Joint Opportunistic Satellite Scheduling and Beamforming for Secure Transmission in Cognitive LEO Satellite Terrestrial Networks

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Abstract. Security is a critical issue for cognitive LEO satellite terrestrial networks (CLSTNs) in the future 6G era. To guarantee the secure transmission of both the satellite and terristrial users under limited power budgets, we propose a joint opportunistic satellite scheduling and beamforming (BF) scheme for the CLSTN. Specifically, we formulate an optimization problem to maximize the secrecy energy efficiency (SEE) of the satellite user under the secrecy constraint of the base station (BS) user, the signal-to-interference plus noise ratio (SINR) requirements of the intended users and the limited power budgets of the transmitters. Since the formulated problem is complex and nonconvex, we first consider the achievable SEE of a given scheduled satellite and transform the original SEE maximization problem into a convex problem based on the Dinkelbach's method and the difference of two-convex functions (D.C.) approximation method. Consequently, we propose a three-tier algorithm to jointly determine the satellite scheduling vector and the BF vectors of the satellite and BS. Simulation results verify the superiority of our proposed scheme over the existing schemes.

Keywords: Physical layer security · Cognitive LEO satellite terrestrial network · Secrecy energy efficiency · Satellite scheduling scheme

1 Introduction

In the upcoming 6G era, large-scale low earth orbit (LEO) satellite constellations will be integrated with terrestrial systems to facilitate global coverage. However,

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due to the dramatic growth of data traffic and the scarcity of spectrum resource, the transmission performance of satellite terrestrial integrated networks (STINs) cannot be well guaranteed. To solve this issue, cognitive radio technology can be incorporated into STINs to construct the cognitive LEO satellite terrestrial networks (CLSTNs) and improve the spectrum utilization efficiency [1]. In the downlink/uplink of CLSTNs, the spectrum can be shared between the LEO satellite systems and the terrestrial systems. Since 6G wireless networks are expected to be an elegant solution for secure and ubiquitous future communication, security should be considered as a critical performance requirement of CLSTNs [2].

To guarantee secure transmission, the confidential messages of CLSTNs should be protected to prevent the eavesdroppers from intercepting it. Traditionally, cryptographic technique is utilized at upper layers to achieve security. However, this method may become unreliable as the processing speed of eavesdroppers is increasing. Recently, physical layer security (PLS) without any need for key distribution and service management has aroused a research upsurge. In physical layer, security is guaranteed when intended users have better signal-to-interference plus noise ratios (SINRs) than the eavesdroppers by exploiting technologies such as jamming or transmit beamforming (BF).

A great deal of effort has been devoted to investigating the PLS in multibeam satellite systems [3–7]. Under the SINR constraints of the satellite users (SUs), robust BF schemes were proposed to maximize the minimum secrecy rate (SR) among all the intended users [3,4]. The authors in [5] investigated the optimal BF design to maximize the minimum secrecy energy efficiency (SEE) of SUs. To further degrade the transmission quality of the wiretap channel, artificial noise (AN) was inserted into the transmit signal to satisfy SR requirements of SUs while minimizing the transmit power of the satellite [6]. The authors in [7] explored a novel dual-beam dual-frequency scheme to enhance the PLS of the desired channel and impair the wiretap channel at the same time. In the above works, [5,6] assumed that perfect channel state informations (CSIs) of eavesdroppers are available while [3,4,7] considered a more realistic scenario where CSIs are imperfect.

In CSTN, the terrestrial base station (BS) can serve as a green jamming source to interfere with eavesdroppers, which further improves the security of transmissions [8–13]. The authors in [9] exploited the jamming from BS and proposed a transmit power minimization scheme while satisfying the SINR requirements of SU, eavesdroppers and terrestrial BS user (BU). To satisfy the requirements of service qualities and SR constraints of SUs, a joint BF and jamming scheme was proposed, which aimed to minimize total transmit power of the satellite and the BS [10]. Individual BF scheme of the satellite and cooperative BF scheme of the satellite and the BS were investigated in [11] to achieve maximal achievable SR of the SU. In [12], the full duplex receivers receive and jam simultaneously to confuse eavesdroppers in an AN-aided BF scheme. The authors in [13] utilized an intelligent reflecting surface to reflect the jamming signals and therefore profitably enhanced its interference effect. However, the above works were devoted to maximizing or guaranteeing SU's secure transmission demands without taking BU's security requirements into account. Also, the above works merely focused on the geostationary orbit (GEO) satellite terrestrial system where there is only one satellite, the existing schemes cannot be adopted directly in CLSTNs where the number of satellites is large. Hence, a satellite scheduling scheme should be properly designed to ensure the secure transmission in CLSTNs.

The conventional satellite scheduling strategies include highest elevation angle/maximal service time priority satellite scheduling schemes [14]. It is proved that multi-satellite scheduling and round-robin satellite scheduling scheme have different impact on PLS in LEO systems [15]. Some researchers have investigated the secrecy performance of opportunistic user scheduling scheme and optimal relay scheduling scheme in the integrated satellite terrestrial relay systems (ISTRSs) [16–18]. The authors in [16] analysed the secrecy outage probability (SOP) of opportunistic user scheduling scheme in ISTRS. [17] and [18] explored the SOP of optimal relay scheduling scheme while [18] incorporated the hardware impairments of transceiver nodes into study additionally. In general, opportunistic satellite scheduling scheme has not been investigated in the existing schemes. Secure transmission in CLSTNs is still an open yet challenging problem, which motivates the work in this paper.

In this paper, we propose a joint opportunistic satellite scheduling and BF scheme to achieve the energy-efficient secure transmission of the SU in the CLSTN. We formulate the maximization problem to maximize the SEE of the SU under transmit power budgets of the satellite and the BS while satisfying the SR constraint of the BU and the SINR requirements of the SU and BU in the CLSTN. To tackle the formulated nonconvex problem, we first consider the case when the scheduled satellite is given. Then, the Dinkelbach's method and the difference of two-convex functions (D.C.) approximation method are exploited to transform the SEE maximization problem into a convex one and solve the problem iteratively. Consequently, a three-tier algorithm is proposed to jointly determine the satellite scheduling vector and BF vectors of the satellite and BS. Finally, the effectiveness of the proposed algorithm is verified by simulation.

The rest of this paper is organized as follows. Section 2 introduces the system model and the optimization problem formulation. Section 3 presents the three-tier algorithm to solve the original problem. Simulation results and relevant analyses are provided in Sect. 4. Section 5 concludes this paper.

2 System Model and Problem Formulation

As shown in Fig. 1, we consider the downlink transmission of a CLSTN which consists of a primary network and a secondary network. The two networks occupy the same wireless spectrum resource in the CLSTN. In the primary network, the satellite transmits confidential messages to the single-antenna SU via N beams while a nearby single-antenna eavesdropper, which is denoted as SE, attempts to decode the information intended to SU. In the secondary network, the BS with M antennas serves a single-antenna BU. BU is wiretapped by another eavesdropper which is denoted as BE. The signals sent by the satellite and BS can also be

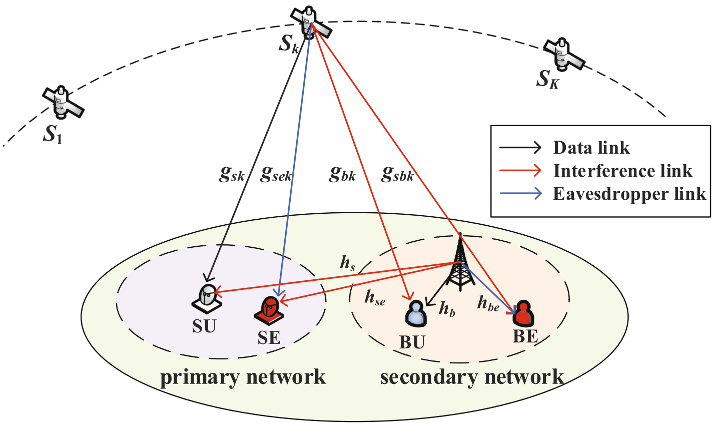

Fig. 1. System model.

utilized as green jamming to the eavesdroppers. There are K satellites in the SU's observable range, SU can only be served by the scheduled satellite within one time slot [14]. The secure transmission is guaranteed by joint opportunistic satellite scheduling and BF of the satellite and BS. In this paper, the CSI of each link is assumed to be perfectly known [6,7].

2.1 Channel Model

In this paper, quasi-static slow-fading is adopted to model the links between each satellite and the users. The links in different beams undergo independent fading. Considering the effects of free space path loss, satellite antenna gain and small-scale fading, the downlink channel coefficient of LEO can be expressed as:

$$g = C_L \sqrt{b(\varphi)} \widetilde{g} \tag{1}$$

where $C_L = \frac{\lambda}{4\pi d}$ describes the free space path loss with the carrier wavelength λ and the distance from the satellite to the user d. $b(\varphi)$ denotes the beam gain coefficient and can be approximated as [13]:

$$b(\varphi) = b_{\max} \left(\frac{J_1(u)}{2u} + 36 \frac{J_3(u)}{u^3} \right)^2 \tag{2}$$

where $u = 2.07123 \frac{\sin \varphi}{\sin(\varphi_{3dB})}$, $b_{\max}$ denotes the maximal gain of the satellite antenna and $J_1(.)$ and $J_3(.)$ describes the first and third order of the first-kind Bessel functions, respectively. φ denotes the angle between beam center and the SU's position with respect to the satellite and φ_{3dB} indicates the 3-dB angle.

The small-scale fading of the satellite channel $\widetilde{g}$ is modeled as Lutz distribution [19], which consists of a combination of Rician fading and lognormally shadowed Rayleigh fading. The phase in Lutz model is uniformly distributed over $[0, 2\pi)$ and the overall probability density function (PDF) of the received power in Lutz model is expressed as:

$$p(S) = (1 - A)p_{Rice}(S) + A \int_0^{\infty} p_{Rayl}(S|S_0)P_{ln}(S_0)dS_0. \tag{3}$$

The PDF of the received power S is expressed as $p_{Rice}(S) = ce^{-c(S+1)}I_0(2c\sqrt{S})$ when S obeys Rician distribution. When S obeys log-normally shadowed Rayleigh distribution, its PDF is expressed as $p_{Rayl}(S|S_0) = \frac{1}{S_0}e^{-\frac{S}{S_0}}$, where S_0 describes the short-term mean received power, which follows the distribution of $p_{ln}(S_0) = \frac{10}{\sqrt{2\pi}\sigma \ln 10}\frac{1}{S_0}\exp\left(-\frac{(10\log S_0 - \mu)^2}{2\sigma^2}\right)$. The percentage of shadowed state A, the mean μ and deviation σ^2 of the lognormally shadowed Rayleigh distribution and the Rice-factor c all depend on the elevation angle of the satellite and the terrestrial environment. The specific values of the four parameters $\mathrm{A}, \mu, \sigma^2$ and c can be obtained by referring to the measured value in [19] or the fitting formula and the figure in [20].

2.2 Signal Model

Denote the signals intend for the SU and BU by x and s, respectively. Assume that $E(x^2) = 1$ and $E(s^2) = 1$, where $E(\cdot)$ denotes the expectations operator on random variables. Let $\mathbf{g}_{sk}, \mathbf{g}_{sek}, \mathbf{g}_{bk}, \mathbf{g}_{bek} \in \mathbb{C}^{N\times 1}$ and $\mathbf{h}_s, \mathbf{h}_{se}, \mathbf{h}_b, \mathbf{h}_{be} \in \mathbb{C}^{M\times 1}$ denote the links of S_k-SU, S_k-SE, S_k-BU, S_k-BE, BS-SU, BS-SE, BS-BU, BS-BE, respectively, where S_k denotes the k-th satellite, $k = 1, 2...K$. When the k-th satellite is scheduled, the signals received at SU, SE, BU and BE are respectively given as:

$$y_{sk} = \mathbf{g}_{sk}^H \mathbf{w}x + \mathbf{h}_s^H \mathbf{v}s + n_s \tag{4}$$
$$y_{sek} = \mathbf{g}_{sek}^H \mathbf{w}x + \mathbf{h}_{se}^H \mathbf{v}s + n_{se} \tag{5}$$
$$y_{bk} = \mathbf{h}_b^H \mathbf{v}s + \mathbf{g}_{bk}^H \mathbf{w}x + n_b \tag{6}$$
$$y_{bek} = \mathbf{h}_{be}^H \mathbf{v}s + \mathbf{g}_{bek}^H \mathbf{w}x + n_{be} \tag{7}$$

where $\mathbf{w} \in \mathbb{C}^{N\times 1}$ and $\mathbf{v} \in \mathbb{C}^{M\times 1}$ are the BF weight vectors of S_k and BS, respectively. $n_i \in \mathcal{CN}(0, \sigma_i^2), i \in \{s, se, b, be\}$ denotes the Gaussian white noise at SU, SE, BU and BE. $\sigma_i^2 = \kappa BT$ with the noise bandwidth B, noise temperature T and Boltzmann constant $\kappa \approx 1.38 \times 10^{-23} J/K$. Then the received SINRs at SU, SE, BU and BE are respectively given by:

$$\gamma_{sk} = \frac{|\mathbf{g}_{sk}^H \mathbf{w}|^2}{|\mathbf{h}_s^H \mathbf{v}|^2 + \sigma_s^2} \tag{8}$$
$$\gamma_{sek} = \frac{|\mathbf{g}_{sek}^H \mathbf{w}|^2}{|\mathbf{h}_{se}^H \mathbf{v}|^2 + \sigma_{se}^2} \tag{9}$$
$$\gamma_{bk} = \frac{|\mathbf{h}_b^H \mathbf{v}|^2}{|\mathbf{g}_{bk}^H \mathbf{w}|^2 + \sigma_b^2} \tag{10}$$
$$\gamma_{bek} = \frac{|\mathbf{h}_{be}^H \mathbf{v}|^2}{|\mathbf{g}_{bek}^H \mathbf{w}|^2 + \sigma_{be}^2}. \tag{11}$$

Then, the achievable SR of SU and BU can be written as:

$$C_{sk} = \max\{\log_2(1+\gamma_{sk}) - \log_2(1+\gamma_{sek}), 0\} \quad (12)$$

$$C_{bk} = \max\{\log_2(1+\gamma_{bk}) - \log_2(1+\gamma_{bek}), 0\}. \quad (13)$$

As a consequence, the SEE of the SU which is defined as the amount of achievable secret bits per unit energy and bandwidth can be expressed as:

$$\eta_{sk} = \frac{C_{sk}}{||\mathbf{w}||^2 + P_{ck} + ||\mathbf{v}||^2 + P_b} \quad (14)$$

where P_{ck} and P_b denotes the constant transmit circuit power consumed by S_k and BS, respectively.

2.3 Problem Formulation

To realize the energy-efficient secure transmission of the SU in the CLSTN, we formulate a SEE maximization problem under the limited power budgets of the satellite and BS while satisfying the SR constraint of the BU, the SINR requirements of the SU and BU by jointly scheduling the opportunistic satellite and optimizing the BF weight vectors of the scheduled satellite and the BS. The optimization problem can be expressed as:

$$\max_{\mathbf{C},\mathbf{v},\mathbf{w}} \ \mathbf{C}^T\eta \quad (15)$$

$$\text{s.t.} \quad \mathbf{C}^T\mathbf{B} \geq \Gamma_b \quad (16)$$

$$\mathbf{C}^T\boldsymbol{\gamma}_s \geq \Lambda_s \quad (17)$$

$$\mathbf{C}^T\boldsymbol{\gamma}_b \geq \Lambda_b \quad (18)$$

$$||\mathbf{w}||^2 \leq P_S \quad (19)$$

$$||\mathbf{v}||^2 \leq P_B \quad (20)$$

$$\sum\nolimits_{i=1}^{K} c_i = 1, c_i \in \{0,1\} \quad (21)$$

where $\mathbf{C} = [c_1, c_2...c_K]^T$ is the scheduling vector of the LEO satellites, $\boldsymbol{\eta} = [\eta_{s1}, \eta_{s2}...\eta_{sK}]^T$ denotes the SEE vector of the SU, $\mathbf{B} = [C_{b1}, C_{b2}...C_{bK}]^T$ represents the SR vector of the BU, $\boldsymbol{\gamma}_s = [\gamma_{s1}, \gamma_{s2}...\gamma_{sK}]^T$ denotes the SINR vector of the SU and $\boldsymbol{\gamma}_b = [\gamma_{b1}, \gamma_{b2}...\gamma_{bK}]^T$ denotes the SINR vector of the BU. Γ_b is the SR threshold of BU to realize the secure transmission and Λ_s and Λ_b denote the SINR requirements of the SU and BU, respectively. P_S and P_B are the power budgets of the scheduled satellite and BS, respectively. The constraint (21) is to ensure that only one satellite can be scheduled at one time slot, where $c_k = 1$ denotes the k-th satellite is scheduled to transmit the confidential signal.

3 Solution of the Optimization Problem

Since there are only K possible values of $\mathbf{C}$, the exhaustive method can be used to search for the optimal value of $\mathbf{C}$. For a fixed $\mathbf{C}$, assume the p-th satellite is scheduled, then, $c_p = 1$ and $c_i = 0, i \in \{1, 2...p-1, p+1, ...K\}$. In this case, the original problem can be written as:

$$\max_{\mathbf{v},\mathbf{w}} \frac{\log_2(1+\gamma_{sp}) - \log_2(1+\gamma_{sep})}{||\mathbf{w}||^2 + P_{cp} + ||\mathbf{v}||^2 + P_b} \tag{22}$$

$$\text{s.t.} \ \log_2\left(\frac{1+\gamma_{bp}}{1+\gamma_{bep}}\right) \geq \Gamma_b \tag{23}$$

$$\gamma_{sp} \geq \Lambda_s \tag{24}$$

$$\gamma_{bp} \geq \Lambda_b \tag{25}$$

$$||\mathbf{w}||^2 \leq P_S \tag{26}$$

$$||\mathbf{v}||^2 \leq P_B \tag{27}$$

The optimization problem in (22)–(27) is nonconvex due to the fractional form of SEE and the presence of the difference of two logarithmic functions [22]. The Dinkelbach's method can be adopted to reformulate the fractional form problem to the equivalent subtractive form by introducing an auxiliary variable η_{sp} [23]. Besides, we denote $\mathbf{H}_s = \mathbf{h}_s\mathbf{h}_s^H$, $\mathbf{H}_{se} = \mathbf{h}_{se}\mathbf{h}_{se}^H$, $\mathbf{H}_b = \mathbf{h}_b\mathbf{h}_b^H$, $\mathbf{H}_{be} = \mathbf{h}_{be}\mathbf{h}_{be}^H$, $\mathbf{G}_{sp} = \mathbf{g}_{sp}\mathbf{g}_{sp}^H$, $\mathbf{G}_{sep} = \mathbf{g}_{sep}\mathbf{g}_{sep}^H$, $\mathbf{G}_{bp} = \mathbf{g}_{bp}\mathbf{g}_{bp}^H$, $\mathbf{G}_{bep} = \mathbf{g}_{bep}\mathbf{g}_{bep}^H$ and introduce relaxations $\mathbf{W} = \mathbf{w}\mathbf{w}^H$ and $\mathbf{V} = \mathbf{v}\mathbf{v}^H$, then, the problem can be transformed as:

$$f(\eta_{sp}) = \max_{\mathbf{W},\mathbf{V}} f_1(\mathbf{W},\mathbf{V}) - f_2(\mathbf{W},\mathbf{V}) - \eta_{sp}(Tr(\mathbf{W}) + P_{cp} + Tr(\mathbf{V}) + P_b) \tag{28}$$

$$\text{s.t.} \quad r_1(\mathbf{W},\mathbf{V}) - r_2(\mathbf{W},\mathbf{V}) \geq \Gamma_b \tag{29}$$

$$Tr(\mathbf{G}_{sp}\mathbf{W}) - \Lambda_s Tr(\mathbf{H}_s\mathbf{V}) \geq \Lambda_s\sigma_s^2 \tag{30}$$

$$Tr(\mathbf{H}_b\mathbf{V}) - \Lambda_b Tr(\mathbf{G}_{bp}\mathbf{W}) \geq \Lambda_b\sigma_b^2 \tag{31}$$

$$Tr(\mathbf{W}) \leq P_S, rank(\mathbf{W}) = 1, \mathbf{W} \geq \mathbf{0} \tag{32}$$

$$Tr(\mathbf{V}) \leq P_B, rank(\mathbf{V}) = 1, \mathbf{V} \geq \mathbf{0} \tag{33}$$

where

$$f_1(\mathbf{W},\mathbf{V}) = \log_2(Tr(\mathbf{G}_{sp}\mathbf{W}) + Tr(\mathbf{H}_s\mathbf{V}) + \sigma_s^2) + \log_2(Tr(\mathbf{H}_{se}\mathbf{V}) + \sigma_{se}^2) \tag{34}$$

$$f_2(\mathbf{W},\mathbf{V}) = \log_2(Tr(\mathbf{H}_s\mathbf{V}) + \sigma_s^2) + \log_2(Tr(\mathbf{G}_{sep}\mathbf{W}) + Tr(\mathbf{H}_{se}\mathbf{V}) + \sigma_{se}^2) \tag{35}$$

$$r_1(\mathbf{W},\mathbf{V}) = \log_2(Tr(\mathbf{H}_b\mathbf{V}) + Tr(\mathbf{G}_{bp}\mathbf{W}) + \sigma_b^2) + \log_2(Tr(\mathbf{G}_{bep}\mathbf{W}) + \sigma_{be}^2) \tag{36}$$

$$r_2(\mathbf{W},\mathbf{V}) = \log_2(Tr(\mathbf{G}_{bp}\mathbf{W}) + \sigma_b^2) + \log_2(Tr(\mathbf{H}_{be}\mathbf{V}) + Tr(\mathbf{G}_{bep}\mathbf{W}) + \sigma_{be}^2). \tag{37}$$

The optimal solution of problem (22)–(27) is denoted as $(\mathbf{W}^*, \mathbf{V}^*)$, which can be acquired from the problem given in (28)–(33) if and only if $f(\eta_{sp}) = 0$ [21]. The transformed problem (28)–(33) is a difference of two-convex functions (D.C.) problem. On the basis of [22], the Frank-and-Wold algorithm can be applied to transform the nonconvex optimization problem into a convex problem and obtain the optimal solution through iterative procedure. We apply the Taylor formula to transform $f_2(\mathbf{W},\mathbf{V})$ and $r_2(\mathbf{W},\mathbf{V})$ into approximate linear functions, which is the so-called D.C. approximation method. The gradients of $f_2(\mathbf{W},\mathbf{V})$ and $r_2(\mathbf{W},\mathbf{V})$ are given by:

$$df_2(\mathbf{W},\mathbf{V}) = \frac{1}{\ln 2}\left(\frac{Tr(\mathbf{H}_s d\mathbf{V})}{Tr(\mathbf{H}_s\mathbf{V})+\sigma_s^2} + \frac{Tr(\mathbf{H}_{se} d\mathbf{V}) + Tr(\mathbf{G}_{sep} d\mathbf{W})}{Tr(\mathbf{G}_{sep}\mathbf{W}) + Tr(\mathbf{H}_{se}\mathbf{V}) + \sigma_{se}^2}\right) \quad (38)$$

$$dr_2(\mathbf{W},\mathbf{V}) = \frac{1}{\ln 2}\left(\frac{Tr(\mathbf{G}_{bp} d\mathbf{W})}{Tr(\mathbf{G}_{bp}\mathbf{W})+\sigma_b^2} + \frac{Tr(\mathbf{G}_{bep} d\mathbf{W}) + Tr(\mathbf{H}_{be} d\mathbf{V})}{Tr(\mathbf{H}_{be}\mathbf{V}) + Tr(\mathbf{G}_{bep}\mathbf{W}) + \sigma_{be}^2}\right). \quad (39)$$

Then, according to the first-order Taylor series expansion, we have:

$$\begin{aligned} f_2(\mathbf{W},\mathbf{V}) \le & f_2(\widetilde{\mathbf{W}},\widetilde{\mathbf{V}}) + \frac{1}{\ln 2}\left(\frac{Tr\Big(\mathbf{H}_{se}\Big(\mathbf{V}-\widetilde{\mathbf{V}}\Big)\Big) + Tr\Big(\mathbf{G}_{sep}(\mathbf{W}-\widetilde{\mathbf{W}})\Big)}{Tr(\mathbf{G}_{sep}\widetilde{\mathbf{W}}) + Tr(\mathbf{H}_{se}\widetilde{\mathbf{V}}) + \sigma_{se}^2}\right) \\ & + \frac{1}{\ln 2}\frac{Tr\Big(\mathbf{H}_s(\mathbf{V}-\widetilde{\mathbf{V}})\Big)}{Tr(\mathbf{H}_s\widetilde{\mathbf{V}})+\sigma_s^2} \end{aligned} \quad (40)$$

$$\begin{aligned} r_2(\mathbf{W},\mathbf{V}) \le & r_2(\widetilde{\mathbf{W}},\widetilde{\mathbf{V}}) + \frac{1}{\ln 2}\left(\frac{Tr\Big(\mathbf{G}_{bep}(\mathbf{W}-\widetilde{\mathbf{W}})\Big) + Tr\Big(\mathbf{H}_{be}(\mathbf{V}-\widetilde{\mathbf{V}})\Big)}{Tr(\mathbf{H}_{be}\widetilde{\mathbf{V}}) + Tr(\mathbf{G}_{bep}\widetilde{\mathbf{W}}) + \sigma_{be}^2}\right) \\ & + \frac{1}{\ln 2}\frac{Tr\Big(\mathbf{G}_{bp}(\mathbf{W}-\widetilde{\mathbf{W}})\Big)}{Tr(\mathbf{G}_{bp}\widetilde{\mathbf{W}})+\sigma_b^2} \end{aligned} \quad (41)$$

where $(\widetilde{\mathbf{W}},\widetilde{\mathbf{V}})$ is in the domin of the functions $f_2(\mathbf{W},\mathbf{V})$ and $r_2(\mathbf{W},\mathbf{V})$. By dropping the rank-1 constraints and substituting (40), (41) into (28)–(33), the problem (28)–(33) can be transformed as:

$$\begin{aligned} \max_{\mathbf{W},\mathbf{V}} \quad & f_1(\mathbf{W},\mathbf{V}) - f_2(\widetilde{\mathbf{W}},\widetilde{\mathbf{V}}) - \frac{Tr\Big(\mathbf{G}_{sep}(\mathbf{W}-\widetilde{\mathbf{W}})\Big)}{\ln 2\Big(Tr(\mathbf{G}_{sep}\widetilde{\mathbf{W}}) + Tr(\mathbf{H}_{se}\widetilde{\mathbf{V}}) + \sigma_{se}^2\Big)} \\ & - \frac{Tr\Big(\mathbf{H}_s(\mathbf{V}-\widetilde{\mathbf{V}})\Big)}{\ln 2\Big(Tr(\mathbf{H}_s\widetilde{\mathbf{V}})+\sigma_s^2\Big)} - \frac{Tr(\mathbf{H}_{se}(\mathbf{V}-\widetilde{\mathbf{V}}))}{\ln 2(Tr(\mathbf{G}_{sep}\widetilde{\mathbf{W}}) + Tr(\mathbf{H}_{se}\widetilde{\mathbf{V}}) + \sigma_{se}^2)} \\ & - \eta_{sp}(Tr(\mathbf{W}) + P_{cp} + Tr(\mathbf{V}) + P_b) \end{aligned} \quad (42)$$

$$\text{s.t.} \quad r_1(\mathbf{W},\mathbf{V}) - r_2(\widetilde{\mathbf{W}},\widetilde{\mathbf{V}}) - \frac{Tr(\mathbf{G}_{bep}(\mathbf{W}-\widetilde{\mathbf{W}}))}{\ln 2(Tr(\mathbf{H}_{be}\widetilde{\mathbf{V}}) + Tr(\mathbf{G}_{bep}\widetilde{\mathbf{W}}) + \sigma_{be}^2)}$$

$$-\frac{Tr(\mathbf{G}_{bp}(\mathbf{W}-\widetilde{\mathbf{W}}))}{\ln 2(Tr(\mathbf{G}_{bp}\widetilde{\mathbf{W}})+\sigma_b^2)} - \frac{Tr(\mathbf{H}_{be}(\mathbf{V}-\widetilde{\mathbf{V}}))}{\ln 2(Tr(\mathbf{H}_{be}\widetilde{\mathbf{V}}) + Tr(\mathbf{G}_{bep}\widetilde{\mathbf{W}}) + \sigma_{be}^2)} \ge \Gamma_b \quad (43)$$

$$Tr(\mathbf{G}_{sp}\mathbf{W}) - \Lambda_s Tr(\mathbf{H}_s\mathbf{V}) \ge \Lambda_s\sigma_s^2 \quad (44)$$

$$Tr(\mathbf{H}_b\mathbf{V}) - \Lambda_b Tr(\mathbf{G}_{bp}\mathbf{W}) \ge \Lambda_b\sigma_b^2 \quad (45)$$

$$Tr(\mathbf{W}) \le P_S, \mathbf{W} \ge \mathbf{0} \quad (46)$$

$$Tr(\mathbf{V}) \le P_B, \mathbf{V} \ge \mathbf{0}. \quad (47)$$

It can be proved the problem (42)–(47) is convex, then the mathematical tool CVX could be used to solve the problem iteratively. Specifically, we denote $(\mathbf{W}^n, \mathbf{V}^n)$ as the solution at n-th iteration, then $(\mathbf{W}^{n+1}, \mathbf{V}^{n+1})$ can be obtained by solving the following convex problem:

$$\max_{\mathbf{W},\mathbf{V}} f_1(\mathbf{W},\mathbf{V}) - f_2(\mathbf{W}^n,\mathbf{V}^n) - \eta_{sp}(Tr(\mathbf{W}) + P_{cp} + Tr(\mathbf{V}) + P_b) \\ - \frac{Tr(\mathbf{H}_{se}(\mathbf{V}-\mathbf{V}^n))}{\ln 2(Tr(\mathbf{G}_{sep}\mathbf{W}^n)+Tr(\mathbf{H}_{se}\mathbf{V}^n)+\sigma_{se}^2)} - \frac{Tr(\mathbf{H}_{s}(\mathbf{V}-\mathbf{V}^n))}{\ln 2(Tr(\mathbf{H}_{s}\mathbf{V}^n)+\sigma_{s}^2)} \\ - \frac{Tr(\mathbf{G}_{sep}(\mathbf{W}-\mathbf{W}^n))}{\ln 2(Tr(\mathbf{G}_{sep}\mathbf{W}^n)+Tr(\mathbf{H}_{se}\mathbf{V}^n)+\sigma_{se}^2)} \tag{48}$$

$$\text{s.t.} \quad r_1(\mathbf{W},\mathbf{V}) - r_2(\mathbf{W}^n,\mathbf{V}^n) - \frac{Tr(\mathbf{G}_{bep}(\mathbf{W}-\mathbf{W}^n))}{\ln 2(Tr(\mathbf{H}_{be}\mathbf{V}^n)+Tr(\mathbf{G}_{bep}\mathbf{W}^n)+\sigma_{be}^2)} \tag{49}$$

$$- \frac{Tr(\mathbf{G}_{bp}(\mathbf{W}-\mathbf{W}^n))}{\ln 2(Tr(\mathbf{G}_{bp}\mathbf{W}^n)+\sigma_{b}^2)} - \frac{Tr(\mathbf{H}_{be}(\mathbf{V}-\mathbf{V}^n))}{\ln 2(Tr(\mathbf{H}_{be}\mathbf{V}^n)+Tr(\mathbf{G}_{bep}\mathbf{W}^n)+\sigma_{be}^2)} \geq \Gamma_b$$

$$(44)\text{–}(47). \tag{50}$$

Based on the above analysis, we propose a three-tier iterative algorithm to obtain the optimal solution of our problem as summarized in Algorithm 1, which consists of three functions, namely main function, outer_iteration function and inner_iteration function. In main function, we obtain the optimal value of the satellite scheduling vector $\mathbf{C}$ by traversing the value of $\mathbf{C}$ through setting $c_p = 1$ and $c_i = 0, i \in \{1, 2...p-1, p+1, ...K\}$ and activating the outer_iteration function to calculate the achievable maximal SEE corresponding to the given $\mathbf{C}$. The outer_iteration function will be called K times to search for the optimal $\mathbf{C}$ and obtain the corresponding BF vectors $(\mathbf{w}_p^*, \mathbf{v}_p^*)$. When the outer_iteration function is activated, the maximal number of iterations i_{max}, the minimum tolerance error ε, the iteration index i and the achievable SEE η_{sp}^i at i-th iteration are initialized. Based on the given η_{sp}^i, the problem (28)–(33) is solved by D.C. approximation method to obtain the matrices $(\mathbf{W}_{sp}^{i+1}, \mathbf{V}_{sp}^{i+1})$ according to the inner_iteration function. The updated matrices $(\mathbf{W}_{sp}^{i+1}, \mathbf{V}_{sp}^{i+1})$ will be used to update the value of η_{sp}^{i+1} according to the Dinkelbach's method until $i > i_{max}$ or the criterion $|\eta_{sp}^{i+1} - \eta_{sp}^i| < \varepsilon$ is satisfied. Then the BF vectors $(\mathbf{w}_p^*, \mathbf{v}_p^*)$ can be obtained through corresponding method. When inner_iteration function is activated, the matrices $(\mathbf{W}_p^j, \mathbf{V}_p^j)$ are updated by formula (48)–(50) until the maximum number of inner_iteration j_{max} is reached or the value of $f^{j+1} = f_1(\mathbf{W}_p^{j+1}, \mathbf{V}_p^{j+1}) - f_2(\mathbf{W}_p^{j+1}, \mathbf{V}_p^{j+1}) - \eta_{sp}^i(Tr(\mathbf{W}_p^{j+1}) + P_{cp} + Tr(\mathbf{V}_p^{j+1}) + P_b)$ satisfies the criterion $|f^{j+1} - f^j| < \varepsilon$. The convergence of outer_iteration and inner_iteration functions have already been approved in [21,23].

Denote by $(\mathbf{W}^*, \mathbf{V}^*)$ the optimal solution of the problem (28)–(33). Note that $(\mathbf{W}^*, \mathbf{V}^*)$ might not be rank-1. If $(\mathbf{W}^*, \mathbf{V}^*)$ are of rank-1, the singular value decomposition method is employed to acquire the optimal BF vectors $(\mathbf{w}^*, \mathbf{v}^*)$. Otherwise, the Gaussian randomization method is utilized to find an approximate solution [6].

Algorithm 1 :The Proposed Three-tier Algorithm.

Input: K, $\boldsymbol{g}_i$,$\boldsymbol{h}_i$,$i \in sj, sej, bj, bej, j \in 1, 2...K$.
Output: Optimal scheduling vector $\mathbf{C}$ with the BF vectors $(\mathbf{w}^*, \mathbf{v}^*)$.
Function: *Main*
1: Initialize $p = 1$.
2: Set $\mathbf{C} = \mathbf{C}_p$ with $c_p = 1$ and $c_i = 0, i \in \{1, 2...p-1, p+1, ...K\}$, call **Function** *Outer_Iteration* to calculate the achievable SEE η_{sp}^* and corresponding $(\mathbf{w}_p^*, \mathbf{v}_p^*)$.
3: Set $\eta(\mathbf{C}_p) = \eta_{sp}^*, p = p + 1$.
4: **if** $p \leq K$ **then**
5: goto step 2.
6: **else**
7: Calculate $\mathbf{C}_t = \arg\max\limits_{\mathbf{C}} \eta(\mathbf{C})$.
8: **end if**
9: Obtain the maximal SEE η^* with the satellite scheduling vector $\mathbf{C} = \mathbf{C}_t$ and corresponding BF vectors $(\mathbf{w}^*, \mathbf{v}^*) = (\mathbf{w}_t^*, \mathbf{v}_t^*)$.
end
Function: *Outer_Iteration*
10: Initialize the maximal number of iterations i_{max} and minimum tolerance error ε.
11: Set $\eta_{sp}^i = 0, i = 0$.
12: Call **Function** *Inner_Iteration* with η_{sp}^i and ε to calculate $(\mathbf{W}_{sp}^{i+1}, \mathbf{V}_{sp}^{i+1})$.
13: Update $\eta_{sp}^{i+1} = \frac{\log_2(1+\gamma_{sp}) - \log_2(1+\gamma_{sep})}{Tr(\mathbf{W}_{sp}^{i+1}) + P_{cp} + Tr(\mathbf{V}_{sp}^{i+1}) + P_b}$.
14: **if** $|\eta_{sp}^{i+1} - \eta_{sp}^i| \geq \varepsilon$ and $i \leq i_{max}$ **then**
15: Update $i = i + 1$, goto step 12.
16: **else**
17: $\eta_{sp}^* = \eta_{sp}^{i+1}, (\mathbf{W}_{sp}^*, \mathbf{V}_{sp}^*) = (\mathbf{W}_{sp}^{i+1}, \mathbf{V}_{sp}^{i+1})$.
18: **end if**
19: **if** $\text{rank}(\mathbf{O}) = 1, \mathbf{O} \in \{\mathbf{W}_{sp}^*, \mathbf{V}_{sp}^*\}$ **then**
20: Use Singular Value Decomposition Method to get $\mathbf{o}, \mathbf{o} \in \{\mathbf{w}_p^*, \mathbf{v}_p^*\}$.
21: **else**
22: Use Gaussian Randomization Method to get $\mathbf{o}, \mathbf{o} \in \{\mathbf{w}_p^*, \mathbf{v}_p^*\}$.
23: **end if**
24: Return η_{sp}^* and $(\mathbf{w}_p^*, \mathbf{v}_p^*)$.
end
Function: *Inner_Iteration*
25: Initialize the maximal number of iterations j_{max}, $(\mathbf{W}_p^0, \mathbf{V}_p^0) = (\mathbf{0}, \mathbf{0})$ and $f^0 = 0$.
26: Set $j = 0$.
27: Compute $(\mathbf{W}_p^{j+1}, \mathbf{V}_p^{j+1})$ of problem (48)-(50) with $(\mathbf{W}_p^j, \mathbf{V}_p^j)$ and η_{sp}^i.
28: Compute $f^{j+1} =$
$f_1(\mathbf{W}_p^{j+1}, \mathbf{V}_p^{j+1}) - f_2(\mathbf{W}_p^{j+1}, \mathbf{V}_p^{j+1}) - \eta_{sp}^i(Tr(\mathbf{W}_p^{j+1}) + P_{cp} + Tr(\mathbf{V}_p^{j+1}) + P_b)$.
29: **if** $|f^{j+1} - f^j| \geq \varepsilon$ and $j \leq j_{max}$ **then**
30: Update $j = j + 1$, goto step 27.
31: **else**
32: Return $(\mathbf{W}_p^{j+1}, \mathbf{V}_p^{j+1})$.
33: **end if**
end

4 Simulation Results

In this section, we provide simulation results to evaluate the performance of our proposed scheme. To conduct comparison, the joint highest elevation angle priority satellite scheduling and BF scheme (JHEASSB) and the joint maximal service time priority satellite scheduling and BF scheme (JMSTSSB) are also presented as counterparts.

The simulated scenario and related parameters are set as follows. We assume that the terrestrial links experience Rayleigh distribution. The distance between the SU and the SE, the BU and the BE are set as 0.1D, 0.1D and 0.11D, respectively, where D denotes the beam diameter of the satellite. The simulated satellite constellation is an iridium satellite-like constellation. The power budgets of the satellite and the BS are set as 35 dBm and 42 dBm, respectively. The elevation angles of the satellites in the visual range of the SU are determined at a fixed time. We set the latitude and the longitude coordinates of the SU as $(75°, 95°)$. According to the scenario we established, there are four satellites in the SU's visual range. The elevation angles of the satellites are 20.0568°, 20.1066°, 27.3138° and 31.1373°, respectively. The scheduled satellite will transmit the confidential signal to the SU via N beams which have the smallest angles between the beam center and SU's position with respect to the satellite among all beams. Unless otherwise specified, the simulation is carried out under the above conditions. Other simulation parameters are summarized in Table 1 [24]. In addition, all of the simulation curves are averaged over 500 random channel realizations.

Table 1. Main simulation parameters.

Parameter	Value
No. of satellites	66
No. of orbital planes	6
Inclination of the orbital plane	86.4°
No. of beams per satellite	48
Beam diameter	400 km
Minimum elevation angle	19°
Altitude of the orbit	780 km
Carrier frequency	20 GHz
Noise bandwidth	500 MHz
Noise temperature	300 K
3 dB angle	14°

Figure 2 depicts the SEE versus the number of beams N utilized for the secure transmission. We can observe that the proposed scheme achieves the maximal

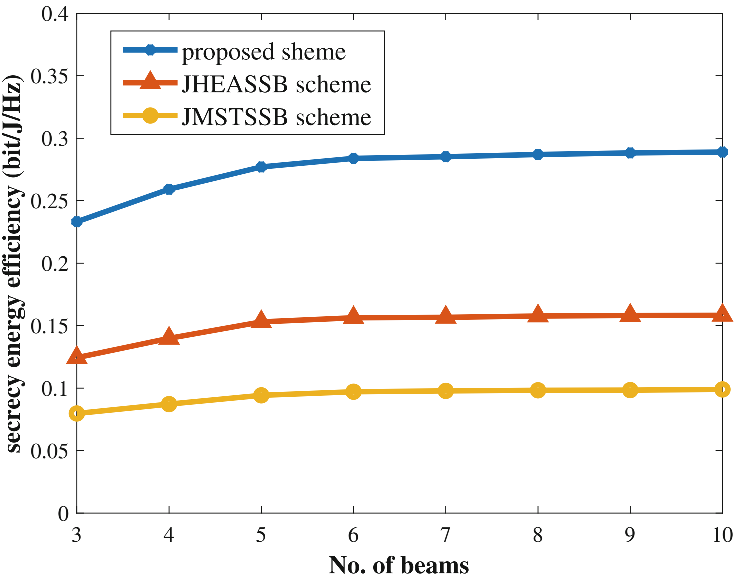

Fig. 2. Achievable SEE versus number of beams.

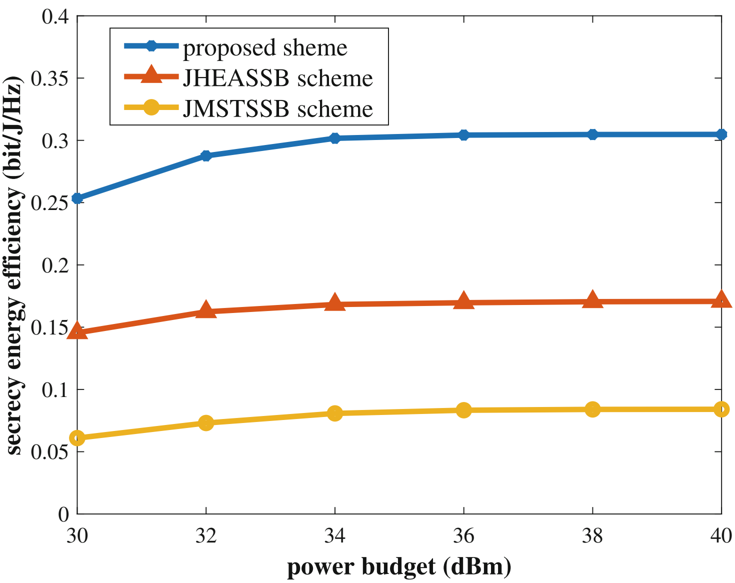

Fig. 3. Achievable SEE versus power budget of satellite.

SEE as compared with the JHEASSB scheme and the JMSTSSB scheme. In our proposed scheme, the achievable SEE is improved about 100% as compared with the JHEASSB and more than 150% as compared with the JMSTSSB, which demonstrates the efficiency of our proposed scheme. The reason for this phenomenon is that the link between the SU and the satellite which has the maximum elevation angle does not always have the best transmission quality, the opportunistic satellite scheduling scheme can ensure the link between the scheduled satellite and SU has the best transmission quality and improve the SEE by BF effectively. As the number of beams for BF increases, all the schemes reach their own SEE floors and remain unchanged. The reason is that when more beam resources are available, the achievable SEE tends to increase. However, the further away from the SU, the smaller beam gain of the beam to SU, thus the beams which far away form the SU are of little use for the secure transmission and the SEE tends to keep constant eventually.

Figure 3 depicts the SEE performance versus the power budget P_{cp} of the proposed scheme, the JHEASSB scheme and the JMSTSSB scheme when the number of beams utilized for secure transmission is set as 6. As the power budget increases, the SEE increases until converges. The SEE of the three schemes are all improved with an increasing transmit power budget P_{cp} in the 30–36 dBm region, which indicates that when more energy resource available, the larger SEE can be obtained within certain power budget bounds. Morever, it can be observed that the proposed scheme obtains the maximal SEE as compared with the other two schemes, which proves the superiority of our proposed scheme.

5 Conclusions

This paper is devoted to enhancing the secrecy performance in the CLSTN. Taking the security performance and energy efficiency into account, we propose a joint opportunistic satellite scheduling and BF scheme to realize the secure transmission of both the SU and BU. An optimization problem is formulated to maximize the SEE of the SU under the SR constraint of the BU, the SINR requirements of the SU and BU and the limited power budgets of the satellite and BS. Considering the case when the scheduled satellite is given, we can transform the SEE maximization problem into a convex one by exploiting the Dinkelbach's method and the D.C. approximation method. Then, a three-tier algorithm is proposed to obtain the optimal satellite scheduling vector and the BF vectors of the satellite and BS jointly. Simulation results confirm the validity of our proposed scheme.

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