Multi-Group Multicast Beamforming in LEO Satellite Communications

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***Abstract*—This paper investigates user grouping and beamforming design in multi-beam low earth orbit (LEO) satellite communication (SATCOM) systems. To serve a great many user terminals (UTs) with a limited number of beams and improve the system performance, we formulate the weighted sum rate (WSR) maximization problem subject to the constraints of the UTs grouping, the satellite total power, and the minimum rate requirements of UTs. For solving this problem, we propose a multi-group multi-beamforming (MGMBF) scheme. In this scheme, all UTs are firstly adaptively grouped based on the channel correlation coefficients. Further, the beam centers are determined to ensure that all UTs are covered. After UTs grouping, slack variables are introduced to convert the beamforming design into a difference-of-convex (DC) programming problem. Moreover, an iterative algorithm is presented to solve the problem based on the convex-concave procedure (CCP), in which the beamforming vectors and slack variables are updated jointly by solving the convex sub-problem. Simulation results demonstrate that the MGMBF scheme improves the WSR by 25.1% compared with the MBIM algorithm, verifying the significant advantages of the proposed scheme.**

Keywords*—LEO satellite communications, beamforming, user grouping, multicast transmission.

I. Introduction

Multi-beam low earth orbit (LEO) satellite communication (SATCOM) systems have drawn much interest because of their advantages of global connectivity and high throughput [1]. Generally, multiple spot beams can be generated using an array feed reflector antenna equipped on a satellite, and each spot beam covers a fixed area. This method uses a lot of spot beams to realize wide-range coverage seamlessly, while the location distribution of user terminals (UTs) is usually nonuniform, which may result in some of the beams covering only a few UTs and the waste of the satellite resources. In contrast, phased array antennas can generate multiple narrow beams with flexible directions [2], which means that a limited number of beams can be expected to cover all UTs in LEO SATCOM. To this end, the multi-beam LEO SATCOM systems equipped with phased array antennas are considered in this paper.

In SATCOM application scenarios, such as live video streaming, where multiple users may be interested in the same popular content [3], multicasting these data to user groups can save satellite resources. In light of the existing SATCOM standards DVB-S2 and DVB-S2X, the multi-user data is encapsulated into the same frame [4]. On this basis, a user multicast group can be served by a single beam. In other words, multiple users share the same beamformer. However, due to the number of users being usually larger than the number of beams, and the single beam coverage is limited, user grouping is necessary to provide efficient service. In addition, in order to significantly improve spectral efficiency, full frequency reuse (FFR) strategy has been suggested, in which each beam utilizes the entire bandwidth [5]. However, inter-beam interference is a crucial issue in FFR, which needs to be handled efficiently.

Some work has been proposed to deal with the aforementioned problems. On the one hand, the user grouping strategies based on time division multiple access were investigated in [6] and [7], in which all users were divided into multiple user groups, and a single beam was used to serve one group in each time slot. Obviously, inter-beam interference can be avoided by using the above strategies. However, in [6] and [7], only a small number of users are served in a given time slot, resulting in most users being idle in each time slot. On the other hand, to mitigate inter-beam interference, beamforming design schemes were presented in [8] and [9] under the total power constraints and user minimum quality of service (QoS) requirements. In addition, a low-complexity precoding design for multi-user scenarios was proposed in [10], which limits inter-beam interference while improving the intra-beam minimum received signal-to-interference-plus-noise ratio (SINR). However, an assumption was made in [8]-[10] that all UTs are naturally located within beams coverage, which is not realistic in multi-beam LEO SATCOM systems equipped with phased array antennas. In fact, from the per-

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spective of SATCOM operators, it would be more interesting to optimize the system performance if all multicast groups are served in a given time slot. As a result, it is required to develop a beamforming solution for multi-group multi-beam LEO satellite communication systems equipped with phased array antennas.

In this paper, we focus on user grouping and beamforming design for multi-beam LEO SATCOM systems. To serve all UTs simultaneously with a limited number of beams while improving the system performance, a system weighted sum rate (WSR) maximization problem is established while satisfying the constraints of UTs grouping and satellite total power, and the minimum rate requirements of UTs. To solve this problem, a multi-group multi-beamforming (MGMBF) scheme is proposed. Specifically, all UTs are firstly adaptively grouped according to the channel correlation coefficient. Further, the beam centers are determined while ensuring that all UTs are covered. Then, the beamforming design problem is transformed into a difference-of-convex (DC) programming problem by utilizing slack variables. Moreover, an iterative algorithm based on the convex-concave procedure (CCP) is presented to address the DC programming problem, which solves a convex sub-problem in each iteration.

The rest of this paper is organized as follows. Section II presents the system model and formulates the WSR maximization problem. The MGMBF scheme is provided in Section III. Simulation results are presented in Section IV. Finally, we conclude this paper in Section V.

II. System Model and Problem Formulation

This section presents the system model, which includes the channel vector model and the received signal model. Then, the system WSR maximization problem is established.

A. System Model

Fig. 1 shows the considered forward link of multi-beam LEO SATCOM systems, where the LEO satellite applies a uniform planar array (UPA) consisting of N_x and N_y elements on the x-axis and y-axis, respectively. Let $N = N_x N_y$ denote the total number of antennas. The UTs send the channel state information (CSI) to the gateway, which delivers the CSI to the LEO satellite through a feed link. The UPA uses CSI to generate N_s beams simultaneously to serve all single antenna UTs, which are randomly distributed within the satellite coverage. The indices set of all UTs and multicast groups are denoted as $\mathcal{K} = \{1, ..., k, ..., K\}$ and $\mathcal{M} = \{1, ..., m, ..., M\}$, respectively. We assume that one multicast group is served by one beam, i.e., $M = N_s$. The binary variable $x_{k,m}$ is defined to represent the grouping results of each UT. If the k-th UT belongs to m-th group, $x_{k,m} = 1$, otherwise, $x_{k,m} = 0$, let $\mathcal{G}_m$ represent the UTs set in the m-th multicast group. Moreover, each UT belongs to only one group, which can be denoted as $\sum_{m=1}^{M} x_{k,m} = 1$.

The downlink channel vector from the LEO satellite to UTs is given by [11][12]

$$\mathbf{h} = \sqrt{\frac{C_L G_r}{P_n \xi_n}} G_s \cdot \mathbf{v}(\phi, \theta) \in \mathbb{C}^{N \times 1}, \tag{1}$$

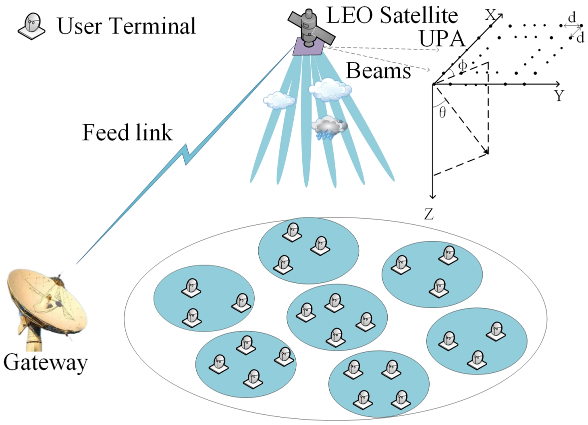

Fig. 1. System model.

where $C_L = (c/4\pi f d_0)^2$ represents the free space loss, d_0 is the distance from the satellite to UT, f is the carrier frequency, and c is the light speed. G_s and G_r are antenna gain of satellite and UTs respectively. $P_n = \kappa BT$ represents the noise at the UTs receiver, where κ is the Boltzman constant, B is the bandwidth, and T is the noise temperature. The rain attenuation coefficient in dB can be expressed as $\xi_{\text{dB}} = 20 \log_{10}(\xi_n)$, which follows a lognormal distribution, i.e., $\ln(\xi_{\text{dB}}) \sim \mathcal{LN}(\mu, \sigma^2)$ [4]. Moreover, the UPA steering vector is given by [11]

$$\mathbf{v}(\phi, \theta) = \mathbf{v}_x \otimes \mathbf{v}_y \in \mathbb{C}^{N \times 1}, \tag{2}$$

where $\mathbf{v}_\vartheta \triangleq [1, e^{j\pi\beta_\vartheta}, ..., e^{j\pi(N_\vartheta - 1)\beta_\vartheta}]^T$, $\vartheta = \{x, y\}$. $\otimes$ represents Kronecker product. $\beta_x = \sin\theta\cos\phi$, $\beta_y = \sin\theta\sin\phi$, where θ and ϕ are the azimuth and elevation angle of departure, respectively.

The received signal of the l-th UT in m-th group can be described as

$$y_{m,l} = \mathbf{h}_{m,l}^H \mathbf{w}_m x_m + \sum_{\ell \neq m} \mathbf{h}_{m,l}^H \mathbf{w}_\ell x_\ell + n_{m,l}, \quad \forall m, \ell \in \mathcal{M}, \forall l \in \mathcal{G}_m, \tag{3}$$

where $\mathbf{h}_{m,l}$ is the channel vector from the LEO satellite to the l-th UT in m-th group, $(.)^H$ denote the Hermitian transpose. $\mathbf{w}_m \in \mathbb{C}^{N \times 1}$ represents the beamforming weight vector for multicast group m, x_m is the initial transmit signal for the m-th group with normalized power. $n_{m,l} \sim \mathcal{CN}(0, N_0)$ is the circular symmetric complex additive Gaussian noise of the UT l in group m with mean zero and variance N_0.

B. Problem Formulation

According to (3), the received SINR of l-th UT in the group m is expressed as

$$\gamma_{m,l} = \frac{|\mathbf{h}_{m,l}^H \mathbf{w}_m|^2}{\sum\limits_{\ell \neq m} |\mathbf{h}_{m,l}^H \mathbf{w}_\ell|^2 + N_0}, \tag{4}$$

and the achievable transmission rate is denoted by $R_{m,l} = \log_2(1 + \gamma_{m,l})$(bit/s/Hz). Moreover, in the multicast transmission scenario, for multicast group m, the achievable rate is determined by the UT with the minimum rate in this group, which is defined as

$$R_m \triangleq \min_{l\in\mathcal{G}_m} R_{m,l}. \quad (5)$$

Considering that all beams are used to serve different multicast groups, and each UT in the same group is required to be within a single beam coverage. Therefore, the restraints associated with the coordinates of UTs are written as

$$\|\mathbf{u}_{m,l} - \mathbf{c}_m\| \le r, \quad (6)$$

where $\mathbf{u}_{m,l}$, $\mathbf{c}_m \in \mathbb{R}^2$ denote the coordinates of the l-th UT in m-th group and the m-th beam center, respectively. $r \triangleq d_h \tan(\alpha_{3\text{dB}}/2)$ represents the beam coverage radius, where d_h is the satellite orbit altitude, and $\alpha_{3\text{dB}}$ is the 3dB angle.

Our goal is to maximize the system WSR by grouping UTs and designing beamformers for each multicast group. Therefore, the problem is formulated as

$$\begin{aligned} \mathcal{P}_1 : &\max_{\{\mathcal{G}_m,\mathbf{w}_m\}_{m=1}^M} \sum_{m=1}^{M} \eta_m R_m \\ \text{s.t. } & C_1 : \|\mathbf{u}_{m,l} - \mathbf{c}_m\| \le r, \forall m, \forall l, \\ & C_2 : \sum_{m=1}^{M} x_{k,m} = 1, \forall k, \forall m, \\ & C_3 : x_{k,m} = \{0,1\}, \forall k, \forall m, \\ & C_4 : R_m \ge R_0, \forall m, \\ & C_5 : \sum_{m=1}^{M} \|\mathbf{w}_m\|^2 \le P, \end{aligned} \quad (7)$$

where η_m is the weight factor determined by the number of UTs in the multicast group m. C_1 is the coordinate constraint of UTs, C_2 and C_3 are the grouping constraints of all UTs, C_4 is the QoS constraint, where R_0 is the minimum transmission rate requirement of the UTs, and C_5 is the satellite total power constraint.

Problem $\mathcal{P}_1$ is challenging for the following reasons. Firstly, the non-convex constraint C_4 makes problem $\mathcal{P}_1$ difficult to solve directly. Secondly, some greedy algorithms can obtain an optimal grouping result, however, bring tremendous processing complexity for the case of a large number of UTs. Additionally, the premise of beamforming design is that each beam center can be determined, and it is unrealistic to use an exhaustive scheme to determine all beam centers. To this end, we propose an MGMBF scheme to solve problem $\mathcal{P}_1$, which can obtain a feasible solution while ensuring convergence.

III. Multi-Group Multi-Beamforming Scheme

In this section, the proposed MGMBF scheme will be used to maximize the system WSR. Firstly, the UTs are grouped according to the adaptive threshold value and channel correlation coefficient, and the beam centers are determined while ensuring that all UTs are covered by beams. Then, the beamforming design problem is converted into a DC programming problem by utilizing slack variables and addressed by an iterative algorithm based on CCP. Finally, the beamforming vectors of each group are obtained.

A. User Grouping

Initially, the UT with the maximum channel gain among all UTs is selected as the first candidate group center, which is given by

$$\nu_1 = \underset{k\in\mathcal{K}}{\text{argmax}} \|\mathbf{h}_k\|_2. \quad (8)$$

Further, we select UTs with channel correlation less than the predetermined threshold λ. Therefore, other candidate group centers can be obtained by

$$\Lambda = \{\nu' \in \mathcal{K}\backslash\nu_1 \mid |\mathbf{h}_{\nu'}^H \mathbf{h}_{\nu_1}| < \lambda\}. \quad (9)$$

After obtaining all candidate group centers $\Omega = \Lambda \cup \nu_1$, we divide the remaining UTs into corresponding multicast groups according to the channel correlation coefficient,

$$m = \underset{\omega\in\Omega}{\text{argmax}} \frac{|\mathbf{h}_k^H \mathbf{h}_\omega|}{\|\mathbf{h}_k\|\|\mathbf{h}_\omega\|}, \forall k \in \mathcal{K}\backslash\Omega. \quad (10)$$

In addition, we also need to determine the corresponding beam center of each group, while ensuring that the UTs in each group are within the beam coverage. The farthest distance of UTs in the m-th group is obtained by

$$d_{i,j}^m = \max\|\mathbf{u}_{m,i} - \mathbf{u}_{m,j}\|, \forall i,j \in \mathcal{G}_m. \quad (11)$$

If $d_{i,j}^m \le 2r$, it means that the beam can cover all UTs in the group, and the distribution center of UTs in the group is taken as the beam center. Otherwise, we consider that the grouping is invalid. In this case, the threshold value needs to be adjusted, i.e., raised appropriately, to regroup until all beam centers are determined.

B. Beamforming Design

So far, the grouping results and beam centers have been obtained. Moreover, from Section II-B, the multicast transmission rate is expressed as $R_m \triangleq \min_{l\in\mathcal{G}_m} \log_2(1+\gamma_{m,l})$. For convenience, let $\mathbf{W} = [\mathbf{w}_1, ..., \mathbf{w}_M]$, problem $\mathcal{P}_1$ can be reformulated as

$$\begin{aligned} \mathcal{P}_2 : &\max_{\mathbf{W}} \sum_{m=1}^{M} \eta_m \min_{l\in\mathcal{G}_m} \log_2(1+\gamma_{m,l}) \\ \text{s.t. } & C_6 : \log_2(1+\gamma_{m,l}) \ge R_0, \forall m, \forall l, \\ & C_5 \text{ in } (7). \end{aligned} \quad (12)$$

Problem $\mathcal{P}_2$ is still intractable because of the non-convex constraint C_6 and objective function in (12). For this purpose, we introduce a slack variable $\tilde{\gamma}_m$ for each group and let $\gamma_0 \triangleq 2^{R_0} - 1$. On the basis of $\tilde{\boldsymbol{\gamma}} = [\tilde{\gamma}_1, ..., \tilde{\gamma}_M]$ and γ_0, problem $\mathcal{P}_2$ can be transformed as

$$\begin{aligned} \mathcal{P}_3 : &\max_{\mathbf{W},\tilde{\boldsymbol{\gamma}}} \sum_{m=1}^{M} \eta_m \log_2(1+\tilde{\gamma}_m) \\ \text{s.t. } & C_7 : \gamma_{m,l} \ge \tilde{\gamma}_m, \forall m, \forall l, \\ & C_8 : \tilde{\gamma}_m \ge \gamma_0, \forall m, \\ & C_5 \text{ in } (7). \end{aligned} \quad (13)$$

Remarks:

- The constraint C_7 is to ensure that $\tilde{\gamma}_m \leq \min_{l\in\mathcal{G}_m}\gamma_{m,l}$, which supplies a lower bound for R_m.
- The constraint C_8 ensures a minimum SINR or rate requirement for each multicast group.
- When problem P_3 reaches the optimal solution, it means that $\tilde{\gamma}_m = \min_{l\in\mathcal{G}_m}\gamma_{m,l}$, and the constraints C_7 and C_8 in (13) are equivalent to constraint C_6 in (12).

To make problem P_3 tractable, we transform the non-convex constraint C_7 in (13) into a DC function. The problem can be rewritten as

$$\begin{aligned}\mathcal{P}_4 : &\max_{\mathbf{W},\tilde{\gamma}} \sum_{m=1}^{M} \eta_m \log_2(1+\tilde{\gamma}_m)\\ \text{s.t. } &C_9 : \mathcal{Q}_{m,l}(\mathbf{W}) - \mathcal{F}_{m,l}(\mathbf{W},\tilde{\gamma}_m) \leq 0,\\ &C_5 \text{ in } (7), C_8 \text{ in } (13),\end{aligned} \tag{14}$$

where $\mathcal{Q}_{m,l}(\mathbf{W}) = \sum\limits_{\ell\neq m} |\mathbf{h}_{m,l}^H\mathbf{w}_\ell|^2 + N_0$ is convex in $\mathbf{W}$, and $\mathcal{F}_{m,l}(\mathbf{W},\tilde{\gamma}_m) = \left(\sum_{m=1}^{M}|\mathbf{h}_{m,l}^H\mathbf{w}_m|^2 + N_0\right)/(1+\tilde{\gamma}_m)$ is also jointly convex in $\mathbf{W}$ and $\tilde{\gamma}_m$. Now problem $\mathcal{P}_4$ is a concave objective maximization problem having DC and convex constraints, which can be well addressed by the CCP-based iterative algorithm [13].

As an efficient tool to solve the DC problem, the CCP-based algorithm iteratively executes convexification and optimization steps to find a stationary point. In the convexification step, the first-order Taylor approximation is used to linearize the concave part of the DC constraint, consequently approximating the DC problem as a convex problem. In the optimization step, the convex sub-problem obtained in the convexification step is solved globally. Specific steps are as follows:

- Convexification: In iteration $t-1$, let $(\mathbf{W},\tilde{\boldsymbol{\gamma}})^{t-1}$ denote the estimates of $\mathbf{W}$ and $\tilde{\boldsymbol{\gamma}}$. In iteration t, the first-order Taylor series expansion at the estimate $(\mathbf{W},\tilde{\boldsymbol{\gamma}})^{t-1}$ is used to replace the concave part of the constraint C_9 in (14), that is,

$$\begin{aligned}&\tilde{\mathcal{F}}_{m,l}(\mathbf{W},\tilde{\gamma}_m)^t \triangleq \mathcal{F}_{m,l}(\mathbf{W},\tilde{\gamma}_m)^{t-1}\\ &+\Re\left\{\nabla^H\mathcal{F}_{m,l}(\mathbf{W},\tilde{\gamma}_m)^{t-1}\begin{bmatrix}\{\mathbf{w}_m-\mathbf{w}_m^{t-1}\}_{m=1}^{M}\\ \tilde{\gamma}_m-\tilde{\gamma}_m^{t-1}\end{bmatrix}\right\},\end{aligned} \tag{15}$$

where

$$\nabla\mathcal{F}_{m,l}(\mathbf{W},\tilde{\gamma}_m)^{t-1} = \begin{bmatrix}\{\dfrac{2\mathbf{h}_{m,l}\mathbf{h}_{m,l}^H\mathbf{w}_m^{t-1}}{1+\tilde{\gamma}_m^{t-1}}\}_{m=1}^{M}\\ -\dfrac{\sum_{m=1}^{M}\left|\mathbf{h}_{m,l}^H\mathbf{w}_m^{t-1}\right|^2+N_0}{\left(1+\tilde{\gamma}_m^{t-1}\right)^2}\end{bmatrix}. \tag{16}$$

- Optimization: The convex sub-problem can be acquired using (15) instead of the concave part of the constraint C_9 in (14), and the next estimate $(\mathbf{W},\tilde{\boldsymbol{\gamma}})^{t+1}$ is updated by solving the sub-problem:

$$\begin{aligned}\mathcal{P}_5 : &\max_{\mathbf{W},\tilde{\gamma}} \sum_{m=1}^{M} \eta_m \log_2(1+\tilde{\gamma}_m)\\ \text{s.t. } &C_{10} : \mathcal{Q}_{m,l}(\mathbf{W}) - \tilde{\mathcal{F}}_{m,l}(\mathbf{W},\tilde{\gamma}_m)^t \leq 0,\\ &C_5 \text{ in } (7), C_8 \text{ in } (13),\end{aligned} \tag{17}$$

Note that a feasible initial point (FIP) is required in the CCP framework to guarantee convergence to a stationary point [14]. In this paper, $\mathbf{W}^0$ can be initialized by a complex Gaussian distribution while satisfying the constraint C_5 in (7), then $\tilde{\gamma}^0$ is acquired by calculating the minimum received SINR of UTs in each group. Take the FIP composed of $\mathbf{W}^0$ and $\tilde{\gamma}^0$ as the initial value of problem $\mathcal{P}_5$, and the system WSR at the t-th iteration is denoted as $\mathcal{P}_5(t)$.

Based on the above detailed derivation, the MGMBF scheme to solve the WSR maximization problem is straightforward and summarized as Algorithm 1.

Algorithm 1 The Proposed MGMBF Scheme for Multi-beam LEO SATCOM Systems

Input: $\mathcal{K}$, $\{\mathbf{u}_1,\mathbf{u}_2,...,\mathbf{u}_K\}$, $\{\mathbf{h}_1,\mathbf{h}_2,...,\mathbf{h}_K\}$, M, R_0, λ.
Output: $\mathbf{W}$.

```
Phase 1: User Grouping
Initialize Λ = ∅, Γ = 0.
while Γ < M do
    Obtain ν_1 according to (8);
    Obtain Λ according to (9);
    update threshold λ;
    Ω = Λ ∪ ν_1, K = K\Ω;
    for k = 1 : |K| do
        Obtain m̃ according to (10);
    end for
    for m = 1 : M do
        Calculate d^m_{i,j} according to (11);
        if d^m_{i,j} > 2r then
            K = K ∪ Ω, Λ = ∅, Γ = 0;
            break
        else
            Γ = Γ + 1;
        end if
    end for
end while
Phase 2: Beamforming Design
Initialize W^0, γ̃^0, Δ, η = [η_1, η_2, ..., η_M]^T, t = 0.
repeat
    Convexification: Use (15) to linearize the concave part
    in (14);
    Optimization: Solve problem P_5 to obtain (W, γ̃)^{t+1};
    update: P_5, t = t + 1.
until P_5(t + 1) − P_5(t)| ≤ Δ.
return W.
```

IV. Simulation Results

In this section, we provide simulation results to evaluate the WSR performance of the proposed MGMBF scheme for the considered system. We assume that all UTs are randomly distributed in an 200×200 km square area. The UPA with

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Orbit altitude	$d_h = 1000$ km
Beam coverage radius	$r = 28$ km
Number of beams	$N_s = 7$
Carrier frequency	$f = 20$ GHz
3dB angle	$\alpha_{3\text{dB}} = 3.2°$
Boltzmann constant	$\kappa = 1.38 \times 10^{-23}$ J/K
Satellite antenna gain	$G_s = 36.7$ dBi
UTs antenna gain	$G_r = 41.7$ dBi
Bandwidth	$B = 50$ MHz
Noise temperature	$T = 300$ K
Rain fading	$\mu = -3.125$, $\sigma = 1.951$

16 antennas ($N_x = N_y = 4$) is equipped on the LEO satellite side. The detailed simulation parameters are listed in Table I [12],[15]. To show the superiority of the MGMBF scheme, we compared three benchmark algorithms in the beamforming design stage, namely, multi-beam interference mitigation (MBIM) [9], minimum mean square error (MMSE) beamforming [16], and zero-forcing (ZF) beamforming [6].

We firstly demonstrate the convergence performance of WSR for different total power budgets, shown in Fig. 2. The system WSR gradually stabilized with the iteration index. At the beginning of the iteration, the WSR is lower and almost the same because the inter-beam interference is severe, and the inter-beam interference also increases with raising total power. However, with an increasing number of iterations, the inter-beam interference is mitigated, and the higher total power budget results in better system performance. In addition, with an increasing total power budget, the number of iterations required to converge grows accordingly to obtain a higher system performance.

Fig. 3 provides the WSR of different schemes versus the number of UTs. Here, we set $P = -5$ dBW and $\gamma_0 = 0.1$. It can be seen that the WSR of the MGMBF scheme increases steadily with the number of UTs. In contrast, the benchmark schemes first increase and then stabilize or even decrease. Moreover, the WSR of the MGMBF scheme is significantly higher than the other three algorithms. For the number of UTs $K = 20$, the system WSR is improved by 25.1% compared with the MBIM scheme. This is because the UTs located at the edge of the beam typically experience more serious inter-beam interference, and the MGMBF scheme can effectively alleviate the interference of these UTs and improve the transmission rate of the worst user in each multicast group. For MBIM, MMSE, and ZF schemes, the increase in the number of UTs means that the probability and proportion of UTs at the beams edge will increase, and the transmission rate achieved by each multicast group is determined by the minimum UT rate. Therefore, although the weight factor increases the WSR at first, the system performance will eventually stabilize or even decrease.

Fig. 4 demonstrates the WSR of the MGMBF scheme versus the satellite total power budget under different SINR requirements, with the number of UTs $K = 30$. On the one hand, when the minimum SINR requirement of each beam

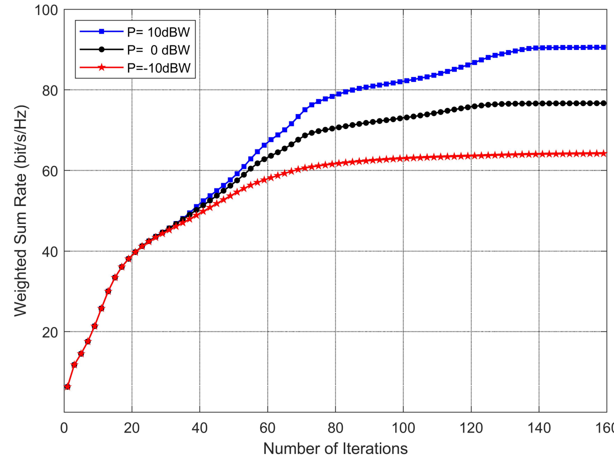

Fig. 2. The convergence performance versus the number of iterations.

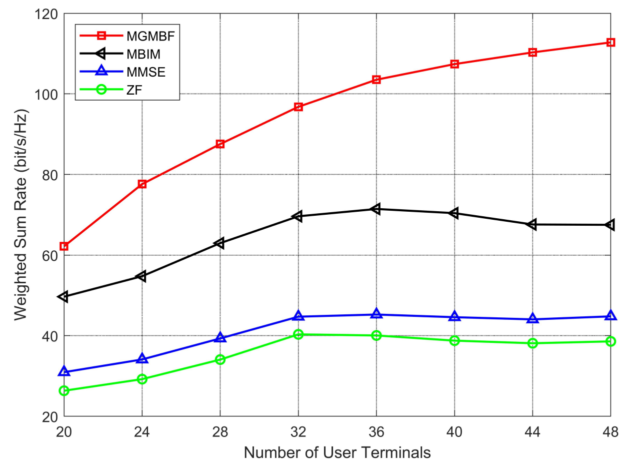

Fig. 3. The WSR for different schemes versus the number of UTs.

is constant, the system WSR rises steadily with the satellite total power budget, which is coincident with the analysis results of Fig. 2. On the other hand, when the total power budget is fixed, the WSR descends as the minimum SINR requirement increases. When $P = 10$ dBW, compared with $\gamma_0 = 0.14$, the system performance is improved by 4.1% at $\gamma_0 = 0.10$. For the MGMBF scheme, after the minimum rate requirements of all beams are satisfied, it is more inclined to optimize the performance of some beams to improve the system WSR. However, when the minimum SINR requirement of UTs increases, due to the total power budget being constant, the achievable transmission rate of some beams needs to be sacrificed to meet the minimum SINR requirement of all multicast groups, resulting in an overall degradation of system performance.

The receiving SINR of the MGMBF scheme versus the azimuth and elevation angles are illustrated in Fig. 5, where a pair of azimuth and elevation angles represent the position of a UT within the satellite coverage area. In the simulations, the number of UTs $K = 30$, the minimum SINR requirement $\gamma_0 = 0.10$, and the total power budget $P = 0$ dBW. It can

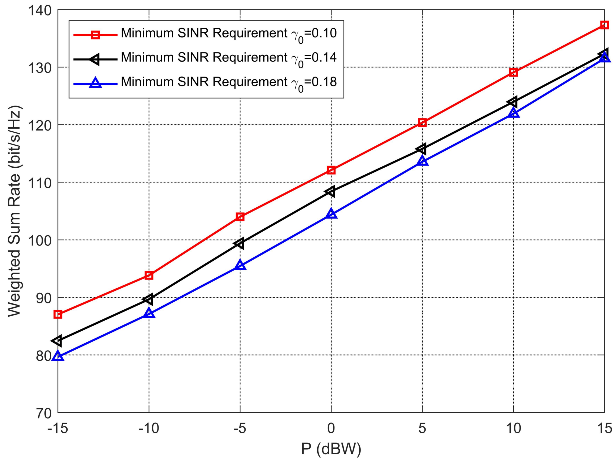

Fig. 4. The WSR versus total power budget for different minimum SINR requirements.

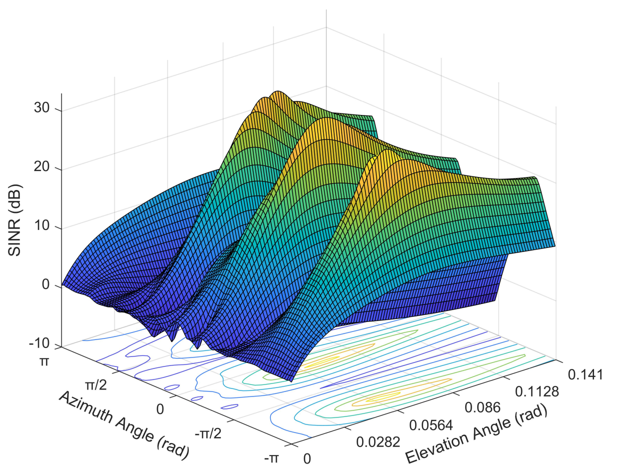

Fig. 5. The receiving SINR versus the azimuth and elevation angles.

be observed that the high received SINR locations are mainly concentrated in three regions, and the highest receiving SINR of these areas is improved by about 18 dB compared with other locations. In order to maximize the system WSR, when the minimum transmission rate of all UTs is guaranteed, the MGMBF scheme utilizes a limited power budget to enhance the transmission rate of multicast groups served by a part of beams. In addition, the location closer to the center of the area has a higher received SINR. In general, UTs located in the beam coverage edge have a greater distance from the satellite than UTs located in the beam coverage center and suffer more severe path loss. Therefore, the received SINR in the central area is always higher than in other locations.

V. Conclusion

This paper proposes an MGMBF scheme to solve the WSR maximization problem in multi-beam LEO SATCOM. In the user grouping stage, all UTs are grouped using the channel correlation coefficient, and the beam centers are determined on the premise that all UTs are within the beam coverage. In the beamforming design stage, an iterative algorithm based on the CCP framework is presented to solve a convex sub-problem in each iteration, and the beamformer for each multicast group is obtained eventually while ensuring convergence. The simulation results indicate that the MGMBF scheme has significant advantages compared with benchmark algorithms. The future work will focus on hybrid beamforming design in multi-beam LEO SATCOM systems.

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