Large-Scale Beam Placement and Resource Allocation Design for MEO-Constellation SATCOM

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***Abstract*—This paper presents a centralized framework for optimizing the joint design of beam placement, power, and bandwidth allocation in an MEO satellite constellation to fulfill the irregular traffic demands of a large number of global users. The problem is formulated as a mixed integer programming problem, which is computationally complex in large-scale systems. To overcome this challenge, a three-stage solution approach is proposed, including user clustering, cluster-related bandwidth and power estimation, and MEO-cluster matching. A greedy algorithm is also included for comparison. The results demonstrate the superiority of the proposed algorithm over the benchmark in terms of satisfying user demands and reducing power consumption.**

***Index Terms*—MEO constellation, user clustering, beam placement, resource allocation.**

I. Introduction

Satellite communications have become an integral part of modern communication networks, providing seamless global connectivity for a wide range of applications such as broadband internet, remote sensing, and global positioning. With the increasing demand for high data rates and low latency communications, Medium Earth Orbit (MEO) constellations have emerged as a promising solution to enhance the capacity and coverage of satellite communication systems [1]. In addition, these Non-geostationary (NGSO) constellations are equipped with next-generation payload and antenna technologies including beam placement and radio resource management (RRM) which can adapt their multi-beam capabilities to the global services [2]. However, the design of such systems is a challenging task due to the large scale of the constellation and the complexity of the system design [1]. Motivated by the advances as well as the challenges of NGSO satellite constellation, the goal of this work is to minimize the power consumption in MEO constellations while meeting the Quality of Service (QoS) requirements of all users.

The beam placement and RRM in satellite communication systems are two critical aspects that have received extensive attention in the literature. A variety of objectives have been proposed for beam placement, including minimizing half power beam footprint [3], managing inter-beam interference [4], and balancing inter-beam traffic loads fairly [5]. The diverse and changing quality of service requirements for different payloads [6], [7] have motivated the development of dynamic RRM solutions for multi-beam satellite communication systems that can accommodate irregular demands from multiple users [8], [9]. However, these solutions can be challenging to implement in large-scale systems consisting of multiple MEO payloads serving thousands of ground users.

In response to recent advancements in MEO satellite constellations, this work focuses on optimizing beam placement, user-beam mapping, and RF resource allocation for global coverage. To address this challenge, a centralized power-minimization framework is proposed for joint beam placement, power, and bandwidth allocation design in MEO constellations. The framework consists of three stages: user clustering, cluster-related bandwidth and power estimation, and MEO-cluster matching. In the first stage, a novel clustering algorithm is proposed to divide users into a number of clusters, each of which can be served by one beam from an MEO. In the second stage, the optimal bandwidth and power consumed by each MEO to meet the demand of each of its corresponding clusters are estimated sequentially. Finally, in the third stage, the MEO-cluster assignment is optimized to minimize the total power consumption, based on the optimal bandwidth and power estimates from the previous stage. The proposed framework provides an efficient power-minimization approach for large-scale MEO constellation systems while ensuring that all users receive the desired Quality of Service (QoS). A greedy mechanism is also presented for comparison purposes. The numerical results show the efficiency and superiority of the proposed algorithm over other benchmark methods.

II. System Model

Let us consider a SATCOM constellation system consisting of N MEO satellites serving K users located on the earth's surface. These satellites move following the equator at the height of h^{MEO} while their longitudes, e.g., MEO n, over the time can be presented as $\theta_n(t)$, i.e., $\theta_n(t) \in [-180°, 180°]$. Let $\mathcal{N}$ and $\mathcal{K}$ be the sets of satellites and users, respectively. Here, one assumes that users' demand traffic over a time window of T time-slots (TSs) is available at SATCOM system, which is denoted as $D_k(t)$ for user k. This constellation is controlled by a ground segment consisting of multiple gateways coordinated by a central controller including an optimization module.

A. Clustering-based Multi-Beam Satellite Communication

In this system, each satellite can create multiple beams for serving users in its coverage area. However, activating a large number of beams is not always a beneficial choice. Moreover, serving multiple users within the same beam may be beneficial in terms of user multiplexing gain. Therefore, one assumes that one beam may cover multiple users in an efficient manner instead of allocating one beam per user. To develop a clustering framework, we introduce the binary variable $\{a_{m,k}\}$, which is defined as, $a_{m,k} = 1$ if user $k \in \mathcal{C}_m$ and $a_{m,k} = 0$

otherwise, where C_m stands for the set of users belonging to cluster m. Additionally, the clustering solution is maintained unchanged during the time window for low-complexity design and one cluster can be served by only one MEO. Once cluster m associates to MEO n, one specific beam focusing on this cluster will be generated by MEO n. Regarding cluster-MEO association, one introduces new variable $\{x_{m,k}(t)\}$ as,

$$x_{n,m} = 1 \text{ if } C_m \text{ is served by MEO } n \text{ at TS } t, \quad (1)$$

otherwise, $x_{n,m} = 0$. To ease the presentation, let us denote $\mathcal{M}$ as the set of all clusters, then, we have

$$(C1): \quad \sum_{\forall n} x_{n,m}(t) \leq 1, \quad \forall m \in \mathcal{M}. \quad (2)$$

1) Beam Gain and Channel Gain Model: Let $\theta^n_{m,k}(t)$ be the angle between the beam center of MEO satellite n at time t to the user k in cluster C_m. The geometry of such angle is illustrated in Fig. 1. The beam radiation pattern function $g^n_{m,k}(t)$ between the beam n and user k can be formulated by following the 3GPP report [10] as

$$g^n_{m,k}(t) = g^{\max}\mathcal{G}(\theta^n_{m,k}(t)), \forall k \in C_m, n \in \mathcal{N}, \quad (3)$$

where $g^{\max}$ indicates the maximum gain and $\mathcal{G}(\theta^n_{m,k}(t))$ is the normalized beam pattern gain which is computed as

$$\mathcal{G}(\theta) = 4\left|J_1(\tfrac{2\pi}{\lambda}r^{\mathsf{ant}}\sin(\theta))/(\tfrac{2\pi}{\lambda}r^{\mathsf{ant}}\sin(\theta))\right|^2, \text{if } 0 < \theta \leq \frac{\pi}{2}, \quad (4)$$

and $\mathcal{G}(\theta) = 1$ if $\theta = 0$, where $J_1(\cdot)$, λ, r^{ant} represent the order-one Bessel function, the carrier wavelength, and the radius of the antenna's circular aperture, respectively. Then, the channel gain from MEO n to user k can be described as $h^n_{m,k}(t) = g^n_{m,k}(t)P_{\mathsf{ls}}(d^n_k(t))$ where $P_{\mathsf{ls}}(d^n_k(t))$ represents the path-loss.

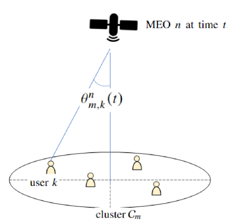

Fig. 1. Geometry of the angle $\theta^n_{m,k}(t)$.

2) Achievable Rate: Denote $P_k(t)$ and $B_k(t)$ as the transmission power and bandwidth allocated to user k at time t. Then, the achievable rate of this user can be described as

$$R_k(t) = \sum_{\forall (n,m)} a_{m,k}x_{n,m}(t)R^n_{m,k}(t), \quad (5)$$

where $R^n_{m,k}(t) = B_k(t)\log_2(1 + P_k(t)h^n_{m,k}(t)/B_k(t)\sigma^2)$ and σ^2 stands for the noise power per Hz at the receivers. Then, the constraint on users demand can be written as

$$(C2): \quad R_k(t) \geq D_k(t), \quad \forall (k,t). \quad (6)$$

B. Power Consumption Model

In our system, one assumes that the digital transparent processors (DTP) are equipped at all payloads based on which the high-power amplifiers (HPAs) and transponders can be switched off dynamically. The total power consumption of all satellites in TS t is mathematically formulated as

$$P^{\mathsf{tot}}(\mathbf{B}(t), \mathbf{P}(t)) = \sum_{\forall n} P^{\mathsf{hw}}_n(\mathbf{B}(t), \mathbf{P}(t)) + \sum_{\forall k} P_k(t), \quad (7)$$

where $P^{\mathsf{hw}}_n(\mathbf{B}(t), \mathbf{P}(t))$ models the hardware power consumption connected to all active beams of MEO n, which is consumed by various hardware components such as signal processing and HPA. Herein, $P^{\mathsf{hw}}_n(\mathbf{B}(t), \mathbf{P}(t))$ is defined as

$$P^{\mathsf{hw}}_n(\mathbf{B}(t), \mathbf{P}(t)) = P^{\mathsf{DC}}_n(\mathbf{B}(t)) + P^{\mathsf{RF}}_n(\mathbf{P}(t))/\rho^{\mathsf{HPA}}, \quad (8)$$

where ρ^{HPA} is the DC to RF power efficiency of the antenna element amplifiers. Additionally, $P^{\mathsf{RF}}_n(\mathbf{P}(t))$ denotes the RF transmission power of beam n which is computed as

$$P^{\mathsf{RF}}_n(\mathbf{P}(t)) = \sum_{\forall (m,k)} a_{m,k}x_{n,m}(t)P_k(t), \quad (9)$$

The DC consumed power according to the onboard signal processing, denoted by $P^{\mathsf{DC}}_n(\mathbf{B}(t))$, is given as

$$P^{\mathsf{DC}}_n(\mathbf{B}(t)) = P^{\mathsf{DC}}_{\mathsf{tot}}B_n(t)/B^{\mathsf{tot}}, \quad (10)$$

where $P^{\mathsf{DC}}_{\mathsf{tot}}$ represents the max DC power and B^{tot}_n í the max BW of MEO. Herein, $B_n(t)$ is estimated as

$$B_n(t) = \sum_{\forall (m,k)} a_{m,k}x_{n,m}(t)B_k(t). \quad (11)$$

Then, if B^{tot}_n is the same for all n, which is denoted as B^{tot}, the total power consumption of all MEOs can be estimated as

$$P^{\mathsf{tot}}(\mathbf{B}(t), \mathbf{P}(t)) = \sum_{\forall k}\left(\frac{\rho^{\mathsf{HPA}}+1}{\rho^{\mathsf{HPA}}}P_k(t) + \frac{P^{\mathsf{DC}}_{\mathsf{tot}}}{B^{\mathsf{tot}}}B_k(t)\right). \quad (12)$$

C. Problem Formulation

This work aims to develop a centralized power-minimization framework of joint beam placement, power and BW allocation for MEO-constellation which is stated as

$$\min_{\mathbf{a},\mathbf{x},\mathbf{B},\mathbf{P}} \sum_{\forall t} P^{\mathsf{tot}}(\mathbf{B}(t), \mathbf{P}(t)) \quad (13a)$$

$$\text{s.t.} \quad \text{constraints } (C1), (C2),$$

$$(C3): \sum_{\forall m} x_{n,m}(t) \sum_{k \in C_m} a_{m,k}B_k(t) \leq B^{\mathsf{tot}}, \ \forall n, \quad (13b)$$

$$(C4): \sum_{\forall m} x_{n,m}(t) \sum_{k \in C_m} a_{m,k}P_k(t) \leq P^{\mathsf{RF}}_{\mathsf{max}}, \ \forall n, \quad (13c)$$

where $(C3)$ and $(C4)$ stand for the constraints on the limited power transmission and BW at every payload.

Remark 1. *This problem is a mixed integer programming which is well-known as NP-hard. Additionally, solving it optimally becomes more challenging in a large-scale global setting with the very huge number of users.*

III. Solution Approach

In this section, a three-stage solution approach is proposed to cope with the challenging problem given in (22). In particular, this solution consists of three stages:

1) User clustering: Scheduling users into separated groups each of which can be served by one beam from an MEO.
2) Cluster-related BW and Power Estimation: Estimating the optimal BW and power by an assigned-to-serve MEO to meet users' demand in a cluster.
3) MEO-Cluster Matching: Optimizing the MEO-serving-cluster assignment to minimize the total power consumption according to the optimal BW and power estimated in the second stage.

A. User Clustering

1) Potential User Clustering Matrix: Assuming the coverage of every generated beam can be defined as the footprint of 3-dB loss from the beam center. The users should be grouped into clusters so that the angle from a satellite to two arbitrary users in a cluster must be not greater than the beam width. Let $\mathbf{U} \in \mathbb{R}^{K \times K}$ be the adjacency matrix whose (k, ℓ)-th element, denoted by $[\mathbf{U}]_{k,\ell}$, is defined as follows

$$[\mathbf{U}]_{k,\ell} = \begin{cases} 1, & \text{if } \theta^{\mathsf{max}}_{k,\ell} < \theta^{\mathsf{beam}}, \\ 0, & \text{otherwise}, \end{cases} \tag{14}$$

where $\theta^{\mathsf{max}}_{k,\ell}$ represents the maximum angle from a point on satellite orbit to users k and ℓ, and θ^{beam} is the beam width. Herein, $\theta^{\mathsf{max}}_{k,\ell} < \theta^{\mathsf{beam}}$ implies that users k and ℓ can be served by one beam; hence, they can be grouped into one cluster. Let O^{MEO} be the MEO orbit line, then $\theta^{\mathsf{max}}_{k,\ell}$ can be defined as

$$\theta^{\mathsf{max}}_{k,\ell} = \max_{X \in O^{MEO}} \measuredangle kX\ell, \tag{15}$$

where $\measuredangle kX\ell$ denotes the angle separating users k and ℓ from X's point of view and O^{MEO} represents the orbit of all MEOs.

Remark 2. *It is worth noting that the angle from any MEO to two users k and ℓ is always less than $\theta^{\mathsf{max}}_{k,\ell}$.*

2) User's Required MEO Bandwidth Estimation: This section aims to estimate amount of MEO BW required to serve a specific ground user. Consider user k with demand $D_k(t)$. Note that user k may be located in a cluster that be covered and served by an activated beam from MEO n. The coverage of that beam is defined by the footprint of 3-dB loss from the beam center. Here, we consider the worst case that user k laying on the boundary of that beam than, $g^{\mathsf{bound}} = g^{\mathsf{max}}/2$. And the distance in the worst case can be defined as

$$\bar{l}_k = \max_t \min_n l^n_k(t), \tag{16}$$

where $l^n_k(t)$ stands for the distance between user k and MEO n at time t. Then, the estimated BW which should be allocated for user k over the time can be presented as, $\bar{B}_k(t)$, where

$$\bar{B}_k(t) \log_2 \left(1 + \frac{P^{\mathsf{max}}_{\mathsf{beam}} g^{\mathsf{bound}} P_{\mathsf{ls}}(\bar{l}_k)}{\bar{B}_k(t)\sigma^2}\right) = D_k(t). \tag{17}$$

Based on $\bar{B}_k(t)$, the simple clustering algorithm is presented in what follows.

3) Time-Window-based Matching Efficiency Factor: In this work, one assumes that the cluster results cannot be changed during a time window of $[0,T]$. Hence, users should be grouped into clusters so that the total required bandwidth of each cluster does not vary too much and also its average is not very far from the peak value during the time window. To do so, we present a new time-window-based matching efficiency factor as follows. Let $\mathcal{S}$ be a set of some arbitrary users. The time-window-based matching efficiency factor corresponding to this set can be described as

$$E(\mathcal{S}) = \int_0^T \sum_{k \in \mathcal{S}} \bar{B}_k(t) dt / (T \times \bar{B}^{\mathsf{max}}(\mathcal{S})), \tag{18}$$

where $\bar{B}^{\mathsf{max}}(\mathcal{S}) = \max_{t \in [0,T]} \sum_{k \in \mathcal{S}} \bar{B}_k(t)$.

Algorithm 1 PROPOSED CLUSTERING ALGORITHM

Initialize: Set $\mathbf{U}^{\mathsf{temp}} = \mathbf{U}$ and cluster index as $id = 0$.
for $k = 1$ to K **do**
  if $[\mathbf{U}^{\mathsf{temp}}]_{k,k} = 1$ **then**
    Update $id = id + 1$ and set id-th cluster as $C_{id} = \{k\}$.
    Update $\mathbf{U}^{\mathsf{temp}}$ by setting all elements on its k-th column to zeros.
    Define the set of potential users which can be added into this cluster as $\mathcal{U}_{id} = \{\ell | [\mathbf{U}^{\mathsf{temp}}]_{k,\ell} = 1\}$.
    while $\bar{B}^{\mathsf{max}}(C_{id}) < B^{\mathsf{beam}}_{\mathsf{max}}$ **do**
      Define the next user to add to id-th cluster as

$$\ell' = \arg \max_{\ell \in \mathcal{U}_{id}} E(C_{id} \cup \{\ell\}) \text{ s.t. } \bar{B}^{\mathsf{max}}(C_{id} \cup \{\ell\}) \le B^{\mathsf{beam}}_{\mathsf{max}}. \tag{19}$$

      if One exists a such user ℓ' as in (19) **then**
        Add user ℓ' into C_{id} as $C_{id} = C_{id} \cup \{\ell\}$.
        Set all elements on ℓ'-th column of $\mathbf{U}^{\mathsf{temp}}$ to zeros.
        Update $\mathcal{U}_{id} = \mathcal{U}_{id} \cap \{m | [\mathbf{U}^{\mathsf{temp}}]_{\ell',m} = 1\}$.
      else
        Break (Stop WHILE loop).
      end if
    end while
  end if
end for

4) A Simple Clustering Algorithm: In what follows, a greedy clustering algorithm is proposed to separate all users into different clusters in a manner that one beam can be placed to serve all users in a cluster and the users are grouped so that the matching efficiency factor of the corresponding cluster is as high as possible. In particular, the proposed clustering approach is summarized in Algorithm 1.

B. MEO-Cluster BW and Power Estimation

1) Beam Center Allocation: The beam center of each cluster can be defined simply based on the coordinates and demands of all users in cluster C_m as follows

$$\mathbf{o}(C_m) = \frac{\sum_{k \in C_m} (\eta + D^{\mathsf{max}}_k) \mathbf{o}_k}{\sum_{k \in C_m} (\eta + D^{\mathsf{max}}_k)} = \frac{\sum_{\forall k} a_{n,k} (\eta + D^{\mathsf{max}}_k) \mathbf{o}_k}{\sum_{\forall k} a_{n,k} (\eta + D^{\mathsf{max}}_k)}, \tag{20}$$

where η is the calibrating factor, $D^{\mathsf{max}}_k = \max_t D_k(t)$, and $\mathbf{o}_k$ be the coordinate of user k.

2) Required BW and Power Estimation: Assume that MEO n having coordinate $\mathbf{o}^{\mathsf{MEO}}_n(t)$ is assigned to serve cluster C_m in TS t. According to $\mathbf{o}(C_m)$ and $\mathbf{o}^{\mathsf{MEO}}_n$, $\theta^n_{m,k}(t)$, so-called the angle from beam center to user k in TS t, can be defined. Based on that, the corresponding channel gain $h^n_{m,k}(t)$ can be estimated. Let $B_{n,k}(t)$ and $P_{n,k}(t)$ be the assigned BW and transmission power to serve user k by MEO n. Then, $B_{n,k}(t)$ and $P_{n,k}(t)$ can be estimated by solving the following problem.

$$\min_{\{B_{n,k}(t), P_{n,k}(t)\}} \Phi_{n,m}(t) = \sum_{\forall k} \left(\frac{\rho^{\mathsf{HPA}} + 1}{\rho^{\mathsf{HPA}}} P_{n,k}(t) + \frac{P^{\mathsf{DC}}_{\mathsf{tot}}}{B^{\mathsf{tot}}} B_{n,k}(t) \right) \tag{21a}$$

$$\text{s.t. } B_{n,k}(t) \log_2 \left(1 + \frac{P_{n,k}(t) h^n_{m,k}(t)}{B_{n,k}(t)\sigma_k}\right) \ge D_k(t), \forall k \in C_m. \tag{21b}$$

Theorem 1. *Problem* (21) *is convex*

Proof: As can be observed, $B_{n,k}(t) \log_2 \left(1 + \frac{P_{n,k}(t) h^n_{m,k}(t)}{B_{n,k}(t)\sigma_k}\right)$ is a joint concave function respected to both $B_{n,k}(t)$ and $P_{n,k}(t)$. Additionally, the objective function is in the linear form of the variables. Thus, problem (21) must be convex. ■

Hence, it can be solved optimally efficiently by employing several convex optimization tools such as CVX, Gurobi [11].

Algorithm 2 PROPOSED ALGORITHM

Employing Algorithm 1 to group all users into clusters.
Defining $\mathcal{M}$, C_m's,and $\mathbf{o}_m$'s.
for TS $t = 1 : T$ **do**
  for MEO $n \in \mathcal{N}$ **do**
    for Cluster $m \in \mathcal{M}$ **do**
      if $\mathbf{o}_m$ locates inside the coverage of MEO n **then**
        Solving problem (21) for MEO n and C_m to obtain the corresponding $B_{n,k}(t)$'s and $B_{n,k}(t)$'s.
      else
        Setting the corresponding $B_{n,k}(t)$'s and $B_{n,k}(t)$'s to *+Inf*.
      end if
    end for
  end for
  Solving problem (22) based on $B^{\star}_{n,k}(t)$'s and $P^{\star}_{n,k}(t)$'s to get the matching results.
end for

Algorithm 3 LOW COMPLEXITY DESIGN

Determine maximum cluster distance $d^{\text{clu}} = 2h^{\text{MEO}} \tan(\theta^{\text{beam}})$.
Exploiting the method in [18] to cluster all users.
for TS $t = 1 : T$ **do**
  Every cluster is connected to its nearest MEO satellite.
  Solving problem (21) for each MEO to obtain the BW and power.
end for

Remark 3. *Note that only the clusters located inside each MEO's field of view (FoV) are considered for estimating the required BW and power. Herein, the FoV of every MEO is defined by its attitude and minimum elevation angle [12], [13].*

C. MEO-Cluster Matching Design

Denote $B^{\star}_{n,k}(t)$ and $P^{\star}_{n,k}(t)$ as the solution of problem (21) for MEO n and user k. Then, the MEO-Cluster matching problem can be stated as

$$\min_{\{x_{n,m}(t)\}'s} \sum_{\forall(n,m)} x_{n,m}(t)\Phi^{\star}_{n,m}(t) \tag{22a}$$

$$\text{s.t.} \quad \sum_{\forall m} x_{n,m}(t) \sum_{k \in C_m} B^{\star}_{n,k}(t) \le B^{\text{max}}_n, \ \forall n, \tag{22b}$$

$$\sum_{\forall m} x_{n,m}(t) \sum_{k \in C_m} P^{\star}_{n,k}(t) \le P^{\text{max}}_n, \ \forall n, \tag{22c}$$

where $\Phi^{\star}_{n,m}(t) = \sum_{\forall k}\left(\frac{\rho^{\text{HPA}}+1}{\rho^{\text{HPA}}}P^{\star}_{n,k}(t) + \frac{P^{\text{DC}}_{\text{tot}}}{B^{\text{tot}}}B^{\star}_{n,k}(t)\right)$. This is an integer linear programming in general which can be solved efficiently by using an *"off-the-shelf"* optimization toolbox, or by employing a relaxation and projection approach introduced in [14]–[16]. Then, the proposed solution approach is summarized in Algorithm 2.

Remark 4. *Note that the cross interference among all clusters is omitted in this work thanks to the narrow beam-width beam patterns of the satellite and that MEO can allocate different frequency bands to adjacent beams [12], [17].*

D. Greedy Solution Approach

As a point of comparison, we also created a greedy solution approach. This involves using the Voronoi clustering algorithm from [18] to divide all users into clusters. The maximum distance for each cluster is calculated based on the beam width, θ^{beam}, and orbit height, $d^{\text{clu}} = 2h^{\text{MEO}} \tan(\theta^{\text{beam}})$. After the clustering is done, each cluster is assigned to its closest MEO. Finally, the bandwidth and power transmission of all users are optimized by solving problem (21) for each MEO. The whole process is outlined in Algorithm 3.

TABLE I
SIMULATION PARAMETERS (PROVIDED BY ESA)

Parameter	Value
Forward link carrier frequency	19 – 21.5 GHz
MEO attitude	8062 km
Earth radius	6378 km
$P^{\text{RF}}_{\text{max}}$	800 W
ρ^{HPA}	0.6
$P^{\text{DC}}_{\text{tot}}$	5000 W
B^{tot}	2500 MHz
Minimum satellite elevation angle	5 degrees
Number of simulated users around a big city	20 – 50
User terminal antenna gain	41.45 dBi
Temperature at user terminals	224.5 K
Channel Model	Refer to [12]

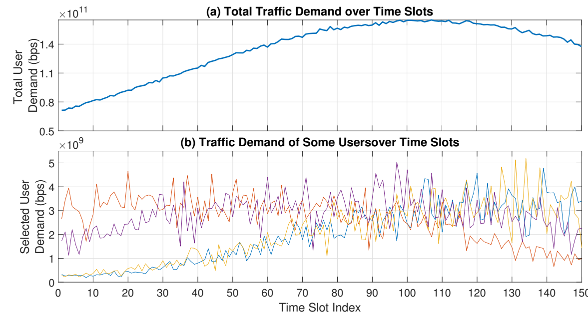

Fig. 2. A realization of user demand over 150 TSs.

TABLE II
BEAM WIDTH AND RADIUS OF SATELLITE ANTENNA

r^{ant}/λ	5	10	15	20
r^{ant}	7.89 (cm)	15.79 (cm)	23.68 (cm)	31.58 (cm)
θ^{beam}	5.88°	2.94°	1.96°	1.46°
d^{clu}	828.09 (km)	413.77 (km)	275.81 (km)	205.44 (km)

IV. NUMERICAL RESULTS

In this section, some simulations conducted for an MEO constellation of 15 payloads orbiting at an altitude of 8062 km will be provided. The simulations were run over a time frame of 150 TSs, each lasting 6 minutes. In this simulation, the users were placed in proximity to major cities each of which contains around 40 users. Then, there was a total of 1112 users over the world. The user demands were randomly generated based on sinusoidal patterns with peak and off-peak periods. The total demand of all users over the 150 TSs is displayed in Fig. 2. The parameters for the simulation are listed in Table I and preliminary numerical results are also provided.

In Table II, we determine the beam width based on the radius of the antennas installed on the payload. By using the normalized beam pattern gain given in (4), the beam width is calculated as the 3dB loss angle, which is defined as $\theta^{\text{beam}} = 2\theta\big|_{\mathcal{G}(\theta)=0.5}$. Figure 3 shows an example of the beam pattern gain for $r^{\text{ant}}/\lambda = 15$. It's worth mentioning that the beam width of 1.96° for $r^{\text{ant}}/\lambda = 15$ is also utilized for the antenna configuration in all subsequent simulations.

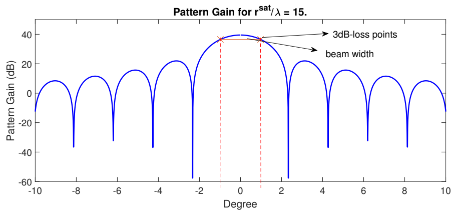

Fig. 3. An example of beam pattern gain for $r^{\text{ant}}/\lambda = 15$.

TABLE III
CLUSTER RESULTS

Method	Number of Cl.	Min/Max Cl. Size	Avg. Cl. Size
Proposed Alg.	386	1/10	2.88
Voronoi [18]	477	1/8	2.33

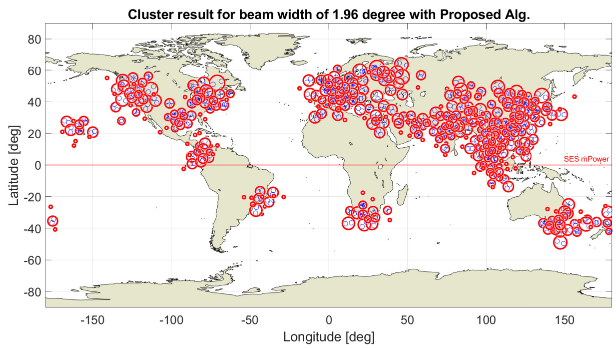

Fig. 4. Proposed Alg. based Clustering result with angle threshold 1.96°.

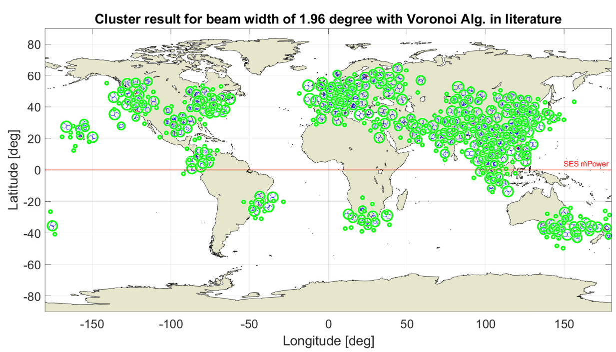

Fig. 5. Voronoi Alg. [18] based Clustering result with angle threshold 1.96°.

TABLE IV
CLUSER-MEO MATCHING RESULTS

Method	Min/Max Clus./MEO	Ser. Clus. Ratio	Satis. User No.
Proposed Alg.	14/55	380/386	1089/1112
Greedy Alg.	7/77	397/477	889/1112

Figs. 4 and 5 demonstrate the clustering results produced by using our proposed method in Algorithm 1 and the distance-based Voronoi method from [18], respectively. These figures show the clustering results based on satellite positions and user demands in TS 1. The information is further outlined in Table III. Our proposed approach can be seen to generate a fewer number of beams compared to the other method.

The results of Cluster-MEO matching obtained through the proposed and greedy algorithms for TS 10 are displayed in Figs. 6 and 7, respectively. The minimum and maximum number of clusters connected to an MEO, the ratios of served

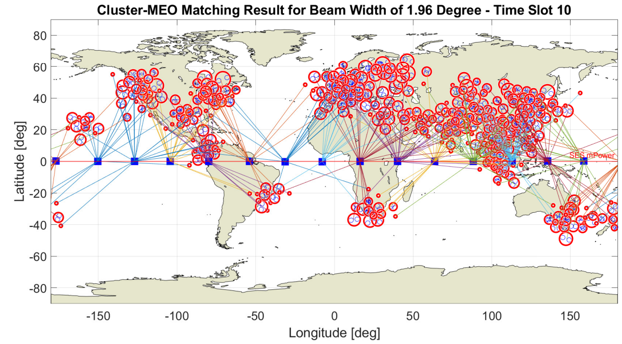

Fig. 6. Matching result for angle threshold 1.96° at TS 10.

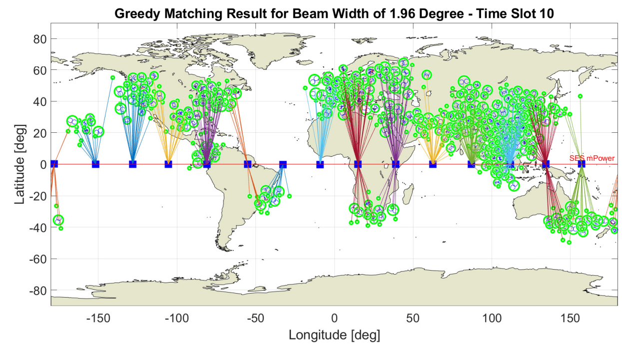

Fig. 7. Greedy matching result for angle threshold 1.96° at TS 10.

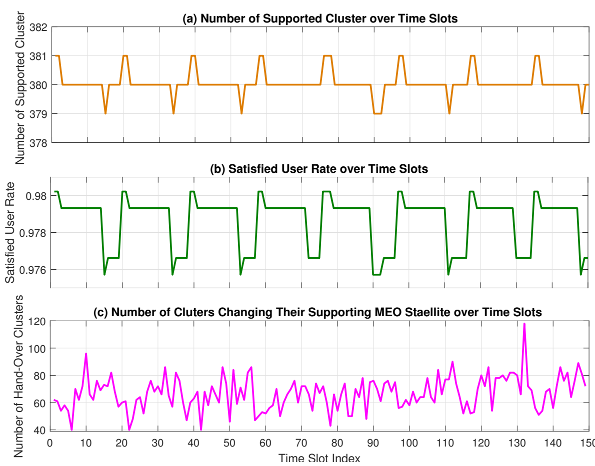

Fig. 8. The results of the proposed algorithm over 150 TSs.

clusters, and the number of satisfied users are also summarized in Table IV. These figures indicate that the proposed method provides a better dynamic beam placement solution compared to the greedy algorithm. Specifically, the nearest-MEO selection framework results in an uneven load distribution across all MEOs, with some MEOs serving a larger number of clusters than others. When an MEO becomes overloaded, we propose to step-by-step remove the cluster with the highest demand until it can accommodate all remaining clusters. Interestingly, the proposed approach is able to satisfy a greater number of users compared to the greedy algorithm.

The results of the proposed algorithm during the observed time window are shown in Fig. 8. In particular, this figure

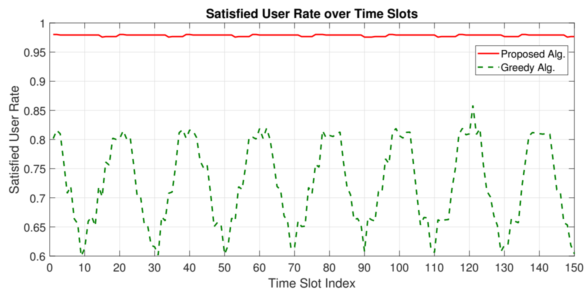

Fig. 9. Satisfied user rate over 150 TSs.

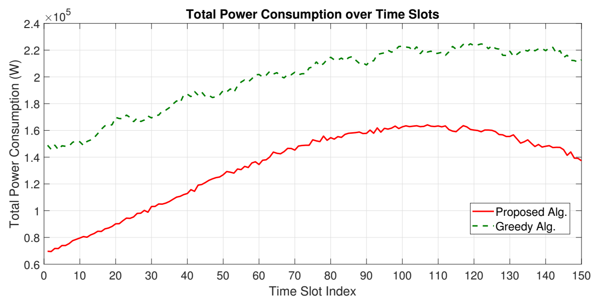

Fig. 10. Total power consumption over 150 TSs.

illustrates the number of supported clusters, the satisfied user rates, and the number of hand-over clusters. The satisfied user rate in each time slot is calculated as the ratio of the number of users whose traffic demand is fulfilled to the total number of users in the simulation. Interestingly, the number of supported clusters and the satisfied user rate both fluctuate periodically with an average cycle duration of approximately 16 TSs, which is also the required time for an MEO satellite to reach the position of its nearest MEO. As seen in Fig. 8-b, the high satisfactory rate, ranging from 0.976 to over 0.98, confirms the efficiency of the proposed algorithm. Additionally, Fig. 8-c shows the number of clusters that change their supporting MEO after each TS, which varies irregularly over time.

Finally, Figs. 9 and 10 illustrate the satisfied user rate and the total power consumption corresponding to the proposed and greedy algorithms over 150 TSs. As can be observed, the proposed approach outperforms the greedy algorithm in terms of satisfying user demands and conserving energy. Our scheme is able to meet the needs of more than 97% of the users, while the greedy algorithm only supports a maximum of 85%, but its uses over a third of our total power consumption. Fig. 10 reveals a clear correlation between the power consumption and user demand over the time window, with higher power consumption observed during the higher-demand TSs.

V. Conclusion

In conclusion, this work presents a centralized power-minimization framework for the joint beam placement, power and bandwidth allocation design in MEO constellations to meet the QoS requirements of all users. The proposed three-stage solution approach addresses the challenging NP-hard problem and provides a practical solution for large-scale MEO constellations with a large number of global users. The results demonstrate that the proposed framework effectively reduces power consumption while meeting the QoS requirements of over 97% of users.

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