Comparative Analysis on the Resource Allocations for Interference-limited LEO Satellite Systems

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***Abstract*—This paper delves into an analysis of the performance of a resource allocation scheme that harnesses beam-hopping technology within a low Earth orbit (LEO) satellite system, all within the confines of an interference-limited scenario. The primary concern lies in ensuring that the operation of the LEO system does not inadvertently trigger radio interference with the geostationary Earth orbit (GEO) satellite network, particularly when both systems share the same frequency band. Given the intricate interplay of multiple system parameters, this paper not only presents simulation outcomes contingent on varying separation distances and antenna gain characteristics but also offers a comprehensive analysis of these results. Beyond the present investigation, the paper also highlights potential avenues for future studies in this realm.**

***Index Terms*—LEO, satellite, beam-hopping, interference, resource allocation**

I. Introduction

Amidst the surging global hunger for information, satellite networks have emerged as a robust augmentation to terrestrial communications, owing to their expansive coverage. Within this landscape, low Earth orbit (LEO) satellite communications have assumed a pivotal role in offering broadband internet access to regions with limited infrastructure. However, rapid development of satellite communication technology has caused a lack of resources for satellite communication systems [1]. Therefore, the strategic design of satellite system models and the effective orchestration of resources have now become critical concerns within the realm of LEO satellite communication networks.

Modern satellites exhibit the capability to employ multi-beam configurations, facilitated by frequency reusing schemes. A notable instance of this is observed with satellites like OneWeb, each equipped with 16 user beams, and Starlink, with each satellite accommodating 8 to 32 configurable beams [2] [3]. While adopting a higher frequency reuse factor can significantly enhance spectral efficiency, it simultaneously introduces heightened complexities in the resource allocation (RA) algorithm. In response to this challenge, research endeavors have been documented, encompassing the exploration of combined machine learning (ML) methodologies to address RA problems within satellite systems [4]-[6].

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For instance, an approach involving ML assisted beam illumination technique has been introduced within the domain of multi-beam satellite systems [4]. This result of this study showed the efficacy of ML-based methodologies in furnishing near-optimal solutions with significantly reduced computational complexity, thus outperforming traditional convex optimization techniques. Central to this ML technique is its integration with the cognitive radio (CR) technology, which empowers systems to sense and capitalize on available spectrum within their environmental context, leveraging unused spectrum resources opportunistically. The cognitive satellite communication paradigm, rooted in CR principles, enables seamless utilization of spectrum resources from alternate communication systems, while maintaining interference at an acceptable threshold.

A prime example of the application of CR principles is the delineation of spectrum sharing arrangements between broadcasting satellite service (BSS) feeder links and fixed satellite service (FSS) downlinks. This can be executed through a straightforward coordination mechanism, defined by establishing cognitive (protection) zones around BSS stations [7]–[9], or alternatively, via an intricate Beam-Hopping (BH) scheme [10]. For example, a BH scheme-based dual satellite coexistence scenario was proposed, wherein power control strategy and exclusion zones were employed to mitigate the risk of harmful interference to the primary system [11].

On the other hand, an RA methodology based on BH was introduced within the context of a LEO constellation system, operating independently of CR technology. This particular endeavor cast the LEO satellite constellation in the role of a secondary system, strategically sharing the spectrum resources attributed to a high throughput GEO satellite communication system [1]. Within this framework, stringent limitations were imposed on the LEO satellite's frequency band and transmission power, to preclude any interference with the GEO satellite system. The central objective of resource allocation (RA) in this investigation lay in the minimization of variance between the traffic demand and the supply. Capitalizing on the insights gleaned from this precedent work, the present paper endeavors to offer a comparative analysis through simulation results, meticulously assessing the performance of the aforementioned RA methodology. This analytical pursuit takes into consideration a range of pivotal system parameters, prominently encompassing separation distances and the antenna gain characteristics of the LEO satellites.

The rest of this paper is organized as follows. Section II reviews the related work on RA schemes for LEO BH satellites. Section III investigates how the BH-based RA scheme works by using the considered system environment. Section IV presents simulation results on the performance of the RA, according to the traffic demand. Finally, conclusions are drawn in section V.

II. Related Works

A. System model

A RA method approach for a BH LEO satellite system has been proposed [1]. This method operates under the premise of a LEO satellite constellation system functioning within polar orbits, while concurrently featuring the presence of a multi-beam Geostationary Earth Orbit (GEO) satellite situated above one of the orbits of the LEO satellite constellation, as visually depicted in Fig. 1. The distinctive feature of the LEO satellite coverage areas is their immobility, an advantageous characteristic that lends itself to the efficient observation or anticipation of the spectrum attributed to the GEO satellite. Facilitating this, the LEO satellites are outfitted with phased array antennas, enabling the formation of focused spotbeams endowed with the capability of persistent orientation. Within this construct, a coverage area comprises multiple subdivisions, aptly referred to as cells, and these cells are proficiently illuminated through the utilization of LEO satellite spotbeams, meticulously orchestrated in a Beam-Hopping fashion.

Functioning as the secondary system, the LEO satellite constellation seamlessly shares the spectral resources with the GEO satellite system during the downlink transmission phase. It is worth noting that the potential for in-line interference manifests predominantly within lower latitudes. To provide a visual context, an illustrative depiction of a hexagonal LEO satellite coverage area, along with the consequential spectrum distribution caused by the presence of a GEO satellite, is presented in Figure 1, adhering to the principle of generality.

B. Interference model

In order to avoid harmful interference to the primary system, stringent constraints are imposed on the transmitting power, frequency band allocation, and the number of illuminated beams utilized by the LEO satellite. Herein, let I_{th} denote the interference threshold level mandated for the GEO satellite system, ensuring a robust degree of protection. Importantly, the interference power arising from each LEO satellite beam towards GEO Earth station (ES) must not surpass this predefined I_{th}.

Therefore the solution of this RA problem will be the illuminated beam pattern with proper bandwidth allocation and power. For this, we first denote the interference power

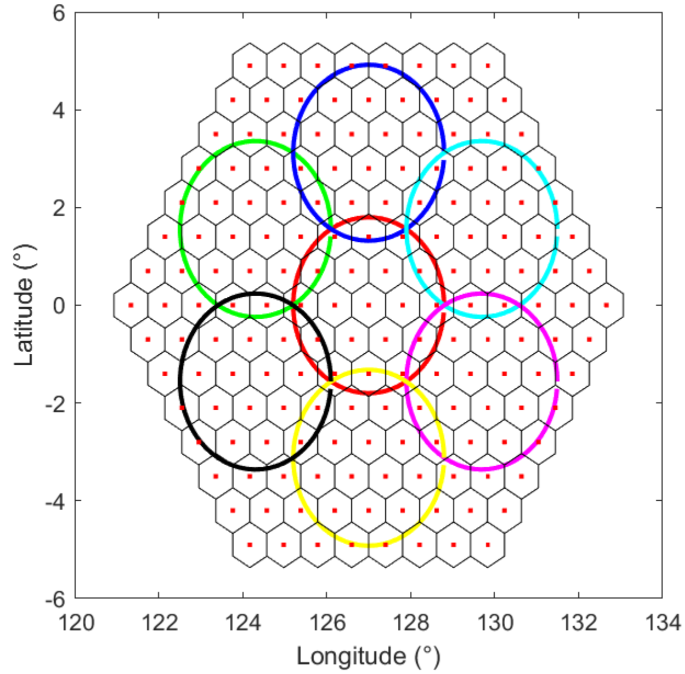

Fig. 1. Coverage model for LEO and GEO systems

stemming from a LEO satellite spot beam, dedicated to serving cell l, towards a GEO ES g as follows [1]:

$$I^L_{l,g} = \epsilon^L_{l,g} P^L_l G^L_t(\theta^L_{l,g}) G^G_r(\theta^{G,L}_g) L^L_g, \tag{1}$$

where the superscripts L and G used in the variables denote for LEO and GEO systems, respectively. Furthermore,

$$\epsilon^L_{l,g} = \begin{cases} 1 & \text{if bandwidths for cell } l \text{ and beam } g \text{ overlap,} \\ 0 & \text{otherwise,} \end{cases}$$

P^L_l denotes the transmit power to cell l from the LEO satellite, $G^L_t(\theta^L_{l,g})$ denotes the transmit antenna gain of LEO satellite with an off-axis angle from cell l to ES g, $G^G_r(\theta^{G,L}_g)$ denotes the receive antenna gain of ES g with an off-axis angle from GEO satellite to LEO satellite, and L^L_g denotes the free space propagation loss from the LEO satellite to the ES g.

Similarly, the interference power from GEO satellite beam g to LEO satellite cell l can be represented as follows:

$$I^G_{g,l} = \epsilon^G_{g,l} P^G_g G^G_t(\theta^G_{g,l}) G^L_r(\theta^{L,G}_l) L^G_l, \tag{2}$$

$$\epsilon^G_{g,l} = \begin{cases} 1 & \text{if bandwidths for beam } g \text{ and cell } l \text{ overlap,} \\ 0 & \text{otherwise,} \end{cases}$$

P^G_g denotes the transmit power from the GEO satellite to the beam serving ES g, $G^G_t(\theta^G_{g,l})$ denotes the transmit antenna gain of GEO satellite beams serving ES g with an off-axis angle from ES g to cell l, $G^L_r(\theta^{L,G}_l)$ denotes the receive antenna gain of user terminal at cell l with an off-axis angle from LEO satellite to GEO satellite, and L^G_l denotes the free space propagation loss from the GEO satellite to the cell l.

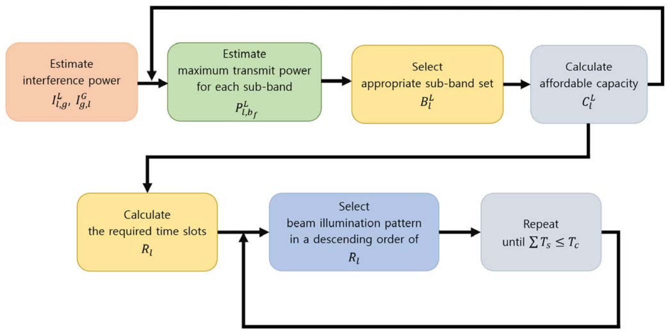

Fig. 2. Resource allocation procedure

C. Beam-hopping based resource allocation

Assuming the GEO satellite employs a multibeam scheme with a frequency reuse factor of F, the total bandwidth can be divided into F sub-bands, b_f, $f = 1, 2, \ldots, F$. The BH-based RA in the previous study utilized the following objective function, in order to minimize the variance between the traffic demand and supply [1]:

$$\min \sum_{i=1}^{N_c} (\rho_l - \chi_l)^2, \tag{3}$$

where N_c is the number of cells of in the coverage area, ρ_l and χ_l denote the traffic demand from cell l and the traffic supply provided to cell l respectively. With the above objective function, the LEO satellite constellation system optimizes RA as the secondary system, under the limited frequency power resources.

In order to find solution for (3), RA was made by using the algorithm as shown in Fig. 2. First, the interference power is estimated by (1) and (2). After that, the maximum available transmit power for each sub-band P^L_{l,b_f} is calculated as follows, in order not to cause harmful interference the GEO satellite system:

$$P^L_{l,b_f} \leq \frac{I_{th}}{\beta_{l,b_f}}, \tag{4}$$

where $\beta_{l,b_f} = \max_g \left\{ \epsilon^L_{l,g} G^L_t(\theta^l_{l,g}) G^G_r(\theta^{G,L}_g) L^l_g \right\}$.

Afterwards, the appropriate sub-band set B^L_l and the affordable capacity C^L_l is obtained by using well-known Shannon's capacity equation below:

$$C^L_l = B^L_l \log_2 \left(1 + \frac{\alpha^L_l P^L_l}{n_0 B^l_l + I^G_{tot,l}} \right), \tag{5}$$

where B^L_l and P^L_l denote the bandwidth and transmit power allocated for the lth cell, respectively. Furthermore, α^L_l denotes the channel coefficient from the LEO satellite to the lth cell, n_0 denotes the noise power spectral density, and $I^G_{tot,l}$ denotes the total interference power to the lth cell from the GEO satellite which is given by:

$$I^G_{tot,l} = \sum_g I^G_{g,l}, \tag{6}$$

In the above (5), the optimum P^L_l and B^L_l are found by the condition that each LEO satellite beam has a single carrier to minimize the back-off of the amplifier and the guard-bands. This condition necessitate the allocation of the continuous sub-bands, and optimal bandwidth and transmitting power can be obtained by solving the following objective function:

$$\begin{aligned} \max_{B^L_l, P^L_l} \quad & C^L_l, && \forall l \\ & B^L_l \subseteq \{b_1, \ldots, b_F\} && \\ \text{, s.t.} \quad & P^L_l \leq P_{tot}/N_b, && \forall b_f \in B^L_l, \\ & P^L_l \leq P^L_{l,b_f}, && \forall b_f \in B^L_l. \end{aligned} \tag{7}$$

After finding the solution of above, and the required time slots of each cell R_l is calculated as follows:

$$R_l = \frac{\rho_l}{C^L_l T_s}, \tag{8}$$

where T_s denotes the duration of a time slot. Then, the illumination pattern is determined by sorting the cells in descending order according to the number of the required time slots. This process will be repeated for a transmission cycle.

III. Investigation of the BH-based RA operation

A. System environment

We investigate the operations of the BH-based RA using a system model similar to the one shown in Fig. 1, where GEO satellite system has multibeam coverage with seven color multiplexing and all beams have the same power and bandwidth. We assume that there is one ES located in each beam of GEO system, and there is one LEO satellite operating in the center of the beams. Furthermore, it was also assumed that the user terminal of the LEO is located at the center of each cell. Table I summarizes the simulation parameters. Each LEO satellite cell generates random traffic demand, having Gaussian distribution with mean value of $E[\rho_l]$ and variance of σ^2_ρ, over time.

B. Investigation of intermediate operations

Since a single-carrier system was assumed for the LEO satellite, the bandwidth allocated to the cell should be a continuous sub-bands which is divided into seven sub-bands from b_1 to b_7. For this purpose, the maximum allowable transmit power at the lth cell for each each sub-band is first estimated using (4), and Figure 3 illustrates an example of bandwidth allocation according to the principle proposed in [1]. Afterwards, the power allocation was regulated to $p_0 = P_{tot}/N_b$. This is because cell l can achieve the maximum transmission capacity when the total allowable power $P^L_l = p0$ is allocated to the allocated continuous sub-band set, $B^L_l = \{b_4, b_5, b_6, b_7\}$.

Given this allocation scheme for continuous sub-bands, the potential for overlapping sub-band assignments among neighboring cells becomes substantial. To circumvent co-channel interference amidst adjacent cells, it becomes imperative to establish a minimum separation distance, denoted as D_s which effectively prohibits the allocation of the same sub-bands

TABLE I
SIMULATION PARAMETERS

Parameter	Value
System parameter	
Frequency band	18.5-19.5 GHz
Noise temperature	293 K
Center point of the coverage area	(127°E, 0°)
GEO satellite system parameter	
Satellite orbit height	35786 Km
Satellite longitude	127°E
Single beam radius	200 Km
Single beam power	10 Watt
Frequency reuse factor	7
Interference threshold I_{th}	-132.5 dBW
LEO satellite constellation system parameter	
Altitude	1000 Km
Satellite longitude	127°E
Number of cells in a GEO beam	19
EIRP density	23 dBW/MHz
Cell radius	52Km
Duration of downlink transmission cycle	50 ms
Length of time slot	1 ms
Number of time slots for BH	50

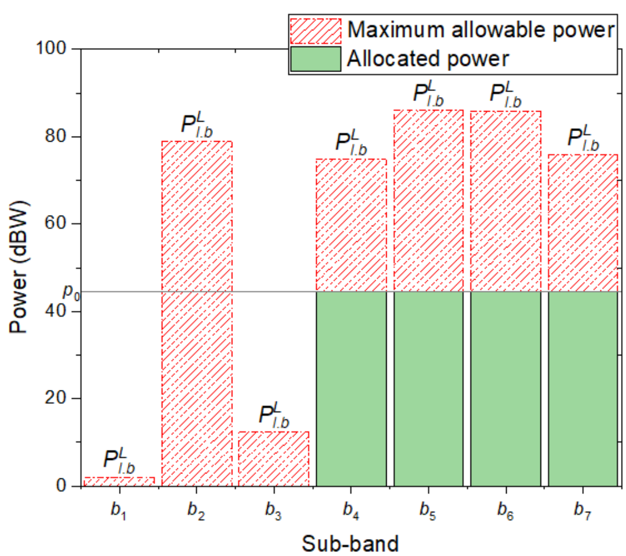

Fig. 3. An example of allocating power and bandwidth given the maximum allowable power estimation.

within the confines of this distance. Furthermore, prior to initiating the illumination of a cell, a critical decision pertains to selecting the specific cell to be illuminated.

Leveraging the temporal versatility inherent to BH satellites, a strategic approach is adopted, favoring cells with pronounced traffic demand or comparatively lower transmission capacities. This is achieved through the allocation of a higher number of time slots to such cells. Cells with limited transmission capacities inherently require a greater number of time slots to adequately accommodate their traffic demand. Consequently, the cell demanding the highest number of time slots attains precedence. In every discrete time slot, the sequential illumination of cells is determined based on the descending order of the required time slots for each cell.

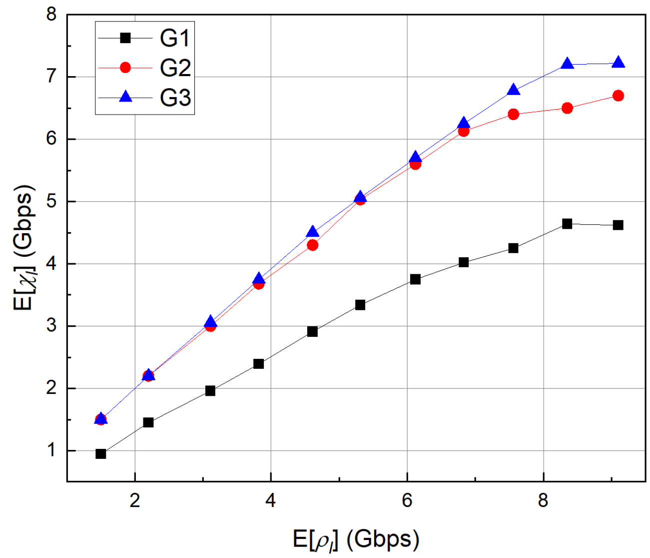

Fig. 4. Total traffic demand versus traffic supply.

IV. Simulation Results

In this section, we investigate the performance of the beam illumination technique according to the transmit antenna gain variations and minimum separation distance, D_s. We adopt the same system parameters and algorithms explained in the previous Section. Figure 4 represents $E[\rho_l]$ versus $E[\chi_l]$ when σ_ρ = 80 (Mbps) and D_s = 200 Km. We set three different conditions for directivity of receive antenna for the LEO satellite. In the legend, G1 scenario represents the case when receive antenna gain of the user terminal for the LEO is estimated by using the antenna gain model given in [11]. On the other hand, G2 represents a scenario when the antenna gain value varies within the range of [maximum, maximum - 3] dB. Lastly, in G3, the receiving antenna gain remains consistently at the maximum level.

The results in Fig. 4 shows that $E[\chi_l] \approx E[\rho_l]$, indicating that the traffic demand are almost fully supported in the investigated range when the LEO satellite transmit antenna is perfectly beamformed as in scenario G3. On the other hand, if we apply the antenna gain pattern due to the random motion of the user terminal [11], the traffic supply is much less than the traffic demand, showing less than 70% of the traffic demand.

Next, Figure 5 shows the $E[\chi_l]$ according to D_s when $E[\rho_l]$ = 480 (Mbps) and σ_ρ = 80 (Mbps). As we increase D_s, the number of illuminated cells decreases, leading to a reduction in the total traffic supply. The previous study set D_s to 200 km as an approximate value to achieve the trade off between spatial multiplexing and co-channel interference [1]. To determine the optimal D_s, additional research is necessary.

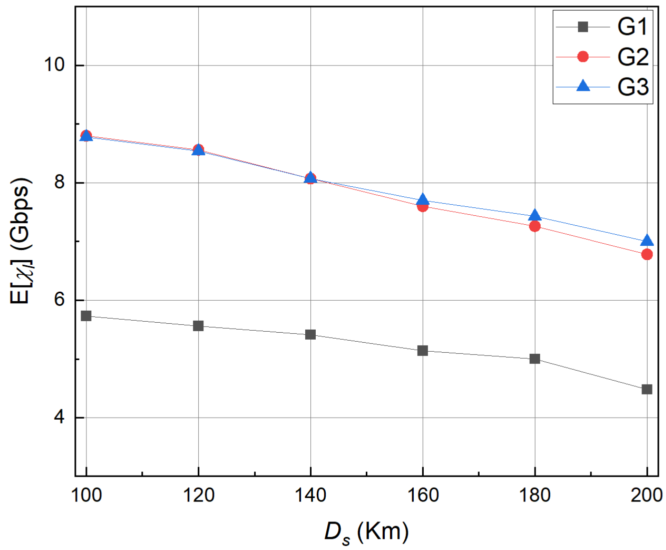

Fig. 5. Total traffic supply according to separation distance.

V. Conclusion and discussion

This paper reviewed the operational principle of the RA method for a BH LEO satellite system, and examined the performance simulation results. The simulation results investigated in this paper revealed that the directivity of receive antenna significantly affects the the performance of the RA scheme. Impact of the separation distance was also investigated without detailed interference analysis. The future study is therefore required to derive the optimum separation distance with multiple LEO satellites in orbit. Additionally, future studies will focus on estimating the performance when the LEO system employs multi-beam technology with frequency reuse.

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