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Beamforming for Dual-Hop Satellite Communications against Eavesdropping

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Abstract—This paper proposes a secure beamforming (BF) scheme for a dual-hop satellite communication system, where a satellite acts as a relay using amplify-and-forward (AF) protocol to assists signal transmission between the terrestrial source and destination, where the target user is intercepted by an eavesdropper (Eve) in the downlink transmission. By assuming that the satellite is deployed with multiple antenna feeds, we first establish an optimization problem to minimize the on-board transmit power subject to the quality-of-service (QoS) and secrecy performance requirement of the destination. Then, based on the method of penalty function, we propose a secure BF scheme to obtain the optimal BF weight vector with analytical form. Finally, computer simulation results are given to demonstrate the effectiveness and superiority of the proposed algorithm.

1. INTRODUCTION

Compared with cellular system, satellite communication (Satcom) can provide seamless connectivity, thus it has been widely used in various fields, such as broadcasting, navigation and disaster relief [1–3]. Based on the orbit altitude, satellite communication can be classified as mobile communication services for low Earth orbit (LEO), global positioning system (GPS) for medium Earth orbit (MEO) and data relay service for geostationary Earth orbit (GEO), respectively [4–8]. However, due to the nature of broadcasting and vast area coverage, privacy and security become a more challenging issue in Satcom. Although security is typically realized by upper layer encryption which cannot guarantee perfect security because the computational ability of potential eavesdroppers (Eves) is becoming more and more powerful, the application of physical layer security (PLS) in Satcom to prevent Eves from overhearing the confidential message has received significant attention recently [9].

Due to spatial discrimination and filtering capabilities [10–15], beamforming (BF), which can be implemented effectively at different multibeam antenna arrays [16–19], can be used to ensure secure communication through enhancing the received signal at intended users while reducing the wiretapping signal at Eve. Specially, considering the characteristics of Satcom, the different planar geometries of antenna arrays for satellite are designed [20, 21] and BF schemes are proposed to improve the security performance of Satcom [22, 23]. In [22], by assuming that the perfect channel state information (CSI) or partial CSI of the eavesdroppers (Eves) is available at the satellite, the authors presented BF algorithm to minimize the total transmit power while guaranteeing secrecy rate for individual intended users. In [23], two BF schemes were proposed so that the interference from terrestrial network was exploited to improve the secrecy performance of Satcom. However, the main drawback of [22, 23] is that only

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downlink BF for secure Satcom is considered. Actually, the satellite is often adopted as a relaying node, which receives signals from a source terminal through uplink channel and forward them to the destination terminal through downlink channel [24, 25]. To the best of our knowledge, the secure communication for dual-hop satellite relaying system is an interest yet open research topic. These observations motivate the work in this paper.

In this paper, we consider a dual-hop satellite relay system operating at Ka band and propose a secure beamforming scheme to minimize the transmit power at satellite under the constraint of quality-of-service (QoS) and secrecy performance requirement of the destination. Specifically, we use the method of mixed penalty function to obtain the analytical optimal BF weight vector, which is different from the previous works, such as [22], where semi-definite programming (SDP) is utilized and only numerical results are obtained. Finally, simulation results verify the superiority of the proposed algorithm.

Notation: Bold letters denote the vectors or matrices, $(\cdot)^H$ the complex conjugate transpose, $\|\cdot\|_F$ the Frobenius norm, $E[\cdot]$ the expectation operator; $\mathrm{tr}(\cdot)$ represents the trace, $\mathbb{C}^{M\times N}$ the $M \times N$ dimensional complex matrix, $\mathbf{I}$ the identity matrix, $\mathrm{vec}(\mathbf{A})$ the vector obtained by stacking all columns of matrix $\mathbf{A}$ on top of each other; $\mathbf{A} \odot \mathbf{B}$ and $\mathbf{A} \otimes \mathbf{B}$ stand for the Hadamard and Kronecker product of $\mathbf{A}$ and $\mathbf{B}$, respectively.

2. SYSTEM MODEL AND PROBLEM FORMULATION

As shown in Fig. 1, we consider an amplify-and-forward (AF) based dual-hop satellite system operating at the Ka band, where a terrestrial source (S) transmits the signal to a terrestrial destination (D) via a satellite relay (R). Meanwhile, an Eve under the satellite coverage area attempts to wiretap the private signal from Sat to D. We assume that the satellite generates N beams on ground that are formed by N antennas feeds on board the satellite, and both of S and D are equipped with a single antenna.

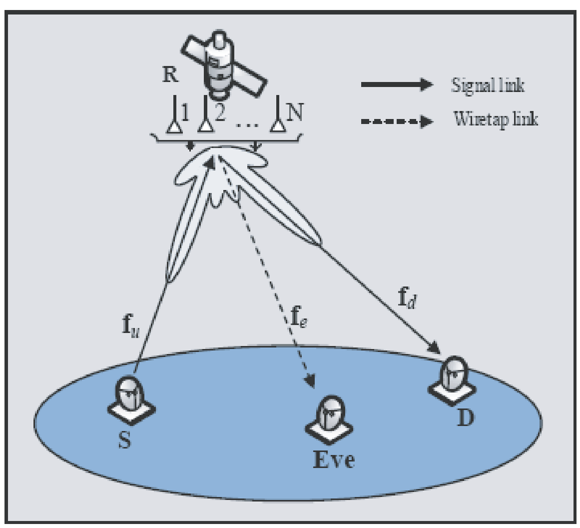

Figure 1. System diagram of satellite relay system.

2.1. Channel Model

In the multibeam satellite relay system, the channel vector $\mathbf{f}_i \in \mathbb{C}^{N\times 1}$ can be uniformly expressed as [22]

$$\mathbf{f}_i = \sqrt{C_{f_i} G_{r_i}} \widetilde{\mathbf{f}}_i \odot \mathbf{b}_i^{1/2}, \quad i \in \{u, d, e\}, \tag{1}$$

where $\mathbf{f}_i$, $i \in \{u, d, e\}$ denote the S-R link, R-D link and R-E link, and C_{f_i} is the free space loss given by

$$C_{f_i} \approx \left(\frac{c}{4\pi f_i d_0}\right)^2, \tag{2}$$

with c being the light speed, f_i the carrier frequency and d_0 the orbital altitude of satellite. Since parabolic antenna is often used for Satcom at Ka band, G_{r_i} in Eq. (1) denoting the antenna gain of S or D can be expressed as [26]

$$G_{r_i}\,[\mathrm{dB}] = \begin{cases} G_{\max}, & 0^\circ < \theta < 1^\circ \\ 32 - 25\log\theta, & 1^\circ \le \theta < 48^\circ \\ -10, & 48^\circ \le \theta \le 180^\circ \end{cases} \tag{3}$$

where $G_{\max}$ is the maximal gain at the boresight, and θ is the off-boresight angle. Meanwhile, $\widetilde{\mathbf{f}}_i \in \mathbb{C}^{N\times 1}$ in Eq. (1) denotes the rain attenuation coefficients vector, which can be written as

$$\widetilde{\mathbf{f}}_i = \xi^{-\frac{1}{2}} e^{-j\boldsymbol{\phi}}, \tag{4}$$

where ξ in dB means rain attenuation coefficient and can be modeled as a lognormal random variable $\mathrm{In}(\xi) \sim \mathcal{N}(\mu, \sigma)$ with μ and σ depending on the system parameter [27], and $\boldsymbol{\phi}$ denotes an $N \times 1$ phase vector uniformly distributed among over $[0, 2\pi)$. Besides, $\mathbf{b}_i^{1/2} = [b_{i,1}, b_{i,2}, \ldots, b_{i,N}]^T$ denotes the beam gain vector which can be approximated by

$$b_{i,k} = G_{s,\max}\left(\frac{J_1(u)}{2u} + 36\frac{J_3(u)}{u^3}\right)^2, \tag{5}$$

where $G_{s,\max}$ represents the maximal satellite antenna gain; $J_1(\cdot)$ and $J_3(\cdot)$ represent the first-kind Bessel function of order 1 and 3; $u = 2.07123 \sin\theta_{i,k}/\sin\theta_{3\,\mathrm{dB}}$ with $\theta_{i,k}$ being the angel of receiver's position with k-th beam boresight and $\theta_{3\,\mathrm{dB}}$ the 3-dB angle.

2.2. Signal Model

The whole communication procedure takes place in two time slots. During the first time slot, S sends the signal s with power $E[|s|^2] = P_s$ to R, and the received signal vector at R can be written as

$$\mathbf{r} = \mathbf{f}_u s + \mathbf{n}, \tag{6}$$

where $\mathbf{n}$ represents the zero mean additive white Gaussian noise (AWGN) satisfying $E[|\mathbf{n}|^2] = \sigma_n^2 \mathbf{I}_N$, where the variance is given by $\sigma_n^2 = kTB$ with k, T, B being the Boltzmans constant, receive noise temperature, and noise bandwidth, respectively. Then, after performing receive BF complex weight $\mathbf{w}_1 \in \mathbb{C}^{N\times 1}$, the output signal at R is given by

$$x = \mathbf{w}_1^H \mathbf{r}, \tag{7}$$

During the second time slot, x is first multiplied by transmit BF vector $\mathbf{w}_2 \in \mathbb{C}^{N\times 1}$, as $\mathbf{t} = \mathbf{w}_2 x$. Then, it is retransmitted to the D.

As a result, the received signal at D and Eve can be, respectively, expressed as

$$y_D = \mathbf{f}_d^H \mathbf{t} + n_d = \mathbf{f}_d^H \mathbf{W} \mathbf{f}_u s + \mathbf{f}_d^H \mathbf{W} \mathbf{n} + n_d, \tag{8}$$

$$y_E = \mathbf{f}_e^H \mathbf{t} + n_e = \mathbf{f}_e^H \mathbf{W} \mathbf{f}_u s + \mathbf{f}_e^H \mathbf{W} \mathbf{n} + n_e, \tag{9}$$

where $\mathbf{W} = \mathbf{w}_2 \mathbf{w}_1^H$, n_d and n_e represent the AWGN at D and Eve, respectively.

By letting $\mathbf{w} = \mathrm{vec}\left(\mathbf{W}^H\right)$, $\mathbf{h}_s = \mathrm{vec}\left(\mathbf{f}_u \mathbf{f}_d^H\right)$ and $\mathbf{h}_n = \mathrm{vec}\left(\mathbf{n}\mathbf{f}_d^H\right)$, along with using the fact $\mathrm{tr}(\mathbf{A}^H\mathbf{B}) = \mathrm{vec}(\mathbf{A})^H \mathrm{vec}(\mathbf{B})$, the output signal and noise power at D can be, respectively, expressed as

$$P_{s,D} = E\left[\left|\mathbf{f}_d^H \mathbf{W} \mathbf{f}_u s\right|^2\right] = P_s E\left[\left|\mathrm{tr}(\mathbf{W}\mathbf{f}_u\mathbf{f}_d^H)\right|^2\right] = P_s E\left[|\mathbf{w}^H \mathbf{h}_s|^2\right] = P_s \mathbf{w}^H \mathbf{H}_s \mathbf{w}, \tag{10}$$

$$P_{n,D} = E\left[|\mathbf{f}_d^H \mathbf{W} \mathbf{n}|^2\right] + \sigma_d^2 = E\left[\left|\mathrm{tr}(\mathbf{W}\mathbf{n}\mathbf{f}_d^H)\right|^2\right] + \sigma_d^2 = E\left[|\mathbf{w}^H \mathbf{h}_n|^2\right] + \sigma_d^2 = \mathbf{w}^H \mathbf{H}_n \mathbf{w} + \sigma_d^2, \tag{11}$$

where $\mathbf{H}_s = E\left[\mathbf{h}_s \mathbf{h}_s^H\right]$ and $\mathbf{H}_n = E\left[\mathbf{h}_n \mathbf{h}_n^H\right]$.

Similarly, by using $\mathbf{g}_s = \mathrm{vec}\left(\mathbf{f}_u \mathbf{f}_e^H\right)$ and $\mathbf{g}_n = \mathrm{vec}\left(\mathbf{n}\mathbf{f}_e^H\right)$, the output signal and noise power at Eve can be, respectively, written as

$$P_{s,E} = E\left[\left|\mathbf{f}_e^H \mathbf{W} \mathbf{f}_u s\right|^2\right] = P_s E\left[\left|\mathrm{tr}(\mathbf{W}\mathbf{f}_u\mathbf{f}_e^H)\right|^2\right] = P_s E\left[|\mathbf{w}^H \mathbf{g}_s|^2\right] = P_s \mathbf{w}^H \mathbf{G}_s \mathbf{w}, \tag{12}$$

$$P_{n,E} = E\left[|\mathbf{f}_e^H \mathbf{W} \mathbf{n}|^2\right] + \sigma_e^2 = E\left[\left|\mathrm{tr}(\mathbf{W}\mathbf{n}\mathbf{f}_e^H)\right|^2\right] + \sigma_e^2 = E\left[|\mathbf{w}^H \mathbf{g}_n|^2\right] + \sigma_e^2 = \mathbf{w}^H \mathbf{G}_n \mathbf{w} + \sigma_e^2, \tag{13}$$

where $\mathbf{G}_s = E\left[\mathbf{g}_s\mathbf{g}_s^H\right]$ and $\mathbf{G}_n = E\left[\mathbf{g}_n\mathbf{g}_n^H\right]$.

Also, the transmit power at satellite is derived as

$$P_t = E\left[\operatorname{tr}\left(\mathbf{t}\mathbf{t}^H\right)\right] = \operatorname{tr}\left(\mathbf{W}\left(P_s\mathbf{R}_f + \mathbf{R}_n\right)\mathbf{W}^H\right) = \mathbf{w}^H\left(\mathbf{I}\otimes\left(P_s\mathbf{R}_f + \mathbf{R}_n\right)\right)\mathbf{w} = \mathbf{w}^H\mathbf{C}\mathbf{w}. \tag{14}$$

From Eqs. (10)–(13), the output SNR at D and Eve can be, respectively, written as

$$\gamma_D = \frac{P_s\mathbf{w}^H\mathbf{H}_s\mathbf{w}}{\mathbf{w}^H\mathbf{H}_n\mathbf{w} + \sigma_d^2}, \quad \gamma_E = \frac{P_s\mathbf{w}^H\mathbf{G}_s\mathbf{w}}{\mathbf{w}^H\mathbf{G}_n\mathbf{w} + \sigma_e^2}. \tag{15}$$

Then, the achievable rate (AR) and achievable secrecy rate (ASR) at D are, respectively, given by [28]

$$C_D = \frac{1}{2}\log_2\left(1 + \gamma_D\right), \quad C_S = \left[\frac{1}{2}\log_2\left(\frac{1+\gamma_D}{1+\gamma_E}\right)\right]^+, \tag{16}$$

where $[x]^+ = \max(x, 0)$ and the scalar factor $1/2$ is because the signal is transmitted at two time slots.

2.3. Problem Formulation

By considering that the on-board transmit power is limited, we aim to minimize the transmit power at satellite while guaranteeing the secure communication for D. To this end, the optimization problem can be formulated as

$$\min_{\mathbf{w}} \quad \mathbf{w}^H\mathbf{C}\mathbf{w} \tag{17a}$$

$$\text{s.t} \quad C_D \geq R_{th,D}, \tag{17b}$$

$$C_S \geq R_{th,S}. \tag{17c}$$

where $R_{th,D}$ and $R_{th,S}$ denote the AR and ASR threshold for the D, respectively.

In the next section, we will propose a secure BF scheme to solve the problem and obtain the optimal weight vector $\mathbf{w}$.

3. PROPOSED SECURE BF SCHEME

By using Eq. (16) into Eq. (17), after some trivial manipulations, the problem in Eq. (17) can be equivalently rewritten as

$$\min_{\mathbf{w}} \quad \mathbf{w}^H\mathbf{C}\mathbf{w} \tag{18a}$$

$$\text{s.t} \quad \gamma_D \geq 2^{2R_{th,D}} - 1, \tag{18b}$$

$$\gamma_E \leq 2^{2(R_{th,D}-R_{th,S})} - 1. \tag{18c}$$

Furthermore, substituting Eq. (15) into Eq. (18) yields

$$\min_{\mathbf{w}} \quad \mathbf{w}^H\mathbf{C}\mathbf{w} \tag{19a}$$

$$\text{s.t} \quad \mathbf{w}^H\left(P_s\mathbf{H}_s - \gamma_{th,D}\mathbf{H}_n\right)\mathbf{w} \geq \gamma_{th,D}\sigma_d^2, \tag{19b}$$

$$\mathbf{w}^H\left(P_s\mathbf{G}_s - \gamma_{th,E}\mathbf{G}_n\right)\mathbf{w} \leq \gamma_{th,E}\sigma_e^2. \tag{19c}$$

where $\gamma_{th,D} = 2^{2R_{th,D}} - 1$ and $\gamma_{th,E} = 2^{2(R_{th,D}-R_{th,S})} - 1$. Note that $(P_s\mathbf{H}_s - \gamma_{th,D}\mathbf{H}_n)$ should be positive definite, otherwise, the optimization problem in Eq. (19) will become infeasible. One can easily show that the inequality constraint in Eq. (19b) is satisfied with equality at the optimum. Suppose that optimal solution $\widetilde{\mathbf{w}}^{opt}$ makes strict inequality in Eq. (19b) true. Because the objective function (19a) and constraint (19c) are monotonic functions with respect to $\|\mathbf{w}\|_F$, $\widetilde{\mathbf{w}}^{opt}$ can be scaled down to satisfy the constraint (19b) with equality while meeting the condition of Eq. (19c), decreasing the objective function and contradicting optimality simultaneously. Therefore, the optimization problem can be equivalently written as

$$\min_{\mathbf{w}} \quad \mathbf{w}^H\mathbf{C}\mathbf{w} \tag{20a}$$

$$\text{s.t} \qquad \mathbf{w}^H \mathbf{C}_1 \mathbf{w} = \alpha, \tag{20b}$$

$$\mathbf{w}^H \mathbf{C}_2 \mathbf{w} \leq \beta. \tag{20c}$$

where $\mathbf{C}_1 = (P_s \mathbf{H}_s - \gamma_{th,D} \mathbf{H}_n)$, $\mathbf{C}_2 = (P_s \mathbf{G}_s - \gamma_{th,E} \mathbf{G}_n)$, $\alpha = \gamma_{th,D} \sigma_d^2$, $\beta = \gamma_{th,E} \sigma_e^2$. Correspondingly, the feasible region S can be expressed as

$$S = \left\{ \mathbf{w} \in {}^{N \times 1} \left| \begin{array}{l} \alpha - \mathbf{w}^H \mathbf{C}_1 \mathbf{w} = 0, \\ \beta - \mathbf{w}^H \mathbf{C}_2 \mathbf{w} \geq 0 \end{array} \right. \right\}. \tag{21}$$

In what follows, we will utilize the mixed penalty function to solve the problem in Eq. (20). It is essential to point out that for $(\mathbf{w}^H \mathbf{C}_1 \mathbf{w} - \alpha)^2$ small enough, the constraint in Eq. (20b) will be satisfied. Also, the strictly feasible region of $\text{In}(\beta - \mathbf{w}^H \mathbf{C}_2 \mathbf{w})$ makes $\mathbf{w}$ not contradict the constraint in Eq. (20c). Consequently, Eqs. (20b)–(20c) are equivalent to make $(\mathbf{w}^H \mathbf{C}_1 \mathbf{w} - \alpha)^2$ as small as possible while keeping $\mathbf{w}$ located at feasible region of $\text{In}(\beta - \mathbf{w}^H \mathbf{C}_2 \mathbf{w})$. For this purpose, we incorporate corresponding objective into the cost function and define the augmented objective function as follow [29]

$$f(\mathbf{w}, \mu) = \mathbf{w}^H \mathbf{C} \mathbf{w} + \frac{\left(\mathbf{w}^H \mathbf{C}_1 \mathbf{w} - \alpha\right)^2}{2\mu} - \mu \text{In}\left(\beta - \mathbf{w}^H \mathbf{C}_2 \mathbf{w}\right), \tag{22}$$

where μ is the penalty parameter, and $\left(\mathbf{w}^H \mathbf{C}_1 \mathbf{w} - \alpha\right)^2$ and $\text{In}(\beta - \mathbf{w}^H \mathbf{C}_2 \mathbf{w})$ correspond to the punishment of augmented objective function. Our goal here is to minimize $\mathbf{w}^H \mathbf{C} \mathbf{w}$ while keeping the punishment of function within a small scale. Then the optimization problem in Eq. (20) can be reformulated to the following alternative formulation

$$\min \ f(\mathbf{w}, \mu). \tag{23}$$

Next, we address the unconstrained optimization problem in Eq. (23) by adopting quasi-Newton method. The gradient $\mathbf{g}(\mathbf{w})$ of $f(\mathbf{w}, \mu)$ with respect to $\mathbf{w}$ is given by

$$\nabla f(\mathbf{w}, u) = \mathbf{C} \mathbf{w} + \frac{\left(\mathbf{w}^H \mathbf{C}_1 \mathbf{w} - \alpha\right)}{u} \mathbf{C}_1 \mathbf{w} + \frac{u \mathbf{C}_2 \mathbf{w}}{\beta - \mathbf{w}^H \mathbf{C}_2 \mathbf{w}}. \tag{24}$$

When the optimal weight vector $\mathbf{w}^*$ that minimizes the function in Eq. (24) is obtained, the gradient $\mathbf{g}(\mathbf{w})$ of $f(\mathbf{w}^*, \mu)$ satisfies $\|\nabla f(\mathbf{w}^*, u)\|^2 = 0$. Then, we can define the search direction as [30]

$$\mathbf{d}^{(k)} = -\left(\mathbf{H}^{(k)}\right)^{-1} \mathbf{g}^{(k)} \tag{25}$$

where $\mathbf{H}^{(k)}(\mathbf{w}, \mu)$ is the symmetric positive definite matrix that serves as an approximation of the Hessian $\nabla^2 f(\mathbf{w}, \mu)$. Various quasi-Newton methods have been investigated for different definitions $\mathbf{H}^{(k)}$. With the most common method of Broyden-Fletcher-Goldfarb-Shanno (BFGS), we can define the symmetric positive definite matrix $\mathbf{H}^{(k)}(\mathbf{w}, \mu)$ by [30]

$$\mathbf{H}^{(k+1)} = \mathbf{H}^{(k)} - \frac{\mathbf{H}^{(k)} \mathbf{s}^{(k)} \left(\mathbf{s}^{(k)}\right)^H \mathbf{H}^{(k)}}{\left(\mathbf{s}^{(k)}\right)^H \mathbf{H}^{(k)} \mathbf{s}^{(k)}} + \frac{\mathbf{y}^{(k)} \left(\mathbf{y}^{(k)}\right)^H}{\left(\mathbf{y}^{(k)}\right)^H \mathbf{s}^{(k)}}, \tag{26a}$$

$$\mathbf{y}^{(k)} = \mathbf{g}^{(k+1)} - \mathbf{g}^{(k)}, \tag{26b}$$

$$\mathbf{s}^{(k)} = \mathbf{w}^{(k+1)} - \mathbf{w}^{(k)}. \tag{26c}$$

Consequently, we update $\mathbf{w}^{(k+1)}$ with $\mathbf{d}^{(k)}$ as

$$\mathbf{w}^{(k+1)} = \mathbf{w}^{(k)} + \tau^{(k)} \mathbf{d}^{(k)}, \tag{27}$$

where $\tau^{(k)}$ is a positive scalar stepsize, satisfying Wolfe-Powell conditions based on line search methods as follows

$$\left. \begin{array}{l} f\left(\mathbf{w}^{(k)} + \tau^{(k)} \mathbf{d}^{(k)}\right) \leq f\left(\mathbf{w}^{(k)}\right) + \rho \tau^{(k)} \left(\mathbf{g}^{(k)}\right)^H \mathbf{d}^{(k)} \\ \nabla f\left(\mathbf{w}^{(k)} + \tau^{(k)} \mathbf{d}^{(k)}\right)^H \mathbf{d}^{(k)} \geq \sigma \left(\mathbf{g}^{(k)}\right)^H \mathbf{d}^{(k)} \end{array} \right\}, \tag{28}$$

where $\rho \in (0, 1)$, $\sigma \in (\rho, 1)$.

Algorithm 1: The proposed secure BF algorithm.

Initialization: set penalty parameters $\mu^{(0)} \in (0,1)$, step $\kappa \in (0,1)$, convergence tolerance $\varepsilon > 0$, $\mathbf{w}^{(0)} := \mathbf{v}_{\min}(\mathbf{C}_2)$, and $m := 0$;
repeat
  Initialization: set $\rho \in (0,1)$, $\sigma \in (\rho,1)$, $\mathbf{H}^{(0)} := \mathbf{I}$, $u^{(m+1)} := \kappa u^{(m)}$, $m := m+1$, and $k := 0$;
  repeat
    (i) Computer $\mathbf{g}^{(k)} := \nabla f\left(\mathbf{w}^{(k)}, u^{(m)}\right)$;
    (ii) Computer $\mathbf{d}^{(k)} := -\left(\mathbf{H}^{(k)}\right)^{-1}\mathbf{g}^{(k)}$;
    (iii) Find the suitable step length $\tau^{(k)}$ by Eq. (28) and computer $\mathbf{w}^{(k+1)} := \mathbf{w}^{(k)} + \tau^{(k)}\mathbf{d}^{(k)}$ by Eq. (27);
    (iv) Update $\mathbf{H}^{(k+1)}$ by Eqs. (26a)–(26c);
    (v) Set $k := k+1$;
  until $\left\| f(\mathbf{w}^{(k+1)}, \mu^{(m)}) - f(\mathbf{w}^{(k)}, \mu^{(m)}) \right\| \le \varepsilon$;
  Obtain the mth iteration optimal solution $\mathbf{w}_{opt}^{(m)} := \mathbf{w}^{(k)}$ respect to $\mu^{(m)}$;
until $\left\{ \frac{1}{2\mu^{(m)}} \left[\left(\mathbf{w}_{opt}^{(m)}\right)^H \mathbf{C}_1 \mathbf{w}_{opt}^{(m)} - \alpha \right]^2 - \mu^{(m)} \mathrm{In} \left[\beta - \left(\mathbf{w}_{opt}^{(m)}\right)^H \mathbf{C}_2 \mathbf{w}_{opt}^{(m)} \right] \right\} \le \varepsilon$;
Obtain the final optimal solution $\mathbf{w}_{opt} := \mathbf{w}_{opt}^{(m)}$;

Specifically, the proposed iterative algorithm based on mixed penalty function is summarized in Algorithm 1.

It is worth mentioning that the initial value $\mathbf{w}^{(0)}$ of the proposed algorithm needs to satisfy the inequality constraints in Eq. (19b), and it can be selected as $\mathbf{w}^{(0)} = \mathbf{v}_{\min}(\mathbf{C}_2)$, where $\mathbf{v}_{\min}(\mathbf{A})$ denotes the vector responding to the minimum eigenvalue of matric $\mathbf{A}$.

4. NUMERICAL RESULTS AND DISCUSSION

In this section, we confirm the validity of the proposed scheme through the simulation results. To conduct comparison, the SDP scheme [22] is introduced which only obtains numerical results selected from a large number of randomly generated rank-one candidates as an approximate optimal solution. The system parameters are shown in Table 1, and the simulation is implemented by Matlab.

Figure 2 shows the minimum total transmit power versus $R_{th,S}$ with different schemes for the case of $N = 7$. It can be observed that the minimum total transmit power increases with increasing secrecy rate thresholds $R_{th,S}$ and rate thresholds $R_{th,D}$, respectively. Meanwhile, it can be seen that the proposed BF saves more power than SDP scheme, verifying that the proposed algorithm can efficiently

Table 1. Parameters of simulation.

Parameter	**Value**
Orbit	GEO
S-R link Frequency band	$f_u = 28\,\mathrm{GHz}$
R-D and R-E link Frequency band	$f_d = f_e = 18\,\mathrm{GHz}$
3 dB angle	$\theta_{3\,\mathrm{dB}} = 0.4^\circ$
Noise bandwidth	$B = 5\,\mathrm{MHz}$
Satellite antenna gain	$G_{s,\max} = 52\,\mathrm{dBi}$
ESs antenna gain	$G_{r_i} = 19.7\,\mathrm{dBi}$
Clear sky temperature	$T = 207^\circ\,\mathrm{K}$

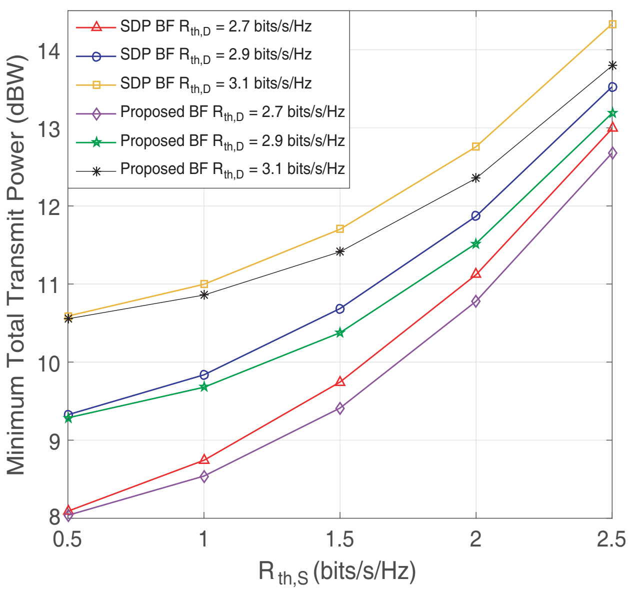

Figure 2. Minimum total transmit power at satellite versus $R_{th,S}$.

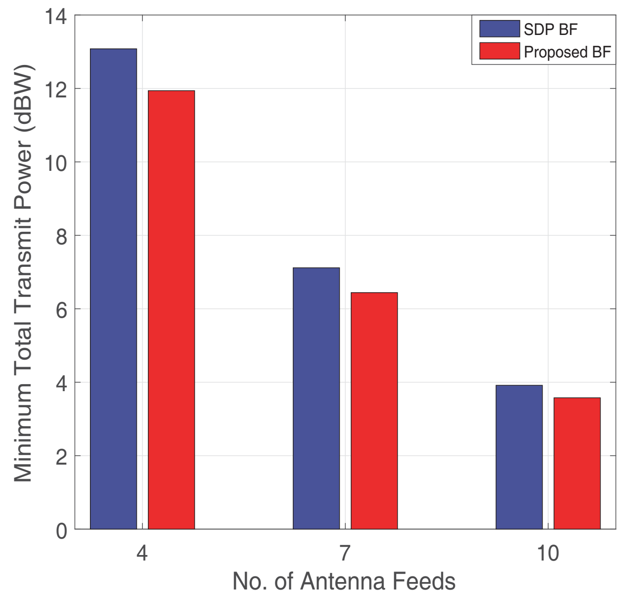

Figure 3. Minimum total transmit power at satellite versus number of antenna feeds.

reduce signal leakage to Eve.

In addition, Fig. 3 depicts the minimum total transmit power versus the number of satellite's antenna feeds with the proposed BF scheme and SDP while $R_{th,S} = 0.5$ bits/s/Hz and $R_{th,D} = 2$ bits/s/Hz. We can observe that the proposed BF scheme has a superior performance to SDP. Furthermore, we can also find that satellite transmit power can be saved with increase of the number of satellite's antenna feeds. This is because increasing antenna feeds can provide more degrees of freedom (DoF) to enhance the received signal power at D and to decrease the desired signal leakage power at Eve.

5. CONCLUSIONS

In this paper, we have studied a secure BF scheme for a dual-hop AF satellite relay system, where the multibeam satellite operates as a relay to assist the signal transmission between S and D, in the presence of an eavesdropper. We aim to minimize on-board transmit power while meeting the QoS and secrecy performance requirement for the D. To solve the non-convex problem, we have proposed a secure BF scheme based on the mixed penalty function to obtain BF weight vector. The simulation results have been given to show the effectiveness and superiority of the proposed algorithm.

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