IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received March 22, 2021, accepted March 31, 2021, date of publication April 6, 2021, date of current version April 15, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3071475

Global Energy Efficiency Optimization of a Ka-Band Multi-Beam LEO Satellite Communication System

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This work was supported in part by the NII's Memorandum of Understanding Grant (MoU) with KTH, and in part by the Grant-in-Aid for Scientific Research (Kakenhi) through the Ministry of Education, Science, Sports, and Culture of Japan under Grant 17K06453.

ABSTRACT We investigate the issue of global energy efficiency optimization in a multi-beam low Earth orbit (LEO) satellite communication system. Current terrestrial networks provide high-quality and low cost communication mainly in densely populated areas. However, the cost of extending wideband coverage to remote areas is unaffordable. LEO satellites provide a low cost solution for offering global coverage by supporting terrestrial networks. We consider downlink transmissions in Ka-band, where a LEO satellite transmits to access points or users directly. Impairments due to Ka-band channels, inter-beam interference as well as Doppler effects are taken into account in our mathematical model. We formulate the problem of jointly optimizing beam assignment and power allocation for maximizing global energy efficiency. Given the intractability of this problem, we propose to divide it into two subproblems: first, beam assignment optimization under fixed power per beam, and second, power allocation optimization under fixed beam assignment. We devise two algorithms, beam-wise power optimization and equal power optimization. These two algorithms solve the subproblems, beam assignment and power allocation, in a different way. Numerical results show that our proposed methods can greatly improve the global energy efficiency compared to the baseline method with a fixed power per beam.

INDEX TERMS Global energy efficiency, Ka-band, LEO, multi-beam, satellite communication.

I. INTRODUCTION

The rapid development of wireless applications has triggered massive demands on high-quality communications such as high sum-rate, low latency, extended coverage, and low power consumption [1]–[3]. Although 5G aims to support high-speed transmissions, massive connectivity, and seamless communications, the global coverage problem remains unsolved [4]. Indeed, sparsely populated areas, such as rural and remote areas, are difficult to be fully covered due to the low return on investments resulting from the tremendous costs of building terrestrial infrastructures and for seldom usage [5]. A satellite has a much wider coverage than the traditional terrestrial base station, and is seamless to geographical inaccessibility. Thus, integrated terrestrial-satellite communication is an ideal solution to this problem, as it can extend the coverage of the current terrestrial networks with much reduced cost, and easier deployment [5]–[7]. Besides, satellite networks can help alleviate the heavy network burden on capacity-limited terrestrial links [8]. Especially, the low Earth orbit (LEO) satellite communication with amplitude below 2000 km has a less power consumption and a shorter propagation delay [9], also the LEO satellite communication is highly expected to incorporate with terrestrial networks [10]. There has been a great number of studies proving that the terrestrial-satellite networks outperform the traditional terrestrial network in terms of data-rate, load [11]–[13] and security problems. In [14], beamforming schemes for optimizing the sum rate, and in [15], [16] the beamforming concerning the security problems are proposed for the satellite-terrestrial network. Additionally, energy efficiency has been pointed out

The associate editor coordinating the review of this manuscript and approving it for publication was Kashif Sharif.

as a key issue in satellite networks, as energy consumption should be limited while maintaining high data-rate performance [17]–[19].

Therefore, in this work, we aim at achieving high global energy efficiency for the downlink transmissions of a LEO satellite communication at Ka-band. LEO satellites have lower orbital altitudes and shorter propagation delays comparing to medium Earth orbit (MEO) and geostationary (GEO) satellites. This property makes the LEO satellites an attractive candidate for real-time, multi-cast, and Internet of Things applications [20]. To provide ubiquitous coverage, thousands of LEO satellites are launched for orbiting over the Earth [9]. Considering feasibility, the satellites' size is minimized to lower the manufacturing cost [20]. Besides ubiquitous coverage, when transmitting in Ka-band, LEO satellite networks can provide high-speed, broadband services. However, at this high frequency, signals suffer severe fading due to rain and tropospheric attenuation [21]. To provide high performance under such challenging environments, each LEO satellite may be equipped with multi-beam antennas with highly directive radiation patterns [22]. The multi-beam antenna system with a multicast transmission triggers beamforming optimization problem [23], [24]. Especially when activating more than one beam, the side lobes of different beams may overlap with each other, causing inter-beam interference [19]. Indeed, unlike for traditional parabolic antennas, the issue of inter-beam interferences becomes more crucial with the advent of digital beamforming techniques for LEO satellites, as with for example, fully-metallic geodesic lens antennas in [25]. Moreover, the mobility of LEO satellites induces Doppler effect [26], [27], resulting into increased interference levels. In mmWave networks, beam assignment and power allocation are effective techniques for mitigating such impairments [28]. Hence, we propose two optimization methods, beam-wise power optimization (BPO) and equal power optimization (EPO), which both account for the channel impairments at Ka-band, the inter-beam interferences, and Doppler effect. In BPO, the power of each beam is optimized individually. In EPO, the beams have an equal power and are turned off to optimize global energy efficiency (GEE). Because of the power difference among beams, our results show that BPO has a slower convergence but attains a higher suboptimal solution compared to EPO.

The main contributions of this paper are listed as follows:

1) We formulate the problem of GEE optimization in terms of joint beam assignment and power allocation, for a multi-beam LEO satellite system serving multiple access points/user terminals in the downlink considering Doppler effect and inter-beam interference.
2) Given the intractability of the original GEE optimization problem, it is decomposed into two sub-problems, namely beam assignment optimization assuming fixed transmit powers, and transmit power allocation optimization assuming fixed beam assignment.
3) Due to the non-linearity and non-concavity of the objective function in each subproblem, we propose to transform them into a tractable form through approximations. Thanks to that, we provide optimized methods to treat each subproblem.
4) We propose two optimization methods, BPO and EPO. Both methods iteratively solve the beam assignment and power allocation subproblems. In the power allocation subproblem, BPO assigns different transmit powers to each beam while EPO assigns equal transmit power to active beams. Thus, BPO achieves a higher GEE while EPO converges faster.
5) Computer simulation results show that the proposed optimization methods enable the GEE of the satellite network to be highly improved, compared to the baseline algorithm where the power per beam is fixed. Moreover, both proposed methods converge to a solution within few iterations, thereby limiting the amount of required computational complexity.

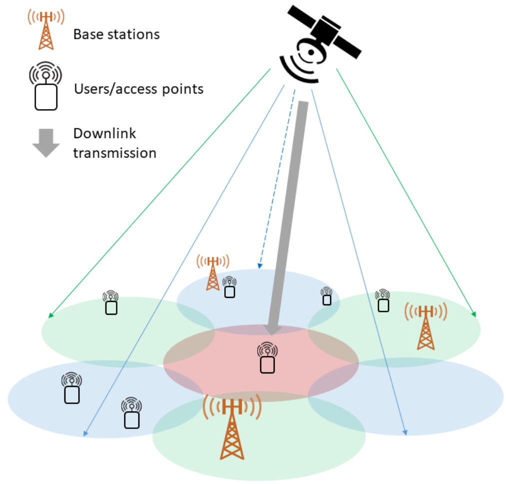


FIGURE 1. System model of the multi-beam LEO satellite network.

The remainder of this paper is organized as follows. In section II, we explain the satellite communication system model including antenna patterns, SINR, interferences, and total consumed power. In section III, we define the overall GEE optimization problem. Then, Section IV describes the details of the Proposed BPO and EPO methods. Computer simulation results are discussed in Section V. Finally, Section VI concludes the paper and gives directions for future work.

II. SYSTEM MODEL

We consider the downlink of a satellite communication system, where transmissions occur from the satellite towards K satellite access points/user terminals, as future LEO satellite systems are envisioned to support direct user device access [29]. The location of access points/user terminals, hereafter simply referred to as users, are known by the satellite. The number of available antenna beams on each satellite is M. We model the directive antenna beam pattern as in [30],

$$\begin{cases} g_t = \dfrac{2\pi - (2\pi - \theta)\delta}{\theta}, \\ g_s = \delta, \end{cases} \tag{1}$$

where g_t is the main lobe gain, g_s the sidelobe gain, $\delta \ll 1$, and θ the antenna beamwidth. The receive antenna gain of user k is denoted as g_k^{ru} and is normally distributed over the range [10, 15] dB [31].

The SINR of user k on beam m is expressed as,

$$\gamma_{k,m} = \frac{p_{k,m} g_t g_k^{ru} L_k}{I_{k,m}^i + I_{k,m}^d + N_0 W}, \tag{2}$$

where $p_{k,m}$ is the transmit power of beam m to user k, L_k the channel attenuation, W the bandwidth, and N_0 the power spectral density of the additive white Gaussian noise (AWGN). The inter-beam interference $I_{k,m}^i$ is defined as [32],

$$I_{k,m}^i = g_s g_k^{ru} L_k \sum_{m' \neq m} \sum_{k' \neq k} p_{k',m'} x_{k',m'}, \tag{3}$$

where $x_{k,m}$ is a binary variable indicating the beam allocation. The inter-carrier interference caused by Doppler effect is given as in [33], [34],

$$I_{k,m}^d = p_{k,m} g_t g_k^{ru} L_k (1 - \mathrm{sinc}^2(f_k T_s)), \tag{4}$$

where T_s is the symbol duration time and f_k is the Doppler shift related to user k expressed as,

$$f_k = \frac{v f_c}{c} \cos \phi_k, \tag{5}$$

where f_c is the carrier frequency, v the velocity of the satellite, c the speed of light, and ϕ_k the angle between the receiving direction of user k and the moving direction of the satellite.

In this work, perfect CSI knowledge is assumed at the satellite scheduler, namely, the Channel State Information (CSI) used during resource allocation optimization will not differ from the actual CSI during the subsequent data transmission. This is a somewhat ideal assumption as this requires the frame length T_f to be very small, in the order of a few symbol times T_s, for guaranteeing that the channel coherence time T_c, the inverse of the maximum Doppler shift, is larger than 2 T_f. However, assuming perfect CSI knowledge enables to quantify the best achievable energy efficiency performance of the proposed and benchmark methods. The effects of imperfect CSI knowledge and their impact on system performance under practical scenarios will be investigated in a future work. Similarly, the computation time required for solving all algorithms will be assumed negligible. However, these computation times should be also integrated in the imperfect CSI model of the follow-up work.

Thus, the achievable sum-rate of user k over all beams is,

$$R_k = \sum_{m=1}^{M} W \log_2(1 + \gamma_{k,m}) x_{k,m}. \tag{6}$$

The power dissipation is modeled by a constant circuit power consumption P_c and a variable power consumption P_a function of the number of active beams [17]. As the high power amplifier is a critical power consuming source in the transmitter, P_a is modeled using the energy efficiency parameter $\rho \in (0, 1]$ and transmit power $p_{k,m}$ [35],

$$P_a = \frac{1}{\rho} \sum_{k=1}^{K} \sum_{m=1}^{M} p_{k,m} x_{k,m}. \tag{7}$$

The total consumed power is hence,

$$P_{\text{tot}} = P_c + P_a. \tag{8}$$

We consider satellite and terrestrial networks sharing the same spectrum resources. Hence, as in [31], the transmit power $p_{k,m}$ should be constrained to protect the performance of the terrestrial network. The interference I_b caused by the satellite towards the base station b in the set $\mathcal{B}$ is,

$$I_b = g_s g_b L_b \sum_{m=1}^{M} \sum_{k=1}^{K} x_{k,m} p_{k,m}, \tag{9}$$

where g_b is the antenna gain of the base station. The interference I_b should be below the permissible interference power $P_r(p)$ defined in ITU-R SM.1448.

III. GLOBAL ENERGY EFFICIENCY OPTIMIZATION PROBLEM

The GEE η is defined as the ratio of the system sum-rate to the total consumed power P_{tot},

$$\eta(\mathbf{X}, \mathbf{P}) = \frac{\sum_{k=1}^{K} R_k}{P_c + \frac{1}{\rho} \sum_{k=1}^{K} \sum_{m=1}^{M} p_{k,m} x_{k,m}}, \tag{10}$$

where variables $\mathbf{X}$ and $\mathbf{P}$ are matrices of dimension $K \times M$ with their (k, m)-th element as $x_{k,m}$ and $p_{k,m}$. Similarly, we define vectors $\mathbf{x}$ of size K and $\mathbf{p}$ of size M, where element $x_k = \sum_m x_{k,m}$ and element $p_m = \sum_k p_{k,m}$. In the considered system, only one user may be allocated to each beam, for each scheduling time instant. Hence, hereafter we will drop the variable $p_{k,m}$ and equivalently make use of p_m, element of vector $\mathbf{p}$ of size M. The set of all K users is denoted as $\mathcal{K}$, and the set of all M beams is denoted as $\mathcal{M}$. The GEE optimization problem is formulated as,

$$\max_{\mathbf{X}, \mathbf{p}} \ \eta(\mathbf{X}, \mathbf{p}) \tag{11}$$

$$\text{s.t.} \ \sum_{m=1}^{M} p_m \leq P_T, \tag{11a}$$

$$p_m \leq P_f, \quad \forall m \in \mathcal{M} \tag{11b}$$

$$g_s g_b L_b \sum_{m=1}^{M} \sum_{k=1}^{K} x_{k,m} p_m \leq P_r(p), \forall b \in \mathcal{B} \tag{11c}$$

$$\sum_{m=1}^{M} x_{k,m} \leq 1, \quad \forall k \in \mathcal{K} \tag{11d}$$

$$\sum_{k=1}^{K} x_{k,m} \leq 1, \quad \forall m \in \mathcal{M} \tag{11e}$$

$$\sum_{m=1}^{M}\sum_{k=1}^{K} x_{k,m} \leq M, \tag{11f}$$

$$x_{k,m} = \{0,1\}, \quad \forall k \in \mathcal{K}, \forall m \in \mathcal{M}, \tag{11g}$$

where P_T is the total available transmit power, and P_f is the maximum transmit power of a single RF chain. Eq. (11a) is the total sum-power budget constraint. Constraint (11b) expresses that transmit power p_m from beam m cannot exceed P_f. Constraint (11c) indicates that the interference received at the base station b should be under the permissible interference power level $P_r(p)$. Constraint (11d) ensures that user k can be allocated only one beam at most, and constraint (11e) makes sure that the beam m is assigned to a unique user. Constraint (11f) ensures that the total number of assigned pairs of beam m and user k is smaller than M. Finally, Eq. (11g) is the binary constraint of the allocation variable $x_{k,m}$. The problem formulated in (11) is a mixed-integer optimization problem given that the indicator variable $\mathbf{X}$ is binary and the power variable $\mathbf{P}$ is continuous, with a non-linear non-convex objective function. Such problems are known to be generally NP-hard, and hence not resolvable within polynomial time. In the sequel, the original problem is simplified and we propose two different suboptimal approaches to solve this problem efficiently.

IV. PROPOSED BEAM AND POWER ALLOCATION METHODS

Given the intractability of the original optimization problem (11), we propose to split it into two subproblems, namely power allocation phase and beam assignment phase. In this section, we explain the details of the two proposed beam and power allocation methods for solving these simplified sub-problems, namely the beam-wise power optimization (BPO) algorithm, and the equal power optimization (EPO) algorithm.

A. PROPOSED BEAM-WISE POWER OPTIMIZATION ALGORITHM

Due to the intractability of problem (11), we propose the beam-wise power optimization (BPO) algorithm to solve it by splitting it into two sub-problems, namely beam assignment and power allocation and by iterating between the two. The beam assignment problem is described in section IV-A1 and the power allocation problem in section IV-A2. The Proposed BPO is described in Algorithm 1.

1) BEAM ASSIGNMENT

In this subproblem, we solve for the beam assignment variable $x_{k,m}$ while keeping the transmit power $p_{k,m}$ fixed. The initial value of the transmit power in the first iteration is chosen as P_{eq},

$$\begin{aligned} p_{k,m} &= \min\left\{P_f, \frac{P_T}{M}, \frac{P_r(p)}{g_s g_b L_b M}\right\} \\ &= P_{\text{eq}}, \quad \forall k \in \mathcal{K}, m \in \mathcal{M}. \end{aligned} \tag{12}$$

Algorithm 1 Proposed BPO: Beam-Wise Power Optimization Algorithm

```
Set $\epsilon$, $\mathbf{L}$
$i = 0$
$\mathbf{p}^{(0)} = P_{\text{eq}}$
do
    $i = i + 1$
    Beam assignment: find $\mathbf{x}^{(i)}$ with fixed $\mathbf{p}^{(i-1)}$.  ▷ Apply Algorithm 2 in Sec. IV-A1
    Power allocation: find $\mathbf{p}^{(i)}$ with fixed $\mathbf{x}^{(i)}$  ▷ Apply Algorithm 3 in Sec. IV-A2
    Update: $\mathbf{p}^* = \mathbf{p}^{(i)}$, $\mathbf{x}^* = \mathbf{x}^{(i)}$
while $|\eta(\mathbf{x}^{(i)}, \mathbf{p}^{(i)}) - \eta(\mathbf{x}^{(i-1)}, \mathbf{p}^{(i-1)})| \geq \epsilon$
Output: $\mathbf{p}^*$, $\mathbf{x}^*$
```

This is to ensure that the fixed transmit power satisfies the power constraints (11a), (11b), and (11c). Indeed, assuming equal fixed power per beam at the first iteration, constraint (11c) is rewritten as,

$$\sum_{m=1}^{M}\sum_{k=1}^{K} x_{k,m} p_{k,m} \leq \frac{P_r(p)}{g_s g_b L_b}, \quad \forall b \in \mathcal{B}, \tag{13}$$

where the right-hand side divided by M is an upper-bound to $p_{k,m}$, and similarly regarding constraint (11a) giving the second term in the minimization of (12). With the power allocation variable $\mathbf{p}$ fixed to the solution of the previous iteration, the power assigned to each beam p_m is fixed, regardless of the user assigned to beam m, i.e., $p_{k,m} = p_m$ for all k. The total power consumed by all beams can hence be simplified as,

$$\sum_{k=1}^{K}\sum_{m=1}^{M} x_{k,m} p_{k,m} = \sum_{m=1}^{M} p_m. \tag{14}$$

Hence, the objective function of (11) can be simplified as,

$$\eta(\mathbf{X}) = \frac{\sum\limits_{k=1}^{K}\sum\limits_{m=1}^{M} W \log_2\left(1 + \frac{p_m g_t g_k^{ru} L_k}{I_{k,m}^{i} + I_{k,m}^{d} + N_0 W}\right) x_{k,m}}{P_c + \frac{1}{\rho}\sum\limits_{m=1}^{M} p_m}, \tag{15}$$

where the inter-beam interference is expressed as,

$$\begin{aligned} I_{k,m}^{i} &= g_s g_k^{ru} L_k \sum_{m' \neq m}\sum_{k' \neq k} x_{k',m'} p_{k',m'} \\ &= g_s g_k^{ru} L_k \sum_{m' \neq m} p_{m'}. \end{aligned} \tag{16}$$

Defining a new matrix $\mathbf{Q}$, in which element $q_{k,m}$ is,

$$q_{k,m} = \frac{W}{P_c + \frac{1}{\rho}\sum\limits_{m=1}^{M} p_m} \log_2\left(1 + \frac{p_m g_t g_k^{ru} L_k}{I_{k,m}^{i} + I_{k,m}^{d} + N_0 W}\right), \tag{17}$$

and using the vector variable $\mathbf{x}$ defined in Sec. III, the beam assignment sub-problem can be formulated as,

$$\max_{\mathbf{x}} \sum_{k=1}^{K}\sum_{m=1}^{M} x_{k,m} q_{k,m} \tag{18}$$

$$\text{s.t.} \sum_{m=1}^{M} x_{k,m} \leq 1, \quad \forall k \in \mathcal{K} \tag{18a}$$

$$\sum_{k=1}^{K} x_{k,m} \leq 1, \quad \forall m \in \mathcal{M} \tag{18b}$$

$$\sum_{k=1}^{K}\sum_{m=1}^{M} x_{k,m} = M, \quad \forall k \in \mathcal{K}, \forall m \in \mathcal{M}. \tag{18c}$$

Problem (18) has a linear objective function in variable $x_{k,m}$ and linear constraints. Therefore, this problem can be efficiently solved by the one-to-one *Hungarian* Algorithm [36] given in Algorithm 2.

Algorithm 2 Proposed BPO Subproblem 1: Beam Assignment Algorithm

```
Initialize: Q
Apply Hungarian Algorithm [36].
Output: x*
```

2) POWER ALLOCATION

Since the beam assignment has been fixed by the solution of the previous step, we can express this subproblem as follows. We use p_k as the element of vector $\mathbf{p}$ of size M. Defining the set $\mathcal{A}$ containing users assigned to one beam, namely $|\mathcal{A}| = M$, the objective function can be written as,

$$\eta\left(\mathbf{p}\right) = \frac{\sum\limits_{k\in\mathcal{A}} W \log_2\left(1 + \frac{p_k g_t g_k^{ru} L_k}{I_k^i + I_k^d + N_0 W}\right)}{P_c + \frac{1}{\rho}\sum\limits_{k\in\mathcal{A}} p_k} = \frac{C(\mathbf{p})}{D(\mathbf{p})}, \tag{19}$$

where I_k^i is the inter-beam interference among users in the set $\mathcal{A}$,

$$I_k^i = g_s g_k^{ru} L_k \sum_{k'\neq k} p_{k'}, \quad \forall k \in \mathcal{A}, \tag{20}$$

and I_k^d is the Doppler interference among users in the set $\mathcal{A}$,

$$I_k^d = p_k g_t g_k^{ru} L_k (1 - \text{sinc}^2(f_k T_s)), \quad \forall k \in \mathcal{A}. \tag{21}$$

The power allocation sub-problem is hence formulated as,

$$\max_{\mathbf{p}} \frac{\sum\limits_{k\in\mathcal{A}} W \log_2\left(1 + \frac{p_k g_t g_k^{ru} L_k}{I_k^i + I_k^d + N_0 W}\right)}{P_c + \frac{1}{\rho}\sum\limits_{k\in\mathcal{A}} p_k}, \tag{22}$$

$$\text{s.t.} \sum_{k\in\mathcal{A}} p_k \leq P_T, \tag{22a}$$

$$p_k \leq P_f, \quad \forall k \in \mathcal{A} \tag{22b}$$

$$\sum_{k\in\mathcal{A}} p_k \leq \frac{P_r(p)}{g_s g_b L_b}. \tag{22c}$$

In problem (22), the objective function is non linear and cannot be solved directly. That is, the numerator $C(\mathbf{p})$ in Eq. (19) is non-linear and non-concave, though the denominator $D(\mathbf{p})$ is affine, so the objective function in problem (22) is not pseudo-concave either. Hence, this sub-problem is intractable in its original form. To apply the fractional transformation method, we first transform the objective function into a pseudo-concave form through first order approximation. We define the value λ^* as,

$$\lambda^* = \frac{\tilde{C}(\mathbf{p}^*)}{D(\mathbf{p}^*)}, \tag{23}$$

where, $\tilde{C}(\mathbf{p})$ is the first order approximation of the numerator $C(\mathbf{p})$, defined as,

$$\tilde{C}(\mathbf{p}^*) = W \sum_{k\in\mathcal{A}} \tilde{R}_k(\mathbf{p}^*). \tag{24}$$

$\tilde{R}_k(\mathbf{p}^*)$ is the lower bound of the sum-rate of user k, where for any feasible power vector $\mathbf{p}_0$,

$$\begin{aligned} R_k(\mathbf{p}) &\geq f_1(\mathbf{p}) - \left(f_2(\mathbf{p}_0) - \nabla_{\mathbf{p}}^T f_2(\mathbf{p}_0)(\mathbf{p} - \mathbf{p}_0)\right) \\ &= \tilde{R}_k(\mathbf{p}), \end{aligned} \tag{25}$$

where $f_1(\mathbf{p})$ and $f_2(\mathbf{p})$ are components of $C(\mathbf{p})$ rewritten as,

$$C(\mathbf{p}) = \sum_{k\in\mathcal{A}} W(f_1\left(\mathbf{p}\right) - f_2\left(\mathbf{p}\right)), \tag{26}$$

where,

$$f_1(\mathbf{p}) = \log_2\left(p_k g_t g_k^{ru} L_k + I_k^i + I_k^d + N_0 W\right), \tag{27}$$

and

$$f_2(\mathbf{p}) = \log_2\left(I_k^i + I_k^d + N_0 W\right). \tag{28}$$

Finally, the power allocation optimization sub-problem is formulated as [37],

$$\max_{\mathbf{p}} \tilde{C}(\mathbf{p}) - \lambda^* D(\mathbf{p}), \tag{29}$$

$$\text{s.t.} \sum_{k\in\mathcal{A}} p_k \leq P_T, \tag{29a}$$

$$p_k \leq P_f, \quad \forall k \in \mathcal{A} \tag{29b}$$

$$\sum_{k\in\mathcal{A}} p_k \leq \frac{P_r(p)}{g_s g_b L_b}. \tag{29c}$$

We solve the optimization problem (29) iteratively. In the first iteration, the value of λ^* is unknown. We set an initial value of λ^* and calculate the power allocation vector $\mathbf{p}$ using Dinkelbach's algorithm. Then λ^* is updated according to Eq. (23). For the second and further iterations, the value of $\mathbf{p}$ is calculated based on the λ^* of previous iteration. In each iteration, the subproblem is solved by standard convex optimization methods [38]. The optimization ends when $\mathbf{p}$ converges. The Proposed BPO power allocation is described in Algorithm 3.

Algorithm 3 Proposed BPO Subproblem 2: Power Allocation Algorithm

```
Initialization: $\mathbf{p}_0$.
repeat
    $\epsilon > 0, n = 0, \lambda_n = 0$
    repeat
        $\mathbf{p}^* = \arg\max\{\tilde{C}(\mathbf{p}) - \lambda_n D(\mathbf{p}) : \sum_{k\in\mathcal{A}} p_k \le P_T, p_k \le P_f, \forall k \in \mathcal{A}, \sum_{k\in\mathcal{A}} p_k \le \frac{P_r(p)}{g_s g_b L_b}\}$.  ▷ Dinkelbach's algorithm
        $F(\lambda_n) = \tilde{C}(\mathbf{p}^*) - \lambda_n D(\mathbf{p}^*)$
        $\lambda_{n+1} = \frac{\tilde{C}(\mathbf{p}^*)}{D(\mathbf{p}^*)}$
        $n = n + 1$
    until $F(\lambda_n) < \epsilon$
    $\mathbf{p}_0 = \mathbf{p}^*$
until convergence
```

B. EQUAL POWER OPTIMIZATION ALGORITHM

As the BPO algorithm optimizes the transmit power of each beam separately, it still requires a high computational complexity and hence, it is time consuming to obtain the power and beam solutions, as will be illustrated in the numerical results. Thus, to speed up the computational time, we propose an algorithm named equal power optimization (EPO), where the transmit powers of every active beam are equal and defined as p_e. Namely, we set p_e as,

$$p_k = p_e, \quad \forall k \in \mathcal{A}. \tag{30}$$

In the EPO algorithm, we solve the optimization problem (11) in three steps. First, we optimize the beam assignment $\mathbf{X}^s$, under the assumption that all beams are active with a fixed transmit power p_0. Second, we find out the optimal transmit power p_e^* based on the fixed solution $\mathbf{X}^s$ given by the previous step. The final step solves the optimal beam assignment $\mathbf{X}^*$ and number of active beams, which can be smaller than M. The rationale of this third step is that, by turning off some beams, more energy can be saved without compromising data transmission, thereby improving the GEE objective function. The general EPO algorithm is described in Algorithm 4,

Algorithm 4 Proposed EPO: Equal Power Optimization Algorithm

```
Set $p_0$
Initial beam assignment: setting all $M$ beams to be active, find $\mathbf{X}^s$ with fixed $p_0$.  ▷ Apply Hungarian algorithm in Sec. IV-B1
Equal power allocation: find $p_e^*$ with fixed $\mathbf{X}^s$.  ▷ in Sec. IV-B2
Active beam optimization: find $\mathbf{X}^*$ for fixed $p_e^*$.  ▷ in Sec. IV-B3
Output: $p_e^*, \mathbf{X}^*$
```

With equal transmit power, the optimized vector variable $\mathbf{p}$ in problem (11) boils down to a scalar variable p_e. The objective function becomes,

$$\eta\left(\mathbf{X}, p_e\right) = \frac{\sum_{k=1}^{K}\sum_{m=1}^{M} W \log_2\left(1 + \frac{p_e g_t g_k^{ru} L_k}{I_{k,m}^i + I_{k,m}^d + N_0 W}\right) x_{k,m}}{P_c + \frac{1}{\rho}\sum_{k=1}^{K}\sum_{m=1}^{M} p_e x_{k,m}}. \tag{31}$$

Then, under equal power per beam, the original optimization problem (11) is simplified as,

$$\max_{\mathbf{X}, p_e} \ \eta(\mathbf{X}, p_e) \tag{32}$$

$$\text{s.t.} \ \sum_{m=1}^{M}\sum_{k=1}^{K} x_{k,m} p_e \le P_T, \tag{32a}$$

$$p_e \le P_f, \tag{32b}$$

$$p_e g_s g_b L_b \sum_{m=1}^{M}\sum_{k=1}^{K} x_{k,m} \le P_r(p), \forall b \in \mathcal{B} \tag{32c}$$

$$\sum_{m=1}^{M} x_{k,m} \le 1, \quad \forall k \in \mathcal{K} \tag{32d}$$

$$\sum_{k=1}^{K} x_{k,m} \le 1, \quad \forall m \in \mathcal{M} \tag{32e}$$

$$\sum_{m=1}^{M}\sum_{k=1}^{K} x_{k,m} \le M, \tag{32f}$$

$$x_{k,m} = \{0, 1\}, \quad \forall k \in \mathcal{K}, \forall m \in \mathcal{M}. \tag{32g}$$

1) INITIAL BEAM ASSIGNMENT

In the first step, we solve for the beam assignment variable $x_{k,m}$ while keeping the transmit power p_e fixed and assuming that all M beams are active, that is $\sum_{m=1}^{M}\sum_{k=1}^{K} x_{k,m} = M$. Then, the transmit power constraint (32c) can be rewritten as,

$$p_e \le \frac{P_r(p)}{g_s g_b L_b M}. \tag{33}$$

We set p_{e0} as the initial value of transmit power p_e. The initial value p_{e0} should satisfy all the transmit power constraints (32a), (32b) and (32c), hence,

$$p_e = \min\left\{P_f, \frac{P_T}{M}, \frac{P_r(p)}{g_s g_b L_b M}\right\} = p_{e0}. \tag{34}$$

The objective function of the initial beam assignment subproblem under equal power is,

$$\eta\left(\mathbf{X}\right) = \frac{\sum_{k=1}^{K}\sum_{m=1}^{M} W \log_2\left(1 + \frac{p_{e0} g_t g_k^{ru} L_k}{I_{k,m}^i + I_{k,m}^d + N_0 W}\right) x_{k,m}}{P_c + M p_{e0}/\rho}, \tag{35}$$

where, the inter-beam interference is fixed as follows,

$$I_{k,m}^i = g_s g_k^{ru} L_k p_{e0} (M - 1). \tag{36}$$

We define a variable $q_{k,m}$ as,

$$q_{k,m} = \frac{\sum_{k=1}^{K}\sum_{m=1}^{M} W\log_2\left(1+\frac{p_{e0}g_t g_k^{ru}L_k}{I_{k,m}^i+I_{k,m}^d+N_0W}\right)}{P_c+Mp_{e0}/\rho}. \tag{37}$$

Finally, the initial beam assignment subproblem becomes,

$$\max_{\mathbf{X}} \sum_{k=1}^{K}\sum_{m=1}^{M} x_{k,m}q_{k,m} \tag{38}$$

$$\text{s.t.} \sum_{k=1}^{K} x_{k,m} \le 1, \quad \forall m \in \mathcal{M} \tag{38a}$$

$$\sum_{m=1}^{M} x_{k,m} \le 1, \quad \forall k \in \mathcal{K} \tag{38b}$$

$$\sum_{m=1}^{M}\sum_{k=1}^{K} x_{k,m} = M \tag{38c}$$

$$x_{k,m} = \{0,1\}, \quad \forall k \in \mathcal{K}, \forall m \in \mathcal{M}. \tag{38d}$$

This is a linear binary assignment problem which can be solved by the one-to-one *Hungarian* algorithm as in Algorithm 2.

2) EQUAL POWER ALLOCATION

In the second step, the transmit power of each beam p_e, which is equal among all beams, is optimized. As the initial beam assignment solution $\mathbf{X}^s$ has been fixed in the previous step, we denote as $\mathcal{A}$ the set of users with allocated beams. The objective function of the power allocation sub-problem becomes,

$$\eta(p_e) = \frac{\sum_{k\in\mathcal{A}} W\log_2(1+\frac{p_e g_t g_k^{ru}L_k}{I_k^i+I_k^d+N_0W})}{P_c+Mp_e/\rho}, \tag{39}$$

where the inter-beam interference is fixed as follows,

$$I_k^i = p_e g_s g_k^{ru} L_k\,(M-1)\,, \tag{40}$$

and the Doppler interference is given as,

$$I_k^d = p_e g_t g_k^{ru} L_k\left(1-\mathrm{sinc}^2(f_k T_s)\right). \tag{41}$$

Thus the equal power allocation sub-problem is formulated as,

$$\max_{\mathbf{p}} \frac{\sum_{k\in\mathcal{A}} W\log_2\left(1+\frac{p_e g_t g_k^{ru}L_k}{I_k^i+I_k^d+N_0W}\right)}{P_c+Mp_e/\rho}, \tag{42}$$

$$\text{s.t. } Mp_e \le P_T \tag{42a}$$

$$p_e \le P_f \tag{42b}$$

$$Mp_e \le \frac{P_r(p)}{g_s g_b L_b}. \tag{42c}$$

As in problem (22), the objective function here is of a fractional form and is not concave nor pseudo-concave. Therefore, we have performed similar transformations as in section IV-A2, in order to obtain a first order approximation. Applying the same transformations as those developed in Eqs. (23)-(28), but for the scalar variable p_e, the power allocation sub-problem can be expressed as,

$$\max_{p_e} \tilde{C}(p_e) - \lambda^* D(p_e) \tag{43}$$

$$\text{s.t. } Mp_e \le P_T \tag{43a}$$

$$p_e \le P_f \tag{43b}$$

$$Mp_e \le \frac{P_r(p)}{g_s g_b L_b}. \tag{43c}$$

As the appropriate value of parameter λ^* is unknown, we solve the optimization sub-problem by iterating over λ and p_e as shown in Algorithm 5.

Algorithm 5 Proposed EPO Subproblem 2: Power Allocation Algorithm

```
Initialization: $p_{e0}$.
repeat
    $\epsilon > 0, n = 0, \lambda_n = 0$
    repeat
        $p_e^* = \arg\max\{\tilde{C}(p_e) - \lambda_n D(p_e) : Mp_e \le P_T, p_e \le P_f, Mp_e \le \frac{P_r(p)}{g_s g_b L_b}\}$    ▷ Dinkelbach's algorithm
        $F(\lambda_n) = \tilde{C}(p_e^*) - \lambda_n D(p_e^*)$
        $\lambda_{n+1} = \frac{\tilde{C}(p_e^*)}{D(p_e^*)}$
        $n = n + 1$
    until $F(\lambda_n) < \epsilon$
    $p_{e0} = p_e^*$
until convergence
```

3) ACTIVE BEAM OPTIMIZATION

From the two previous steps, we have obtained the initial beam assignment solution $\mathbf{X}^s$ and optimal equal power allocation solution p_e^*, assuming the maximum number of active beams M. However, the optimal beam assignment solution $\mathbf{X}^*$ does not necessarily occur in the case where all available beams are used. In the last step, the number of active beams is optimized where the transmit power p_e^* and the initial beam assignment $\mathbf{X}^s$ are given. We define a new variable $\mathbf{y}$, a vector of size K, whose k-th element y_k indicates whether user k is allocated an active beam or not. And y_k is initialized from the sub-optimal beam assignment solution $\mathbf{X}^s$,

$$y_k = \sum_{m=1}^{M} x_{k,m}, \quad k \in \mathcal{A}. \tag{44}$$

The active beam optimization sub-problem can be expressed as,

$$\max_{\mathbf{y}} \frac{\sum_{k\in\mathcal{A}} W\log_2\left(1+\frac{p_e g_t g_k^{ru}L_k}{I_k^i+I_k^d+N_0\,W}\right)y_k}{P_c+\frac{p_e}{\rho}\sum_{k\in\mathcal{A}} y_k} \tag{45}$$

$$\text{s.t. } \sum_{k\in\mathcal{A}} y_k \le M \tag{45a}$$

$$y_k = \{0,1\}, \quad k \in \mathcal{A}. \tag{45b}$$

As the inter-beam interference term and the denominator of the objective function, both contain the binary optimization variable, the objective function is non-linear and hence the one-to-one Hungarian algorithm used so far is inapplicable. Therefore, we adopt an iterative resolution whereby the number of active beams is fixed and decreased at each iteration. We define B as number of the active beams at each iteration, where $B \in [1, M]$. As y_k is initialized from $\mathbf{X}^s$, the constraint on the number of active beams is given by,

$$\sum_{k\in\mathcal{A}} y_k = \sum_{k\in\mathcal{A}} \sum_{m=1}^{M} x_{k,m} = B, \tag{46}$$

expressed as,

$$\sum_{k'\neq k} y_{k'} = B - 1. \tag{47}$$

The objective function becomes,

$$\eta(\mathbf{y}) = \frac{\sum\limits_{k\in\mathcal{A}} W \log_2\left(1 + \frac{p_e g_t g_k^{ru} L_k}{I_k^i + I_k^d + N_0 W}\right) y_k}{P_c + B p_e/\rho}, \tag{48}$$

where the inter-beam interference I_k^i varies with the number of active beams,

$$I_k^i = p_e g_s g_k^{ru} L_k (B-1). \tag{49}$$

The Doppler shift interference is expressed as,

$$I_k^d = p_e g_t g_k^{ru} L_k (1 - \mathrm{sinc}^2(f_k T_s)), \quad k \in \mathcal{A}. \tag{50}$$

Given the number of active beams B varying from M to 1, the active beam optimization sub-problem is formulated as,

$$\max_{\mathbf{y}} \ \eta(\mathbf{y}) \tag{51}$$

$$\text{s.t.} \sum_{k\in\mathcal{A}} y_k = B \tag{51a}$$

$$y_k = \{0, 1\}, \quad k \in \mathcal{A}. \tag{51b}$$

The problem (51) is solved by a *Greedy* method. The solutions of vector $\mathbf{y}$ are different combinations of binary digits, 0 and 1, whose sum is fixed as B. For each fixed value of B, applying the Greedy method, the vector $\mathbf{y}$ maximizing the GEE is retained. Finally, the optimal number of active beams B^* is derived. The number of active beam sub-problem (45) is solved as described in Algorithm 6.

Algorithm 6 Proposed EPO Subproblem 3: Active Beam Optimization

```
Initialization: $p_e, X^s$.
$\vec{\eta} = \mathrm{zeros}(M)$
for $i = M$ to 1 do
    $B = i$
    $\mathbf{y}^* = \arg\max\{\eta(\mathbf{y}) : \sum_{k\in\mathcal{A}} y_k = B, y_k = \{0,1\}, k \in \mathcal{A}.\}$    ▷ Apply Greedy algorithm.
    $\vec{\eta}(i) = \eta(\mathbf{y}^*)$
end
$\eta^* = \max\{\vec{\eta}\}, B^* = \arg\max\{\vec{\eta}\}$
Output: $\eta^*, B^*$
```

TABLE 1. Simulation parameters.

Parameter	Value
Orbital altitude h [39]	780 km
Orbital velocity v	7.46 km/s
Center frequency f_c [31]	20 GHz
Bandwidth W [31]	28 MHz
Symbol duration time T_s [39]	1 μs
Rain fading parameter (μ, σ) [40]	(-2.6 dB, 1.6 dB)
Noise spectral density N_0	-174 dBw/Hz
Number of antenna beams M [40]	7
Satellite antenna gain g_t [31]	52.1 dB
Satellite antenna side lobe g_s	5 dB
Users' antenna gains [31]	[10 15] dB
Base station gain g_b	5 dB
Maximum transmit power P_f	0 dBw
Permissible interference power $P_r(p)$	-111 dBw
Circuit power dissipation P_c [35]	10 dBw
Amplifier efficiency ρ [35]	0.8

V. NUMERICAL EVALUATION

A. SIMULATION SETUP

The proposed and benchmark algorithms are evaluated in a Ka-band downlink satellite system, where the LEO satellite's altitude h is fixed to 780 km. In this orbit, the satellite's velocity v is around 7.46 km/s. The number of available satellite beams M is set to 7. Satellite users (or access points) are uniformly distributed within the satellite's coverage. Fig. 2 is a snapshot of the user positions in sky view, where the satellite is located at $(x, y) = (0, 0)$. The channel attenuation L_k is modeled following [31] as,

$$L_k = d_k |h_k|^2, \tag{52}$$

where d_k is user k's path loss given by the Friis formula and h_k is the channel fading coefficient following the log-normal distribution. The downlink signal center frequency is taken as 20 GHz, with a bandwidth W of 28 MHz. Other simulation parameters are given in Table 1. All results were obtained by averaging over a 1000 channel independent realizations, unless stated otherwise.

B. BENCHMARK ALGORITHM

To evaluate the performance of the proposed algorithms, we consider a fixed power optimization (FPO) algorithm aiming at GEE optimization as a performance benchmark. By the fixed power allocation, we ensure a low computational complexity which is primordial for LEO satellite systems (give reference). In addition, this is not an oversimplified benchmark since the user-to-beam assignment is still optimized for GEE maximization. Here, the transmit power on each beam is fixed as the maximum available power, and all beams are active, namely,

$$p_{k,m} = \min\left\{P_f, \frac{P_T}{M}, \frac{P_r(p)}{g_s g_b L_b M}\right\}, \quad \forall k \in \mathcal{K}, m \in \mathcal{M}. \tag{53}$$

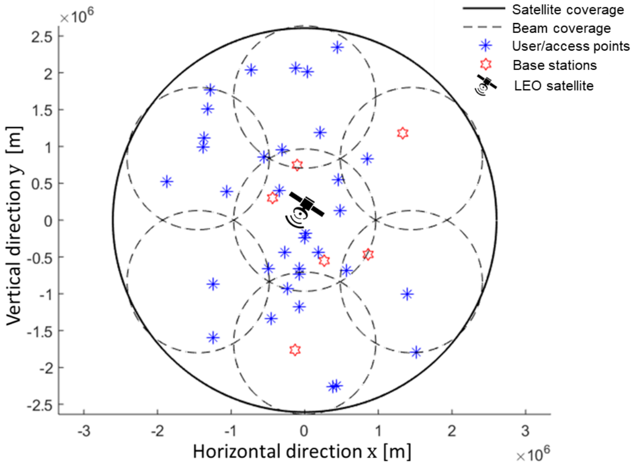


FIGURE 2. The locations of users/access points and base stations under the satellite coverage.

Eq. (53) ensures that constraints (11a), (11b), and (11c) are satisfied. Thus, the beam assignment problem is optimized through the *Hungarian* algorithm as in Algorithm 2.

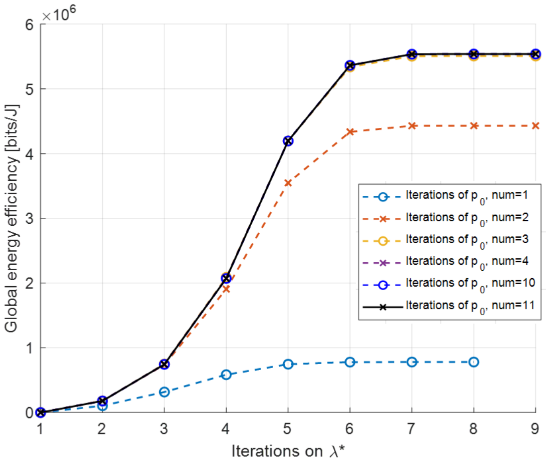
C. SIMULATION RESULTS

We first verify the convergence of the proposed power allocation method in BPO and EPO algorithms. Then we compared the ergodic GEE, sum-rate, and consumed power of the Proposed BPO, EPO, and the benchmark FPO algorithms.

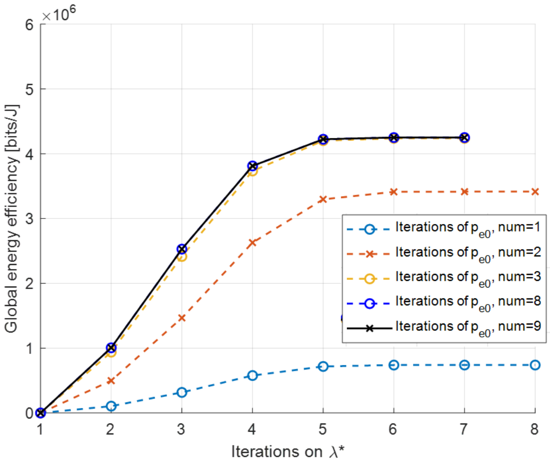
1) CONVERGENCE BEHAVIORS

In the BPO and EPO algorithms, there are two iterative blocks in the power allocation, one over λ^* and the other, over feasible points $\mathbf{p_0}$. Fig. 3 shows the convergence in terms of GEE for one channel instance and 30 users. We observe that, the BPO algorithm converges after 8 or 9 iterations of λ^* under the same $\mathbf{p_0}$ and approaches optimum in the third iteration of $\mathbf{p_0}$. The EPO algorithm converges after 7 or 8 iterations of λ^* under p_{e0} and approaches optimum in the third iteration of p_{e0} also. In Fig. 3, the achieved GEE level of BPO algorithm is final but the one achieved by EPO algorithm is still an intermediate solution, as EPO is finalized after the active beam optimization step in section IV-B3. As expected in Fig. 3, the GEE of Proposed BPO algorithm is larger than that of Proposed EPO algorithm.

Next, Fig. 4 shows the effect of the number of active beams for the Proposed EPO algorithm. The GEEs for different number of users K are calculated under the same channel instance. When the number of users is 5, the GEE decreases as the number of active beams increases, due to the lack of multi-user diversity over beams. For larger values of K, we observe a trade-off point, namely, the best number of active beams is $B^* = 2$ for $K = 10$ and 20, and $B^* = 4$ for $K = 30$. Depending on the number of activated beams, we observe a significant variation of the achievable GEE level. This behavior validates the effectiveness of the third step in the Proposed EPO algorithm.



(a) Proposed BPO algorithm.



(b) Proposed EPO algorithm.

FIGURE 3. The GEE convergence behaviors against λ^* and p_0 of the proposed power allocation methods in a) BPO and b) EPO given in algorithm 3 and algorithm 4. The number of users K is 30 and the channel instance is the same.

2) SYSTEM PERFORMANCE

Next, we compare the performance of Proposed BPO, Proposed EPO and conventional FPO algorithms. Their ergodic GEE, sum-rate, and consumed power are compared with different number of users, $K = 5, 10, 20, 30$. Note that, when the number of users K is 5, it is smaller than the number of active beams $M = 7$, i.e., $K < M$. In this case, $M - K$ beams should be turned off in all algorithms.

Firstly, the ergodic GEE is plotted in Fig. 5. As expected, the Proposed BPO and EPO algorithms achieve much higher GEEs than the conventional FPO. Since the conventional FPO always transmits with maximum available power, it consumes more power than the two proposed algorithms. Additionally, by iterating between beam assignment and power allocation, the Proposed BPO and EPO tend to allocate user-beam pairs with lower inter-beam interference. That is, the Proposed BPO and EPO algorithms can significantly improve the GEE by reducing the transmit power and inter-beam interference. The Proposed BPO achieves the highest GEE performance as

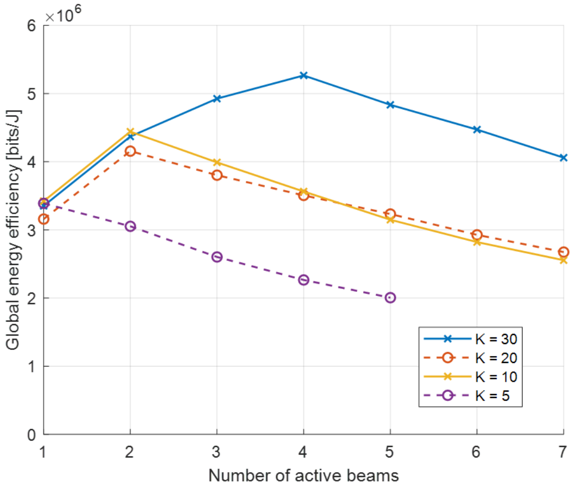


FIGURE 4. **The GEE against varying number of active beams and different number of users, proposed EPO algorithm.**

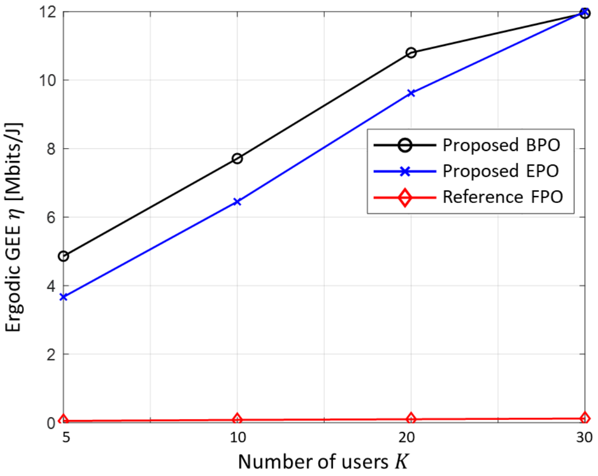


FIGURE 5. **The ergodic GEE against varying number of users over 1000 channel realizations.**

the transmit powers of each beam are optimized. From Fig. 5, the ergodic GEEs for all algorithms increase as the number of users grows. This is expected due to the multi-user diversity effect.

Next, Fig. 6 compares the sum-rate performance of all algorithms. It is observed that the conventional FPO provides the largest sum-rate, given that it transmits with maximum power, while controlling the harmful effects of inter-beam interference by means of user-to-beam assignment optimization.

Although the sum-rate of the Proposed BPO and EPO are smaller than that of FPO, the consumed power of FPO is considerable, as shown in Fig. 7. Since in conventional FPO, the transmit power is fixed, its consumed power remains constant to 69.31 dBm when the number of users K becomes larger than that of beams M. As observed, two beams are turned off when $K = 5$ so that the consumed power is smaller. The Proposed BPO achieves around 30 dB savings in power, namely more than 99.7% reduction compared to Reference FPO, while largely outperforming GEE as seen in Fig. 5.

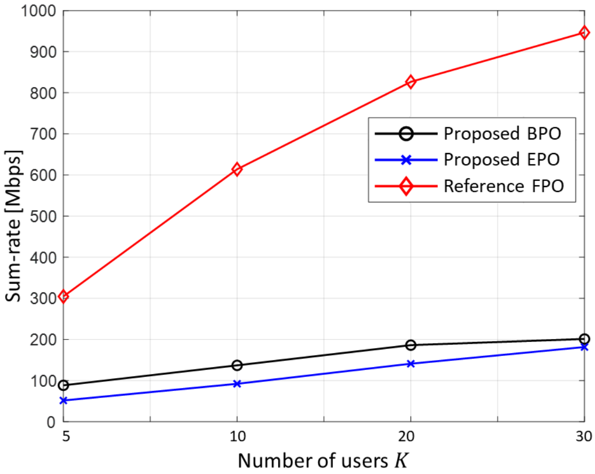


FIGURE 6. **The sum-rate against varying number of users.**

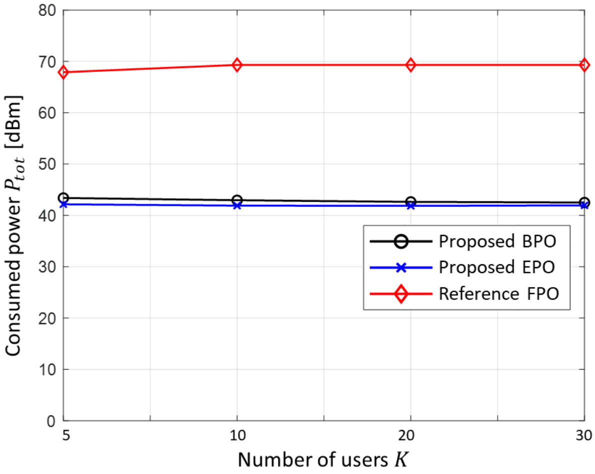


FIGURE 7. **The transmit power consumption against varying number of users.**

We evaluate the computational complexity of each algorithm in terms of their computational running times, averaged over 1000 channel realizations. As shown in Fig. 8, the Proposed BPO requires a longer time than the other two algorithms. This is due to its iterative procedure between the beam assignment subproblem and the power allocation subproblem, which is time consuming. As the number of users increases, the computational time increases too. By contrast, the computational times of Proposed EPO and the Reference FPO have only small variations against the number of users. The Reference FPO is the most computationally-efficient algorithm as expected. Although the Proposed BPO has the highest computational complexity, it is maximum 7 times higher than that required by Proposed EPO algorithm while drastically improving the GEE performance compared to Reference FPO. Hence, Proposed BPO and EPO algorithms provide different trade-off levels in terms of GEE and induced computational costs, the former further improving the GEE of the latter, at the price of higher computational complexity.

These promising results illustrate the efficiency and applicability of the Proposed BPO and EPO algorithms to improve

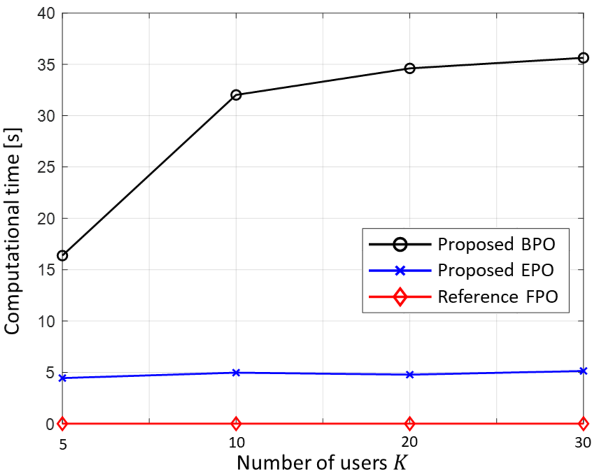


FIGURE 8. **The computational times against varying number of users.**

the energy-efficiency of future integrated terrestrial-satellite networks.

VI. CONCLUSION

In this work, we have investigated the GEE optimization problem in the downlink of a Ka-band multi-beam LEO satellite communication system. The influence of inter-beam interferences arising from the satellite's multi-beam antenna, as well as the Doppler interference caused by the mobility of the LEO satellite, have been accounted for in our model. Given the mathematical intractability of the initial GEE optimization problem, we have proposed two algorithms, BPO and EPO. Both algorithms iterate between two subproblems, the beam assignment optimization under fixed power and power allocation optimization under the beam assignment solution of the previous step. In BPO, the transmit power of each beam is optimized in the power allocation subproblem. While in EPO, the transmit power is fixed for all beams, resulting into a scalar optimization variable in the power allocation subproblem. In addition, the beam activation is further optimized in the Proposed EPO algorithm. Computer simulation results showed that the Proposed BPO and EPO algorithms considerably outperform the benchmark FPO algorithm, by realizing significant energy savings. In particular, BPO achieved highest GEE at the cost of a higher computational complexity, while EPO achieved a slightly lower GEE but with significantly lower complexity. These promising results illustrate the efficiency and applicability of the proposed methods to improve the energy-efficiency of future integrated terrestrial-satellite networks. In the future work, we will further integrate fairness and QoS requirements in this problem, for enabling IoT applications supported by terrestrial-satellite networks.

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