Efficient Seamless Coverage of High Throughput Satellites with Irregular Coverage Shapes

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Abstract*—High throughput satellites (HTS), which can provide wide coverage, are recognized as a promising extension and supplement to achieve global coverage for the space-air-ground integrated network (SAGIN). Different to current literature on seamless coverage of HTS which considers that the shapes of multi-spot beam coverage regions are regular, this paper considers a practical HTS system, in which the multi-spot beams with irregular coverage regions are discussed, and the limitations of spot beam resource and coverage overlapping are taken into account. In order to achieve efficient seamless coverage of HTS, a grid division based multi-spot beam footprint planning (GD-MBFP) scheme is proposed with a given maximum coverage overlap ratio, aiming to minimize the number of spot beams. Meanwhile, for GD-MBFP scheme, a grid division based single-spot beam coverage calculation (GD-SBCC) method is proposed to obtain the irregular coverage regions of spot beams accurately. Numerical results validate the effectiveness of the proposed GD-MBFP scheme. Given a maximum coverage overlap ratio of $\eta_{\max}$=30%, the number of spot beams achieving seamless coverage with the proposed GD-MBFP scheme is only 37.9% of that achieving seamless coverage with cellular beam footprint planning (CBFP) scheme. Meanwhile, the average SINR of UTs with the proposed GD-MBFP scheme is 1.58 times that with CBFP scheme. The average throughput of spot beam with the proposed GD-MBFP scheme is improved by 30.4% than that with CBFP scheme.

***Index Terms*—High throughput satellites, multi-spot beam footprint planning, irregular coverage, seamless coverage.**

I. Introduction

With the development of wireless communications [1-5], the demand for smart communication services is increasing rapidly, and the key of global coverage for Internet of everything (IoE) has been receiving significant attention from both industry and academia. Meanwhile, considering the limitation of terrestrial communication network, the space-air-ground integrated network (SAGIN) has been proposed, in which satellites play an irreplaceable role to achieve global coverage [6-9]. Lately, compared to the traditional single-wide beam architecture, high throughput satellites (HTS) with multi-spot beams have been provided to satisfy the rising traffic demand [10-12]. HTS can realize seamless wide coverage with multi-spot beam footprint planning scheme. The multi-spot beam footprint planning of HTS has ignited intense research activities in recent years.

Firstly, to design a multi-spot beam footprint scheme, it is necessary to focus on the works of coverage characteristics of a single-spot beam. Existing works assume that the coverage region of a single-spot beam is regular (i.e. ellipse) and focus on obtaining the parameters of the ellipse region formed by this spot beam, which are called as ellipse region-based works in this paper. For example, [13] assumes that the coverage region of the orthographic projective beam of geostationary earth orbit (GEO) HTS is circular and the coverage region of the inclined projective beam is ellipse. Then formulas are derived to calculate elliptic coverage regions located in different positions with various parameters (such as semi-major axis and semi-minor axis). Furthermore, to obtain the coverage region of a single-spot beam, an ellipse parameter calculating method is proposed in [14] by collecting the edge point set of the region. To obtain the plane and spherical coverage region of a single-spot beam, geometric theorems are employed in [15]. Although the assumption that the shape of the coverage region formed by a single-spot beam is a regular ellipse is adopted in existing works, the real coverage region is a non-elliptic polygonal, due to the curvature of the Earth [16]. In other words, the real shape of the coverage region formed by a single-spot beam is irregular in practice and the irregularity increases with the latitude. Considering the irregular region of a single-spot beam, the results obtained from these ellipse region-based works may be seriously deviated from the real values and cannot be adopted in practical HTS systems.

Secondly, in order to provide seamless coverage, multi-spot beam footprint planning schemes have attracted much attention, which assume that the coverage regions of multi-spot beams are ellipses [17-20]. For example, [17] proposes a hexagonal grid footprint planning to provide seamless coverage with specified number of overlapping fixed-size spot beams. [18] proposes a footprint planning using two kinds

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of spot beams with different sizes, in order to achieve the seamless coverage of China with the minimum number of spot beams. [19] proposes a footprint planning with flexible multi-beam size to balance the traffic between spot beams, in which the number of spot beams is fixed. [20] discusses the relationship between the positions of multi-spot beams and the overall throughput of HTS system, then proposes a multi-spot beam arrangement to improve the overall throughput.

Considering that the coverage region of a single-spot beam is irregular in practice, existing works on multi-spot beam footprint planning are not suitable for real HTS systems. Moreover, due to the inaccurate analysis of the coverage regions of spot beams, existing multi-spot beam footprint planning would lead to excessive overlapping and increase the number of spot beams for seamless coverage. In order to realize seamless coverage and improve the performance of HTS system, it is critical to design an efficient multi-spot beam footprint planning, in which the irregular coverage regions of multi-spot beams are considered.

Therefore, different to existing works, this paper proposes a grid division based multi-spot beam footprint planning (GD-MBFP) scheme to achieve efficient seamless coverage, where the multi-spot beams with irregular coverage regions are discussed. Firstly, to obtain the irregular coverage regions of spot beams accurately, a grid division (GD) method is adopted with equal longitude and latitude intervals to model the whole region to be covered and the formula of coverage overlap ratio is derived. Then a GD based single-spot beam coverage calculation (GD-SBCC) method is proposed to obtain the coverage region of a single-spot beam. Considering the limitation of spot beam resource and the inevitability of the coverage overlapping, a GD based multi-spot beam footprint planning (GD-MBFP) scheme is proposed with a given maximum coverage overlap ratio, targeting to minimizing the number of spot beams and guaranteeing efficient seamless coverage. The performance of the proposed GD-MBFP for real HTS systems is demonstrated via simulations. Given a maximum coverage overlap ratio $\eta_{\max} = 30\%$, it is shown that the number of spot beams for seamless coverage with the proposed GD-MBFP scheme is 37.9% of that for seamless coverage with cellular beam footprint planning (CBFP) scheme which is adopted in real HTS systems. Meanwhile, the average SINR of UTs with the proposed GD-MBFP scheme is 1.58 times that with CBFP scheme. The average throughput of spot beam with the proposed GD-MBFP scheme is increased by 30.4% than that with CBFP scheme.

The rest of the paper is organized as follows. The system model is presented in Sec II. In Sec III, a GD-SBCC method is proposed to obtain the irregular coverage region of a single-spot beam. Based GD-SBCC, a GD-MBFP scheme is proposed to provide efficient seamless coverage with minimized spot beams. In Sec IV, the performance of the proposed GD-MBFP is demonstrated via simulations. Finally, conclusions are drawn in Sec V.

Notation: N_+ denotes the set of positive integers. $\|\cdot\|$ denotes the 0 norm of a matrix. $\lceil\cdot\rceil$ denotes the ceiling function. $\mathbf{I}$ denotes a matrix with all elements 1.

II. System Model

A. A High Throughput Satellite System

A HTS system working in the Ka band is considered in this paper, where there are one HTS S, one gateway/network control center (NCC) and multiple satellite user terminals (UTs). The HTS S can provide K spot beams. Define C_Ω as the whole region to be covered and C_k as the coverage region irradiated on the ground of spot beam k ($k \in [1, K]$). Note that C_k is determined by the center and width of spot beam k. Define P_k as the center position of spot beam k ($k \in [1, K]$), and $\mathbf{P} = \{P_k \mid k \in [1, K]\}$ as the set of spot centers. To achieve seamless coverage of the whole region, the HTS can adjust the center and width of these spot beams through NCC.

The spot beam center is somewhere the transmission antenna radiation gain is maximum. The spot beam width can be indicated by the half-power beam angle θ_{3dB}, which is the angle between the directions where the transmission antenna radiation gain falls to half of the gain value of the beam center [19]. In the HTS system, assume that all spot beams have the same beam width in this paper [21].

B. Region Grid Model

This paper employs a grid division (GD) method to describe the whole region and the coverage regions of spot beams. With GD method, C_Ω can be discretized into multiple equal longitude and latitude intervals by dividing unit longitude into $d(d \in N_+)$ parts equally, and so is the unit latitude. So, the dividing precision is defined as $\delta = 1/d, \delta \in (0, 1]$. Assume that each grid can be totally decided by its center for a given δ. Hence, the whole region to be covered C_Ω can be descripted by the grid centers formed by GD method.

Assume that C_Ω is a regular region and the longitude and latitude range of C_Ω is $[Lon_{\min}, Lon_{\max}]$ and $[Lat_{\min}, Lat_{\max}]$, respectively, where $Lon_{\min}, Lon_{\max} \in [0°, 180°E]$, $Lat_{\min}, Lat_{\max} \in [0°, 90°N]$, $Lon_{\max} > Lon_{\min}$, and $Lat_{\max} > Lat_{\min}$. In the region grid model, the whole region to be covered C_Ω can be represented by a non-empty matrix $\mathbf{C_\Omega} = \left(c_{ij}^{\Omega}\right)_{M\times N}$, where $M = \frac{Lon_{\max} - Lon_{\min}}{\delta} + 1$, $N = \frac{Lat_{\max} - Lat_{\min}}{\delta} + 1$, and c_{ij}^{Ω} is the mapping of latitude and longitude position $(Lon_{\min} + \frac{2i-1}{2}\delta, Lat_{\min} + \frac{2j-1}{2}\delta)$ of the grid center g_{ij}. Define $c_{ij}^{\Omega} = 1$ when grid center g_{ij} is in the region C_Ω, otherwise $c_{ij}^{\Omega} = 0$. As all grid centers are in region C_Ω, then $c_{ij}^{\Omega} = 1, \forall c_{ij}^{\Omega} \in \mathbf{C_\Omega}$.

Similarly, the coverage region C_k of spot beam k can be represented by a non-empty matrix $\mathbf{C}_{\boldsymbol{k}} = \left(c_{xy}^{k}\right)_{M\times N}$, $k \in [1, K]$. Define $c_{xy}^{k} = 1$ when the grid center g_{xy} is in region C_k, otherwise $c_{xy}^{k} = 0$. Obviously, $\mathbf{C}_{\boldsymbol{k}} \subseteq \mathbf{C_\Omega}$. Assuming that each grid can be totally decided by its center, the beam center P_k of spot beam k can be accurately approximated by a grid center in region C_k, and the latitude and longitude position of P_k is $\left(Lon_{\min} + \frac{x_{P_k}}{2}\delta, Lat_{\min} + \frac{y_{P_k}}{2}\delta\right)$. Define the mapping of P_k as $c_{xy}^{P_k}$, and $c_{xy}^{P_k} = 1$.

Note that excessive overlap coverage will increase the number of spot beams to achieve seamless coverage. Considering the inevitability of coverage overlapping, define coverage overlap ratio η as the number of overlapped grids divided by the total number of grids. Define the coverage overlap ratio $\eta_{h,g}$ of spot beam h and spot beam g as the number of overlapped grids $Num_{lap}^{h,g} = \|\mathbf{C}_{\boldsymbol{h}} \cap \mathbf{C}_{\boldsymbol{g}}\|_0$ divided by the total number of grids covered by these two spot beams $Num_{total}^{h,g} = \|\mathbf{C}_{\boldsymbol{h}} \cup \mathbf{C}_{\boldsymbol{g}}\|_0$. $\eta_{h,g}$ is given by

$$\eta_{h,g} = \frac{Num_{lap}^{h,g}}{Num_{total}^{h,g}}, \forall h,g \in [1,K], h \neq g. \tag{1}$$

Similarly, the number of grids overlapped of the whole region C_Ω can be expressed as

$$Num_{lap}^{\Omega} = \left\| \left\lceil \frac{\mathbf{U} - \mathbf{I}_{M\times N}}{\max_{a\in[1,M],b\in[1,N]}\left(u_{ab}-1\right)} \right\rceil \right\|_0, \tag{2}$$

where $\mathbf{U} = \sum_{k\in[K]} \mathbf{C}_{\boldsymbol{k}} = (u_{ab})_{M\times N}$. The total number of grids of C_Ω can be expressed as

$$Num_{total}^{\Omega} = M \times N. \tag{3}$$

Then, the overlap coverage ratio η_Ω of the whole region is given by

$$\eta_\Omega = \frac{Num_{lap}^{\Omega}}{Num_{total}^{\Omega}}. \tag{4}$$

III. Grid Division Based Multi-Spot Beam Footprint Planning with Irregular Coverage

To provide efficient seamless coverage with minimized number of spot beams, a grid division based multi-spot beam footprint planning (GD-MBFP) scheme will be proposed. Firstly, in order to obtain the irregular coverage regions of spot beams accurately, this paper proposes a GD based single-spot beam coverage calculation (GD-SBCC) method. Secondly, considering that spot beam resource is limited and coverage overlapping is inevitable, a GD based multi-spot beam footprint planning (GD-MBFP) scheme is designed, targeting to minimize the number of spot beams while guaranteeing seamless coverage.

A. Grid Division Based Single-Spot Beam Coverage Calculation (GD-SBCC)

In this section, we firstly propose a grid division based single-spot beam coverage calculation (GD-SBCC) method to calculate the coverage region of a single-spot beam with irregular shape.

Assume that point A is a grid center g_{xy} in region C_Ω, and the latitude and longitude position of point A is $\left(Lon_{\min} + \frac{2x-1}{2}\delta, Lat_{\min} + \frac{2y-1}{2}\delta\right)$, $x \in [1,M]$, $y \in [1,N]$. Then, analyze whether point A is within the coverage region C_k. Define θ_{A,P_k} as the angle between the directions between HTS S to point A and HTS S to beam center P_k. According to the definition of coverage region C_k, it can be known that if point A is in region C_k, θ_{A,P_k} must less than or equal to θ_{3dB}.

Given the longitude and latitude position of a beam center P_k, θ_{A,P_k} can be calculated using the theorems of geometric mathematics. Note that all grid centers g_{xy} ($x \in [1,M]$, $y \in [1,N]$) satisfying $c_{xy}^k = 1$ form the coverage region C_k. Thus, the matrix $\mathbf{C}_{\boldsymbol{k}}$ ($k \in [1,K]$) of the irregular coverage region C_k can be obtained using (5), given by

$$c_{xy}^k = \begin{cases} 1, & \text{for } \theta_{A,P_k} \le \theta_{3dB} \\ 0, & \text{for } \theta_{A,P_k} > \theta_{3dB} \end{cases}, c_{xy}^k \in \mathbf{C}_{\boldsymbol{k}}, k \in [1,K]. \tag{5}$$

B. Grid Division Based Multi-Spot Beam Footprint Planning (GD-MBFP)

Considering the limitation of spot beam resource and the inevitability of coverage overlapping, the goal of the proposed GD-MBFP scheme is to provide seamless coverage with minimized number of spot beams, for a given maximum coverage overlap ratio. The multi-spot beam footprint planning problems can be formulated as follows:

$$\min \quad K \tag{6}$$

$$\text{s.t. } \mathbf{C}_{\boldsymbol{\Omega}} \subset \bigcup_{k=1}^{K} \mathbf{C}_{\boldsymbol{k}}, \quad \forall k \in [1,K], K \in N_+, \tag{6a}$$

$$\mathbf{C}_{\boldsymbol{k}} \neq \varnothing, \tag{6b}$$

$$\eta_{h,g} \le \eta_{\max}, \quad \forall h,g \in [K], h \neq g, \tag{6c}$$

$$\eta_\Omega \le \eta_{\max}, \tag{6d}$$

$$K \le K_{\max}. \tag{6e}$$

In (6), the first constriaint (6a) ensures seamless coverage. The second constriaint (6b) ensures that each spot beam is not empty. The constriaint (6c) and (6d) means the coverage overlap constraint. The last constriaint (6e) means the limitation of spot beam resource. However, this optimization problem is NP-hard. A simulated annealing (SA) algorithm adopted in [22] is employed to solve this optimization problem, which is summarized in Algorithm 1.

In this SA algorithm, we adopt GD method to model the whole coverage region C_Ω. Generate the set of center positions $\mathbf{P}_{current}$ of multi-spot beams and obtain the coverage region of each spot beam through GD-SBCC method. Note the center positions of multi-spot beams are not completely random and they must satisfy (6c), in order to ensure the coverage overlap ratio of each two spot beams meet performance requirement of HTS system. Then, analyze whether the system is seamlessly covered according to (6a). If (6a) is satisfied, calculate the coverage overlap ratio $\eta_{\Omega_{current}}$ according to (2-4). The center position set $\mathbf{P}_{current}$ of spot beams is recorded as the current optimal $\mathbf{P}^*$ if $\eta_{\Omega_{current}} \le \eta_{last}$ is satisfied, where η_{last} is the last optimal coverage overlap ratio and the initial optimal coverage overlap ratio is $\eta_{\max}$. In order to avoid falling into local optimum, define ε as the non-optimal acceptable probability. The SA algorithm accepts the sub-optimal $\mathbf{P}_{current}$ as the optimal solution when $e^{-\frac{(\eta_\Omega - \eta_{last})}{t_0}} > \varepsilon$, where t_0 is the initial temperature in this SA algorithm. Increase the number of spot beams K until seamless coverage is satisfied. Finally, we can obtain the optimal $\mathbf{P}^*$.

Algorithm 1 Proposed GD-MBFP Algorithm.

Input: Parameters of system model, R_s, R_e, (Lon_s, Lat_s), θ_{3dB}, $[Lon_{\min}, Lon_{\max}]$, $[Lat_{\min}, Lat_{\max}]$, δ, $\eta_{\max}$, $K_{\max}$. Set the initial temperature t_0 and non-optimal acceptable probability ε.

Output: K^*, $\mathbf{C}_{\boldsymbol{k}}^*$, $\mathbf{P}^*$, η_{Ω}^*;

Region grid and compute matrix $\mathbf{C}_{\mathbf{\Omega}}$;
for $k = 1$: $k \leq K_{\max}$ **do**
    Generate $\mathbf{P}_{current}$ and $\mathbf{C}_{\boldsymbol{k}_{current}}$;
    while $\mathbf{C}_{\mathbf{\Omega}} \subset \cup_{k=1}^{K} \mathbf{C}_{\mathbf{k}_{current}}$ **do**
        Compute the overlap coverage ratio $\eta_{\Omega_{current}}$ by using Eq. (2-4);
        if $\eta_{\Omega_{current}} \leq \eta_{last}$ **then**
            $K^* \Leftarrow k_{current}$, $\mathbf{C}_{\boldsymbol{k}}^* \Leftarrow \mathbf{C}_{\boldsymbol{k}_{current}}$, $\mathbf{P}^* \Leftarrow \mathbf{P}_{current}$, update $\mathbf{P}^*$;
        else
            while $e^{-\frac{(\eta_{\Omega} - \eta_{last})}{t_0}} > \varepsilon$ **do**
                $K^* \Leftarrow k$, $\mathbf{C}_{\boldsymbol{k}}^* \Leftarrow \mathbf{C}_{\boldsymbol{k}}$, $\mathbf{P}^* \Leftarrow \mathbf{P}_{current}$;
            end while
        end if
        $k = k + 1$.
    end while
end for

IV. Performance Evaluation

In this section, the performance of the proposed GD-MBFP for real HTS system is demonstrated via simulations. Since the cellular beam footprint planning (CBFP) is adopted in real HTS systems [17], we adopt CBFP scheme as a baseline.

We consider a GEO HTS system, and the half-power beam angle $\theta_{3dB} = 0.3°$ and the frequency reuse factor $R = 7$. Considering the coverage overlapping is inevitable, we assume that a maximum coverage overlap ratio $\eta_{\max} = 30\%$ for the proposed GD-MBFP and the longitude and latitude range of whole region C_{Ω} to be covered seamlessly is $[120°E, 150°E]$ and $[30°N, 60°N]$, respectively. The multi-spot beam antenna radiation pattern follows rec.ITU-S.672 [23], where $\theta_b = 0.15°$, $a = 2.88$, $b = 6.32$. Specific simulation parameters are shown in Table I.

To verify the performance of HTS system, we simulate the multi-spot beam footprint planning using CBFP and the proposed GD-MBFP scheme and the results are shown in Fig. 1, Fig. 2 and Fig. 3.

We obtain the footprint planning of CBFP scheme when it adopted in an ideal HTS system and in a real HTS system. Fig. 1 and Fig. 2 shows the ideal footprint planning and the real footprint planning of CBFP, respectively. From Fig. 1 and Fig. 2, it can be seen that the shape of the coverage region of one spot beam is irregular in practice and the irregularity increases with the latitude. Hence, the CBFP scheme assuming that the shape of coverage region is circular is not suitable for real HTS systems. At the same time, the footprint planning of CBFP scheme results in a large overlap, which will degrade the performance of HTS system.

Note that the proposed GD-MBFP scheme is designed for the irregular coverage of spot beams, that is, the proposed GD-MBFP scheme is suitable for real HTS systems. Fig. 3 shows the footprint planning of proposed GD-MBFP scheme, given a maximum coverage overlap ratio. With GD-SBCC method, irregular coverage regions of spot beams can be obtained accurately, which can be seen directly from Fig. 3. As shown in TABLE II, we measure the effectiveness of proposed GD-MBFP scheme and CBFP scheme by two metrics: coverage overlap ratio and the number of spot beams for seamless coverage. Compared to CBFP scheme, it can be seen that the proposed GD-MBFP scheme needs fewer spot beams for seamless coverage to coverage the whole region C_{Ω}. CBFP scheme needs 132 spot beams to achieve seamless coverage, that is because the coverage region shape of CBFP is deviated from the real shape. Moreover, the coverage overlap ratio of CBFP scheme is almost 100%, which is too high for HTS system even if frequency reuse technology is adopted. The number of spot beams achieving seamless coverage with the proposed GD-MBFP scheme is only 37.9% of that achieving seamless coverage with CBFP scheme. At the same time, the coverage overlap ratio can be reduced from almost 100% to 29% with the proposed GD-MBFP scheme, thus the inter-beam interference can be alleviated. Thus, the proposed GD-MBFP scheme can achieve efficient seamless coverage, achieving to provide seamless coverage with minimized number of spot beams.

TABLE I
Summary of Simulation Parameters

Parameters	Values
Satellite system	GEO HTS
Distance from the satellite to the center of the Earth R_s	35786 km
Earth radius R_e	6371 km
Position of satellite (Lon_s, Lat_s)	$(110°E, 0°)$
Downlink frequency band B	20 GHz
Frequency reuse factor R	7
Bandwidth of each beam	500 MHz
Number of satellite UTs L	100
Half-power beam angle θ_{3dB}	$0.3°$
Maximum antenna gain	41.6 dBi
Power of each beam	30 dBW
Path loss on the downlink	209.5 dB
Receiver antenna gain	40 dBi
User terminal receiving G/T	18.5 dBi
Boltzmann constant	-228.6 dB/k/Hz
Rain attenuation	3.95 dB
Free space path loss	209.5 dB
Noise temperature	29 dB
Noise bandwidth	80.9 dBHz
Dividing precision δ	10
Initial temperature	$100°C$
non-optimal acceptable probability ε	0.05

TABLE II
Number of spot beams to coverage the whole region

Whole region	Scheme	Number of spot beams	Coverage overlap ratio
C_{Ω}	GD-MBFP	50	29%
	CBFP	132	≈100%

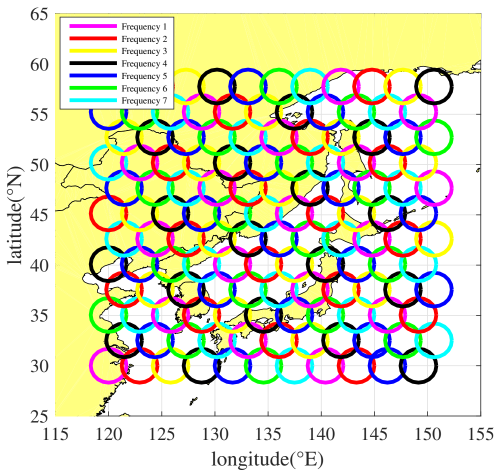

Fig. 1. CBFP scheme in a ideal HTS system.

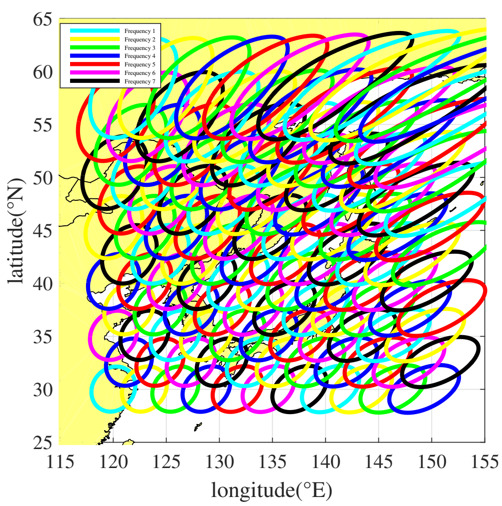

Fig. 2. CBFP scheme in a real HTS system.

In addition to the number of spot beams and coverage overlap ratio, we also discuss the performance of HTS system. Assume each spot beam contains L satellite UTs whose positions are randomly generated. The SINR performance of UTs is evaluated for the proposed GD-MBFP and CBFP scheme and the SINR of UTs is calculated according to [24]. Fig. 4 shows the cumulative distribution function (CDF) of SINR of UTs. As shown in TABLE III, the average SINR of UTs can reach 8.15 dB with GD-MBFP, which is 1.58 times that with CBFP. It can be seen that the maximum SINR of CBFP is almost the same as that of proposed GD-MBFP scheme. However, the minimum SINR shows that the communication performance of some users with the CBFP scheme is poor, that is because excessive overlapping leads to serious inter-beam interference. Different to CBFP scheme, adverse impact of excessive overlapping on system performance is considered in proposed GD-MBFP scheme, and results show that the proposed GD-MBFP scheme has better SINR performance than CBFP.

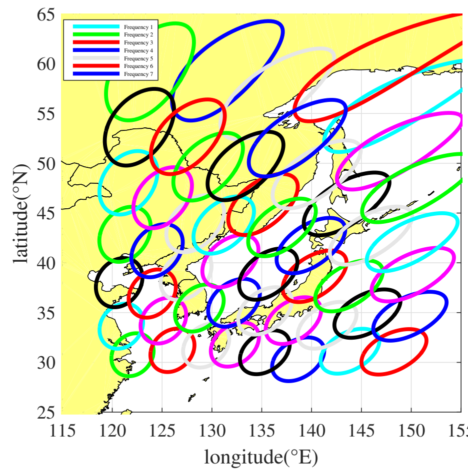

Fig. 3. Proposed GD-MBFP scheme in a real HTS system.

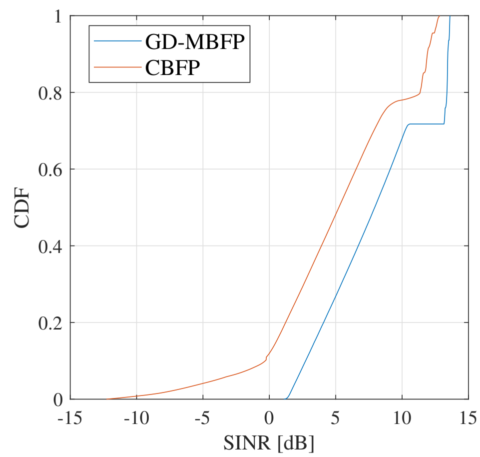

Fig. 4. CDF results of the SINR of UTs.

TABLE III
CDF RESULTS OF THE SINR OF UTS

Scheme	Min SINR [dB]	Max SINR [dB]	Mean SINR [dB]
GD-MBFP	1.10	13.61	8.15
CBFP	-12.27	12.84	5.17

Then, we evaluate the throughput performance of spot beam for the proposed GD-MBFP and CBFP scheme and the spot beam throughput is calculated according to [24]. Fig.5 shows CDF of spot beam throughput. As shown in TABLE IV, with GD-MBFP, the average throughput of spot beam can reach to 1.03Gbps with the proposed GD-MBFP scheme, which is improved by 30.4% than that with CBFP scheme. The minimum throughput of spot beams is 0.34 Gbps, which shows that the performance of some spot beams with the CBFP scheme is poor. At the same time, it can be seen that the minimum throughput with proposed GD-MBFP scheme is larger than the maximum throughput of CBFP scheme, which shows throughput performance of the proposed GD-MBFP scheme is better than that of CBFP.

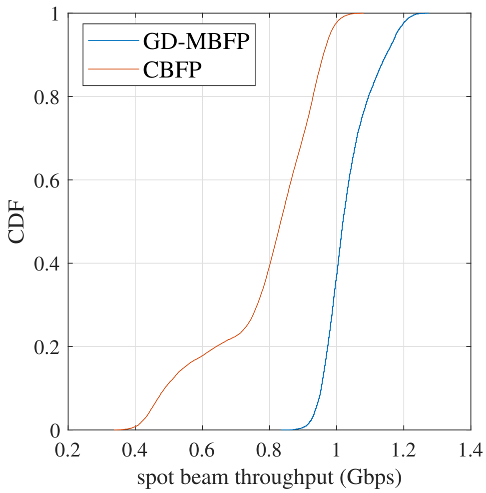

Fig. 5. CDF results of spot beam throughout.

TABLE IV
CDF RESULTS OF SPOT BEAM THROUGHOUT

Scheme	Min (Gbps)	Max (Gbps)	Mean (Gbps)
GD-MBFP	0.83	1.27	1.03
CBFP	0.34	1.08	0.79

V. CONCLUSIONS

In this paper, a practical HTS system with irregular coverage regions of multi-spot beams is considered. A grid division (GD) based multi-spot beam footprint planning (GD-MBFP) scheme is proposed to minimize the number of spot beams for efficient seamless coverage, with a given maximum coverage overlap ratio. To obtain the irregular coverage regions of multi-spot beams, a grid division based single-spot beam coverage calculation (GD-SBCC) method is proposed, which is the basis of GD-MBFP scheme. The numerical results show a significant improvement with the proposed GD-MBFP scheme in terms of the number of spot beams for seamless coverage.

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