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Cooperative Beam Association and Power Allocation in UD-LEO Satellite Communication Networks: A Spectrum Sharing Manner

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Abstract: In recent years, the ultra-dense low Earth orbit (LEO) satellite communication (UD-LSC) networks such as SpaceX and OneWeb are under rapid development to provide worldwide and broadband services. However, the deployment of thousands of LEO satellites into space leads to the shortage of the orbital and the frequency resources. Spectrum sharing between geostationary Earth orbit (GEO) satellite systems and LEO satellite systems seems to be a promising way to alleviate the problem of restricted spectrum resources. In this paper, a joint cooperative beam association and power allocation scheme for the UD-LSC network to share the same spectrum with a GEO satellite system is considered. By exploiting the cooperative transmission between multiple LEO satellites, we first propose a many-to-many match game-based beam association (MGBA) algorithm to obtain a stable matching between LEO satellites and beam cells, and then, we propose a successive convex approximation (SCA)-based power allocation (SPA) algorithm to iteratively acquire the sub-optimal power allocation matrix. Simulation results show that the proposed MGBA-SPA scheme outperforms other contrast schemes from the perspective of communication satisfaction, and it realizes the balance between the traffic request and the provided capacity of each ground beam cell.

Keywords: UD-LSC; spectrum sharing; beam association; power allocation

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1. Introduction

As an indispensable part of the future 6G vision [1,2], the ultra-dense low Earth orbit (LEO) satellite communication (UD-LSC) networks such as SpaceX and OneWeb can provide low latency, seamless coverage, and broadband communication [3]. However, the rapid construction of these constellations makes the competition between orbit resources and frequency resources in space distinctly fierce. Spectrum sharing between different communication systems is a promising approach to ease the spectrum environment [4], but the deployment of a large amount of LEO satellites brings in significant inter-system interference with the geostationary Earth orbit (GEO) satellite communication systems in service and intra-system interference between LEO satellites due to the dense topology. To track this problem, advanced interference mitigation technologies should be taken into consideration.

Many efforts have been devoted to addressing the inter-system interference when spectrum sharing between the GEO and LEO communication systems is adopted. The cognitive radio (CR) technology [5] that senses the unused spectrum and takes opportunistic access is considered in the LEO satellite systems [6] to share the same frequency with GEO satellites, but the available resource of the secondary system is rigorously restricted. In [7], the interference effect from the LEO satellite communication system to the GEO satellite communication system is analyzed by BER performance. Simulation results show that the off-axis angle between the LEO satellite and the GEO satellite has a significant influence on interference. However, specific solutions for dealing with the inter-system interference are not included. In [8], the adaptive power control (APC) technique that adapts the transmit power of the NGEO satellite/terminal in order to guarantee that the interference to the GEO link is below the tolerable interference limit is proposed. However, only mitigating interference from the power domain will seriously affect the service performance of the NGEO system. In [9], the in-line interference was mitigated by adjusting the direction of phased array antennas of LEO satellites. In this paper, both the angular domain and power domain are taken into consideration to achieve spectrum sharing between the GEO and the UD-LSC networks.

The above related research works focused on the in-line interference between low-dense LEO satellite constellations and the GEO satellite. With the dense topology of the UD-LSC networks, the intra-system interference in UD-LSC networks should be further considered. The intra-system interference is the interference between different beams of the same or adjacent LEO satellites. Generally, segmenting the spectrum in two or four colors with different polarization modes is a promising way to suppress the intra-system interference. However, the spectrum efficiency is correspondingly decreased. The on-board or on-ground precoding/beamforming with aggressive full frequency reuse (FFR) is researched in [10] to address the severe interference, and a frame-based multigroup multicast precoding scheme is proposed based on DVB-S2X protocol [11]. However, the computation of high-dimensional beamforming matrices is a challenging task. In the UD-LSC network, not only does the interference between the beams of one single LEO satellite need to be considered but also the interference between adjacent multiple LEO satellites.

In this paper, spectrum sharing between the GEO satellite and the UD-LSC network is studied. For simplicity, this paper focuses on analyzing the spectrum sharing between GEO and UD-LSC networks, and it does not consider MEO and other systems. However, the research method can be extended to scenarios where there are other systems. The main contributions of this paper are summarized as follows.

- We first propose a multi-satellite cooperative framework for UD-LSC networks to share the same spectrum with the GEO satellite, taking both the inter-system interference and intra-system interference into consideration. By exploiting the dense topology of LEO satellites and jointly considering the angular domain and power domain, the cooperative beam association and power allocation scheme for multiple LEO satellites serving the same coverage area is adopted.
- A multiple LEO satellite to multiple ground beam cell association problem is formulated, and a many-to-many match game-based beam association (MGBA) algorithm is proposed for the spectrum sharing between the GEO and UD-LSC networks. Different from the non-cooperative game scheme in [12], we set the preference function of both LEO satellites and all beam cells as the sum satisfaction of beams to avoid selfish power allocation results. Then, with the matched beam association results, a multi-satellite power allocation optimization problem is formulated with non-convex interference constraints, and a successive convex approximation (SCA)-based power allocation (SPA) algorithm is proposed to maximize the satisfaction of beams.
- Simulations and discussions for the spectrum sharing between the GEO and UD-LSC networks are presented in this paper. Simulation results show that the proposed MGBA-SPA scheme can provide better satisfaction results compared with other schemes and achieve the balance between the traffic requests and provided capacity for all beam cells.

The rest of this paper is organized as follows: Section 2 describes the coexistence model of the GEO satellite systems and the UD-LSC network. Then, the signal model and the interference model are given. The joint beam association and power allocation problem are also formulated. In Section 3, the many-to-many match game-based beam association algorithm and the successive convex approximation-based power allocation algorithm are proposed. Section 4 presents and analyzes the simulation results. Section 5 concludes this paper.

2. System Model

2.1. Coexistence Model

Consider a spectrum-sharing scenario between the UD-LEO satellite communication (UD-LSC) system and a GEO beam-hopping satellite communication system, as shown in Figure 1. There are M LEO beam cells (LBCs) on the ground, which are served by the UD-LSC system. As a result of the dense topology of LEO satellites of the UD-LSC system, more than one LEO satellite is available for each ground LBC at every time snapshot. We assume that there are K LEO satellites at time snapshot t that can totally provide $K \cdot L$ beams to serve the ground M LBCs, where L is the number of provided beams of each LEO satellite. Simultaneously, a GEO satellite forms G GEO beam cells (GBCs) that overlap the same coverage area with the UD-LSC system, as shown in Figure 1 (beams with green lines and black lines). The GEO satellite system employs the beam-hopping technique that lets partial beams work to realize flexible resource management. With the improvement of bandwidth requirements for multimedia services and considering the shortage of frequency resources of both GEO and LEO satellite communication systems, we assume that multiple beams of each satellite communication system provide services in a full-frequency reuse (FFR) manner. The inter-system interference (IGI) between the UD-LSC and GEO systems should be seriously considered.

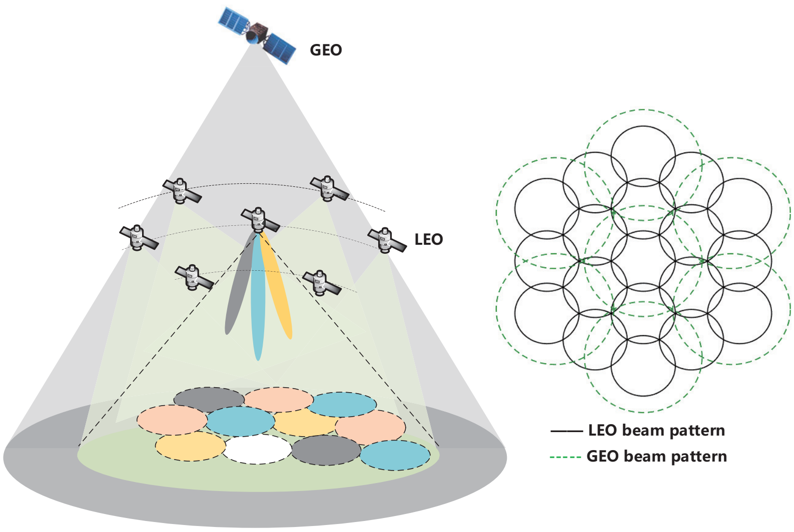

Figure 1. A typical coexistence scenario of the UD-LEO satellite system and a GEO satellite system.

2.2. Signal and Interference Model

For UD-LSC systems, the received signal to interference and noise ratio (SINR) of each ground LBC can be expressed as (1). In this paper, we propose a multi-satellite cooperative scheme to serve ground M LBCs. In Formula (1), the beam association matrix $V \in \mathbb{Z}^{K \times M}$, which is composed by elements $v_{k,m}$, is used to indicate that the LEO satellite k serves the beam m when $v_{k,m} = 1$ and otherwise $v_{k,m} = 0$. $P_{k,m}$, G_{tx}, G_{rx}, and P_{rx} denote the transmit power from satellite k to beam m, the transmit antenna gain, the received antenna gain, and the received power of ground user terminals, respectively. $h_{k,m}$ denotes the channel gain from the LEO satellite k to LBC m. In this paper, we consider a 3GPP-NTN based channel model in [1] as (2).

$$R_{k,m} = \frac{v_{k,m} P_{k,m} G_{tx} h_{k,m} G_{rx} P_{rx}}{I_L(k,m) + I_G(k,m) + N_0 \cdot BW} \tag{1}$$

In (1), $I_L(k,m)$ and $I_G(k,m)$ represent the interference from LEO satellites and the GEO satellites, respectively. N_0 is the power spectrum density of the noise, and BW is the beam bandwidth. The interference from the UD-LSC system to the GEO communication system is expressed as (3) and (4).

$$h_{k,m} = 10^{\left(\frac{PL^{FS}_{k,m} + PL^{A}_{k,m} + PL^{SM}_{k,m} + PL^{SL}_{k,m} + PL^{AD}_{k,m}}{10}\right)} \tag{2}$$

In (2), $PL^{FS}_{k,m}$ is free space path loss, $PL^{A}_{k,m}$ is atmospheric path loss due to gases and rain fades, $PL^{SM}_{k,m}$ is shadowing margin, $PL^{SL}_{k,m}$ is scintillation loss, and $PL^{AD}_{k,m}$ is additional loss, for example degradation due to feeder links [14].

$$I_L(k,m) = \sum_{i=1}^{K} \sum_{j=1, i \neq m}^{M} v_{i,j} P_{i,j} G_{tx}\left(\alpha^{k,m}_{i,j}\right) h_{i,j} G_{rx}\left(\beta^{k,m}_{i,j}\right) P_{rx} \tag{3}$$

$$I_G(k,m) = \sum_{g=1}^{G} v_{k,m} P^G_g G^G_{tx}\left(\gamma^g_{k,m}\right) h^G_{g,m} G_{rx}\left(\theta^g_{k,m}\right) P_{rx} \tag{4}$$

In Figure 2, we can observe that $\alpha^{k,m}_{i,j}$ and $\beta^{k,m}_{i,j}$ represent the off-axis angles from the LEO satellite i to LBC m at the UD-LSC transmitter and the UD-LSC receiver, respectively. $\gamma^g_{k,m}$ and $\theta^g_{k,m}$ represent the off-axis angle from GEO satellites to LBC m at the GEO transmitter and the UD-LSC receiver, respectively. The antenna gain of the GEO and LEO satellite systems can be modeled as (5) [13].

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

where θ denotes the off-axis angle and G_0 denotes the maximum beam gain.$J_1(\cdot)$ and $J_3(\cdot)$ represent first kind and third kind Bessel function, respectively. Here, $u(\theta) = 2.07123 sin(\theta)/sin(\theta_{3dB})$.

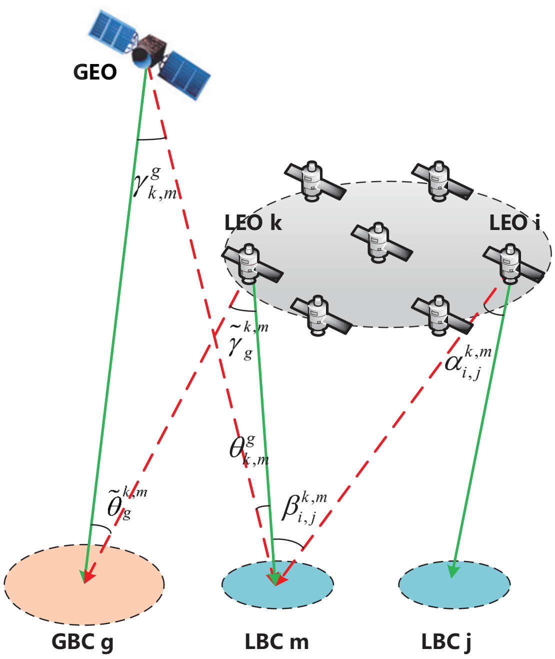

Figure 2. The GEO-LEO interference model and the definitions of different off-axis angles.

2.3. Problem Formulation

Sections 2.1 and 2.2 above have described the coexistence, signal, and interference model for the GEO and LEO satellite spectrum-sharing scenario. To track the interference between the GEO communication system and the UD-LSC system, we take the joint beam association problem from LEO satellites and the power allocation problem between multiple LEO beams into consideration. On one hand, the way the LEO satellites and the LBCs are associated determines the off-axis angle between the interfering link and the interfered link, which in turn determines the severity of the interference. On the other hand, traffic requests of different LBCs on the ground are uneven, and power allocation of LEO satellites for the LBCs determines the communication satisfaction. In this paper, the communication satisfaction is defined as (6). When $\sum_{k=1}^{K} C_{k,m} = T_m$, LBC m has a maximum communication satisfaction $\Gamma_m = 1$.

$$\Gamma_m = \begin{cases} 1, & \text{if } \sum_{k=1}^{K} C_{k,m} \geq T_m \\ \left(\sum_{k=1}^{K} C_{k,m}\right)/T_m, & \text{if } \sum_{k=1}^{K} C_{k,m} < T_m \end{cases} \tag{6}$$

We further propose an optimization problem as (7) to achieve the maximum satisfaction of all LBCs.

$$\mathbf{P1}: \min_{\{P_{k,m}\},\{v_{k,m}\},\forall k,\forall m.} \max \ \Phi_m \tag{7}$$

$$\text{s.t. } C_{k,m} = BW \cdot \log_2(1 + R_{k,m}) \tag{7a}$$

$$\sum_{k=1}^{K} C_{k,m} \leq T_m \tag{7b}$$

$$\Phi_m = T_m - \sum_{k=1}^{K} C_{k,m} \tag{7c}$$

$$\sum_{m=1}^{M} v_{k,m} \leq L, \forall k \tag{7d}$$

$$\sum_{m=1}^{M} P_{k,m} \leq P_{s,\max}, \forall k \tag{7e}$$

$$\sum_{k=1}^{K} \sum_{m=1}^{M} v_{k,m} P_{k,m} G_{tx}\left(\tilde{\gamma}_g^{k,m}\right) h_{k,g}^{L} G_{rx}^{G}\left(\tilde{\theta}_g^{k,m}\right) P_{rx}^{G} \leq I_0, \forall g \tag{7f}$$

In (7), the target of the optimization problem is the sum of Φ_m and total consumed power $\sum_{k=1}^{K} \sum_{m=1}^{M} P_{k,m}$. Φ_m is the gap between traffic requests and provided capacity as described in constraint (6) . By minimizing Φ_m, we can obtain a better Γ_m. (7a) is the Shannon capacity of LBC m that is provided by LEO satellites k. (7b) indicates that the UD-LSC system works in a cooperative manner in which the sum capacity of LEO satellites needs to be lower than the traffic requests so that no additional capacity is wasted. Not all visible K LEO satellites are involved in collaboration; if $v_{k,m} = 0$, $C_{k,m} = 0$. (7d) shows that the total number of beams for each LEO satellite cannot be larger than the maximum number of beam L. (7e) is the total power constraint for each LEO satellite. (7f) indicates that the interference from LEO satellites must not exceed the interference threshold I_0 of the GEO terminal, which is determined by I/N parameters of different types of GEO terminals.

3. The Cooperative Beam Association and Power Allocation Scheme

The optimization problem **P1** is a mixed-integer nonlinear programming (MINLP) problem with binary beam association variables $\{v_{k,m}\}, \forall k, \forall m$ and power allocation variables $\{P_{k,m}\}, \forall k, \forall m$. Due to the non-convex constraints as (7b) and (7c), problem **P1** is non-convex and difficult to solve. In addition, the beam association variables and power allocation variables are coupled, and it is difficult to obtain a global optimal solution of **P1**.

In this paper, the above MINLP and non-convex problem is decomposed into two sub-problems. We first propose a many-to-many matching game-based algorithm to solve the multiple LEO satellites and LBCs association sub-problem. Then, an SCA-based iterative algorithm is proposed to solve the power allocation sub-problem for multiple LEO satellite beams.

3.1. Matching Game-Based Beam Association

The matching game is a promising approach to manage communication resources. For the UD-LSC system, each LBC can be served by multiple LEO satellites, and meanwhile, each LEO satellite can form L downlink beams to provide communication services. Then, a many-to-many matching game can be modeled.

Definition 1. *Given two disjoint sets, $\mathcal{S} = \{1, 2, \cdots, K\}$ of LEO satellites, and $\mathcal{LB} = \{1, 2, \cdots, M\}$ of LBCs, a many-to-many matching Θ is a mapping from the set $\mathcal{S} \cup \mathcal{LB} \cup \{0\}$ into the set of all subsets of $\mathcal{S} \cup \mathcal{LB} \cup \{0\}$ such that for every $k \in \mathcal{S}$ and $m \in \mathcal{LB}$, (1): $\Theta(k) \subseteq \mathcal{LB}$ and $\Theta(m) \subseteq \mathcal{S}$; (2): $|\Theta(k)| \leq L$ and $|\Theta(m)| \leq K$; (3): $k \in \Theta(m) \Leftrightarrow m \in \Theta(k)$.*

For LEO satellites and LBCs, we define the preferences as the sum communication satisfaction, as shown in (8).

$$PF_m(k) = PF_k(m) = \sum_{m=1}^{M} \Gamma_m \tag{8}$$

With different beam association results, the sum communication satisfaction $\sum_{m=1}^{M} \Gamma_m$, i.e., $PF_m(k)$ and $PF_k(m)$, dynamically changes. Different from the traditional preferences introduced in [14] whose preference list is unchanged, the preference of LEO satellites for different LBCs and the preference of LEO satellites for different LBCs are influenced by each other so that Θ is a matching model with externalities [15]. Different from the traditional Gale–Shapley algorithm, swap matching is considered that every two objects are able to exchange their matches.

Definition 2. *Given a matching Θ with $m_p \in \Theta(k_i)$, $m_q \in \Theta(k_j)$, and $m_p \notin \Theta(k_j)$, $m_q \notin \Theta(k_i)$, a swap matching Θ_{jq}^{ip} is defined by the function $m_q \in \Theta_{jq}^{ip}(k_i)$, $m_p \in \Theta_{jq}^{ip}(k_j)$ and $m_q \notin \Theta_{jq}^{ip}(k_j)$, $m_p \in \Theta_{jq}^{ip}(k_i)$.*

Definition 3. *Given a matching Θ and a pair (k_i, k_j) with k_i and k_j matched in Θ, if there exist $m_p \in \Theta(k_i)$ and $m_q \in \Theta(k_j)$ such that: (1): $\forall t \in \{k_i, k_j, m_p, m_q\}, PF_t(\Theta_{jq}^{ip}(t)) \geq PF_t(\Theta(t))$; (2):$\exists t \in \{k_i, k_j, m_p, m_q\}, PF_t(\Theta_{jq}^{ip}(t)) > PF_t(\Theta(t))$, then (k_i, k_j) is a swap-blocking pair in Θ.*

The concept of swap matching and a swap-blocking pair is defined above. It can be seen that swap matching is such a matching that two objects exchange their matches while keeping all other objects' matching states unchanged. By searching and swapping the blocked pairs, we can find a stable matching. The many-to-many matching game-based scheme to solve the multiple LEO satellites and LBCs association can be summarized as Algorithm 1.

Algorithm 1 Proposed swap-matching game-based beam association algorithm.

Step 1: Initialization.
(a) Initialize the power allocation matrix $\mathbf{P}$ with proportion based on traffic requirements of each LBC.
(b) Initialize the beam association matrix $\mathbf{V}$ in which LEO satellites and ground LBCs are randomly matched with each other subject to $|\Theta(k)| \leq L$ and $|\Theta(m)| \leq K$.
Step 2: Swap matching.
For each matched LEO satellite k_j in Θ, it keeps searching $\mathcal{S} \backslash \{k_j\}$ for a swap-blocking pair (k_i, k_j) along with $m_p \in \Theta(k_i)$ and $m_q \in \Theta(k_j)$,
(i) If there exist such a swap-blocking pair, k_i exchanges its match m_p with k_j for m_q, then set $\Theta = \Theta_{jq}^{ip}$.
(ii) Else, k_i keeps its matches.
until no swap-blocking pair exists, and a stable match is formed.

3.2. SCA-Based Power Allocation

By solving the beam association problem, we can reformulate the optimization problem as **P2**.

$$\mathbf{P2}: \min_{\{P_{k,m}\},\forall k,\forall m.} \max \left(\Phi_m + \sum_{k=1}^{K}\sum_{m=1}^{M} P_{k,m}\right) \tag{9}$$

$$\text{s.t.} \sum_{k=1}^{K} BW \cdot \log_2(1+R_{k,m}) \le T_m \tag{9a}$$

$$(7c), (7e), (7f) \tag{9b}$$

To simplify the optimization target, an auxiliary variable λ is introduced to replace the $\Phi_m + \sum_{k=1}^{K}\sum_{m=1}^{M} P_{k,m}$. Take (1), (9a), and (9b) into the optimization problem, **P2** can be further expressed as **P3**.

$$\mathbf{P3}: \min_{\{P_{k,m}\},\forall k,\forall m,\lambda} \lambda \tag{10}$$

$$\text{s.t.} \sum_{k=1}^{K} log_2\left(1+\frac{v_{k,m}P_{k,m}G_{tx}h_{k,m}G_{rx}P_{rx}}{I_L(k,m)+I_G(k,m)+N_0\cdot BW}\right) \le T_m \tag{10a}$$

$$T_m - \sum_{k=1}^{K} log_2\left(1+\frac{v_{k,m}P_{k,m}G_{tx}h_{k,m}G_{rx}P_{rx}}{I_L(k,m)+I_G(k,m)+N_0\cdot BW}\right) + \sum_{k=1}^{K}\sum_{m=1}^{M} P_{k,m} \le \lambda \tag{10b}$$

$$(7e), (7f) \tag{10c}$$

The optimization problem **P3** is still a non-convex problem due to non-convex constraints (10a) and (10b). To tackle it, the SCA method is adopted. Since $I_L(k,m)$ as (3) contains $P_{k,m}$, we cannot directly make a first-order Tayor expansion for (10a) and (10b). We first split the fractional form in the logarithmic function into the different operations of two logarithmic functions.

$$\begin{aligned} &\textstyle\sum_{k=1}^{K} \log_2\left(1+\frac{v_{k,m}P_{k,m}G_{tx}h_{k,m}G_{rx}P_{rx}}{I_L(k,m)+I_G(k,m)+N_0\cdot BW}\right) \le T_m \\ &\Leftrightarrow \textstyle\sum_{k=1}^{K} [\log_2(v_{k,m}P_{k,m}G_{tx}h_{k,m}G_{rx}P_{rx} + I_L(k,m)+I_G(k,m)+N_0\cdot BW) \\ &\ -\log_2(I_L(k,m)+I_G(k,m)+N_0\cdot BW))] \le T_m \end{aligned} \tag{11}$$

In (11), $-\log_2(I_L(k,m)+I_G(k,m)+N_0\cdot BW)$ is convex, let $T_{k,m} = I_G(k,m)+N_0\cdot BW$, and we take a first-order Tayor expansion for the first part of (11) as (12).

$$\begin{aligned} &\log_2\left(\textstyle\sum_{i=1}^{K}\sum_{j=1,i\neq m}^{M} v_{i,j}P_{i,j}G_{tx}\left(\alpha_{i,j}^{k,m}\right)h_{i,j}G_{rx}\left(\beta_{i,j}^{k,m}\right)P_{rx} + T_{k,m} + v_{k,m}P_{k,m}G_{tx}h_{k,m}G_{rx}P_{rx}\right) \\ &\approx \log_2\left(\textstyle\sum_{i=1}^{K}\sum_{j=1,i\neq m}^{M} v_{i,j}P_{i,j}^{(t)}G_{tx}\left(\alpha_{i,j}^{k,m}\right)h_{i,j}G_{rx}\left(\beta_{i,j}^{k,m}\right)P_{rx} + T_{k,m} + v_{k,m}P_{k,m}^{(t)}G_{tx}h_{k,m}G_{rx}P_{rx}\right) \\ &+\frac{\sum_{i=1}^{K}\sum_{j=1,i\neq m}^{M} v_{i,j}G_{tx}\left(\alpha_{i,j}^{k,m}\right)h_{i,j}G_{rx}\left(\beta_{i,j}^{k,m}\right)P_{rx}\cdot\left(P_{i,j}-P_{i,j}^{(t)}\right)+v_{k,m}G_{tx}h_{k,m}G_{rx}P_{rx}\cdot\left(P_{k,m}-P_{k,m}^{(t)}\right)}{\left(\sum_{i=1}^{K}\sum_{j=1,i\neq n}^{M} v_{i,j}P_{i,j}^{(t)}G_{tx}\left(\alpha_{i,j}^{k,m}\right)h_{i,j}G_{rx}\left(\beta_{i,j}^{k,m}\right)P_{rx}+T_{k,m}+v_{k,m}P_{k,m}^{(t)}G_{tx}h_{k,m}G_{rx}P_{rx}\right)\cdot\ln 2} = V_1(k,m) \end{aligned} \tag{12}$$

Then, constraint (11) can be written as (13). With the same operation, we can approximate (10b) as (14) with SCA.

$$\sum_{i=1}^{K}[V_1(k,m) - \log_2(I_L(k,m)+I_G(k,m)+N_0\cdot BW)] \le T_m \tag{13}$$

$$T_m - \sum_{k=1}^{K} \log_2(I_L(k,m)+T_{k,m}+v_{k,m}P_{k,m}G_{tx}h_{k,m}G_{rx}P_{rx}) - V_2(k,m)) + \sum_{k=1}^{K}\sum_{m=1}^{M} P_{k,m} \le \lambda \tag{14}$$

where

$$
\begin{aligned}
V_2(k,m) = &\log_2\left(\sum_{i=1}^{K}\sum_{j=1,i\neq n}^{M} v_{i,j}G_{tx}\left(\alpha_{i,j}^{k,m}\right)P_{i,j}^{(t)}h_{i,j}G_{ix}\left(\beta_{i,j}^{k,m}\right)P_{rx}+T_{k,m}\right)\\
&+\frac{\sum_{i=1}^{K}\sum_{j=1,i\neq n}^{M} v_{i,j}G_{ix}\left(\alpha_{i,j}^{k,m}\right)h_{i,j}G_{ix}\left(\beta_{i,j}^{k,m}\right)P_{rx}\cdot\left(P_{i,j}-P_{i,j}^{(t)}\right)}{\left(\sum_{i=1}^{K}\sum_{j=1,i\neq n}^{M} v_{i,j}G_{ix}\left(\alpha_{i,j}^{k,m}\right)P_{i,j}^{(t)}h_{i,j}G_{ix}\left(\beta_{i,j}^{k,m}\right)P_{ix}+T_{k,m}\right)\cdot\ln 2}
\end{aligned}. \quad (15)
$$

Then, the approximated convex problem **P4** is formed by replacing (10a), (10b) as (13), (14), which can be optimally solved by the CVX toolbox. The proposed SCA-based power allocation algorithm is given in detail as Algorithm 2.

Algorithm 2 Proposed SCA-bead multi-satellite multi-beam power allocation algorithm.

Initialize variable $P_{k,m}^{(0)}$ with $P_{k,m}^{(0)} = 0$;
while the interference constraint (10d) and the capacity constraint (14) are not satisfied **do**
  $P_{k,m}^{(0)} = 0.5P_{k,m}^{(0)}$;
end while
Set $t := 1$;
while $\frac{\lambda^{(t)}-\lambda^{(t-1)}}{\lambda^{(t-1)}} \geq 10^{-3}$ **do**
  Solve problem P4 by CVX to obtain $P_{k,m}^{(t)}$;
  Set $t = t+1$;
end while
Return $P_{k,m}^{(t)}$.

3.3. Complexity Analysis

The proposed MGBA-SPA scheme solves the beam correlation sub-problem and the power allocation sub-problem successively, forming Algorithms 1 and 2. The computational complexity of Algorithm 1 is determined by the maximum number of swaps in the swap match process, which can be represented as $O((K+1)^2(2ML+L^2))$. In Algorithm 2, the computational complexity of using the interior-point method in CVX is $O((KL)^{3.5}N_i)$ [16], where N_i is the iteration times of the SCA method. Therefore, the total computational complexity of the MGBA-SPA scheme with the worst case is $O((K+1)^2(2ML+L^2))) + (KL)^{3.5}N_i)$. The proposed MGBA-SPA scheme can be calculated by the ground gateway station in polynomial time.

4. Simulation Results

In this section, the performance of the UD-LSC system to cooperatively serve multiple LBCs while sharing spectrum with the GEO satellite communication system is simulated by MATLAB. In the simulation scenario, there are 19 LBCs and seven GBCs on the ground, as shown in Figure 1. Actually, the footprint of satellites on the Earth's surface is not circular, especially the beam far away from the center of the satellite's coverage area. The shape of the footprint and different EIRPs are given parameters to calculate the interfered link and the interfering link; then, the SINR of each link can be further calculated. It has an effect on the calculation result of SINR but has no effect on the implementation of the algorithm. Each LEO satellite forms 7 beams to serve ground cells and cooperate with other LEO satellites. The FFR scheme for multiple GEO and LEO beams is assumed to pursue high-spectrum efficiency. The GEO satellite system only shares the beam-hopping parameters with the LEO satellite system, so that the wide coverage of the GEO satellite has little impact with the cooperation with LEO satellites. The uneven traffic demands of different LBCs are assumed. The main parameters of the two systems are listed in Table 1, referring to 3GPP TR 38.821 [17].

Table 1. The main parameters of UD-LSC and GEO satellite systems.

Type	Parameter	Value
Common:		
	Frequency	20 GHz
	Bandwidth	100 MHz
The GEO satellite system:		
	Satellite orbit height	35,786 Km
	Equivalent isotropically radiated power (EIRP)	40 dBW/MHz
	Satellite Tx antenna max gain	58.5 dBi
	3 dB beamwidth	0.1765 degree
	Satellite beam diameter	110 Km
	I/N of terminals	−12.2 dB
The UD-LSC system:		
	Satellite orbit height	1200 Km
	The number of the LEO orbit planes	18
	The number of LEO satellites in each orbit plane	75
	EIRP	10 dBW/MHz
	Satellite Tx antenna max gain	38.5 dBi
	3 dB beamwidth	1.7647 degree
	Satellite beam diameter	40 Km

To verify the effectiveness of the proposed MGBA-SPA scheme solving the joint beam association and power allocation problem, as a contrast, we give four baseline schemes as follows.

- Match game-based beam association with uniform power allocation (MGBA-UPA). In the MGBA-UPA scheme, the proposed Algorithm 1 is adopted to finish the beam association. Then, a uniform power allocation between L LEO beams of each LEO satellite is used.
- Match game-based beam association with traffic-based power allocation (MGBA-TPA). In the MGBA-TPA scheme, after Algorithm 1 is implemented, the transmit power is allocated as $P_{k,m} = P_{s,max} \cdot (T(m)/T_{total})$.
- Random beam association with uniform power allocation (RBA-UPA). In the RBA-UPA scheme, the LBCs and LEO satellites are associated randomly. Then, the UPA method is adopted.
- Random beam association with traffic-based power allocation (RBA-TPA). In the RBA-TPA scheme, the random association between LEOs and LBCs is adopted. Then, the transmit power of each LEO satellite is allocated based on the traffic request of each beam cell.

Figures 3–5 simulate the sum of satisfactory performance of the proposed MGBA-SPA scheme and four related baseline schemes. The sum of satisfaction can be calculated as $\Phi_{sum} = \sum_{m=1}^{M} \Phi_(m)$. To evaluate the cooperation between LEO satellites, a performance comparison against the number of LEO satellites is simulated in Figure 3, where the number of active beams of the GEO system is three and the average traffic per LBC is 0.5 Gbps. Simulation results show that the proposed MGBA-SPA scheme outperforms other baseline schemes with a different number of cooperative satellites. As the number of cooperative satellites increases, the performance of the MGBA-SPA scheme tends to stabilize, $\Phi_{sum} \approx 16$, since $four$ LEO satellites can bring enough degrees of freedom in the angle domain to mitigate the inter-system interference and inter-beam interference. As for four baseline schemes, the sum of satisfaction is improved by consuming more power, which comes from more LEO satellites. In addition, the match game-based beam association scheme obviously has better performance than the random scheme.

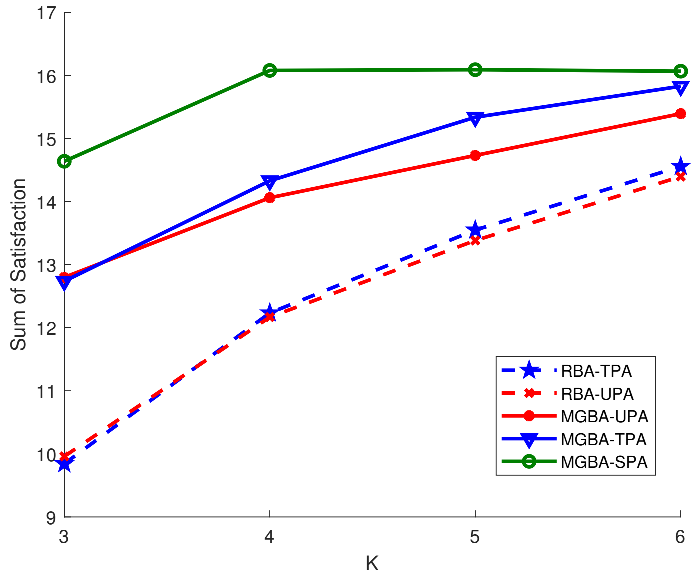

Figure 3. The sum of satisfaction performance comparison against different numbers of cooperative LEO satellites K.

Figure 4 simulates the sum of satisfaction performance comparison against a different number of active GEO beams G, where we set $K = 4$, and the average traffic is 0.5 Gbps. As the number of active beams of the GEO satellite system increases, the LEO satellite system suffers more interference, so that the satisfaction level gradually decreases. When $G <= 4$, the proposed MGPA-SPA scheme outperforms other baseline schemes. When $G >= 5$, the MGBA-UPA scheme has a larger sum of satisfaction than the MGBA-SPA. Compared with MGBA-UPA, MGBA-SPA includes a constraint that the interference to GEO terminals does not exceed the threshold. Therefore, MGBA-SPA is more sensitive to the number of active beams in the GEO system.

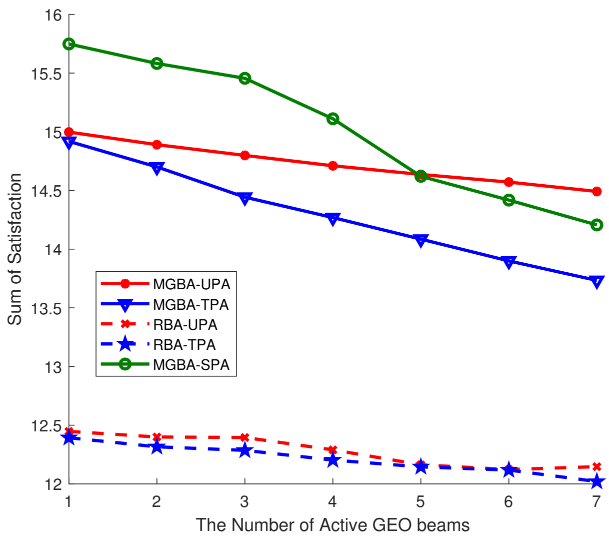

Figure 4. The sum of satisfaction performance comparison against different numbers of active GEO beams G.

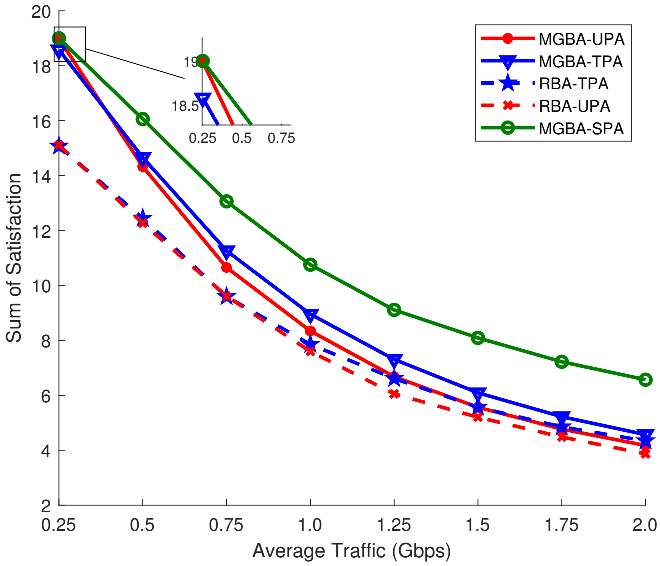

Figure 5. The sum of satisfaction performance comparison against different average traffic requests of LBCs.

Figure 5 simulates the sum of satisfaction performance comparison against different average traffic requests of LBCs, where we set $K = 4$ and $G = 3$. Since the transmit power is fixed, the sum of satisfaction declines for all schemes with the increase of the average traffic demand. When the average traffic $T_{aver} = 0.25$ Gbps, both the MGBA-UPA and MGBA-SPA scheme can achieve a maximum sum of satisfaction, $\Phi_{sum} = 19$. With $T_{aver} > 1$ Gbps, the performance gap between the proposed MGBA-SPA scheme and the others is about 2.

Figure 6 simulates the provided capacity of the proposed MGBA-SPA scheme of each ground LBC, where $K = 4$, $G = 3$, and the average traffic is 0.25 Gbps. The simulation result in Figure 6 indicates that the proposed algorithm can achieve the traffic balancing for all 19 LBCs. The fairness between different cells is guaranteed. From Figure 6, we can find that some beams have wasted capacity, such as beam indexes 2, 4, and 7, since the power allocation matrix P is a relaxed solution by adopting SCA.

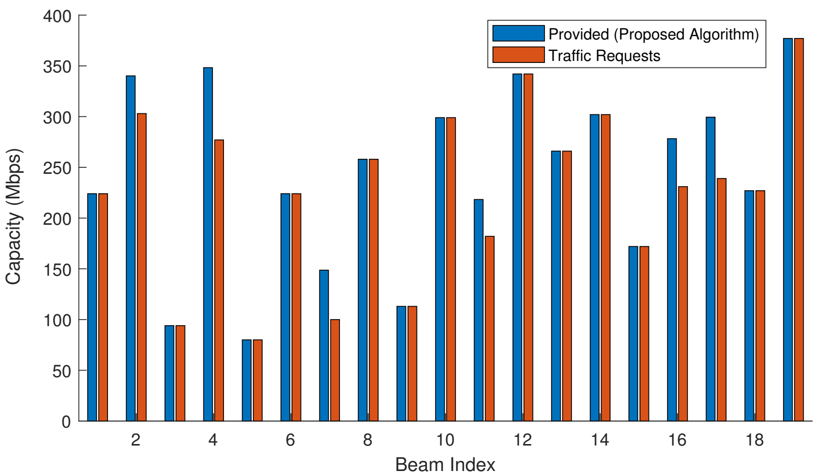

Figure 6. Provided capacity of the proposed MGBA-SPA scheme of each ground LBC.

5. Conclusions

In this paper, spectrum sharing between the GEO satellite system and the UD-LSC network is considered. To address the interference among different systems and different beams, by exploiting the dense topology of LEO satellites, we propose a multi-satellite cooperative beam association and power allocation scheme. A multiple LEO satellite to multiple ground beam cell association problem is first formulated, and a many-to-many match game-based beam association (MGBA) algorithm is proposed to obtain a stable matching. Then, with the matched beam association results, a multi-satellite power allocation optimization problem is formulated with non-convex interference constraints and a successive convex approximation (SCA)-based power allocation (SPA) algorithm is proposed to maximize the satisfaction of beams. Simulation results show that the proposed MGBA-SPA scheme outperforms the MGBA-UPA, MGBA-TPA, RBA-UPA, and RBA-TPA schemes.

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References

1. Giordani, M.; Polese, M.; Mezzavilla, M.; Rangan, S.; Zorzi, M. Toward 6G Networks: Use Cases and Technologies. *IEEE Commun. Mag.* **2020**, *58*, 55–61. [CrossRef]
2. Giordani, M.; Zorzi, M. Non-Terrestrial Networks in the 6G Era: Challenges and Opportunities. *IEEE Netw.* **2021**, *35*, 244–251. [CrossRef]
3. Deng, R.; Di, B.; Zhang, H.; Kuang, L.; Song, L. Ultra-Dense LEO Satellite Constellations: How Many LEO Satellites Do We Need? *IEEE Trans. Wirel. Commun.* **2021**, *20*, 4843–4857. [CrossRef]
4. Peha, J.M. Approaches to spectrum sharing. *IEEE Commun. Mag.* **2005**, *43*, 10–12. [CrossRef]
5. Srinivasa, S.; Jafar, S.A. Cognitive radios for dynamic spectrum access-The Throughput Potential of Cognitive Radio: A Theoretical Perspective. *IEEE Commun. Mag.* **2007**, *45*, 73–79. [CrossRef]
6. Wang, C.; Bian, D.; Shi, S.; Xu, J.; Zhang, G. A Novel Cognitive Satellite Network With GEO and LEO Broadband Systems in the Downlink Case. *IEEE Access* **2018**, *6*, 25987–26000. [CrossRef]
7. Park, C.-S.; Kang, C.-G.; Choi, Y.-S.; Oh, C.-H. Interference Analysis of Geostationary Satellite Networks in the Presence of Moving Non-Geostationary Satellites. In Proceedings of the IEEE International Conference on Information Technology Convergence and Services, Philippines, PA, USA, 11–13 August 2010.
8. Sharma, S.K.; Chatzinotas, S.; Ottersten, B. In-line interference mitigation techniques for spectral coexistence of GEO and NGEO satellites. *Int. J. Satell. Commun. Netw.* **2014**, *34*, 11–39. [CrossRef]
9. Zhang, C.; Jin, J.; Zhang, H.; Li, T. Spectral coexistence between LEO and GEO satellites by optimizing direction normal of phased array antennas. *China Commun.* **2018**, *15*, 18–27. [CrossRef]
10. Christopoulos, D.; Chatzinotas, S.; Ottersten, B. Multicast Multigroup Precoding and User Scheduling for Frame-Based Satellite Communications. *IEEE Trans. Wirel. Commun.* **2015**, *14*, 4695–4707. [CrossRef]
11. Digital Video Broadcasting (DVB). Second Generation Framing Structure, Channel Coding and Modulation Systems for Broadcasting, Interactive Services, News Gathering and Other Broad-Band Satellite Applications. In *Part 2: DVB-S2 Extensions (DVB-S2X)*; ETSI EN 302 307-2 V1.1.1; European Broadcasting Union (EBU): Geneva, Switzerland, 2014.
12. Tsiropoulou, E.E.; Katsinis, G.K.; Papavassiliou, S. Distributed Uplink Power Control in Multiservice Wireless Networks via a Game Theoretic Approach with Convex Pricing. *IEEE Trans. Parallel Distrib. Syst.* **2012**, *23*, 61–68. [CrossRef]
13. Cui, G.; Zhu, Q.; Xu, L.; Wang, W. Secure Beamforming and Jamming for Multibeam Satellite Systems With Correlated Wiretap Channels. *IEEE Trans. Veh. Technol.* **2020**, *69*, 12348–12353. [CrossRef]
14. Roth, A.; Sotomayor, M. *Two-Sided Matching: A Study in Game Theoretic Modeling and Analysis*; Cambridge University Press: Cambridge, UK, 1992.
15. Baron, E.; Lee, C.; Chong, A.; Hassibi, B.; Wierman, A. Peer effects and stability in matching markets. In Proceedings of the International Symposium on Algorithmic Game Theory, Amalfi, Italy, 17–19 August 2011.

16. Murty, K.G.; Kabadi, S.N. Some NP-complete problems in quadratic and nonlinear programming. *Math. Program.* **1987**, *39*, 117–129. [CrossRef]
17. 3GPP. Available online: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3525 (accessed on 18 January 2022).