemes are presented in Section V. The performance of the proposed schemes are evaluated via simulations in Section VI. Finally, conclusions are drawn for this paper in Section VII.

II. Related Work

Due to the increasing size of satellite networks, it is a challenging problem to find an efficient spectrum sharing method to suppress the collinear interference[1] between the GEO and the LEO satellites. In this section, we discuss in detail several schemes that have been widely discussed in recent years. These schemes can be roughly classified into three categories: cognitive radio techniques, exclusion zone based methods and hybrid methods.

A. Cognitive Radio Techniques

Cognitive radio technology can effectively improve the efficiency of spectrum resource utilization and address the problem of scarcity of spectrum resource. In satellite networks, cognitive radio technique is an effective solution for supporting co-existence of two or more satellite systems [10], which enables different satellite systems to work simultaneously on the coverage area using the same spectrum band. In [7], the authors proposed a spectrum strategy to address the interference between the GEO and non-geostationary (NGEO) satellite networks. By using hypothesis testing as well as maximum a posteriori to differentiate the GEO signal from the interfering NGEO and noise, and then identify the specific power level utilized by the GEO system. In [11], different cognitive techniques such as underlay, overlay, interweave and database related techniques are discussed in the context of satellite communication. In [12], Ng *et al.* studied the resource allocation algorithm for cognitive radio secondary networks with simultaneous wireless power transfer and secure communication. A multi-objective optimization framework was proposed for the design of a Pareto-optimal resource allocation algorithm based on the weighted Tchebycheff approach.

B. Exclusion Zone Based Methods

When the LEO satellite is moving to the GEO coverage area, it will lead to serious inline interference problem. In this way, some schemes are designed by setting "Exclusion Zone (EZ)" to the LEO satellite, which forces the LEO satellite within the EZ to turn off its beams to avoid interference to the GEO satellite ground users. One famous scheme is the progressive pitch method proposed by OneWeb, in which the spot beams tilt at different angles at different latitudes to avoid strong interference to GEO satellites [13]. For example, when one LEO satellite is over the Equator and just below a GEO satellite, it should be turned off and its neighbour at low latitudes could adjust the satellite attitude to cover the users near the Equator. In [14], in a LEO-GEO co-existing scenario, the authors implemented exclusive angel strategy to reduce the in-line downlink interference from the LEO satellite to the GEO satellite users. In [15], the authors considered a dual satellite spectral coexistence scenario of two multibeam satellites with a primary satellite having larger beams and a secondary satellite having smaller beams. A cognitive beamhopping system was proposed with the objective of enhancing the system spectral efficiency while protecting

[1]In a LEO-GEO coexisting system, collinear interference occurs when one LEO satellite moves near the line between the GEO satellite and its ground user, the angle between its transmitting antenna and the GEO ground user's receiving antenna is small, then the transmitted signal by the LEO satellite will cause strong interference to the GEO ground user.

the Primary Users (PUs). The EZ methods also used in other cognitive environments. In an cognitive radio network, Wei *et al.* proposed a three region scheme (black region, grey region and white region) [16]. In the black region, only the primary user has exclusive right to use the spectrum; In the white region, secondary users can utilize the same spectrum without causing severe interference to the primary user; And in the grey region, secondary users are required to sense the radio spectrum environment and detect the frequency bands which are not occupied by the primary user.

C. Hybrid Methods

As the problem of spectrum scarcity becomes serious, it is difficult to rely on only one technique to effectively improve the spectrum sharing efficiency. Thus, some hybrid methods are proposed in the past few years to improve the effectiveness of spectrum sharing between different types of satellite systems. In [17], the authors jointly considered the EZ technique and dynamic frequency allocation technique, where a keep-out region is defined to guarantee the spectral co-existence based on the interference analysis in the worst case. A dynamic frequency allocation technique is used to deal with the dynamic configuration caused by the satellite motion. In [18], the authors proposed a beam hopping scheme and a resource allocation scheme to maximize the throughput and minimizing demand-supply variance in cognitive satellites networks. In multi-antenna scenarios, precoding is a powerful interference cancellation technique since the spatial diversity provided by the antenna array can effectively mitigate the interference from unwanted sources. In [19], Joroughi *et al.* considered a multi-gateway multi-beam satellite system with multiple feeds per beam. In order to improve the system throughput and spectral efficiency, the authors designed a precoding scheme based on a regularized singular value block decomposition of the channel matrix so that both inter-cluster and intra-cluster interference can be minimized. In addition, the authors also analysed several gateway cooperative schemes in order to reduce inter-gateway communications. In [20], three types of interference mitigation techniques: range-based, traffic-aware, and cognitive power control techniques are investigated to mitigate the in-line interference caused by an NGSO satellite to the geostationary satellite orbit (GSO) Earth terminal, while the Non-GSO satellite is crossing the GSO satellite's illumination zone. Moreover, several interference cancellation techniques like beamforming, multi-antenna and spread spectrum techniques are also discussed in satellite networks to improve spectrum efficiency.

With the advancement of satellite production and rocket technology, the number of LEO satellite launches has increased substantially in recent years. As an example, SpaceX plans to launch nearly 12,000 satellites and as of 25 November 2020, 955 of them have been launched. Therefore, LEO satellites will play a more important role in the next few years. However, the aforementioned techniques, both cognitive radio and exclusive zone require LEO satellites to remain silent within the range that will cause interference to GEO satellites,

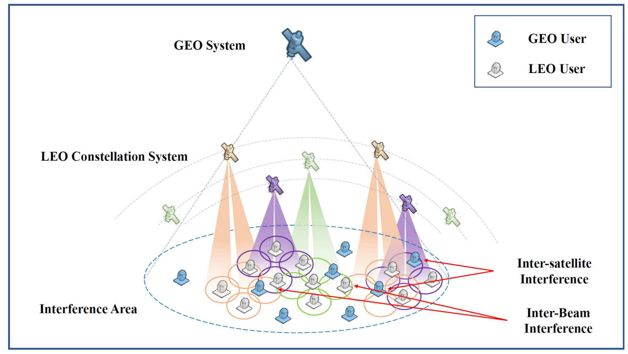


Fig. 1. Cognitive satellite system with the GEO and LEO satellites systems.

which will seriously affect the service quality of the LEO system.

In order to address this issue, we propose a low-complexity flexible spectrum sharing method for multiple LEO scenarios. Different from the existing cognitive radio based or exclusive zone based methods, LEO satellites are not required to keep silence within the cover range of a GEO satellite in our proposed scheme, and their throughput can be optimized under the premise that the QoS of GEO satellite should be guaranteed.

III. System Model

A. Co-Existing Multi-Beam Satellite System

We consider in this paper a co-existing multi-beam satellite system where GEO satellites share spectrum resources with multiple multi-beam LEO satellites. Note that the whole network is controlled by a network management center (NMC),[2] who is in charge of the optimisation the radio resource allocation by scheduling frame, frequency and bandwidth, transmitting power, and beam steering dynamically [13]. All satellites need to communicate periodically with the NMC.

As illustrated in Fig. 1, we consider a scenario where K GEO users and M LEO users are located randomly within the coverage of a beam of the GEO satellite. The GEO satellite serves its users using super-frame technique (all GEO users can be served simultaneously in each time slot, more details about super-frame can be found in [21], [22]). For the LEO satellite users, due to high mobility of the LEO satellites and the random arrival of user traffic, we assume they are served via Time-division multiple access (TDMA) scheme, and thus the allocation of time slots can adaptively adjusted to meet the diverse requirements of different users, which can effectively reduce the transmission delay.

We also assume that the LEO satellites with multiple orbital planes in the same constellation work within the same frequency band, and can share transmission information for all LEO ground users through internal gateways. Through gateway interconnection and sharing, ground users can obtain the position of satellites and adjust the antenna angle under the guidance of the ground control center. In addition, the antennas of all ground users always track the corresponding satellites,

[2] or each system has its own NMC

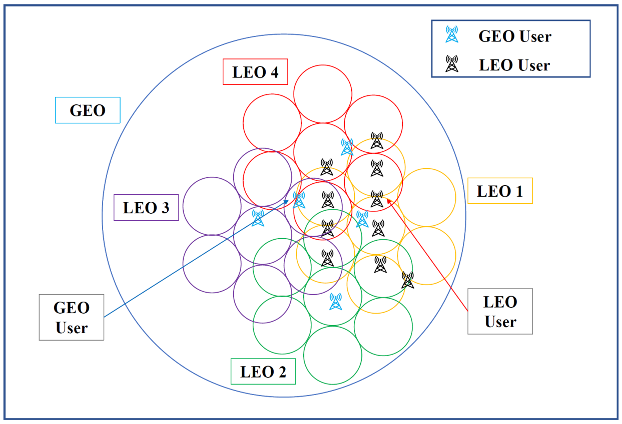


Fig. 2. Beams diagram of cognitive satellite system within the cover range of a GEO beam.

and multiple LEO satellite beams can cooperatively serve ground users since user messages can be effectively shared among all LEO satellites in the same constellation. On the other hand, if the LEO satellite beam does not transmit signals required by a certain ground user, it will cause interference to this user. An example of beams diagram is given in Fig. 2, where four LEO satellites are in the cover range of a GEO beam. It can be observed that LEO users and GEO users are randomly distributed, where GEO users are served by the same GEO beam and LEO users are served by multiple LEO satellites in different orbits.

B. Signal Model

In the study of satellite communication systems, the signal fading problem is an important topic. Channel states in a satellite communication system are significantly different from other wireless networks due to the long propagation range and high mobility of satellites, there is a strong line-of-sight (LOS) component in satellite to mobile communication [23]. Based on the Recommendation ITU-R P.530 [24], in the design of LOS radio-relay systems, several propagation effects must be considered including: diffraction fading, attenuation due to atmospheric gases or solid particles in the atmosphere and variation of the angle-of-arrival and angle-of-launch. For satellites operating at Ku-Ka bands, rain attenuation is the most dominant cause of signal degradation in satellite-ground communications [25], which can be modelled as follows:

$$A_R = a \times R^b \times d_{sg}, \tag{1}$$

where A_R is the rain attenuation measured in decibels (dB), which is log-normally distributed [26]. R represents the rainfall probability and d_{sg} represents the distance between the satellite and the ground user. The value of variables a and b depend on the antennas' frequencies and polarization. In order to reflect the real satellite communication scenarios, we also consider the cloud or fog attenuation A_C which can be modelled as [27]:

$$A_C = \frac{LK_1}{\sin\theta}, \tag{2}$$

where θ is the elevation angle. L is the columnar water content. K_1 is attenuation coefficient. In this paper, we assume that A_R and A_C remain unchanged within the cover range of a GEO beam.

In this way, the total attenuation can be given by $A_T = A_R + A_C$ and the signal S received by the ground user can be modelled as:

$$S = \frac{\text{EIRP} \cdot G_R}{PL + A_T} = \frac{P_T G_T G_R}{PL + A_T}, \tag{3}$$

where EIRP denotes the equivalent isotropic radiated power of the transmitter, P_T is the transmit power, G_T and G_R denote the gain of the transmit antenna and the receive antenna receptively and PL represents the free space propagation loss, which can be formulated as:

$$PL = \left(\frac{4\pi d}{c/f}\right)^2. \tag{4}$$

The antenna gain is strongly related to the off-boresight angle of the transmitter or receiver in the beam direction. The off-boresight angle can be calculated based on the position of the satellite and user. Particularly, the off-boresight angle of receiver θ_R for the desired user is 0 because the user's antenna continues tracking the satellite. The expression to calculate the antenna gain is:

$$G = G_0 \left[\frac{J_1(\mu)}{2\mu} + 36\frac{J_3(\mu)}{\mu^3}\right]^2, \tag{5}$$

where $\mu = 2.07123 sin(\theta)/sin(\theta_{3dB})$; J_1 and J_3 are the first and third order Bessel functions, respectively; θ is the off-boresight angle; θ_{3dB} is the angle that corresponds to the 3dB beamwidth; G_0 is the maximum antenna gain when the off-boresight angle is 0, which can be given by:

$$G_0 = \eta \frac{4\pi A}{(c/f)^2}, \tag{6}$$

where A denotes the antenna area, η represents the antenna efficiency, c is the velocity of light and f is the frequency.

We define the channel gain from the i-th beam of the LEO satellite to the k-th user of the LEO system u_k^L as $h_{i,k}^L$, which can be given by $h_{i,k}^L = \frac{G_T G_R}{PL_{i,k}^L + A_T}$, and $g_{i,g}^L$ as the channel gain from the i-th beam of the LEO satellite to the g-th user of the GEO system u_g^G. Similarly, the channel gain from the GEO satellite to the ground user u_g^G and the channel gain from the GEO satellite to the ground user u_k^L are defined as h_g^G and g_k^G respectively.

Since satellite communication uses a very large bandwidth, the satellite channel can be assumed to be block fading, which remains constant for a block of large number of symbols. In this way, the channel gains h_g^G and g_k^G can be effectively estimated using training symbols, because both training and data symbols would experience the same magnitude of fading. Specifically, both LEO and GEO satellites periodically embed training symbols at the beginning of the data frame and transmit them to ground users. The ground users can then estimate the channel state through, for example, an maximum-likelihood (ML) decoder [28], [29] and communicate the channel state information (CSI) with their NMCs through the gateway.

Hence, in a co-existing multi-beam GEO and LEO satellite system, the signal received at a GEO user g can be given by:

$$y_g^G = h_g^G P^G s_g^G + \sum_i \tau_G^L g_{i,g}^L P_i^L s_i^L + Z_g^G, \tag{7}$$

where the first term is the desired signal for the g-th ground user of the GEO system, s_g^G is the normalized signal symbol, i.e. $\mathbb{E}[|s_g^G|^2] = 1$. The second term denotes the interference signals from the LEO satellites, where τ_G^L is the interference factor to the GEO system. $Z_g^G = kT_g^G B$ is the noise received at the g-th ground user of the GEO system, where T_n represents the equivalent noise temperature of the receiver, B represents the transponder bandwidth, and k is Boltzmann constant.

In this way, the SINR at ground user u_g^G can be obtained from (7) as:

$$\mathrm{SINR}_g^G = \frac{h_g^G P^G}{\sum_i \tau_G^L g_{i,g}^L P_i^L + \sigma_g^2}. \tag{8}$$

In a LEO system, since multiple LEO satellites serve a group of ground users at the same time, the matching problem between satellite beams and the ground users needs to be considered. To this end, we introduce a binary indicator variable $x_{i,k}^L \in \{0,1\}$. If $x_{i,k}^L = 1$, it means that the beam B_i^L carries the information for the ground user u_k^L, otherwise (i.e.,$x_{i,k}^L = 0$), the beam B_i^L may cause interference to the ground user u_k^L. In this way, the signal received at a LEO user k can be given by:

$$y_k^L = \sum_i x_{i,k}^L h_{i,k}^L P_i^L s_k^L + \sum_i \left(1 - x_{i,k}^L\right) h_{i,k}^L P_i^L s_{p\neq k}^L + \tau_L^G g_k^G P^G s_g^G + Z_k^L, \tag{9}$$

where the first term denotes the desired signal for ground user u_k^L. The second term and the third terms represent the interference from other beams of the LEO system and the GEO satellite beam respectively. And Z^L is the additive noise received at u_k^L.

Similar to (8), the SINR at ground user u_k^L can be given by:

$$\mathrm{SINR}_k^L = \frac{\sum_{i=1}^{N_{LB}} x_{i,k}^L h_{i,k}^L P_i^L}{\sum_{i=1}^{N_{LB}} \left(1 - x_{i,k}^L\right) P_i^L h_{i,k}^L + \tau_L^G \cdot g_k^G P^G + \sigma_k^2}. \tag{10}$$

IV. Cooperative Spectrum Sharing Problem

As illustrated in Fig. 2, in a co-existing multi-beam GEO and LEO satellite system, the GEO satellites are stationary relative to the Earth but LEO satellites move relatively. When LEO satellites pass through the equatorial region, the collinear interference between LEO and GEO satellites may result in the failure of decoding of the received signals at some ground users. In order to eliminate interference between co-frequency LEO and GEO satellites, in this paper, we propose to adopt the cognitive radio technique and set the GEO satellite as primary user, the LEO satellites as secondary user.

In this way, the received SINR at any GEO ground user u_g^G should be higher than a pre-fixed threshold λ_{th}, which can be given by

$$\mathrm{SINR}_g^G \geq \lambda_{th}, \quad \forall g \in \mathcal{N}_u^G \tag{11}$$

where $\mathcal{N}_u^G$ denotes the set of GEO system ground users. For the LEO system, the space-ground channel capacity for LEO ground user u_k^L can be given by:

$$C_k^L = b_L \log\left(1 + \frac{\sum_i x_{i,k}^L h_{i,k}^L P_i^L}{\sum_i (1 - x_{i,k}^L) P_i^L h_{i,k}^L + \tau_L^G \cdot g_k^G P^G + \sigma^2}\right), \tag{12}$$

where b_L is the channel bandwidth in hertz.

In our considered scenario, due to the existence of multiple LEO satellites within the coverage of a GEO beam, ground users can be served by different LEO beams in different time slots and in one time slot several beams can serve one ground user cooperatively using the Maximum-ratio combining (MRC) [30] scheme, which can effectively combat noise and fading by taking advantage of spatial diversity provided by different transmit antennas. MRC scheme is suitable for satellite networks since the communication links between satellites in the space subnet are reliable and the clock equipped on satellites can ensure good synchronization in multi-beam cooperation.

Therefore, for each LEO ground user, data transmission and scheduling problems need to be considered jointly. To this end, we assume that for the entire LEO system, data for each ground user u_k^L queued up in a virtual queue q_k^L and we use $Q_k(t)$ to represent the backlog of ground user u_k^L at time t. The queueing dynamics of $Q_k(t)$ satisfies the following condition:

$$Q_k(t+1) = \max(Q_k(t) - S_k(t),\ 0) + A_k(t), \quad \forall k \in \mathcal{N}_u^L \tag{13}$$

where $S_k(t)$ denotes the data rate offered to user u_k^L within time slot t and $A_k(t)$ is the amount of data that arrives within the time slot t for user u_k^L, which follows a Poisson distribution with parameter λ.

As aforementioned, in a co-existing multi-beam satellite system where the GEO satellite is considered as primary user, it is desired to maximize the total transmission rate of the LEO system and ensure the fairness of the service at the same time. To this end, this cooperative spectrum sharing problem can be modelled as an optimization problem as follow:

$$\max_{\mathbf{P}} \sum_{k \in N_{LU}} Q_k R_k^L \tag{14}$$

$$s.t.\ \frac{h_g^G P^G}{\sum_{i=1}^{N_B^L} \tau_G^L \cdot g_{i,g}^L P_i^L + Z^G} \geqslant \gamma_{th}, \quad \forall g \in \mathcal{N}_u^G, \tag{14a}$$

$$R_k^L \leq C_k^L, \quad k \in \mathcal{N}_u^L, \tag{14b}$$

$$x_{i,k}^L \in \{0,1\}, \quad x_{i,k}^L \in \mathcal{X}^L, \tag{14c}$$

$$0 \leqslant P_i^L \leqslant P_{max}^L, \quad \forall i \in \mathcal{N}_B^L, \tag{14d}$$

$$0 \leqslant P^G \leqslant P_{max}^G. \tag{14e}$$

where $\mathbf{P} = \{P_1^L, P_2^L, \dots, P_{N_U^L}^L\}$ denotes the proportion of transmit power allocated to each LEO ground user, P_{max}^L and P_{max}^G denote the transmit power budgets of the LEO beam and GEO beam respectively, $\mathcal{N}_u^G$ and $\mathcal{N}_u^L$ denotes the ground user set of GEO and LEO systems respectively, we have $|\mathcal{N}_u^G| = N_U^G$ and $|\mathcal{N}_u^L| = N_U^L$ and R_k^L denotes the transmission rate for LEO ground user u_k^L. Similarly, $\mathcal{N}_B^L$ is the set of LEO beams, we have $|\mathcal{N}_B^L| = N_B^L$. In this way, (14d) and (14e) correspond to the power constraints of LEO beams and the GEO beam respectively. In the objective function, Q_k is used as a weight. While solving the optimisation problem (14), the ground users with larger queue backlog will have higher priority in time resource allocation even the transmission rate is low. It can help to reduce the transmission delay of the worst-case users, which ensures service fairness.

This problem is a mixed integer nonlinear programming (MINLP) problem since variables $x_{i,k}^L$ is binary, which is difficult to obtain the optimal solution in polynomial time. Therefore, further relaxation and approximation are necessary. In next section, we propose to transform the above MINLP problem into three tractable sub-problems that can be effectively solved.

V. Problem Relaxation and Approximation

As given in the previous section, the spectrum sharing problem in a co-existing multi-beam satellite system can be modelled as a MINLP problem, which cannot be solved directly. In this section, we provide a heuristic algorithm wherein the original MINLP problem are disassembled into three sub-problems: beam and user allocation (BUA) problem, beam power control (BPC) problem and time proportional allocation (TPA) problem.

A. Beam and User Allocation

Based on the diagram given in Fig. 2, each LEO beam may need to serve several ground user within its cover range. Thus, in order to improve the throughput of the system, it is desired to group the ground users and let the beams cooperatively serve the user-groups via TDMA scheme. In this part, based on the matching relationship between beams and users, we propose a grouping algorithm for ground users to reduce the interference between users in the same group.

In this way, we set a $N_B^L \times N_U^L$ matrix $\mathcal{H}$ as follow:

$$\mathcal{H} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N_U^L} \\ h_{21} & h_{22} & \cdots & h_{2N_U^L} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_B^L 1} & h_{N_B^L 2} & \cdots & h_{N_B^L N_U^L} \end{bmatrix}, \tag{15}$$

wherein each element h_{ij} represents the channel state between the i-th beam and the j-th ground user.

Then, we introduce a prefixed threshold th and use the sign function to clarify the matching relationship between the beams and the ground users. If $m_{ij} = \mathrm{sgn}\left(\lfloor * \rfloor \frac{|h_{ij}|^2}{th}\right) = 1$, it means that the LEO beam B_i^L can serve the ground user u_j^L. Otherwise, B_i^L cannot serve u_j^L due to the poor channel quality. In this way, matrix $\mathcal{M}$ can be obtained as follow:

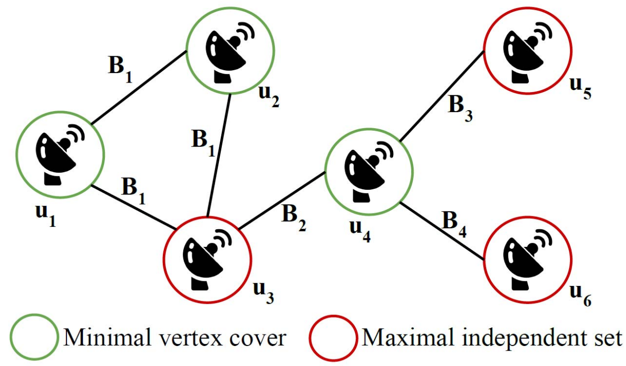


Fig. 3. Matching between the LEO beams and the ground users.

$$\mathcal{M} = \begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1N_U^L} \\ m_{21} & m_{22} & \cdots & m_{2N_U^L} \\ \vdots & \vdots & \ddots & \vdots \\ m_{N_B^L 1} & m_{N_B^L 2} & \cdots & m_{N_B^L N_U^L} \end{bmatrix}. \tag{16}$$

Based on the matching relationship between the LEO beams and the ground users, the matrix $\mathcal{M}$ can be converted into a graph $G = \{V, E\}$, where the vertices are the ground users and the edges are the LEO beams that can serve them. For ground users which are covered by only one LEO beam, there is no grouping issue.

For example, based on a 4×6 matrix $\mathcal{M}^*$ given as follow:

$$\mathcal{M}^* = \begin{bmatrix} 1\,1\,1\,0\,0\,0 \\ 0\,0\,1\,1\,0\,0 \\ 0\,0\,0\,1\,1\,0 \\ 0\,0\,0\,1\,0\,1 \end{bmatrix}, \tag{17}$$

a graph can be obtained as in Fig. 3. Since each edge in this graph represents that two ground users are covered by the same LEO beam, finding user sets that can be served simultaneously is to find independent sets of this graph. Then, using TDMA scheme, different user groups can be served in different time slots. At the same time, in order to maximize the transmission efficiency, it is desired to maximize the number of ground users in each user group to reduce the number of time slots needed.

In an undirected graph, the maximum independent set is the complement of the minimum vertex cover. However, finding the minimum vertex cover in a graph is an NP-hard problem. Therefore, as given in Algorithm 1, we propose a heuristic algorithm to find multiple minimal vertex covers, where the union of them is the complete set of ground users. Then by taking complements, the maximal independent sets can be obtained.

Note that in our proposed BUA algorithm, the resulting maximal independent sets only need to cover all ground users, and does not need to guarantee the grouping optimality. Subsequently, we will discuss the time proportional algorithm for each user groups to ensure the optimality of resource allocation. For example, for the scenario given in Fig. 3, we can

Algorithm 1 Ground User Grouping Algorithm

Input LEO ground user set $\mathbf{S}$.
Output Maximal independent sets $\mathbf{I}_k$.
$k \leftarrow 1$
repeat
  Find a minimal vertex cover $\mathbf{C}_k$.
  Obtain a maximal independent set $\mathbf{I}_k = \mathbf{S} \setminus \mathbf{C}_k$.
  $k \leftarrow k+1$
until $\cup_{i=1}^{k-1} \mathbf{I}_i = \mathbf{S}$.

get 3 independent sets $(\{u_3, u_5, u_6\},\ \{u_2, u_4\}\ and\ \{u_1, u_4\})$, covering all 6 ground users. In each one of them, the intra-group interference is lower than the prefixed threshold th, which can be ignored in the following analysis.

B. Beam Power Control

By adopting the BUA algorithm given in the previous subsection, multiple LEO ground user groups can be obtained, wherein the interference between LEO beams can be cancelled. We use $\mathcal{D} = \{d_1, d_2, \cdots, d_i, \cdots, d_{N_G}\}$ to represent the set of all candidate user groups, where N_G denotes the total number of candidate groups.

Since for each candidate group i, matrix $\mathcal{X}_i^L$ is fixed, the power allocation problem in group i can be given by:

$$\max_{\mathbf{P}}\ f_o(\mathbf{P}) = \sum_{k \in N_U^L} R_k^L \tag{18}$$

$$s.t.\ \frac{h_g^G P^G}{\sum_{i=1}^{N_B^L} \tau_G^L \cdot g_{i,g}^L P_i^L + \sigma^2} \geqslant \gamma_{th}, \quad \forall g \in \mathcal{N}_u^G, \tag{18a}$$

$$0 \leqslant P_i^L \leqslant P_{max}^L, \quad \forall i \in \mathcal{N}_B^L, \tag{18b}$$

$$0 \leqslant P^G \leqslant P_{max}^G \quad . \tag{18c}$$

where R_k^L can be given by:

$$R_k^L = b_L \log\left(1 + \frac{\sum_{i=1}^{N_B{}^L} x_{i,k}^L h_{i,k}^L P_i^L}{\tau_L^G \cdot g_k^G P^G + \sigma^2}\right), \tag{19}$$

Since $x_{i,k}^L$ is given for each ground user set, the only challenge to solve this problem is the ratio terms in its objective function and in (18b), which are non-convex. In order to address this issue, we adopt in this paper a novel quadratic transform technique for tackling this multiple-ratio concave-convex Fractional programming (FP) problem [31].

Specifically, given a sequence of nondecreasing functions $f_m(\cdot)$ and a sequence of ratios A_m/B_m for $m = 1, \ldots, M$, the sum-of-functions-of-ratio problem:

$$\begin{aligned} &\max_{\mathbf{x}}\ \sum_{m=1}^{M} f_m\left(\frac{A_m(\mathbf{x})}{B_m(\mathbf{x})}\right) \\ &s.t.\ \mathbf{x} \in \chi, \end{aligned} \tag{20}$$

can be equivalently transformed to

$$\begin{aligned} &\max_{\mathbf{x},y}\ \sum_{m=1}^{M} f_m\left(2y_m\sqrt{A_m(\mathbf{x})} - y_m^2 B_m(\mathbf{x})\right) \\ &s.t.\ \mathbf{x} \in \chi, \\ &\qquad y_m \in \mathbb{R}, \quad m = 1, \ldots, M. \end{aligned} \tag{21}$$

In this way, the objective function in (18) can be equivalently transformed to:

$$\begin{aligned} f_o^{DIR}(\mathbf{P}, \mathbf{y}) = \sum_{i \in N_{LU}} b_L log\Bigg(&1 + 2y_i\sqrt{\sum_{i=1}^{N_B^L} x_{i,k}^L h_{i,k}^L P_i^L} \\ &- y_i^2\left(\tau_L^G \cdot g_k^G P^G + Z^L\right)\Bigg), \end{aligned} \tag{22}$$

where $\mathbf{y}$ is a vector $\left(\mathbf{y} = \left[y_1, y_2, \ldots, y_{N_B^L}\right]\right)$. For each LEO beam the optimal y_i^* can be given by:

$$y_i^* = \frac{\sqrt{\sum_{i=1}^{N_{LB}} x_{i,k}^L h_{i,k}^L P_i^L}}{\tau_L^G \cdot g_k^G P^G + Z^L}. \tag{23}$$

And for constraint (18b), since the numerator and denominator are all positive, it can be transformed into:

$$h_g^G P^G - \left(\sum_{i=1}^{N_B^L} \tau_G^L \cdot g_{i,g}^L P_i^L + Z^G\right) \cdot \gamma_{th} \geqslant 0 \quad \forall g \in \mathcal{N}_U^G. \tag{24}$$

Then, the non-convex optimization problem (18) can be reformulated as follows:

$$\begin{aligned} &\max_{\mathbf{P}} f_o^{DIR}(\mathbf{P}, \mathbf{y}) \\ &s.t.\ (24), (18b), (18c). \end{aligned} \tag{25}$$

It can be observed that the problem (24) is convex when $\mathbf{y}$ is fixed. Thus, we propose to solve this problem as shown in Algorithm 2. Firstly, fix the value of vector $\mathbf{y}$ and solve the problem (25) iteratively; then update the value of $\mathbf{y}$ according to (23). This procedure is repeated until converge.

Algorithm 2 Beam Power Control Algorithm

Initialization: Set $\mathbf{P}$ to a feasible value.
repeat
  Update $\mathbf{y}$ by (23).
  Update $\mathbf{P}$ by solving the convex optimization problem (25) with fixed $\mathbf{y}$.
until converge.

This algorithm can guarantee converge since with fixed $\mathbf{y}$, the convex problem (25) can converge to a fixed point, and the objective function has a non-decreasing convergence result. At the same time, the update of $\mathbf{y}$ is a non-decreasing iterative process. Hence, the convex optimization problem (25) eventually converges to a local optimum. The optimality proof of the quadratic transform technique is given in [31]. Moreover, the initial point needs to ensure that the problem (25) is solvable.

C. Time Proportional Allocation

Through the beam and user allocation algorithm and beam power control algorithm, the ground users have been divided into several groups and the service rate for each group have been maximized. As aforementioned, in our considered system, data for each ground user queued in an independent virtual queue and since the GEO satellite is considered as primary user, its quality of service (QoS) should be guaranteed at all times, which makes it difficult to guarantee the QoS of LEO ground users, As a result, if only maximize the throughput for user groups, the backlog of virtual queues for certain ground users may increase rapidly, which seriously affect the timeliness of the service.

In order to address this issue, we propose a TDMA scheme to allocate time resource in each time slot to different user groups. By using the backlog of virtual queue as weight, the stability of the queues and the timeliness of the service can be guaranteed.

In this way, the inter-group time slot allocation problem can be formulated as the following optimization problem:

$$\max_{\mathbf{P}_t} f_t(\mathbf{P}_t^T) = \sum_{d}^{N_G} \sum_{k}^{N_U^L} Q_k \cdot r_{k,d} \cdot p_{t,d}^T \tag{26}$$

$$s.t. \ Q_k - \sum_{d}^{N_G} r_{k,d} \cdot p_{t,d}^T \geqslant 0, \quad \forall k \in \mathcal{N}_U^L, \tag{26a}$$

$$p_{t,d}^T \geqslant 0, \tag{26b}$$

$$\sum_{d}^{N_G} p_{t,d}^T \leqslant 1, \tag{26c}$$

where vector $\mathbf{P}_t^T = \{p_{t,1}^T, p_{t,2}^T, \cdots, p_{t,d}^T, \cdots, p_{t,N_G}^T\}$ is the proportion of time allocated to each user group in time slot t. If $p_{t,d}^T = 0$, it means that no time resource is allocated to the user group d in time slot t. $r_{k,d}$ is the service rate for ground user u_k^L in group d, which can be obtained by solving problem (25). Moreover, in problem (26), constrain (26a) indicates that backlog for each virtual queue should be positive and constrain (26c) denotes the limit of time resources in time slot t.

As given in Algorithm 3, we convert the original NP-hard MINLP problem into three polynomial-level complexity sub-problems (BUA, BPC and TPA), to address ground user grouping issue, beam power allocation in each independent set and system stability issue respectively and thus the original problem can be effectively solved.

Algorithm 3 Cooperative Spectrum Sharing Problem

Input Initial transmit power $\mathbf{P}_0^G$ and $\mathbf{P}_0^L$, channel vectors $\mathbf{h}^L$, $\mathbf{h}^G$, $\mathbf{g}^L$ and $\mathbf{g}^G$
2: **Output** LEO ground user sets $\mathcal{D}$, LEO beam-ground user matching matrices$\mathcal{X}_i^L$, GEO and LEO satellites transmit power vectors $\mathbf{P}^L$ and $\mathbf{P}^G$, time proportion vector $\mathbf{P}_t^T$.
BUA algorithm:
4: Ground user grouping via Algorithm 1.
BPC algorithm:
6: **for** $d_i \in \mathcal{D}$ **do**
Maximize throughput for each user group via Algorithm 2
8: **end for**
TPA algorithm:
10: **for** $t_i \in T_{N_T}$ **do**
Solve optimization problem (26)
12: **end for**

D. System Stability Analysis

As aforementioned, the data arrival for each ground user can be considered as a Poisson process with arrival rate $\vec{\lambda} = \{\lambda_k\}_{k=1}^{N_U^L}$. The stability of the system depends on whether it can carry the amount of data brought by the application and provide effective services to users. In this part, by adopting the Lyapunov drift analysis, we will derive the conditions under which our proposed scheduling method is stable under different data arrival rates.

Recalling that $Q_k(t)$ is the queue backlog for user u_k^L at time slot t and vector $\mathbf{Q}(t) = \{Q_k(t)\}_{k=1}^{N_U^L}$. Then the quadratic Lyapunov function for time slot t can be given by:

$$L(t) = \frac{1}{2} \sum_{k=1}^{N_{LU}} Q_k(t)^2. \tag{27}$$

And the Lyapunov drift from time slot t to time slot $t+1$ can be represented as:

$$\Delta L(t) = L(t+1) - L(t). \tag{28}$$

In this way, the one-step conditional Lyapunov drift [32] from time t to time $t+T$ can be given by:

$$\begin{aligned}
\Delta L(t) &\triangleq \mathbb{E}\ \left[L\left(\mathbf{Q}(t+1)\right) - L(\mathbf{Q}(t)) | \mathbf{Q}(t)\right] \\
&= \mathbb{E}\ \left[\frac{1}{2}\sum_{k=1}^{N_{LU}} \left(Q_k(t) - S_k(t) + A_k(t)\right)^2 \right. \\
&\qquad \left. -\frac{1}{2}\sum_{k=1}^{N_{LU}} \left(Q_k(t)\right)^2 | \mathbf{Q}(t)\right] \\
&= \mathbb{E}\ \left[\sum_{k=1}^{N_{LU}} \left(Q_k(t)A_k(t) - Q_k(t)S_k(t)\right) \right. \\
&\qquad \left. +\frac{1}{2}\sum_{k=1}^{N_{LU}} \left(A_k(t) - S_k(t)\right)^2 | \mathbf{Q}(t)\right] \\
&= \sum_{k=1}^{N_{LU}} Q_k(t)\ \mathbb{E}\ \left[\left(A_k(t) - S_k(t)\right) | \mathbf{Q}(t)\right] \\
&\qquad + \frac{1}{2}\sum_{k=1}^{N_{LU}} \left[\lambda_k -\ \mathbb{E}\ \left(S_k(t) | \mathbf{Q}(t)\right)\right],
\end{aligned} \tag{29}$$

where $S_k(t) = \sum_d^{N_G} \sum_k^{N_U^L} \cdot \hat{r}_{k,d} \cdot \hat{p}_{t,d}^T$ is the service rate for ground user u_k^L at time slot t, where $\hat{r}_{k,d}$ and $\hat{p}_{t,d}^T$ can be obtained by solving the optimization problem (26). Since the queue backlog Q_k is considered in calculating of $S_k(t)$, the conditional expectations $\mathbb{E}\ [(A_k(t) - S_k(t))|\mathbf{Q}(t)]$ and $\mathbb{E}\ [(S_k(t)|\mathbf{Q}(t))]$ cannot be calculated directly.

TABLE I
ORBITAL PARAMETERS OF THE GEO AND LEO SYSTEMS

parameter	GEO	LEO Constellation
Semimajor axis	42164.1 km	7828.14 - 8828.14 km
Inclination angle	0°	90°
Argument of perigee	0°	0°
Right ascension of ascending node	0°	0°

In order to simplify the analysis, we propose to solve the following optimization problem:

$$\max_{\mathbf{P}_t} f_t(\mathbf{P}_t^T) = \sum_d^{N_G} \sum_k^{N_U^L} \cdot r_{k,d} \cdot p_{t,d}^T$$
$$s.t.\ (26a), (26b), (26c), \tag{30}$$

to obtain $r_{k,d}^*$ and $p_{t,d}^{*T}$. Since the queue backlogs are not considered in (30), the optimality of $r_{k,d}^*$ and $p_{t,d}^{*T}$ cannot be guaranteed.

In this way, $S_k^*(t) = \sum_d^{N_G} \sum_k^{N_U^L} \cdot r_{k,d}^* \cdot p_{t,d}^{*T}$ is considered as a lower bound of $S_k(t)$ where we have:

$$\sum_{k=1}^{N_U^L} S_k(t) \geqslant \sum_{k=1}^{N_U^L} S_k^*(t). \tag{31}$$

Thus, using $S_k^*(t)$ in (29) yields:

$$\Delta L(t) = \sum_{k=1}^{N_U^L} Q_k(t) \left(A_k(t) - S_k^*(t)\right) + \frac{1}{2} \sum_{k=1}^{N_U^L} \left(\lambda_k - S_k^*(t)\right). \tag{32}$$

Based on the Lyapunov Drift Lemma [33], the conditional Lyapunov drift $\Delta L(t)$ satisfies:

$$\Delta L(t) \leqslant \mathcal{B} - \epsilon \sum_{k=1}^{N_U^L} Q_k(t), \tag{33}$$

for some positive constants B and ϵ. Plugging (32) into this inequality thus yields:

$$\mathcal{B} = \frac{1}{2} \sum_{k=1}^{N_U^L} \left(\lambda_k - \sum_d^{N_G} \cdot r_{k,d}^* \cdot p_{t,d}^{*T}\right), \tag{34}$$

$$\epsilon = \sum_{k=1}^{N_U^L} \left(\sum_d^{N_G} r_{k,d}^* \cdot p_{t,d}^{*T} - A_k(t)\right). \tag{35}$$

Since $S_k^*(t)$ is a lower bound of $S_k(t)$, the system stability holds for all rate vectors $\vec{\lambda}$ satisfy constrain (33).

VI. SIMULATION RESULTS

In this section, we evaluate the proposed cooperative beam sharing scheme using simulation results. In order to simulate the real space communication environment, we use real orbit parameters of GEO and LEO satellite systems in simulations, which are listed in Table I.

Moreover, due to the huge height difference between the GEO satellites and the LEO satellites, we consider in this paper the case when one GEO satellite beam and 4 multi-beam LEO satellites cover the equatorial region at the same time, where 10 LEO ground users and 5 GEO ground users are evenly distributed within this region. As a result, the interference of the downlink transmissions between two satellite systems is serious, which is convenient for verifying the effectiveness of our proposed spectrum sharing scheme. In order to simplify the analysis, we assume that the beam frequencies of the GEO and LEO are the same and there is no interference between the beams of the same satellite. Parameter settings are summarized in Table II. We focus on broadband satellite communication with high transmit power. Other satellite technical parameters are set following some recent research papers [34]–[36].

TABLE II
MAIN SIMULATION PARAMETERS

Parameter	Notation	Value
Frequency band	f	19 GHz(Ka)
Noise temperature of receive antenna	T_n	293 K
Antenna efficiency	η	55%
Antenna diameter of GEO satellite	D_G	0.6 m
Antenna diameter of LEO satellite	D_L	0.2 m
Antenna diameter of recieve user	D_U	0.3 m
Number of LEO beam	N_B^L	7
Number of LEO system users	N_U^L	10
Bandwidth of GEO beam	b_G	200 MHz
Bandwidth of LEO beam	b_L	25 MHz
Maximum power of GEO beam	P_{max}^G	500 W
Maximum power of LEO beam	P_{max}^L	10 W

In order to evaluate the optimality of the quadratic transform technique adopted in our proposed BPC algorithm, we select the Dinkelbach's Transform [37] as a benchmark scheme. Through Dinkelbach's Transform, by introducing a vector $\left(\mathbf{y}^d = \{y_i\}_{i=1}^{N_U^L}\right)$, where

$$y_i^d = \frac{\sum_{i=1}^{N_B^L} x_{i,k}^L h_{i,k}^L P_i^L}{\tau_L^G \cdot g_k^G P^G + Z^L}, \tag{36}$$

the objective function in (18) can be reformulated as:

$$f_o^{DIR}(\mathbf{P}, \mathbf{y}^d) = \sum_{i \in N_U^L} b_L \log \left(1 + \sum_{i=1}^{N_B^L} x_{i,k}^L h_{i,k}^L P_i^L - y_i^d \left(\tau_L^G \cdot g_k^G P^G + Z^L\right)\right). \tag{37}$$

Similar to the quadratic transform, this optimization problem can also be solved using Algorithm 2.

Then, we evaluate the performance of our proposed cooperative beam sharing scheme (CBSS-MQR). In order to make a fair comparison, we also consider the following three schemes:

- Beam hopping scheme (BHS) [35] is a widely adopted scheme which can effectively reduce the co-linear interference between the LEO and the GEO satellites. In this work, we consider BHS to evaluate whether continuous power allocation optimization can effectively improve the transmission efficiency of the multi-beam satellite system.

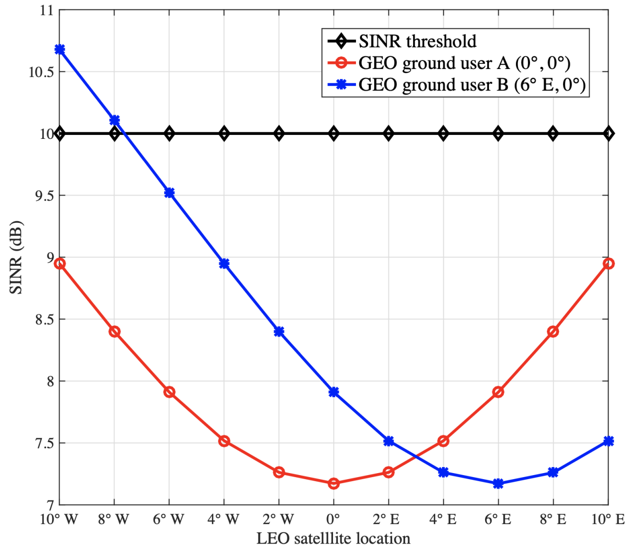


Fig. 4. Interference caused by the LEO system to the GEO ground users while crossing the coverage of a GEO beam.

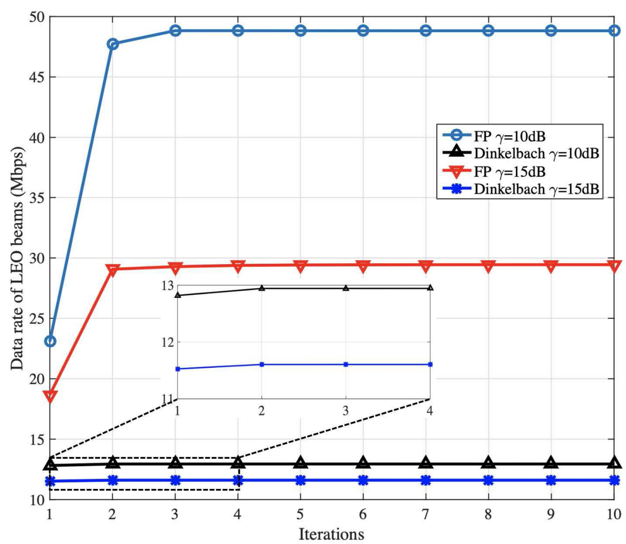
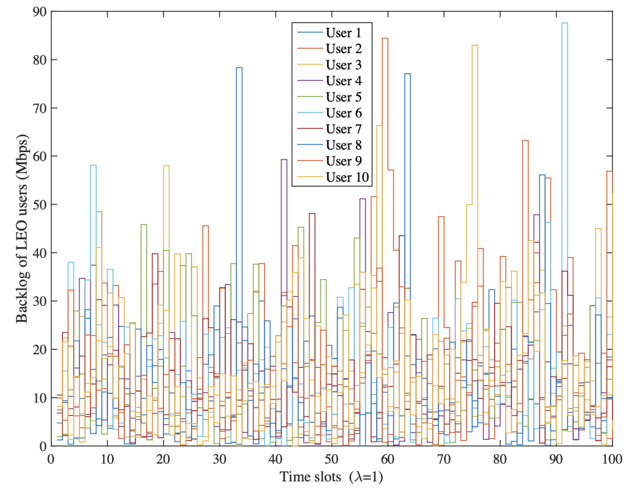


Fig. 5. Convergence comparison between Dinkelbach scheme and FP scheme under different thresholds.

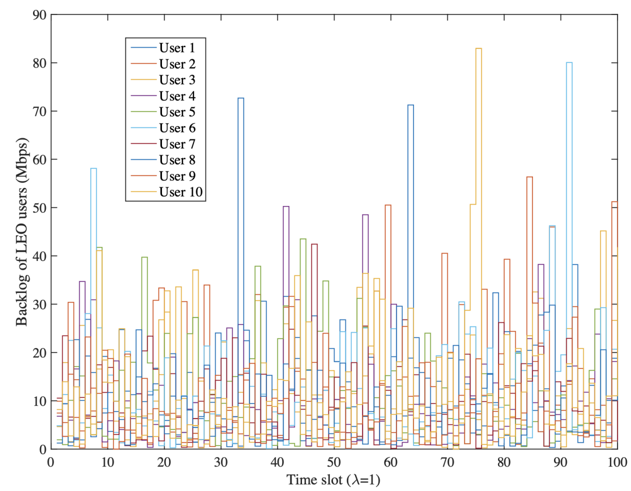
- Cooperative beam-hopping scheme (CBHS) is a modified version of BHS. We optimized it by allowing multiple beams cooperatively serve the same ground user, which can increase the transmission rate.
- CBSS-MR scheme is also a CBSS method but only the throughput of each ground user is maximized, which is given in problem (30) as a lower bound of our proposed CBSS-MQR.

A. Interference Evaluation

Firstly, we design a simulation to mainly evaluate the interference caused by the LEO system to the GEO system. Specifically, we consider a scenario where two GEO ground users A and B are located at $(0°, 0°)$ and $(6°\text{ E}, 0°)$ respectively. One GEO spot beam provides services for them and its beam centre point located at $(0°, 0°)$. The receiving antennas of the two ground users all point to the GEO satellite, and their angles are $0°$ and $1.06°$ respectively. The transmit power of the GEO spot beam is set to 3W which can ensure that the received SINR at both ground users is above 20dB. Then, we assume that a LEO satellite passes through the coverage of this GEO spot beam along the equator and continues to provide services for its ground users during this procedure. The transmit power of each LEO spot beam is 0.5W.



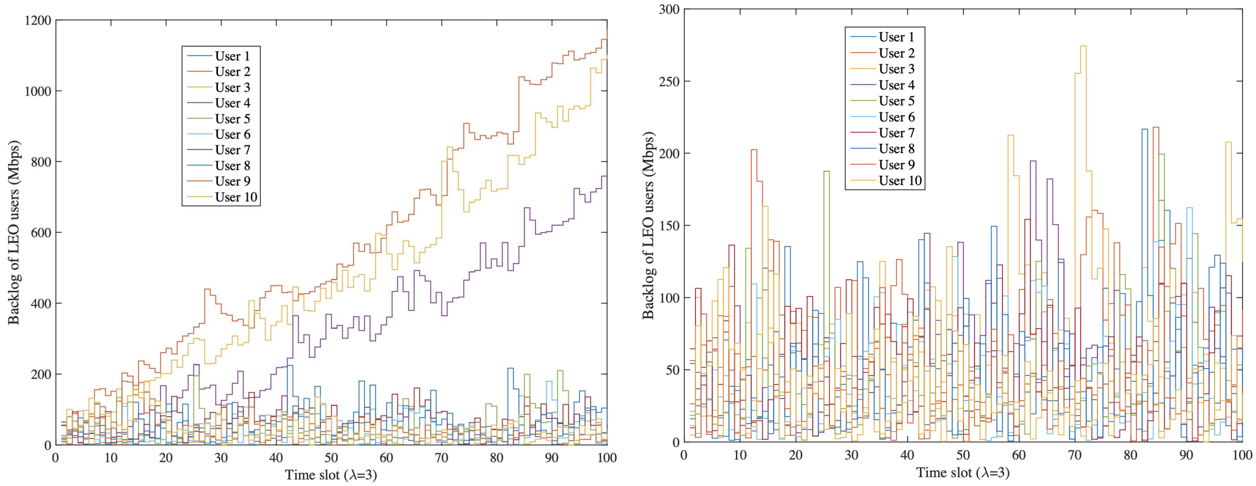
(a) CBHS method



(b) CBSS-MQR method

Fig. 6. Evolution of queue backlogs for LEO ground users ($\lambda = 1$).

We noted the SINR received by both GEO ground users when the LEO satellite moved from 10 degrees west longitude to 10 degrees east longitude, which is illustrated in Fig. 4. It can be observed that as the LEO satellite approaches the GEO ground users, the SINR of the signals received by the two GEO ground users decreases rapidly, and the worst-case scenarios occur when the LEO satellite moves between the GEO satellite and its ground users ($(0°, 0°)$ and $(6°\text{ E}, 0°)$ in our defined scenario). At the same time, it can also be observed that the interference caused by LEO satellites within 10 longitudes around each GEO ground user will make the GEO system's QoS lower than the preset threshold



(a) CBHS method

(b) CBSS-MQR method

Fig. 7. Evolution of queue backlogs for LEO ground users ($\lambda = 3$).

(10 dB in this case). This means that if the traditional cognitive radio or exclusive zone techniques are used to ensure the QoS of the GEO system, the LEO system will be prohibited from providing services within a range of at least 1,000 kilometres around each GEO ground user due to their exclusive design, which is unacceptable for LEO service providers.

B. Convergence

In our discussed scenario, GEO ground users are considered as primary users and LEO ground users as secondary users. In this way, SINR thresholds should be set for the GEO ground users, which means that the receiving signal SINR at all GEO ground users should be higher than this prefixed threshold. As given in Fig. 5, We demonstrate the convergence behaviour of FP and Dinkelbach scheme under two different GEO ground user SINR thresholds: 10 dB and 15dB. It can be observed that both algorithms converge rapidly (within 5 iterations), which shows that the decomposition of the original NP-hard MINLP problem into three consecutive polynomial complexity sub-problems greatly reduces the complexity of problem solving and makes it better to adapt the fast changing satellite communication environment.

At the same time, it can also be observed that FP method performs significantly better than Dinkelbach scheme. Under both SINR thresholds, FP method can achieve a higher transmission rate for the worst case LEO ground user.

C. System Stability

Then we evaluate the stability of network using two algorithm: our proposed CBSS-MQR and CBHS. We use the change of queue backlogs for LEO ground users within 100 continuous time windows to measure the impact of different algorithms on the stability of the system. Note that data for all LEO users arriving randomly follows the same Poisson process with arrival rate λ. In order to facilitate the comparison, we use the same data set for both schemes. As illustrated in Fig. 6, it can be observed that when λ value is small ($\lambda = 1$), both CBSS-MQR and CBHS methods can guarantee the stability of the system.

However, as the user data arrival rate increases, when the average arrival rate $\lambda = 3$, the CBHS method cannot guarantee the stability of all user queues. It can be observed that in Fig. 7, the queue backlog of user 2, user 4 and user 10 go to infinity. But in our proposed CBSS-MQR method, all user queues remain stable. This shows that our proposed algorithm can flexibly respond to the variation of user data arrival rate while effectively improving the total throughput of the system.

D. Network Throughput

In this part, we analysis the achievable network throughput for all three methods: BHS, CBHS and our proposed CBSS-MQR method, evaluate the LEO ground user receiving data rate in each time slot. Note that in the case of $\lambda = 1$, the time resources in each time slot are not fully used, thus, we normalized the receiving data rate in each time slot by using the amount of received data divides the transmission time. In this way, the cumulative distribution function (CDF) of LEO ground user receiving data rate achieved by all these three methods is given in Fig. 8, where each curve is plotted based on the received data by all 10 LEO ground users in 500 continuous time slots. It can be observed that in both cases of $\lambda = 1$ and $\lambda = 3$ the LEO user receiving rate with BHS algorithm is lower than the other two methods, which indicates the importance of inter-beam cooperation. And compared with CBHS, our proposed CBSS-MQR method can achieve higher data rate in both scenarios.

Then, we consider the achievable network throughput of different methods. Let λ vary from 1 to 8, each point in Fig. 9 represents the average transmission rate achieved by this algorithm in one time slot, where each point is obtained based on the simulation results of 500 consecutive time slots. It can be seen from the figure that the user data rate achieved by BHS methods is much lower than other beam cooperation methods. At the same time, it can be observed that when the value of

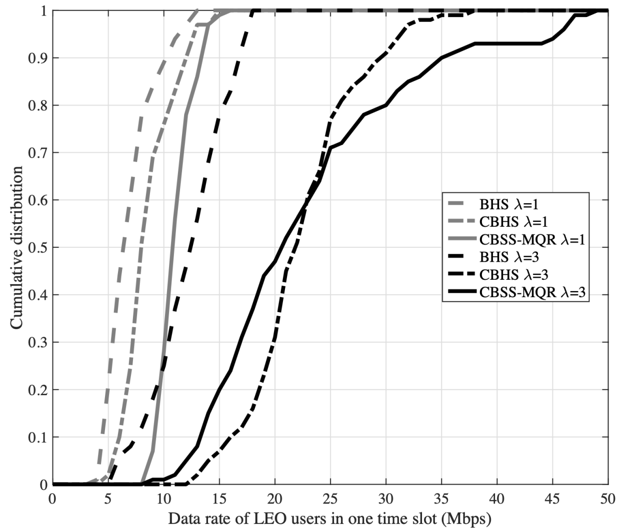


Fig. 8. CDF of LEO ground user receiving data rate in one time slot.

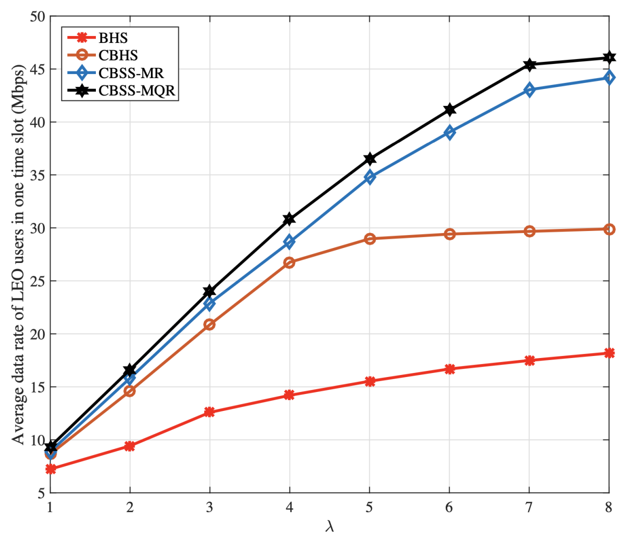


Fig. 9. Achievable network throughput of different methods.

λ is less than or equal to 4, the user data rates of CBHS, CBSS-MR and CBSS-MQR increase at a similar rate. But when the value of λ exceeds 4, CBHS method reaches its capacity limit. This shows that compared with CBHS method, our proposed CBSS-MQR can greatly improves the system capacity. In addition, CBSS-MR In addition, compared with CBSS-MQR method, the CBSS-MR algorithm performs sub-optimally, which confirmed our assumption that the CBSS-MR method is a lower bound of CBSS-MQR algorithm.

VII. Conclusion

In this paper, we propose a flexible spectrum sharing and cooperative transmission method to address the collinear interference issue caused by LEO satellites while passing through the coverage area of the GEO beam, and allows the LEO satellites to provide services for multiple LEO ground users. In our proposed scheme, the problem is modelled as a MINLP problem, which is non-tractable. Then by adopting several relaxation and approximation schemes, this problem are divided into three sub-problems, which significantly reduced the complexity, makes our proposed scheme suitable for the dynamic satellite networks. Moreover, in order to maximize the capacity of our proposed method, we take the queue backlog of each user into consideration and adopt the Lyapunov drift analysis to derive the stability condition of the system. Simulation results show that our propose algorithm can greatly improve the throughput of the overall system.

As the number of LEO satellites continues to increase, multiple LEO satellite constellations may have to work in the same frequency band and the spectrum resources should be wisely shared. Thus, for future work, we will discuss the scheduling and interference cancellation issues in multiple LEO satellite constellations cases.

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