Collaborative Interference Suppression for LEO Satellite Beam Hopping Systems

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***Abstract*—This paper proposes interference suppression strategies for Low Earth Orbit (LEO) multi-satellite communication systems. A two-dimensional satellite-cell matching algorithm based on a utility function is introduced to mitigate partial interference. Additionally, a beam hopping (BH) pattern optimization algorithm is developed using satellite priority to minimize inter-satellite interference and enable collaborative BH transmission. To further suppress interference and address the impact of imperfect channel state information (CSI), a robust precoding algorithm leveraging multi-satellite cooperation is presented. Numerical results validate the effectiveness of the proposed algorithms in interference suppression, demonstrating their resilience in channel estimation errors.**

***Index Terms*—Low Earth Orbit(LEO), multi-satellite communication systems, beam hopping(BH), robust precoding.**

I. Introduction

Low Earth Orbit (LEO) satellite communication systems are essential for achieving global coverage and ubiquitous connectivity [1]. Compared to satellites in higher orbits, LEO satellites offer advantages such as low transmission latency, wide coverage, and flexible deployment. These characteristics enable high-speed, low-latency communication services for users worldwide, making LEO systems particularly suitable for emergency communications and remote area coverage [2].

Beam hopping (BH) has emerged as a pivotal technology for addressing the non-uniform distribution of terrestrial user traffic. By dynamically allocating beams in both time and space, BH enhances onboard resource utilization and mitigates inter-beam interference, making it a critical technology for LEO satellite communication systems [3]. However, LEO satellite communication systems are vulnerable to significant co-channel interference (CCI) due to the dense deployment of beams, posing substantial challenges for BH systems [4].

Existing research predominantly addresses CCI through BH pattern optimization and precoding algorithm design. In [5], a low-complexity precoding algorithm was introduced using angle information instead of channel state information (CSI). In [6], a BH pattern with selective precoding was proposed to improve resource utilization. Hybrid precoding design for satellite communication systems was investigated in [7]. Additionally, joint resource allocation and interference suppression strategies were explored in [8]. Nevertheless, most existing strategies are tailored for single-satellite systems and fail to consider collaborative interference suppression across multiple satellites. Furthermore, channel estimation errors caused by the high dynamics and latency in LEO systems exacerbate the interference challenges.

In this context, we present the following key contributions:

- A two-dimensional satellite-cell matching algorithm based on a utility function to mitigate interference caused by overlapping service areas in multi-satellite systems.
- A satellite-priority-based BH pattern optimization algorithm to minimize inter-satellite CCI and enable collaborative BH transmission.
- A robust precoding algorithm leveraging multi-satellite cooperation to suppress inter-satellite interference and mitigate the effects of imperfect CSI.

II. System Model

This section presents the system model of multi-satellite collaborative BH. The diagram of multi-satellite collaborative BH is shown in Fig. 1. We consider a downlink LEO multi-satellite communication system with full frequency reuse.

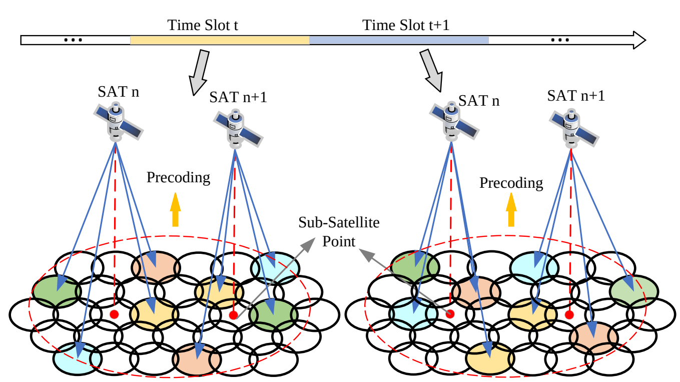

Fig. 1. Multi-satellite collaborative BH system.

A. Multi-Satellite Beam Hopping Pattern

Suppose that the system includes N_S satellites, which are equipped with an $N_{Tx} \times N_{Ty}$ uniform planar array (UPA) antenna. The number of satellite antenna elements is $N_T = N_{Tx} \cdot N_{Ty}$. Terrestrial users are equipped with a single antenna. Each satellite simultaneously generates N_B beams to serve N_C cells within its coverage area, where cell i of the satellite n contains K_i^n users. Each BH cycle consists of N_{TS} time slots, and the duration of each time slot is T. Therefore, the duration of each BH cycle is $N_{TS} \cdot T$.

In contrast to the single-satellite BH pattern, we suppose that each satellite in the proposed system can cover N_C cells. Due to the overlapping coverage areas between adjacent satellites, the number of cells within the coverage range of the entire system is less than $N_S \cdot N_C$. Let $\mathbf{A}_{\rm BH} = \left[\mathbf{a}_1^1, ..., \mathbf{a}_{N_{TS}}^1, ..., \mathbf{a}_1^n, ..., \mathbf{a}_{N_{TS}}^n, ..., \mathbf{a}_1^{N_s}, ..., \mathbf{a}_{N_{TS}}^{N_s}\right]$ represent BH pattern, where $\mathbf{a}_t^n$ denotes the vector of satellite n serving cells in time slot t, which can be expressed as $\mathbf{a}_t^n = \left[a_{t,1}^n, a_{t,2}^n, ..., a_{t,N_C}^n\right]^T$. And $a_{t,i}^n \in \{0, 1\}$ represents whether cell i of satellite n is served or not in time slot t.

B. Channel Model

The channel matrix of satellite n in time slot t can be expressed as $\mathbf{H}_n[t] = \left[\mathbf{h}_{n,1}[t], \mathbf{h}_{n,2}[t], ..., \mathbf{h}_{n,N_B}[t]\right]$, where $\mathbf{h}_{n,i}[t] \in \mathbb{C}^{N_T \times K_i^n}$ denotes channel vector from satellite n to cell i. Since the satellite is equipped with a UPA antenna array, the channel vector can be expressed as

$$\mathbf{h}_{n,i}\left[t\right] = \sqrt{\psi_{n,i}}\tilde{\mathbf{h}}_{n,i}(\theta, \phi), \tag{1}$$

where $\psi_{n,i}$ denotes the large-scale fading coefficient from satellite n to cell i, $\tilde{\mathbf{h}}_{n,i}(\theta, \phi)$ denotes the array response vector, θ and ϕ represent the elevation and azimuth of the line of sight path respectively.

The channel matrix can be expressed as the Hadamard product of the channel gain vector and the channel phase vector. Considering the channel estimation error, the channel matrix can be further expressed as

$$\begin{aligned} \mathbf{h}_{n,i} &= \bar{\mathbf{h}}_{n,i} \odot \mathbf{q}_{n,i} + \Delta\bar{\mathbf{h}}_{n,i} \odot \mathbf{q}_{n,i} \\ &= \mathrm{Diag}(\bar{\mathbf{h}}_{n,i} + \Delta\bar{\mathbf{h}}_{n,i}) \cdot \mathbf{q}_{n,i}, \end{aligned} \tag{2}$$

where $\bar{\mathbf{h}}_{n,i}$ is the estimated channel vector, $\Delta\bar{\mathbf{h}}_{n,i}$ is the channel error vector caused by the channel gain error, $\mathbf{q}_{n,i} = e^{j\Delta\theta_{n,i}}$ is the channel error vector caused by phase error, $\Delta\theta_{n,i}$ is the channel phase error vector.

C. Signal Model

Defining $\mathcal{I}_t^n \triangleq \left\{i \in \{1, 2, ..., N_C\} \mid a_{t,j}^n = 1\right\}$ as a set of satellite n serving cells in time slot t. This set includes the indices of all cells served by the satellite n in time slot t. The received signal at cell i in time slot t can be represented as

$$\begin{aligned} \mathbf{y}_{n,i}[t] = &\mathbf{h}_{n,i}^T\left[t\right]\mathbf{w}_{n,i}\left[t\right]\mathbf{s}_n\left[t\right] + \sum_{i \neq i, i \in \mathcal{I}_t}^{N_B - 1} \mathbf{h}_{n,i}^T\left[t\right]\mathbf{w}_{n,i}\left[t\right]\mathbf{s}_n\left[t\right] \\ &+ \sum_{n' \neq n}^{N_S - 1} \mathbf{h}_{n',i}^T\left[t\right]\mathbf{w}_{n'}\left[t\right]\mathbf{s}_{n'}\left[t\right] + \mathbf{n}_{n,i}\left[t\right], \end{aligned} \tag{3}$$

where $\mathbf{w}_n\left[t\right] = \left[\mathbf{w}_{n,1}, ..., \mathbf{w}_{n,N_B}\right] \in \mathbb{C}^{N_T \times N_B}$ denotes the precoding matrix, $\mathbf{s}_n[t] \in \mathbb{C}^{N_B \times K_i^n}$ is the data stream, $\mathbf{n}_{n,i}[t]$ is the additive white Gaussian noise of zero mean and variance σ_T^2.

We employ spectral efficiency (SE) as the performance metric for interference assessment. The SE for cell i served by satellite n in time slot t is expressed as

$$\eta_{n,i}[t] = \log_2(1 + \gamma_{n,i}[t]), \tag{4}$$

where $\gamma_{n,i}[t]$ is the signal-to-interference-plus-noise ratio (SINR), which is expressed as

$$\gamma_{n,i}\left[t\right] = \frac{\left\|\mathbf{h}_{n,i}^T\left[t\right]\mathbf{w}_{n,i}\left[t\right]\right\|^2}{\sum\limits_{i' \neq i, i \in \mathcal{I}_t}^{N_B - 1}\left\|\mathbf{h}_{n,i}^T\left[t\right]\mathbf{w}_{n,i'}\left[t\right]\right\|^2 + \sum\limits_{n' \neq n}^{N_S - 1}\left\|\mathbf{h}_{n',i}^T\left[t\right]\mathbf{w}_{n',:}\left[t\right]\right\|^2 + \sigma_T^2} \tag{5}$$

III. Proposed Multi-Satellite Interference Suppression Algorithms

This section presents the proposed interference suppression algorithm for multi-satellite cooperative systems, including a two-dimensional satellite-cell matching algorithm, BH pattern optimization algorithm, and robust precoding algorithm.

A. Two-Dimensional Satellite-Cell Matching Algorithm

In LEO constellations, adjacent satellites inevitably create overlapping coverage areas. When multiple satellites concurrently serve these doubly-covered cells, the system experiences significantly aggravated interference conditions due to coherent signal superposition.

To improve user satisfaction and satellite load balancing, we propose a two-dimensional matching algorithm based on the utility function. The utility function $U_n(i)$ of cell i selected by satellite n can be expressed as

$$U_n\left(i\right) = \begin{bmatrix} \alpha_1\left(\frac{\rho_{n,max} - \sqrt{(\rho_{n,i} - \bar{\rho}_n)^2}}{\rho_{n,\max} - \rho_{n,\min}}\right)^\beta + \\ \\ \alpha_2\left(\frac{\tau_{n,\max} - \tau_{n,i}}{\tau_{n,\max} - \tau_{n,\min}}\right)^\beta \end{bmatrix}^{\frac{1}{\beta}}, \tag{6}$$

where $\rho_{n,i}$ denotes the load of the satellite n serving cell i, $\rho_{n,\max}$ and $\rho_{n,\min}$ respectively represent the maximum and minimum load intervals, $\bar{\rho}_n$ is the average value of the load for satellite n, $\tau_{n,i}$ is the propagation from satellite n to cell

i, $\tau_{n,\max}$ and $\tau_{n,\min}$ respectively represent the maximum and minimum propagation delay, α_1 and α_2 are weighting factors, which satisfy $\sum_i \alpha_i = 1$ and $\alpha_i \in (0,1)$, β is used to measure the substitution elasticity of each indicator.

The utility function $U_i(n)$ of satellite n selected by cell i can be expressed as

$$U_i\left(n\right) = \left[\gamma_1\left(\frac{P_{i,\max}-P_{i,n}}{P_{i,\max}-P_{i,\min}}\right)^{\beta} + \gamma_1\left(\frac{\xi_{i,n}}{\xi_{i,\max}}\right)^{\beta}\right]^{\frac{1}{\beta}}, \quad (7)$$

where $P_{i,n}$ is the transmission power, expressed as $P_{i,n} = \mathrm{Tr}(\mathbf{w}_{n,i}^H \mathbf{w}_{n,i})$, $P_{i,\max}$ and $P_{i,\min}$ respectively represent the maximum and minimum transmission power, $\xi_{i,n}$ represents the visible window, $\xi_{i,\max}$ is the maximum value of the visible window, γ_1 and γ_2 are weighting factors, which satisfy $\sum_i \gamma_i = 1$ and $\gamma_i \in (0,1)$.

To achieve optimal satellite-cell matching, we formulate an optimization problem that maximizes the utility function. The specific optimization problem is as follows

$$\begin{aligned} &\max_{\Omega(n),\forall n} \sum_n U_n(i) + \sum_i U_i(n) \\ &\text{s.t.} \sum_{n=1}^{N_s} o_{n,i} = 1, \forall n, i. \end{aligned} \quad (8)$$

where $\mathbf{\Omega}(n) = \left[o_{n,1}, o_{n,2}, ..., o_{n,N_C}\right]$ denotes the coverage area of the satellite n, $o_{n,i} \in \{0,1\}$ is a boolean variable, $o_{n,i} = 1$ indicates that the cell i is within the coverage of satellite n. Then, the satellite-cell matching relationship can be obtained by solving the optimization problem.

B. Beam Hopping Pattern Design

Following the satellite-cell matching, each satellite is allocated distinct service cells, effectively eliminating redundant coverage scenarios. On this basis, we propose a multi-satellite collaborative BH pattern optimization algorithm to suppress CCI. The specific optimization problem is formulated as

$$\begin{aligned} &\max_{\mathbf{A}_{\mathrm{BH}},\mathbf{W}_n[t],\mathbf{\Omega}(n),\forall n,t} \sum_{n=1}^{N_S}\sum_{t=1}^{N_{TS}}\sum_{i\in\mathcal{I}_t^n}^{N_B} \log_2\left(1+\gamma_{n,i}[t]\right) \\ &\text{s.t.C1}: \sum_{t=1}^{N_{TS}} a_{t,i}^n \geq 1, \forall n, i, \\ &\quad \text{C2}: \sum_{n'\neq n}^{N_S} o_{t,i}^n = 0, \forall i, t, \\ &\quad \text{C3}: \sum_i a_{t,i}^n = N_B, \forall n, t, \\ &\quad \text{C4}: P_n \leq P_{\max}, \forall n, \\ &\quad \text{C5}: R_{n,i} \geq r_{n,i}, \forall i, \end{aligned} \quad (9)$$

where constraint C1 imposes each cell must be served at least once in BH cycle, constraint C2 ensures each cell will not be served by other satellites in BH cycle, constraint C3 imposes each satellite only serves N_B cells simultaneously, constraint C4 is the maximum transmit power constraint. Constraint C5 is the minimum data rate requirement.

Since the coverage areas of adjacent satellites do not overlap, the satellites can be considered independent when inter-satellite interference is ignored. Based on this, the BH pattern optimization problem is solved separately for each satellite, and the served cells in each time slot are constrained to obtain the final BH pattern. For satellite n, set the number of cells within its coverage as N_C^n. To significantly reduce computation time and further suppress inter-beam interference, we calculate the distances between cells and assign inter-cell weights based on these distances, as shown below

$$\kappa\left(m,n\right) = \begin{cases} 1, d_{m,n} \geq D_0 \\ 0, d_{m,n} < D_0 \end{cases}, \quad (10)$$

where $d_{m,n}$ is the distance between cell m and cell n, D_0 represents the minimum spatial separation distance, $\kappa\left(m,n\right)$ represents the weight between cell m and cell n, and $\kappa\left(m,n\right) = 1$ means cell m and cell n can be served by satellites simultaneously. Defining $\mathcal{A}_C^n = \{\mathcal{I}_t^n \mid \kappa\left(i,j\right) = 1, i,j \in \mathcal{I}_t^n\}$ as the candidate BH set. Each vector in $\mathcal{A}_C^n$ is composed of N_B cell indexes satisfying the constraint $\kappa\left(m,n\right) = 1$.

The utility function can quantify satellite characteristics and service requirements, providing an objective measure of the priority of each satellite. Therefore, $\sum_i U_n(i)$ is selected as the priority measurement index for the satellite. Without losing generality, we assume that satellites with smaller indexes have higher priority. Then, set the priority of each cell for satellite n. These cells are sorted in descending order based on their data traffic demand, and priority is assigned according to this order. Without losing generality, we assume that cells with smaller indexes have higher priority.

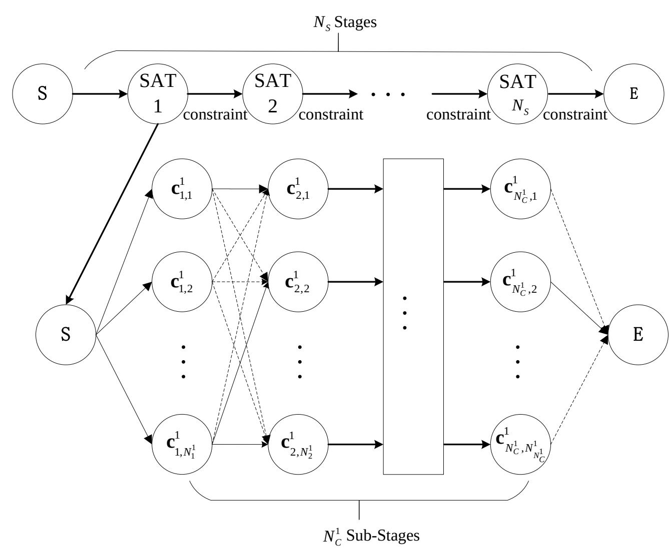

Fig. 2. Viterbi algorithm in multi-satellite cooperative systems.

As shown in Fig. 2, we apply the Viterbi algorithm to solve the optimization problem. The entire process is divided into N_S stages. For satellite 1, its stage is further divided into N_C^1 sub-stages based on cell priority, with each sub-stage corresponding to a specific cell. Set $\mathcal{C}_i^1 = \left\{\mathbf{c}_{i,1}^1, \mathbf{c}_{i,2}^1, ..., \mathbf{c}_{i,N_i^1}^1\right\}$ as the state of cell i in satellite 1, each vector is selected from the candidate BH set $\mathcal{A}_C^1$, and the priority of cell i in each vector is the highest.

To obtain the BH pattern with the highest SE, set the path length of each state to the sum of SE, that is

$$L\left(\mathbf{c}_{i,j}^1\right) = \sum_{m \in \mathbf{c}_{i,j}^1}^{N_B} \log_2\left(1+\gamma_{1,m}\right). \tag{11}$$

In contrast to the conventional Viterbi algorithm that identifies the shortest path, our proposed method determines the longest path as the optimal solution to maximize SE. Set $J_{1,i}\left(\mathbf{c}_{i,j}^1\right)$ as the reward of the candidate vector j of cell i, expressed as

$$J_{1,i}\left(\mathbf{c}_{i,j}^1\right) = \begin{cases} \max\left(J_{1,i-1}\left(\mathbf{c}_{i-1,j}^1\right) + L\left(\mathbf{c}_{i,j}^1\right)\right) & i>1 \\ L\left(\mathbf{c}_{i,j}^1\right) & i=1 \end{cases}. \tag{12}$$

Each candidate vector on the maximum reward path is selected to update candidate set $\mathcal{A}_C^1$. Then we obtain the optimized BH pattern matrix $\mathbf{A}_{\text{opt}}^1$ from $\mathcal{A}_C^1$. In contrast to satellite 1, the BH pattern optimization for satellite 2 must account for inter-satellite interference through the specific constraints to avoid adjacent cells being served simultaneously and reduce CCI. Specifically, in time slot t, all cells selected in $\mathbf{A}_{\text{opt}}^2$ must satisfy a minimum spatial separation distance from active cells in $\mathbf{A}_{\text{opt}}^1[t,:]$. Finally, by solving each stage in turn, the multi-satellite cooperative BH pattern $\mathbf{A}_{\text{opt}}$ is obtained, which is expressed as $\mathbf{A}_{\text{opt}} = \left[\mathbf{A}_{\text{opt}}^1, ..., \mathbf{A}_{\text{opt}}^n, ..., \mathbf{A}_{\text{opt}}^{N_s}\right]$.

C. Robust Precoding Algorithm

Firstly, we introduce the auxiliary variable $\mathbf{W}_{n,i} = \mathbf{w}_{n,i}\mathbf{w}_{n,i}^H$ to replace the precoding matrix. Then, to further suppress the CCI, we formulate the SE maximization as a constrained optimization problem. The robust precoding optimization problem based on multi-satellite cooperation in BH systems can be expressed as

$$\begin{aligned} &\max_{\mathbf{W}_{n,i}[t],\forall n,t} \sum_{n=1}^{N_S} \sum_{i|\mathbf{A}_{\text{opt}}^n[t,i]=1}^{N_B} \log\left(1+\gamma_{n,i}[t]\right) \\ &\text{s.t.} \mathrm{C1}: \Pr\left\{\gamma_{n,i}[t] \geq \Gamma_{n,i}\right\} \geq 1-p_{n,i}, \forall n,t,i, \\ &\quad \mathrm{C2}: \sum_{i|\mathbf{A}_{\text{opt}}^n[t,i]=1}^{N_B} \mathrm{Tr}\left(\mathbf{W}_{n,i}[t]\right) \leq P_{\max}, \forall n,t, \\ &\quad \mathrm{C3}: \mathbf{W}_{n,i}[t] \succeq 0, \forall n, \\ &\quad \mathrm{C4}: \mathrm{Rank}\left(\mathbf{W}_{n,i}[t]\right) = 1, \forall n, \end{aligned} \tag{13}$$

where constraint C1 is the outage probability constraint, $\Gamma_{n,i}$ is the SINR threshold of normal communication in cell i of satellite n, $p_{n,i}$ is the outage probability threshold, constraint C2 is the power constraint, P_{max} is the satellite maximum transmit power, constraints C3 and C4 are positive semidefinite constraints of auxiliary variable $\mathbf{W}_{n,i}$.

Due to the complex fractional problem and probability constraints, the optimization problem is a non-convex form, which needs to be transformed into a convex form. The objective function adopts an iterative approximation method. According to [9], we introduce $\alpha_{n,i}$ and $\mu_{n,i}$, which respectively meet the following requirements

$$\frac{\alpha_{n,i}^{[k]}}{2\mu_{n,i}^{[k]}}\mu_{n,i}^2 + \frac{\mu_{n,i}^{[k]}}{2\alpha_{n,i}^{[k]}}\alpha_{n,i}^2 \leq \mathrm{Tr}\left(\mathbf{H}_{n,i}\mathbf{W}_{n,i}\right), \tag{14}$$

$$\mu_{n,i} \geq \sum_{j \neq i}^{N_B-1} \mathrm{Tr}\left(\mathbf{H}_{n,i}\mathbf{W}_{n,j}\right) + \sum_{n' \neq n}^{N_B-1} \mathrm{Tr}\left(\mathbf{H}_{n',i}\mathbf{W}_{n',i}\right) + \sigma_T^2, \tag{15}$$

where $[k]$ is the number of iterations. Due to the complex probabilistic constraints, the constraint C1 of the optimization problem is also non-convex, which is difficult to solve. According to [10], Bernstein-type inequality is used to deal with probability constraints. In combination with equation (2), the SINR of cell i in satellite n in time slot t can be expressed as

$$\gamma_{n,i}[t] \approx \frac{\mathbf{h}_{n,i}^H \cdot \mathbf{W}_{n,i} \cdot \mathbf{h}_{n,i}}{\mathbf{h}_{n,i}^H \cdot \left(\sum_{j \neq i}\mathbf{W}_{n,j} + \sum_{n' \neq n}\mathbf{W}_{n'}\right) \cdot \mathbf{h}_{n,i} + \sigma_T^2}. \tag{16}$$

The conditions for constraining the SINR of C1 can be further expressed as

$$\frac{\mathbf{h}_{n,i}^H \cdot \mathbf{W}_{n,i} \cdot \mathbf{h}_{n,i}}{\Gamma_{n,i}} - \mathbf{h}_{n,i}^H \cdot \left(\sum_{j \neq i}\mathbf{W}_{n,j} + \sum_{n' \neq n}\mathbf{W}_{n'}\right) \cdot \mathbf{h}_{n,i} \geq \sigma_T^2. \tag{17}$$

Defining $\mathbf{Z}_{n,i} = \frac{\mathbf{W}_{n,i}}{\Gamma_{n,i}} - \sum_{j \neq i}\mathbf{W}_{n,j} - \sum_{n' \neq n}\mathbf{W}_{n'}$, and according to the identity $\mathbf{a}^H\mathbf{B}\mathbf{a} = \mathrm{Tr}\left(\mathbf{B}\mathbf{a}\mathbf{a}^H\right)$, it can be converted to

$$\mathrm{Tr}\Big(\mathrm{Diag}^H(\overline{\mathbf{h}}_{n,i} + \Delta\overline{\mathbf{h}}_{n,i}) \cdot \mathbf{Z}_{n,i} \cdot \mathrm{Diag}(\overline{\mathbf{h}}_{n,i} + \Delta\overline{\mathbf{h}}_{n,i}) \cdot \mathbf{q}_{n,i}\mathbf{q}_{n,i}^H\Big) \geq \sigma_T^2. \tag{18}$$

Defining $\mathbf{A}_{n,i} = \left(\mathbf{q}_{n,i}\mathbf{q}_{n,i}^H \otimes \mathbf{Z}_{n,i}\right)$, according to the identity $\mathrm{Tr}\left(\mathbf{ABCD}\right) = \mathrm{vec}^H\left(\mathbf{A}^H\right)\left(\mathbf{D}^T \otimes \mathbf{B}\right)\mathrm{vec}(\mathbf{C})$, the constraint C1 can be further expressed as

$$\Pr\left\{\mathbf{E}_{n,i}^H\mathbf{A}_{n,i}\mathbf{E}_{n,i} + 2\mathrm{Re}\left\{\mathbf{E}_{n,i}^H\mathbf{J}_{n,i}\right\} + \mathbf{c}_{n,i} \geq 0\right\} \geq 1-p_{n,i}, \tag{19}$$

where $\mathbf{E}_{n,i} = \mathrm{vec}\left(\mathrm{Diag}\left(\Delta\overline{\mathbf{h}}_{n,i}\right)\right)$, $\mathbf{J}_{n,i} = \mathbf{A}_{n,i} \cdot \mathrm{vec}\left(\mathrm{Diag}\left(\overline{\mathbf{h}}_{n,i}\right)\right)$ and $\mathbf{c}_{n,i} = \mathrm{vec}^H\left(\mathrm{Diag}\left(\overline{\mathbf{h}}_{n,i}\right)\right) \cdot \mathbf{A}_{n,i} \cdot \mathrm{vec}\left(\mathrm{Diag}\left(\overline{\mathbf{h}}_{n,i}\right)\right) - \sigma_T^2$. To meet the requirements of Bernstein-type Inequality [11], defining $\mathbf{E}_{n,i} = \mathbf{e}_{n,i} \cdot \mathbf{\Phi}_{n,i}$, and $\mathbf{e}_{n,i} \sim \mathcal{CN}\left(0, \mathbf{I}_{N_T^2}\right)$, $\mathbf{\Phi}_{n,i}$ denotes the vector related to the mean value of channel error. According to Bernstein-type Inequality, the above formula can be further transformed into

$$\begin{cases} \mathrm{Tr}\left(\mathbf{A}_{n,i}\cdot\mathbf{\Phi}_{n,i}\right)-\sqrt{-2\ln\left(p_{n,i}\right)}x_{n,i}+\ln\left(p_{n,i}\right)y_{n,i}+c_{n,i}\geq 0, \\ \left\| \begin{matrix} \left(\left(\mathbf{\Phi}_{n,i}^{1/2}\right)^{H}\otimes\mathbf{\Phi}_{n,i}^{1/2}\right)\mathrm{vec}\left(\mathbf{A}_{n,i}\right), \\ \sqrt{2}\mathbf{\Phi}_{n,i}^{1/2}\cdot\mathbf{A}_{n,i}\cdot\mathrm{vec}\left(\mathrm{Diag}\left(\overline{\mathbf{h}}_{n,i}\right)\right) \end{matrix} \right\| \leq x_{n,i}, \\ y_{n,i}\mathbf{I}+\mathbf{A}_{n,i}\cdot\mathbf{\Phi}_{n,i}\succeq 0, y_{n,i}\geq 0, \end{cases} \tag{20}$$

where $x_{n,i}$ and $y_{n,i}$ are slack variables.

The final optimization problem after transformation is as follows:

$$\begin{aligned} &\max_{\mathbf{W}_{n,i}[t],\forall n,t} \sum_{n=1}^{N_S}\sum_{i|\mathbf{A}_{\mathrm{opt}}^{n}[t,i]=1}^{N_B}\log\left(1+\alpha_{n,i}\right) \\ &\quad \mathrm{s.t.C1}:(14),(15),(20), \\ &\quad \mathrm{C2}:\sum_{i|\mathbf{A}_{\mathrm{opt}}^{n}[t,i]=1}^{N_B}\mathrm{Tr}\left(\mathbf{W}_{n,i}\left[t\right]\right)\leq P_{\max},\forall n,t, \\ &\quad \mathrm{C3}:\mathbf{W}_{n,i}[t]\succeq 0,\forall n, \\ &\quad \mathrm{C4}:\mathrm{Rank}\left(\mathbf{W}_{n,i}\left[t\right]\right)=1,\forall n. \end{aligned} \tag{21}$$

In the solution procedure, we initially relax constraints C3 and C4, as prior work [10] has demonstrated that the optimal solution obtained via semidefinite relaxation (SDR) typically satisfies the rank-one constraint inherently. The final precoding matrices are then derived by solving the convexified optimization problem using the SDR solver.

IV. Simulation Results

This section shows the performance of the proposed interference suppression algorithms. The parameters are depicted in Table I. In addition, to support multi-satellite cooperative broadband communication, the satellite altitude is set to 300 km, the center frequency is 30 GHz, the bandwidth is 10 MHz, the number of satellites is set to 2, and each satellite covers 19 cells.

Fig. 3 presents the SE performance of the proposed two-dimensional satellite-cell matching algorithm. Compared with the BH system without the matching algorithm, the proposed algorithm improves the system performance by 1.9%. The results show that the proposed matching algorithm can help the BH system to improve the SE and suppress interference.

Fig. 4 depicts the total system SE performance of different interference suppression methods versus maximum transmit power. The results show that the SE performance of the proposed BH algorithm is better than that of the existing multi-satellite cooperative BH algorithm, which is 23.1% and 95.6% higher than that of MSDBC-BH [12] and LB-IA-BH [13], respectively. Moreover, the robust precoding performance of the proposed BH system is better than that of other conventional precoding algorithms

TABLE I
PARAMETERS FOR SIMULATION

Parameter	Value
Number of cells	34
Number of beams generated by single satellite	4
Transmitting antenna	2×2 UPA
Number of time slots	34
Minimum distance between cells	45.46 km
Mean phase error	5°
Mean gain error	0.1 dB
Number of iterations	12

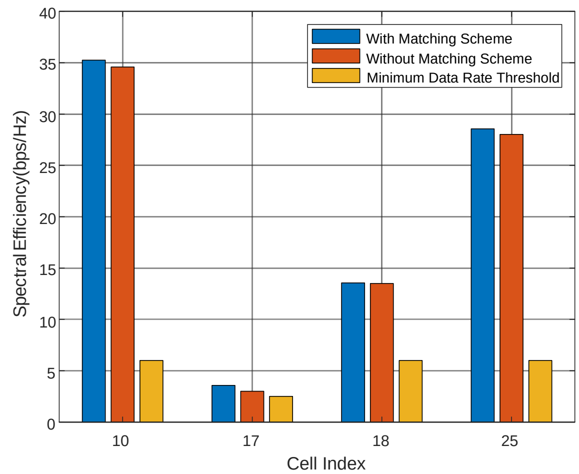

Fig. 3. SE performance of the proposed two-dimensional satellite-cell matching algorithm with $P_{\max}=300$ W, $\Gamma_{n,i}=-10$ dB, $p_{n,i}=0.01$.

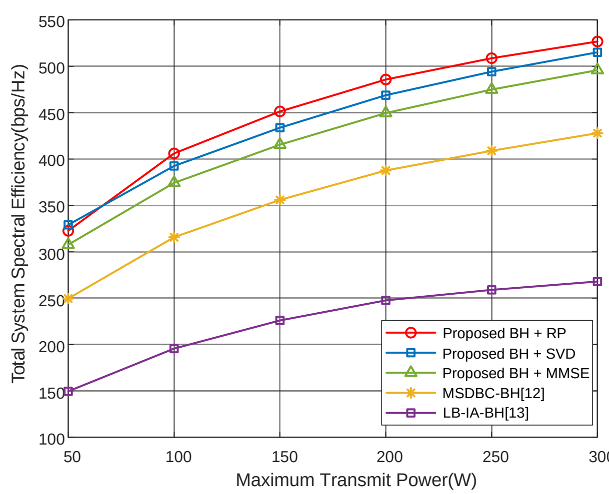

Fig. 4. Total system SE performance of the proposed interference suppression methods and other methods versus maximum transmit power with $\Gamma_{n,i}=-10$ dB, $p_{n,i}=0.01$.

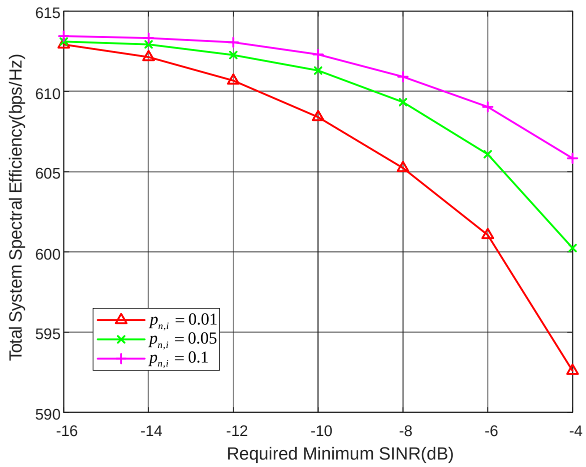

Fig. 5. Total system SE performance versus required the minimum SINR with $P_{\max} = 300$ W.

and is improved by 2.3% and 6.2% compared with SVD precoding and MMSE precoding, respectively.

Furthermore, Fig. 5 illustrates the total system SE performance versus the required minimum SINR. The results show that when considering the outage probability, the system performance of the proposed robust precoding algorithm decreases as the required minimum SINR increases. Additionally, a higher outage probability corresponds to greater SE of the system.

V. Conclusion

This paper investigated interference suppression strategies for multi-satellite BH systems. A utility function-based two-dimensional satellite-cell matching algorithm was introduced to reduce partial CCI. Additionally, a priority-based BH pattern optimization algorithm was designed to mitigate inter-satellite interference and facilitate collaborative BH transmission. A robust precoding algorithm, incorporating multi-satellite cooperation, was further proposed to suppress interference and manage the impact of imperfect CSI. Numerical results demonstrated the superior spectral efficiency and resilience of the proposed methods in challenging scenarios with imperfect CSI.

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