Power-Efficient Secure Beamforming in Cognitive Satellite-Terrestrial Networks

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***Abstract*—This paper proposes a power-efficient secure beamforming (BF) algorithm for cognitive satellite-terrestrial wireless networks, where the satellite network termed as the primary network under the intercept of an eavesdropper shares the spectrum of the primary network with the terrestrial secondary network. Specifically, we propose a optimal BF scheme with the objective of minimizing the transmit power of the terrestrial base station (BS), while meeting the secrecy rate constraint of the primary user and the communication rate constraint of the secondary user. Then, we use constraint transformation and semidefinite relaxation (SDR) method to convert the nonconvex optimization problem into the convex optimization problem. Thus, the optimal BF weight vector can be solved by semidefinite program (SDP) method. Finally, the results of computer simulation verify the effectiveness and superiority of the proposed BF algorithm.**

***Index Terms*—Physical layer security, satellite communication, power-efficient, convex optimization, secrecy rate.**

I. INTRODUCTION

Satellite communication has its own unique advantages because of its long communication distance, wide coverage, flexible networking, and etc [1]. It is not only an indispensable means of military communication, but also a prospective application in many civil fields, such as broadcasting, navigation, rescue and emergency communication. However, the spectrum resources licensed to satellite communication are underutilized and the terrestrial spectrum resources are increasingly strained, thus the incorporation of spectrum sharing approach for satellite and terrestrial networks has a extensive research prospect [2]. In recent years, cognitive radio network (CRN) is considered as one of the main schemes to improve spectrum efficiency, by constituting a hybrid architecture known as cognitive satellite terrestrial networks [3], [4].

Satellite communication is easily eavesdropped because of its broadcasting characteristics, thus it is crucial to study the security issues of satellite communication. Traditional satellite communication security is achieved by encryption, for example, the advanced encryption standard [5]. However, with the increasing ability of the eavesdropper's computation and decoding, the traditional encryption method has been unable to guarantee the absolute safety [6]. In addition to encryption, the security of information transmission can also be implemented in the physical layer based on the information security theory [7]. Although the problem of physical layer security in terrestrial wireless communication systems has been widely studied, the research on physical layer security of satellite communication is still limited. In [8], the expression of the secrecy outage probability and ergodic secrecy rate for the downlink land mobile satellite systems was derived. A joint design of power control and BF algorithm was proposed in [9]. By assuming that the channel state information of the eavesdropper was completely known or partially known, different BF schemes to minimize the satellite's transmit power were proposed by satisfying each user's secrecy rate [10]. In addition, [11] studied the security problem of satellite communication based on network coding. By using SDP method, the optimal BF weight vector under the maximum security rate sum constraint condition was obtained. In [12], an optimal BF algorithm based on convex optimization SDP scheme is proposed for the multiple-input and multiple-output cognitive wireless channel security communication problem. The authors of [13] studied the security issues in cognitive radio networks, and proposed a secondary network to assist primary users in reducing eavesdropped probability of primary users. At present, the research on the physical layer security in cognitive satellite-terrestrial wireless network is quite limited, and there are still many key problems need to be solved.

Despite the security and privacy concerns, the efficient resource allocation mechanisms have recently gained significant interest in cognitive satellite-terrestrial networks since the power/energy consumed on-board the satellite strongly affect the playload and mission operation [14]. The emerging environmental issues and resource cost concerns have received critical attention in system design for future wireless communications [15].

In this paper, the security problem in cognitive satellite-terrestrial wireless network is studied, and a power-efficient secure BF algorithm for improving the secrecy rate of the system is proposed. The hybrid network includes the satellite communication network and the terrestrial secondary network. The satellite network is termed as the primary network. First, we propose a optimal BF scheme with the objective of minimizing the transmit power of the BS, while meeting the secrecy rate constraint of the primary user and the communication rate constraint of the secondary user. Then, the introduction of new intermediate variables converts the

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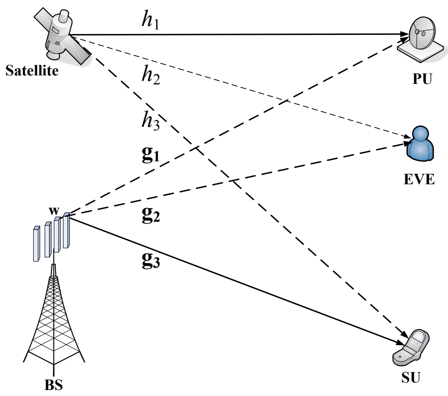

Fig. 1: System model cognitive satellite-terrestrial network.

original optimization problem into quadratically constrained quadratic program (QCQP) problem. By using SDR method to relax the limiting condition, the original optimization becomes a SDP problem, which can be solved with the help of standard numerical optimization packages,such as CVX [16]. The simulation results show that the proposed BF algorithm can improve the secrecy rate of the primary user of the satellite communication system.

II. SYSTEM MODEL

As shown in Fig. 1, this paper studies a hybrid satellite-terrestrial wireless network. The satellite communication network is the primary network, which includes a primary user (PU) and a malicious eavesdropper (EVE), while the terrestrial network is a secondary network, including the terrestrial base station (BS) and a secondary user (SU). In this architecture, the satellite, the PU, the EVE and the SU are equipped with the single antenna respectively, while the terrestrial BS is installed with the N transmit antenna.

A. Satellite Channel Model

The satellite channel and the terrestrial wireless fading channel are modeled respectively. For satellite channel, when propagating through clouds, snow, rain and hail in the troposphere, radio waves suffer from attenuation. Out of these reasons, rain attenuation constitutes the important factor and we need to take the effect of rain attenuation into account in the course of our analysis especially [17].

1) Rain Attenuation: Using the modeling method for the impact of above-mentioned conditions, the coefficient of rain attenuation can be given as

$$\widetilde{h}_m = \beta^{-\frac{1}{2}} e^{-j\phi} \left(m = 1, 2, 3\right), \tag{1}$$

where φ represents a $N \times 1$ phase vector uniformly distributed over $[0, 2\pi)$. The resulting distribution of power gain in dB, $\beta_{dB} = 20\log_{10}(\beta)$, is commonly modeled as a lognormal random variable $\ln(\beta_{dB}) \sim N(\mu, \delta)$,where μ and δ depends on the location of the receiver, working frequency, polarization mode and elevation angle toward the satellite.

2) Beam Gain: The beam gain is the average signal to interference-plus-noise ratios(SINR) at each receiver and it is relative to the satellite antenna pattern and the receiver's position. According to the [18], [19], the beam gain at the receiver can be approximated by

$$b\left(m\right) = b_m^{\max} \left(\frac{J_1\left(u_m\right)}{2u_m} + 36 \frac{J_3\left(u_m\right)}{{u_m}^3} \right)^2, \tag{2}$$

and μ_m can be written as

$$u_m = 2.07123 \sin \theta_m / \sin \left(\theta_{3dB}\right)_m \left(m = 1, 2, 3\right), \tag{3}$$

where J_1 and J_3 are the first-kind of Bessel function of order 1 and 3. Define the $m-\mathrm{th}$ receiver's position based on the angle θ_m between the beam center and the location of m-th receiver with respect to the satellite and $\left(\theta_{3\mathrm{dB}}\right)_m$ is termed as its $3-\mathrm{dB}$ angle. The coefficient $b_m^{\max}$ denotes the gain at boresight, and $b\left(m\right)\left(m = 1, 2, 3\right)$ represents the beam gain of the PU, the EVE and the SU respectively. Integrated (1) and (2), the satellite channel of the receiver can be expressed as

$$h_m = \widetilde{h}_m * \left(b\left(m\right)\right)^{\frac{1}{2}}. \tag{4}$$

B. Terrestrial Channel Model

For the terrestrial wireless fading channel, we assume that it obeys the related Rayleigh fading [20], the instantaneous channel vector between the BS and the receiver can be described as

$$\mathbf{g}_i = \sum\nolimits_{l=1}^{L_i} \rho_{i,l} \mathbf{a}_i\left(\alpha_l\right), \tag{5}$$

among them, L_i and $\rho_{i,l}$ are the number of multipath signal and the fading coefficient respectively. And $\alpha_l \in [\overline{\alpha_i} - \Delta\alpha/2, \overline{\alpha_i} + \Delta\alpha/2]$ is the Direction of Arrival (DOA) of the $l-\mathrm{th}$ path signal, with $\overline{\alpha_i}$ and $\Delta\alpha$ representing the average cluster angle DOA and the angular spread respectively. As the terrestrial BS adopts an uniform linear array antenna, the array element guidance vector can be expressed as

$$\begin{aligned} &\mathbf{a}_i\left(\alpha_l\right) \\ &= \left[1, \exp\left(jkd\sin\left(\alpha_l\right)\right), ..., \exp\left(jkd\left(N-1\right)\sin\left(\alpha_l\right)\right)\right]^{\mathrm{T}}. \end{aligned} \tag{6}$$

where d represents the inter-element spacing and k the wave-number.

C. Signal Model

From Fig. 1 and channel models, it can be found that the signals received by the PU, the EVE and the SU can be respectively expressed as

$$y_1 = \sqrt{P_0} h_1 s_0 + {\mathbf{g}_1}^{\mathbf{H}} \mathbf{w} s_1 + n_1, \tag{7a}$$

$$y_2 = \sqrt{P_0} h_2 s_0 + {\mathbf{g}_2}^{\mathbf{H}} \mathbf{w} s_1 + n_2, \tag{7b}$$

$$y_3 = \sqrt{P_0} h_3 s_0 + {\mathbf{g}_3}^{\mathbf{H}} \mathbf{w} s_1 + n_3, \tag{7c}$$

where the signal transmitted by the satellite is s_0 and the signal transmitted by the terrestrial BS is s_1 with unit average power $\mathrm{E}\left[\left|s_i\right|^2\right] = 1\left(i = 0, 1\right)$. In addition, P_0 represents the satellite transmit power, $\mathbf{w} \in \mathbb{C}^{N\times 1}$ is the beamforming weight vector of the terrestrial BS, and $n_i\,(i=1,2,3)$ is assumed to be zero-mean additive white Gaussian(AWGN) noise of the PU, the EVE and the SU obeying $\mathrm{E}\left[\left|n_i\right|^2\right]=1\,(i=1,2,3)$. Then $h_i\,(i=1,2,3)$ represents the channel vectors between the satellite and the PU, the EVE, and the SU. Meanwhile, $\mathbf{g}_i \in \mathbb{C}^{N\times 1}(i=1,2,3)$ is the channel vector between the terrestrial BS and the PU, the EVE, the SU represtively. According to this, the SINR of the signal received by the PU, the EVE and the SU can be represented as

$$\gamma_{pu}=\frac{P_0\left|h_1\right|^2}{\left|\mathbf{g}_1{}^{\mathbf{H}}\mathbf{w}\right|^2+E\left[\left|n_1\right|^2\right]}, \tag{8a}$$

$$\gamma_{eve}=\frac{P_0\left|h_2\right|^2}{\left|\mathbf{g}_2{}^{\mathbf{H}}\mathbf{w}\right|^2+E\left[\left|n_2\right|^2\right]}, \tag{8b}$$

$$\gamma_{su}=\frac{\left|\mathbf{g}_3{}^{\mathbf{H}}\mathbf{w}\right|^2}{P_0\left|h_3\right|^2+E\left[\left|n_3\right|^2\right]}, \tag{8c}$$

according to the [21], the communication rate of the PU, the EVE, and the SU can be given by

$$C_{pu}=\log_2\left(1+\gamma_{pu}\right), \tag{9a}$$

$$C_{eve}=\log_2\left(1+\gamma_{eve}\right), \tag{9b}$$

$$C_{su}=\log_2\left(1+\gamma_{su}\right). \tag{9c}$$

Further, it is known from the document [22] that the secrecy rate of the PU can be expressed as

$$C_1=\left\{\begin{array}{cc} C_{pu}-C_{eve}, \gamma_{pu}>\gamma_{eve} \\ 0, \quad \gamma_{pu}\le\gamma_{eve}. \end{array}\right. \tag{10}$$

III. PROPOSED BF SCHEME

As a power-limited system power by solar panels or battery, the energy consumptions in the cognitive satellite terrestrial networks has become a serious concerns. In this section, the optimization problem is designed by minimizing the transmit power of the terrestrial BS, with the secrecy rate constraint of the PU and the communication rate constraint of the SU satisfying the requirements. Thus, the optimization problem can be established as

$$\min_{\mathbf{w}} \quad \left\|\mathbf{w}\right\|^2 \tag{11a}$$

$$s.t. \quad C_{su}\ge\gamma_2, \tag{11b}$$

$$C_1\ge\gamma_1, \tag{11c}$$

where γ_2 denotes the communication rate threshold of the SU, and γ_1 denotes the secrecy rate threshold of the PU. By substituting $(9a)$, $(9b)$ and $(9c)$ into (11) ,we can get

$$\min_{\mathbf{w}} \quad \left\|\mathbf{w}\right\|^2 \tag{12a}$$

$$s.t. \quad \log_2\left(1+\gamma_{su}\right)\ge\gamma_2, \tag{12b}$$

$$\log_2\left(1+\gamma_{pu}\right)-\log_2\left(1+\gamma_{eve}\right)\ge\gamma_1. \tag{12c}$$

Where substituting $(8a)$, $(8b)$, and $(8c)$ into (12), the optimization problem in (12) can be reformulated as

$$\min_{\mathbf{w}} \quad \left\|\mathbf{w}\right\|^2 \tag{13a}$$

$$s.t. \quad \left|\mathbf{g}_3{}^{\mathbf{H}}\mathbf{w}\right|^2-\left(2^{\gamma_2}-1\right)\left(P_0\left|h_3\right|^2+{\delta_3}^2\right)\ge 0, \tag{13b}$$

$$\begin{aligned}&\left(1+\frac{P_0\left|h_1\right|^2}{\left|\mathbf{g}_1{}^{\mathbf{H}}\mathbf{w}\right|^2+{\delta_1}^2}-2^{\gamma_1}\right)\\ &\left(\left|\mathbf{g}_2{}^{\mathbf{H}}\mathbf{w}\right|^2+{\delta_2}^2\right)-2^{\gamma_1}P_0\left|h_2\right|^2\ge 0.\end{aligned} \tag{13c}$$

The design of BF algorithm makes the signal transmitted by the terrestrial BS almost no interference to the PU, meanwhile results in a certain interference to the EVE and a decrease of the EVE's SINR. It ensures the secondary network communication requirements and achieves the purpose of increasing secrecy rate of the PU. The constraint condition $(13c)$ is a biquadratic problem about the weight vector after deployment. It is not a QCQP problem, so the traditional SDP method can not be applied directly. Here we introduce a new variable ζ_0, and add a new constraint condition$\left|\mathbf{g}_1{}^{\mathbf{H}}\mathbf{w}\right|^2\le\zeta_0$. The new constraint condition means the interference from the terrestrial network to the PU is lower than the fixed threshold ζ_0, which further guarantees the secrecy rate of the PU to satisfy the requirements. In this way, the original optimization problem can be converted to the QCQP problem. The following is a restructured optimization problem

$$\min_{\mathbf{w}} \quad \left\|\mathbf{w}\right\|^2 \tag{14a}$$

$$s.t. \quad \left|\mathbf{g}_3{}^{\mathbf{H}}\mathbf{w}\right|^2-\left(2^{\gamma_2}-1\right)\left(P_0\left|h_3\right|^2+{\delta_3}^2\right)\ge 0, \tag{14b}$$

$$\begin{aligned}&\left(1+\frac{P_0\left|h_1\right|^2}{\zeta_0+{\delta_1}^2}-2^{\gamma_1}\right)\\ &\left(\left|\mathbf{g}_2{}^{\mathbf{H}}\mathbf{w}\right|^2+{\delta_2}^2\right)-2^{\gamma_1}P_0\left|h_2\right|^2\ge 0,\end{aligned} \tag{14c}$$

$$\left|\mathbf{g}_1{}^{\mathbf{H}}\mathbf{w}\right|^2\le\zeta_0. \tag{14d}$$

Then we introduce a new matrix variable $\mathbf{W}=\mathbf{w}\mathbf{w}^{\mathbf{H}}$,which is the Hermitian matrix. So we can turn the optimization problem (14) into the SDP problem, that is

$$\min_{\mathbf{w}} \quad tr\left(\mathbf{W}\right) \tag{15a}$$

$$s.t. \quad tr\left(\mathbf{G}_3\mathbf{W}\right)-\left(2^{\gamma_2}-1\right)\left(P_0\left|h_3\right|^2+{\delta_3}^2\right)\ge 0, \tag{15b}$$

$$\begin{aligned}&\left(1+\frac{P_0\left|h_1\right|^2}{\zeta_0+{\delta_1}^2}-2^{\gamma_1}\right)\\ &\left(tr\left(\mathbf{G}_2\mathbf{W}\right)+{\delta_2}^2\right)-2^{\gamma_1}P_0\left|h_2\right|^2\ge 0,\end{aligned} \tag{15c}$$

$$tr\left(\mathbf{G}_1\mathbf{W}\right)-\zeta_0\le 0, \tag{15d}$$

$$\mathbf{W}\succeq 0, \quad rank\left(\mathbf{W}\right)=1, \tag{15e}$$

where $tr\left(\mathbf{W}\right)$ represents the trace of the matrix $\mathbf{W}$, $rank\left(\mathbf{W}\right)$ represents the rank of the matrix $\mathbf{W}$, and $\mathbf{G}_i=\mathbf{g}_i\mathbf{g}_i{}^{\mathbf{H}}\,(i=1,2,3)$ is the autocorrelation matrix of the terrestrial BS channel vector. It is obvious that the objective function in $(15a)$ is linear and the constraints $(15b)$, $(15c)$ and $(15d)$ are all convex. But the constraint $(15e)$ does not satisfy the convex optimization condition. Thus we use the SDR method to drop the non-convex rank-one constraint $(15e)$, so the optimization problem can be expressed as

$$\min_{\mathbf{w}} \quad tr\left(\mathbf{W}\right) \tag{16a}$$

$$s.t. \quad tr\left(\mathbf{G}_3\mathbf{W}\right) - \left(2^{\gamma_2} - 1\right)\left(P_0|h_3|^2 + {\delta_3}^2\right) \geq 0, \tag{16b}$$

$$\left(1 + \frac{P_0|h_1|^2}{\zeta_0 + {\delta_1}^2} - 2^{\gamma_1}\right) \left(tr\left(\mathbf{G}_2\mathbf{W}\right) + {\delta_2}^2\right) - 2^{\gamma_1}P_0|h_2|^2 \geq 0, \tag{16c}$$

$$tr\left(\mathbf{G}_1\mathbf{W}\right) - \zeta_0 \leq 0, \tag{16d}$$

$$\mathbf{W}\succeq 0. \tag{16e}$$

Now the optimization problem becomes a convex SDP problem, which can be solved through using standard mathematical optimization tools [23]. The transmit BF weight vector $\mathbf{w}$ can be retrieved from $\mathbf{W}$.

IV. NUMERICAL RESULTS

In this section, the proposed scheme is verified by comparison through numerical simulations. Throughout our paper, we assume $\zeta_0 = -8\text{dB}, -6\text{dB}, -4\text{dB}, -2\text{dB}, 0\text{dB}$ and $\theta_{3\text{dB}} = 0.4°$. In the satellite network, lognormal distribution parameters are $\mu = -3.125$ and $\delta = 1.591$ [24], the angle between the beam center and the location of the PU, the EVE, and the SU with respect to the satellite is $\theta_1 = 0.0001°$, $\theta_2 = 0.2857°$ and $\theta_3 = 0.4944°$. For the terrestrial network, the PU, the EVE, and the SU are located in the directions of $\alpha_1 = 10°$, $\alpha_2 = 25°$, and $\alpha_3 = 60°$, respectively, while all of them are assumed to have a spread angle of $\Delta\alpha = 3°$. The terrestrial BS, which is equipped with a uniform linear array with $N = 8$ elements spaced half a wavelength apart from each other.

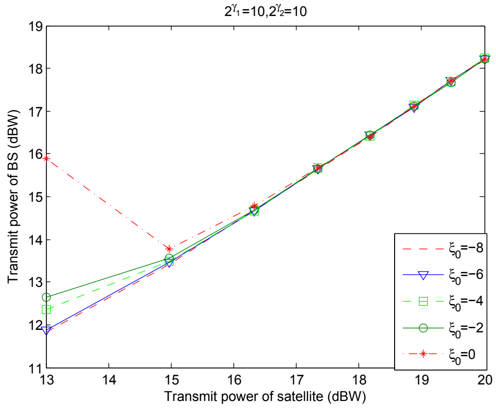

Fig. 2: Transmit power of BS versus transmit power of satellite.

Fig. 2 depicts the variation of the transmit power of the terrestrial BS versus the transmit power of the satellite with $2^{\gamma_1} = 10$ and $2^{\gamma_2} = 10$, when ζ_0 takes different values. When the transmit power of the satellite is lower, the curve of $\zeta_0 = 0\text{dB}$ is obviously different from the others. Because the restriction is more relaxed, the transmit power of terrestrial BS in the direction of the PU will be relatively large. Besides, as satellite transmit power increases, the terrestrial BS can reduce its transmit power to increase communication rate both the PU and the EVE. But PU's rate increases faster than that of EVE, hence the secrecy rate of the PU still satisfies the requirements. As ζ_0 decreases, this phenomenon becomes less obvious. When the satellite transmit power is large, the value of ζ_0 has marginal influence on the system.

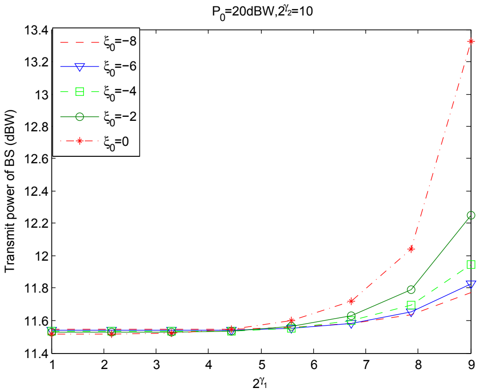

Fig. 3: Transmit power of BS versus 2^{γ_1}.

Fig. 3 shows the variation of the terrestrial BS transmit power with the threshold 2^{γ_1}. When ζ_0 is taken different values, we consider the satellite transmit power $P_0 = 20\text{dBW}$ and $2^{\gamma_2} = 10$. When 2^{γ_1} is small, the increase of 2^{γ_1} has little effect on the transmit power of the terrestrial BS. As the value of 2^{γ_1} increases, the growth of the terrestrial BS's transmit power is more obvious. Because the satellite transmit power is fixed, with the increase of the PU's secrecy rate requirements, the terrestrial BS increases the transmit power to make the PU satisfy the requirements.

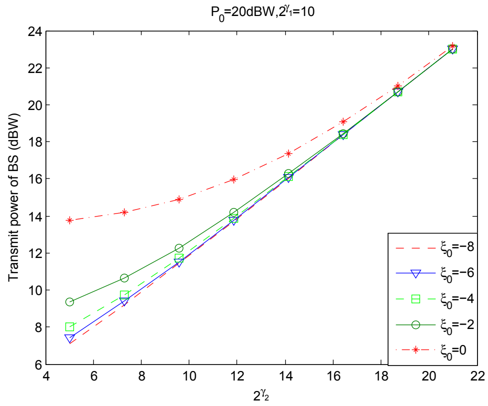

Fig. 4: Transmit power of BS versus 2^{γ_2}.

Fig. 4 illustrates the transmit power of the terrestrial BS versus 2^{γ_2} with $P_0 = 20\text{dBW}$ and $2^{\gamma_1} = 10$. As can be seen, the transmit power of the terrestrial BS improves as the value of 2^{γ_2} increases. When 2^{γ_2} is small, the terrestrial BS transmit power is affected obviously. With 2^{γ_2} increasing gradually, the terrestrial BS increases its transmit power so that the communication rate of the SU can be improved at same time. For a specific value of 2^{γ_2}, the smaller the value of ζ_0 is, the lower BS's transmit power is required. With 2^{γ_2} gradually increasing, the gap between the curves is becoming smaller. When 2^{γ_2} is larger, the transmit power of terrestrial BS increases, but the difference between curves is very small.

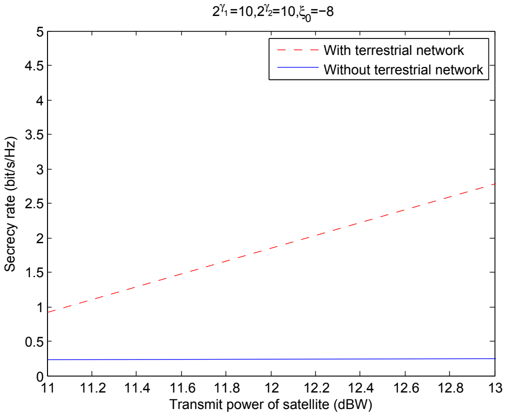

Fig. 5: Secrecy rate of the PU under different networks.

Fig. 5 shows the secrecy rate of the PU under different networks. Two curves represent the secrecy rate curve of the PU with the terrestrial network and without the terrestrial network. As the transmit power of satellite gradually increasing according to the simulation results, the secrecy rate without terrestrial network changes slowly, but the existence of the terrestrial makes the PU's secrecy rate increasing fast. Meanwhile, the secrecy rate with the terrestrial network is always higher than it without the terrestrial network. The simulation results fully demonstrate that hybrid satellite-terrestrial wireless network can improve the secrecy rate of the PU.

V. CONCLUSIONS

In this paper, we have investigated a power-efficient secure BF algorithm for cognitive satellite-terrestrial wireless networks. Then, the optimization problem based on minimizing the transmit power of the terrestrial BS is proposed with the secrecy rate constraint of the PU and the communication rate constraint of the SU satisfying the requirements. Next, the original optimization problem is converted by constraint transformation and SDR method. Further, the optimization problem becomes a convex problem, and the BF weight vector can be solved by SDP method. Finally, the simulation results show that the proposed BF algorithm has some effectiveness and superiority.

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