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Stackelberg Game Based Secure Transmission Strategy for Cognitive Satellite Terrestrial Networks

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***Abstract*—Recently, the secure transmission in cognitive satellite terrestrial network (CSTN) has gained much attention, where the interference from the terrestrial network is utilized to enhance the security of the satellite network, provided that these two networks share the spectrum. In the existing literature, the satellite and terrestrial networks are assumed to be naturally willing to cooperate with each other to improve the performance of the entire CSTN system. However, these two networks generally belong to different authorities in practice and will not cooperate if their own benefits are impaired. From this perspective, we propose a Stackelberg game based secure transmission strategy for the CSTN to motivate cooperation, where the satellite network acts as the leader and the terrestrial network acts as the follower. Specifically, we model the utility function of the satellite network as the secrecy rate assisted by the terrestrial network. Moreover, the utility function of the terrestrial network is modeled as its obtained transmission rate discounted by the cost of total transmission energy. On this basis, we adopt the backward induction method to determine the Stackelberg equilibrium, from which both the utilities of the satellite and terrestrial networks are maximized. Finally, simulation results are presented to validate our theoretical results.**

***Index Terms*—Cognitive satellite terrestrial network, Stackelberg game, physical layer security.**

I. Introduction

Benefiting from both satellite and terrestrial systems, the hybrid satellite terrestrial network is becoming a promising infrastructure to provide high throughput with ubiquitous coverage in future B5G/6G networks [1] [2]. However, the security issues in satellite communications have been increasing rapidly due to the broadcasting nature and inherent openness with the vast coverage [3] [4]. Moreover, with the growing demands for broadband applications and services, the available frequency resources have become scarce because of the dedicated frequency allocation of the standardized wireless systems [5]. To tackle these issues, researchers have introduced cooperation into satellite terrestrial network based on the cognitive radio concept, referred to as cognitive satellite terrestrial network (CSTN) [6]. Specifically, the physical layer security technique is adopted to utilize the interference from the terrestrial network as a green source to enhance the secure satellite communication, provided that these two networks share the spectrum [7].

In the realm of CSTN, the authors in [8] proposed a robust beamforming framework for CSTN where the terrestrial base station (BS) serving as a green interference resource to enhance the security of the satellite link. In [9], the authors proposed a joint beamforming scheme for CSTN with software-defined architecture to minimize the total transmit power while guaranteeing both the secrecy rate of the satellite network and the quality of the service of the terrestrial network. For a CSTN multicasting communication system, the authors in [10] jointly optimized the beamforming vectors of the satellite and the BS to minimize the total transmit power. Considering the energy-constrained characteristic of the satellite network, the authors in [11] studied a joint beamforming scheme to maximize the secure energy efficiency of the primary satellite network while satisfying the transmission requirements of both satellite and terrestrial users. To further enhance the secure transmission of the satellite network, the artificial noise (AN) was adopted at BS to confuse eavesdroppers (Eves) in [12] and [13]. Specifically, in [12], the authors jointly optimized the cooperative beamforming and AN to minimize the transmit power of information signal under the secrecy rate and information rate constraints of satellite and terrestrial users, respectively. Extending [12] to a more practical scenario with multi-cell terrestrial networks and multi-Eve, the authors in [13] investigated a joint beamforming and AN scheme to minimize the total transmit power of the satellite and BSs. The aforementioned works all assume that the primary satellite network and the secondary terrestrial network are naturally willing to cooperate with each other. Under this assumption, these two networks aim to maximize the performance of the entire CSTN system during cooperation regardless of their own performance. However, as we know that the satellite and terrestrial networks of the CSTN generally belong to different authorities in practice. In such a scenario, these two networks always have their own interests and will not cooperate if their own benefits are impaired. Thus, how to incentivize the satellite and terrestrial networks to participate in cooperation becomes a challenging issue.

To this end, we propose a Stackelberg game based secure transmission strategy for CSTN to motivate the satellite and terrestrial networks in participation of cooperation, where the channel state information (CSI) of the Eve is imperfect. In the considered CSTN, the primary satellite network acting as the leader recruits the secondary terrestrial node as a cooperative jammer to enhance its secure communication. In return, the secondary terrestrial node acting as the follower is compensated by a fraction of spectrum access time to achieve its own transmission. Specifically, for the satellite network, we

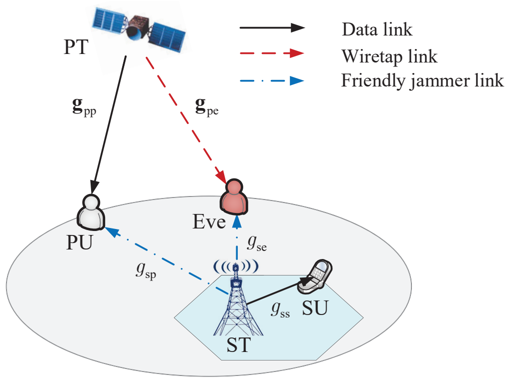

Fig. 1. System model of the considered CSTN.

formulate the utility function as the secrecy rate assisted by the terrestrial node. For the terrestrial network, we formulate the utility function as its obtained transmission rate discounted by the cost of total transmission energy. Then we adopt the backward induction method to derive the Stackelberg equilibrium (SE), from which the optimal time fraction and power allocation strategies are obtained for satellite and terrestrial networks, respectively. Finally, simulation results are presented to validate our theoretical analysis.

The remainder of the paper is organized as follows. Section II introduces the system model. Section III models and analyzes the Stackelberg game based secure transmission strategy. The performance of the proposed secure transmission strategy through numerical simulations is presented in section IV. Finally, conclusions are made in section V.

II. System Model

As illustrated in Fig. 1, we consider a downlink CSTN, where the satellite regarded as the primary transmitter (PT) communicates with the primary user (PU) in the presence of an Eve attempting to overhear its messages. Herein, the secondary transmitter (ST) can be recruited as a cooperative jammer to safeguard secure satellite communication. In return, the ST obtains the spectrum access opportunity to transmit data to the intended secondary user (SU). It is assumed that the PT is equipped with N_{S} antennas and all other nodes are equipped with a single antenna[1].

A. Channel Model

We suppose that the satellite links $\mathbf{g}_{\mathrm{p}i}$ for $i \in \{\mathrm{p}, \mathrm{e}\}$ undergo widely-adopted Shadowed-Rician (SR) fading [10], which can be expressed as

$$\mathbf{g}_{\mathrm{p}i}=\sqrt{L_{\mathrm{p}i}}\mathbf{h}_{\mathrm{p}i}, \tag{1}$$

where $L_{\mathrm{p}i}$ represents the propagation loss, including the effects of path loss and the satellite beam pattern, which is written as

$$L_{\mathrm{p}i} = C_{\mathrm{p}i} b\left(\varphi_{\mathrm{p}i}\right), \tag{2}$$

where $C_{\mathrm{p}i}$ denotes the path loss of the PT $\to$ receiver-i link. $b\left(\varphi_{\mathrm{p}i}\right)$ denotes the satellite beam pattern at receiver-i and can be calculated as

$$b(\varphi_{\mathrm{p}i})=b_{\max}\left(\frac{J_1(u_{\mathrm{p}i})}{2u_{\mathrm{p}i}}+36\frac{J_3(u_{\mathrm{p}i})}{u_{\mathrm{p}i}^3}\right)^2, u_{\mathrm{p}i}=2.07123\frac{\sin\varphi_{\mathrm{p}i}}{\sin\varphi_{3\mathrm{dB}}}, \tag{3}$$

where $b_{\max}$ is the maximum satellite antenna gain, $\varphi_{\mathrm{p}i}$ is the angle between the beam center and the receiver-i, and $\varphi_{3\mathrm{dB}}$ is the 3-dB angle. $J_1\left(\cdot\right)$ and $J_3\left(\cdot\right)$ represent the first-kind Bessel function of order 1 and 3, respectively. Moreover, the satellite channel fading term $\mathbf{h}_{\mathrm{p}i}$ can be described as

$$\mathbf{h}_{\mathrm{p}i} = A\exp\left(j\boldsymbol{\psi}_{\mathbf{p}i}\right) + Z\exp\left(j\boldsymbol{\phi}_{\mathbf{p}i}\right), \tag{4}$$

where $\boldsymbol{\psi}_{\mathbf{p}i} \in [0, 2\pi)$ denotes the stationary random phase and $\boldsymbol{\phi}_{\mathbf{p}i} \in [0, 2\pi)$ denotes the deterministic phase of the line-of-sight (LOS) component. In addition, A and Z are the amplitudes of the scattering and the LOS components, which are independent stationary random processes following Rayleigh and Nakagami-m distributions, respectively. Similar to [3], the SR fading distribution can be characterized with parameters (Ω, b, m), where Ω denotes the average power of the LOS component, $2b$ denotes the average power of the multipath component, and m is the Nakagami-m parameter corresponding to the fading severity.

Furthermore, let the terrestrial links $g_{\mathrm{s}j}$ for $j \in \{\mathrm{e}, \mathrm{s}\}$ experience Nakagami-m fading, which can be given as

$$g_{\mathrm{s}j} = \sqrt{L_{\mathrm{s}j}}h_{\mathrm{s}j}, \tag{5}$$

where $L_{\mathrm{s}j}$ represents the path loss of the ST $\to$ receiver-j link and $h_{\mathrm{s}j} \sim$ Nakagami $\left(m_{\mathrm{s}j}, \Omega_{\mathrm{s}j}\right)$ with $m_{\mathrm{s}j}$ and $\Omega_{\mathrm{s}j}$ being the shape and scale parameters, respectively.

B. Signal Model

In our proposed system, the PT is willing to preserve a fraction $0 < \alpha \leq 1$ of the transmission time slot T for its own secure communication assisted by cooperative jamming from the ST, and compensate the remaining fraction $(1-\alpha)T$ for the secondary transmission. Thus, the whole transmission is divided into two phases as follows.

Phase I: During the first phase αT, the PT transmits its confidential signals to the intended PU, which are illegally overheard by the Eve. To enhance secure satellite communication, the ST acting as a cooperative jammer transmits the AN to interfere with the Eve. It is assumed that an apriori knowledge of the transmitted AN can be obtained by the PU[2]. Thus, after removing the AN, the received signal at the PU is given as

$$y_{\mathrm{p}} = \sqrt{P_{\mathrm{p}}}\mathbf{g}_{\mathrm{pp}}^H\mathbf{w}x_{\mathrm{p}} + n_{\mathrm{p}}, \tag{6}$$

where x_{p} is the transmitted signal by the PT, $\mathbf{g}_{\mathrm{pp}} \in \mathbb{C}^{N_{\mathrm{S}}\times 1}$ is the channel coefficient of the PT $\to$ PU link, and $\mathbf{w} \in \mathbb{C}^{N_{\mathrm{S}}\times 1}$ is the beamforming vector of the PT. P_{p} is the transmit power at the PT and $n_{\mathrm{p}} \sim \mathcal{CN}\left(0, \sigma_{\mathrm{p}}^2\right)$ is the noise at the PU. Note that we mainly focus on optimizing the fraction of transmission time slot at the PT, which determines the jamming

[1]We mainly focus on designing a Stackelberg game to incentivize the cooperation between the PT and the ST, hence a simple scenario with a single antenna assumption at the ST is considered for simplicity of analysis.

[2]One practical solution is that the ST and the PU adopt the same pseudo-random generator with finite states, and only the state needs to be sent to the PU via a secure control channel. This can be implemented with a small amount of overhead [14].

power provided by the ST. Hence, we adopt the maximum ratio transmission beamforming at the PT to realize spatial multiplexing with low computation complexity. Meanwhile, the received signal at the Eve can be written as

$$y_{\rm e} = \sqrt{P_{\rm p}}\mathbf{g}_{\rm pe}^H\mathbf{w}x_{\rm p} + \sqrt{P_{\rm J}}g_{\rm se}z + n_{\rm e}, \tag{7}$$

where z is the AN transmitted by the ST. $\mathbf{g}_{\rm pe} \in \mathbb{C}^{N_{\rm S}\times 1}$ and $g_{\rm se}$ are the channel coefficients of the PT $\rightarrow$ Eve and ST $\rightarrow$ Eve links, respectively. $P_{\rm J}$ is the jamming power at the ST and $n_{\rm e} \sim \mathcal{CN}\left(0,\sigma_{\rm e}^2\right)$ is the noise at the Eve. **Phase II**: To compensate the cooperative jamming, the ST is rewarded to conduct its own transmission during the second phase $(1-\alpha)T$, and the received signal at the SU is

$$y_{\rm s} = \sqrt{P_{\rm s}}g_{\rm ss}x_{\rm s} + n_{\rm s}, \tag{8}$$

where $x_{\rm s}$ is the transmitted signal by the ST and $g_{\rm ss}$ is the channel coefficient of the ST $\rightarrow$ SU link. $P_{\rm s}$ is the transmit power at the ST and $n_{\rm s} \sim \mathcal{CN}\left(0,\sigma_{\rm s}^2\right)$ is the noise at the SU.

Based on the above model, the secrecy rate of the PU assisted by the ST in the first phase αT can be given by

$$R_{\rm P\,sec}\left(\alpha, P_{\rm J}\right) = \alpha T[R_{\rm P} - R_{\rm E}\left(P_{\rm J}\right)]^+, \tag{9}$$

where $[x]^+ = \max\{x, 0\}$. $R_{\rm P}$ and $R_{\rm E}\left(P_{\rm J}\right)$ denote the information rates at the PU and the Eve, respectively, i.e.,

$$\left\{\begin{array}{l} R_{\rm P} = \log_2\left(1 + \frac{P_{\rm p}\left|\mathbf{g}_{\rm pp}^H\mathbf{w}\right|^2}{\sigma_{\rm p}^2}\right), \\ R_{\rm E}\left(P_{\rm J}\right) = \log_2\left(1 + \frac{P_{\rm p}\left|\mathbf{g}_{\rm pe}^H\mathbf{w}\right|^2}{P_{\rm J}\left|g_{\rm se}\right|^2 + \sigma_{\rm e}^2}\right). \end{array}\right. \tag{10}$$

Note that since the location information of the Eve is uncertain, it is difficult for the PT and the ST to obtain accurate CSI of the Eve in practical scenarios. Thus, similar to [15], we assume that only imperfect CSI for PT $\rightarrow$ Eve and ST $\rightarrow$ Eve links is available, which can be modeled as

$$\tilde{\mathbf{g}}_{\rm pe} = \sqrt{L_{\rm pe}}\left(\mathbf{h}_{\rm pe} + \Delta\mathbf{h}_{\rm pe}\right), \tilde{g}_{\rm se} = \sqrt{L_{\rm se}}\left(h_{\rm se} + \Delta h_{\rm se}\right), \tag{11}$$

where $\Delta\mathbf{h}_{\rm pe}$ and $\Delta h_{\rm se}$ denote the channel estimate uncertainties of these two links, respectively. Herein, $\|\Delta\mathbf{h}_{\rm pe}\|_2 \le \varepsilon_{\rm p}$ and $\|\Delta h_{\rm se}\| \le \varepsilon_{\rm s}$ with $\varepsilon_{\rm p}$ and $\varepsilon_{\rm s}$ being non-negative bounds. To guarantee the secrecy performance, in this work we focus on the worst case, i.e., $\Delta\mathbf{h}_{\rm pe} = \varepsilon_{\rm p}\mathbf{I}_{N_{\rm S}}$ and $\Delta h_{\rm se} = -\varepsilon_{\rm s}$. By substituting (11) into (10), the secrecy rate of the PU can be reformulated as $\tilde{R}_{\rm P\,sec}\left(\alpha, P_{\rm J}\right) = \alpha\left[R_{\rm P} - \tilde{R}_{\rm E}\left(P_{\rm J}\right)\right]^+$.

Furthermore, the obtained transmission rate of the SU during the second phase $(1-\alpha)T$ can be expressed as

$$R_{\rm S}\left(P_{\rm s}, \alpha\right) = (1-\alpha)T\log_2\left(1 + \frac{P_{\rm s}\left|g_{\rm ss}\right|^2}{\sigma_{\rm s}^2}\right). \tag{12}$$

III. Stackelberg Game Formulation and Analysis

In this paper, both the primary satellite network and the secondary terrestrial network of the CSTN are considered as rational and selfish entities making decisions independently to maximize their own utilities. Moreover, the primary satellite as spectrum owner always has the first priority, while the secondary terrestrial network tries to maximize its benefit given the existence of the primary network. In such a hierarchical scenario, the Stackelberg game provides an appropriate framework to analyze the interactions between these two networks [16]. Specifically, the PT termed as the game leader firstly determines the time fraction αT preserved for its secret communication, and the ST termed as the follower then decides the amount of cooperative jamming power $P_{\rm J}$ allocated to the PU.

Under the Stackelberg game, the PT aims to maximize its secrecy rate assisted by cooperative jamming from the ST, hence the utility of the PT can be formulated as

Original leader problem:

$$\max_{\alpha} \quad U_{\rm P}\left(\alpha, P_{\rm J}\right) = \tilde{R}_{\rm P\,sec}\left(\alpha, P_{\rm J}\right), \tag{13-a}$$

$$\text{s.t.} \quad 0 < \alpha \le 1, \tag{13-b}$$

$$\tilde{R}_{\rm P\,sec}\left(\alpha, P_{\rm J}\right) \ge \tilde{R}_{\rm P\,sec}^0, \tag{13-c}$$

where the constraint (13-c) represents that the secrecy rate of the PU with the ST's cooperation should be no worse than that without cooperation, i.e., $\tilde{R}_{\rm p\,sec}^0$, which is calculated as $\tilde{R}_{\rm p\,sec}^0 = T\left[R_{\rm P} - \tilde{R}_{\rm E}^0\right]^+$ with $\tilde{R}_{\rm E}^0 = \log_2\left(1 + \frac{P_{\rm p}\left|\tilde{\mathbf{g}}_{\rm pe}^H\mathbf{w}\right|^2}{\sigma_{\rm e}^2}\right)$.

On the other hand, the utility of the ST is defined as its achievable transmission rate during the rewarding fraction $(1-\alpha)T$ priced by the cost of the overall consumed transmission energy, that is,

Original follower problem:

$$\max_{P_{\rm J}} \quad U_{\rm S}\left(P_{\rm J}, P_{\rm s}, \alpha\right)$$

$$= R_{\rm S}\left(P_{\rm s}, \alpha\right) - C_1\alpha TP_{\rm J} - C_2(1-\alpha)TP_{\rm s}, \tag{14-a}$$

$$\text{s.t.} \quad \alpha TP_{\rm J} + (1-\alpha)TP_{\rm s} \le TP_{\rm s}^{\max}, \tag{14-b}$$

where C_1 and C_2 denote the cost per unit jamming and transmit power of the ST, respectively. Besides, $P_{\rm s}{}^{\max}$ of the energy constraint (14-b) denotes the maximum power available at the ST. Herein, we assume that the self-interested ST will exhaust available energy to improve its transmission rate resulting in $\alpha TP_{\rm J} + (1-\alpha)TP_{\rm s} = TP_{\rm s}^{\max}$.

Therefore, by substituting $P_{\rm J} = [P_{\rm s}^{\max} - (1-\alpha)P_{\rm s}]/\alpha$ into (13) and (14), we can reformulate the *Original leader problem* and *Original follower problem*, respectively as

Leader problem:

$$\max_{\alpha} \quad U_{\rm P}\left(\alpha, P_{\rm s}\right) = \tilde{R}_{\rm P\,sec}\left(\alpha, P_{\rm s}\right), \tag{15-a}$$

$$\text{s.t.} \quad (13-b), \tag{15-b}$$

$$\tilde{R}_{\rm P\,sec}\left(\alpha, P_{\rm s}\right) \ge \tilde{R}_{\rm P\,sec}^0, \tag{15-c}$$

and

Follower problem:

$$\max_{P_{\rm s}} \; U_{\rm S}(P_{\rm s}, \alpha) = R_{\rm S}(P_{\rm s}, \alpha) - \Delta C(1-\alpha)TP_{\rm s} - C_1TP_{\rm s}^{\max}, \tag{16}$$

where $\Delta C = C_2 - C_1$. Notice that the first part of (16) reflects the ST's satisfaction of accessing the spectrum, in terms of transmission rate it can achieve, while the remaining part stands for its expense, in terms of energy required to achieve this satisfaction.

Generally, the solution of such a Stackelberg game is the SE from which neither the leader (PT) nor the follower (ST) has an incentive to unilaterally deviate. For the proposed game, the SE is defined as follows.

Definition 1. Let $P_{\rm s}^*$ be the optimal power allocation of *Follower problem* and α^* be the best time fraction of *Leader problem*. Then, the outcome $(P_{\rm s}^*, \alpha^*)$ is the SE for the proposed Stackelberg game if the following conditions are satisfied for any $(P_{\rm s}, \alpha)$:

$$\left\{ \begin{array}{l} U_{\rm S}\left(P_{\rm s}^*, \alpha^*\right) \geq U_{\rm S}\left(P_{\rm s}, \alpha^*\right), \\ U_{\rm P}\left(\alpha^*, P_{\rm s}^*\right) \geq U_{\rm p}\left(\alpha, P_{\rm s}^*\right). \end{array} \right. \tag{17}$$

Before deriving the SE, we firstly confirm the existence of equilibrium, for which we have the following proposition.

Proposition 1. *There exists SE for the proposed Stackelberg game.*

Proof. To prove the concavity of the ST's utility function, the second derivative of (16) with respective to $P_{\rm s}$ can be derived as

$$\frac{\partial^2 U_{\rm S}}{\partial^2 P_{\rm s}} = -\frac{(1-\alpha)\,T}{\ln 2}\left(\frac{|g_{\rm ss}|^2}{P_{\rm s}|g_{\rm ss}|^2 + \sigma_{\rm s}^2}\right)^2 < 0. \tag{18}$$

As seen in (18), $U_{\rm S}$ is strictly concave in terms of $P_{\rm s}$ for a given α.

Due to the concavity of $U_{\rm S}$, the optimal transmit power $P_{\rm s}^*$ is unique. According to [17], for a two-player Stackelberg game, the equilibrium exists if the best-response strategy set of the follower is a singleton. Since the uniqueness of the ST's optimal strategy has been proved, we can obtain the conclusion that there exists SE for the game. □

Based on the availability of SE, we can obtain the SE outcome by adopting the backward induction method [18]. Specifically, we firstly obtain the optimal power allocation of the ST and the best time fraction of the PT is then derived.

A. Analysis of the Optimal Power Allocation for the ST

Aware of the time fraction strategy selected by the PT, the ST optimizes its transmit power to maximize its utility. By solving the *Follower problem* in (16), we can obtain the optimal power policy for the ST with the following theorem:

Theorem 1. *Given the time fraction of the PT, the optimal power strategy of the ST denoted as $P_{\rm s}^*$ can be expressed as*

$$P_{\rm s}^* = \left\{ \begin{array}{l} \left[\hat{P}_{\rm s}\right]_{P_{\rm s1}}^{P_{\rm s2}}, |g_{\rm ss}|^2 > \ln 2\Delta C \sigma_{\rm s}^2 \text{ and } \alpha \leq \alpha_{\max}, \\ \\ \frac{P_{\rm s}^{\max}}{1-\alpha}, \text{otherwise}, \end{array} \right. \tag{19}$$

where $[x]_{x_{\min}}^{x_{\max}} = \min(\max(x_{\min}, x), x_{\max})$. $\hat{P}_{\rm s} = \frac{1}{|g_{\rm ss}|^2}\left(\frac{|g_{\rm ss}|^2}{\ln 2\Delta C} - \sigma_{\rm s}^2\right)$, $P_{\rm s1} = -\frac{1}{\ln 2\Delta C}\left[\mathcal{W}\left(-Ae^{\left(\frac{\ln 2 C_1 P_{\rm s}^{\max}}{1-\alpha} - A\right)}\right) + A\right]$, $P_{\rm s2} = -\frac{1}{\ln 2\Delta C}\left[\mathcal{W}_{-1}\left(-Ae^{\left(\frac{\ln 2 C_1 P_{\rm s}^{\max}}{1-\alpha} - A\right)}\right) + A\right]$ *with* $A = \ln 2\Delta C \frac{\sigma_{\rm s}^2}{|g_{\rm ss}|^2}$ *and $\mathcal{W}_l(x)$ is the branch of the multi-valued Lambert W function [19]. Moreover,* $\alpha_{\max} = 1 - \frac{C_1 P_{\rm s}^{\max}}{\log_2\left(1 + \hat{P}_{\rm s}\frac{|g_{\rm ss}|^2}{\sigma_{\rm s}^2}\right) - \Delta C \hat{P}_{\rm s}}$.

Proof. Considering the ST is a rational individual, the necessary condition that the ST is willing to cooperate with the PT is $U_{\rm S} \geq 0$. From the proof of **Proposition 1**, we can see $U_{\rm S}$ is concave with $P_{\rm s}$ and negative when $P_{\rm s} = 0$ and $P_{\rm s} \to \infty$. Thus, for such a function to have a positive value over a certain range of $P_{\rm s}$, the conditions: (i) $\partial U_{\rm S}/\partial P_{\rm s}|_{P_{\rm s}=0} > 0$ and (ii) $U_{\rm S} \geq 0$ when $\partial U_{\rm S}/\partial P_{\rm s} = 0$ must hold, i.e.,

$$|g_{\rm ss}|^2 > \ln 2\Delta C \sigma_{\rm s}^2 \text{ and } \alpha \leq \alpha_{\max}. \tag{20}$$

Under these conditions, we can firstly derive the solutions of $U_{\rm S} = 0$ as $P_{\rm s1}$ and $P_{\rm s2}$. Then, based on the concavity of $U_{\rm S}$, the optimal solution of $U_{\rm S}$, i.e., $\hat{P}_{\rm s}$ can be obtained by solving $\partial U_{\rm S}/\partial P_{\rm s} = 0$. Hence, the optimal power strategy of the ST can be obtained as $P_{\rm s}^* = \left[\hat{P}_{\rm s}\right]_{P_{\rm s1}}^{P_{\rm s2}}$ in this case.

Otherwise, if the conditions in (18) are not satisfied, the ST will preserve the whole energy for its own transmission instead of cooperating with the PT. In this situation, the optimal power strategy of the ST is $P_{\rm s}^* = \frac{P_{\rm s}^{\max}}{1-\alpha}$.

Accordingly, the optimal power strategy of the ST is given in (19). □

B. Analysis of the Best Time Fraction for the PT

Knowing the best response of the ST, the PT as the game leader determines the best time fraction α^* to maximize its secrecy rate. Therefore, by substituting the results in (19) to the *Leader problem* in (15), we obtain

$$\max_{\alpha} \quad U_{\rm p}\left(\alpha, P_{\rm s}^*\right) = \tilde{R}_{\rm P\,sec}\left(\alpha, P_{\rm s}^*\right), \tag{21-a}$$

$$\text{s.t.} \quad (15-b), (15-c), \tag{21-b}$$

where the constraint (15-c) can be equivalently transformed into $\alpha \geq \alpha_{\min}$ with $\alpha_{\min} = \tilde{R}_{\rm P\,sec}^0 \Big/ \left(R_{\rm P} - \tilde{R}_{\rm E}\left(P_{\rm s}^*\right)\right)$. Then, (21) can be rewritten as

$$\max_{\alpha} \quad U_{\rm p}\left(\alpha, P_{\rm s}^*\right) = \tilde{R}_{\rm P\,sec}\left(\alpha, P_{\rm s}^*\right), \tag{22-a}$$

$$\text{s.t.} \quad \alpha \in \Omega_{\rm P}\left(\alpha\right), \tag{22-b}$$

where $\Omega_{\rm P}(\alpha)$ is the feasible strategy set of the PT, which is defined as

$$\Omega_{\rm P}\left(\alpha\right) = \left\{\alpha \left| \alpha \in \left\{ \begin{array}{l} \alpha_{\min} < \alpha \leq \alpha_{\max}, \alpha_{\min} \leq \alpha_{\max} \\ \{1\}, \alpha_{\min} > \alpha_{\max} \end{array} \right. \right.\right\}. \tag{23}$$

Note that if $\alpha_{\min} > \alpha_{\max}$, the PT and the ST cannot benefit from the cooperation simultaneously so that the PT will choose the strategy $\alpha = 1$ to reject cooperating with the ST. Based on the above analysis, we can conclude that the best time fraction of the PT is

$$\alpha^* = \arg\max U_{\rm p}\left(\alpha, P_{\rm s}^*\right), \tag{24}$$

which can be efficiently calculated by numerical methods such as bi-directional search.

Following the above backward induction procedure, we can obtain the SE of the proposed Stackelberg game, i.e., $(P_{\rm s}^*, \alpha^*)$ according to (19) and (24).

IV. Results and Analysis

In this section, numerical simulations are conducted to validate our theoretical results. In the simulations, we consider the CSTN with a low earth orbit satellite, of which the direct link distance is assumed to be $d = 1000$ Km. There are three different shadowing experienced by the satellite links $\mathbf{h}_{{\rm p}i}$

TABLE I
SYSTEM PARAMETERS

Frequency f_c	2 GHz (L/S band)
Number of antennas at the PT N_{S}	2
Maximal satellite antenna gain $b_{\max}$	17 dBi
Beam angle of PT$\rightarrow$PU link φ_{pp}	0.2°
3-dB angle $\varphi_{3\mathrm{dB}}$	0.4°
Transmit power of the PT P_{p}	10 W
Noise power σ^2	-114 dBm
Satellite link path loss model [21]	$92.45 + 20\lg f_c$ $+20\lg d(\mathrm{Km})$
Terrestrial link path loss model [21]	$128.1 + 37.6\lg d(\mathrm{Km})$

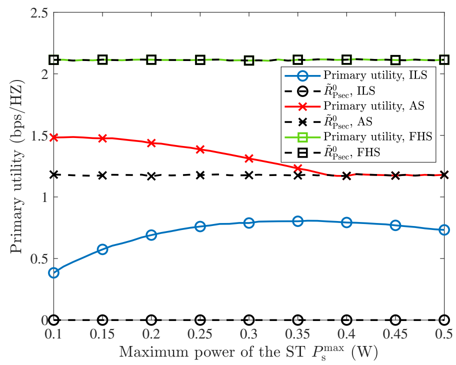

Fig. 2. Primary utility with respect to the maximum power of the ST $P_{\mathrm{s}}^{\max}$ ($\varphi_{\mathrm{pe}} = 0.4^{\circ}$).

for $i \in \{\mathrm{p}, \mathrm{e}\}$, including infrequent light shadowing (ILS) with $(\Omega, b, m) = (1.29, 0.875, 10)$, average shadowing (AS) with $(\Omega, b, m) = (0.279, 0.251, 5)$, and frequent heavy shadowing (FHS) with $(\Omega, b, m) = \left(8.97 \times 10^{-4}, 0.063, 2\right)$ [20]. Specifically, the satellite link $\mathbf{h}_{\mathrm{pp}}$ experiences AS shadowing while the wiretap link $\mathbf{h}_{\mathrm{pe}}$ is assumed to experience the above three shadowing, respectively. The duration of the transmission time slot is assumed to be $T = 1$. The bounds of channel uncertainties are set as $\varepsilon_{\mathrm{p}} = \varepsilon_{\mathrm{s}} = 0.1$. Furthermore, the values of C_1 and C_2 are set as 3 and 6 [bps/Hz/W], respectively. The other system parameters are provided in Table I.

We firstly analyze the primary and secondary utilities with respect to the maximum power of the ST $P_{\mathrm{s}}^{\max}$ for various shadowing scenarios in Fig. 2 and Fig. 3, respectively. In these two figures, we can observe that the primary utility and the corresponding secondary utility arrive at the turning points simultaneously, illustrating that the cooperative situation between the PT and the ST changes as $P_{\mathrm{s}}^{\max}$ increases. As depicted in Fig. 2, the $\tilde{R}^0_{\mathrm{P\,sec}}$ curve, which is plotted as a benchmark for the primary utility, increases when the shadowing experienced by the Eve becomes severer. Besides, the primary utility increases firstly and then decreases with the increase of $P_{\mathrm{s}}^{\max}$ in the ILS scenario. This is because that for a smaller $P_{\mathrm{s}}^{\max}$, the primary utility is dominated by the cooperative jamming power, which is positively associated with $P_{\mathrm{s}}^{\max}$. As $P_{\mathrm{s}}^{\max}$ increases, the primary utility will be dominated by the allocated time fraction, which is negatively associated with $P_{\mathrm{s}}^{\max}$ since more time fraction $(1-\alpha)$ needs to be compensated for secondary transmission. For the AS scenario, the primary utility decreases firstly and then remains

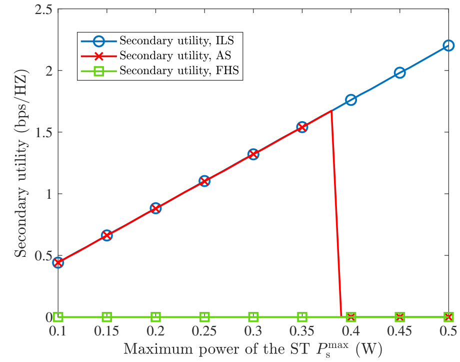

Fig. 3. Secondary utility with respect to the maximum power of the ST $P_{\mathrm{s}}^{\max}$ ($\varphi_{\mathrm{pe}} = 0.4^{\circ}$).

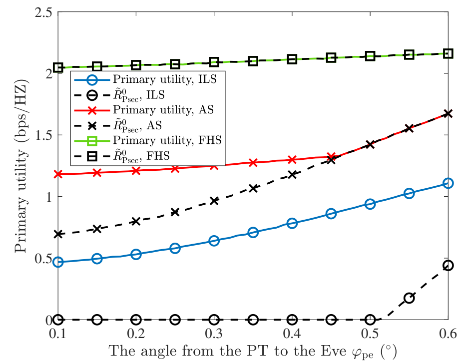

Fig. 4. Primary utility versus the angle from the PT to the Eve φ_{pe} ($P_{\mathrm{s}}^{\max} = 0.3$ W).

at $\tilde{R}^0_{\mathrm{P\,sec}}$ with the increase of $P_{\mathrm{s}}^{\max}$. The reason is that the primary utility is dominated by the allocated time fraction when $\tilde{R}^0_{\mathrm{P\,sec}}$ increases. Furthermore, as $P_{\mathrm{s}}^{\max}$ continues to increase, the PT cannot allocate enough time fraction to guarantee both its secrecy rate and the non-negative secondary utility. In this case, the PT will not cooperate with the ST so that the primary utility degrades to $\tilde{R}^0_{\mathrm{P\,sec}}$. While for the FHS scenario, the PT is always unwilling to cooperate with the ST due to the high $\tilde{R}^0_{\mathrm{P\,sec}}$, resulting in that the primary utility remains at $\tilde{R}^0_{\mathrm{P\,sec}}$. Moreover, Fig. 3 shows that as $P_{\mathrm{s}}^{\max}$ increases, the secondary utility increases in the ILS scenario because of the increased time fraction $(1-\alpha)$ obtained from cooperation. For the AS scenario, the secondary utility increases firstly and then turns to zero owing to the failure of cooperation caused by the increasing $P_{\mathrm{s}}^{\max}$. Besides, the secondary utility remains at zero in the FHS scenario since the PT rejects cooperating with the ST.

Considering that the quality of the wiretap link is one of the most important factors for the secrecy rate performance, we evaluate the primary and secondary utilities versus the angle from the PT to the Eve φ_{pe} in Fig. 4 and Fig. 5, respectively. For Fig. 4, we can see that the $\tilde{R}^0_{\mathrm{P\,sec}}$ curve in the AS scenario increases with the increase of φ_{pe} since the quality of the wiretap link is getting worse. However, for the ILS and FHS scenarios, the impact of φ_{pe} can almost be ignored due to the light and heavy shadowing experienced by the wiretap link,

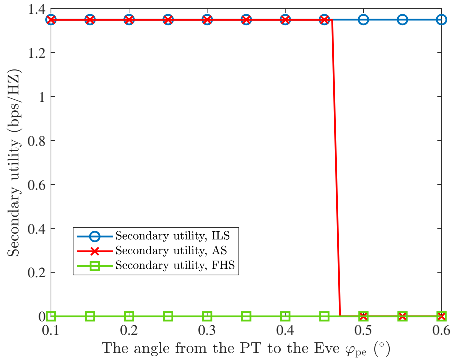

Fig. 5. Secondary utility versus the angle from the PT to the Eve φ_{pe} ($P_{\mathrm{s}}^{\max} = 0.3$ W).

respectively. Hence, the $\tilde{R}_{\mathrm{P\,sec}}^{0}$ curve only slightly increases when φ_{pe} is large in the ILS scenario and remains almost constant in the FHS scenario. Moreover, the primary utility is larger than $\tilde{R}_{\mathrm{P\,sec}}^{0}$ in the ILS scenario due to the cooperative jamming assisted by the ST. Although the optimal power and time fraction strategies determined by (19) and (24) are fixed, the beamforming gain at Eve decreases as φ_{pe} increases resulting in the increase of the primary utility. On the contrary, the primary utility remains at $\tilde{R}_{\mathrm{P\,sec}}^{0}$ in the FHS scenario, demonstrating that the PT is unwilling to cooperate with the ST due to the high $\tilde{R}_{\mathrm{P\,sec}}^{0}$. For the AS scenario, the primary utility firstly increases slightly (greater than $\tilde{R}_{\mathrm{P\,sec}}^{0}$) and then turns to $\tilde{R}_{\mathrm{P\,sec}}^{0}$ with the increase of φ_{pe}. This is because that as φ_{pe} increases, the secrecy rate assisted by the ST will be worse than $\tilde{R}_{\mathrm{P\,sec}}^{0}$ so that the PT will reject the cooperation. For Fig. 5, we can observe that for the ILS and FHS scenarios, the secondary utility remains at a positive constant and zero, respectively. This phenomenon indicates that the PT is always willing and unwilling to cooperate with the ST in these two scenarios, respectively. Additionally, for the AS scenario, the secondary utility remains at a positive constant and then turns to zero with the increase of φ_{pe}. This is due to the failure of the cooperation when $\tilde{R}_{\mathrm{P\,sec}}^{0}$ increases to a certain degree.

V. Conclusions

In this paper, we have proposed a Stackelberg game based secure transmission strategy for a CSTN under imperfect CSI. In the considered CSTN, the primary satellite network termed as the leader recruits the secondary terrestrial node as a cooperative jammer to realize secure satellite transmission. In return, the secondary terrestrial node termed as the follower is compensated by spectrum access time to achieve its own transmission. Specifically, we have designed the utility function based on the secrecy rate assisted by the ST for the satellite network. For the terrestrial network, we have designed the utility function based on its obtained transmission rate discounted by the cost of total consumed energy. Then, we have derived the optimal strategies for these two networks to maximize their respective utilities by exploiting the Stackelberg equilibrium. Finally, we have conducted numerical simulations to validate our theoretical analysis.

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