Green Interference Based Symbiotic Security in Integrated Satellite-Terrestrial Communications

Zhisheng Yin, Member, IEEE, Nan Cheng, Member, IEEE, Tom H. Luan, Senior Member, IEEE, Yilong Hui, Member, IEEE, and Wei Wang, Member, IEEE

Abstract—In this paper, we investigate secure transmissions in integrated satellite-terrestrial communications and the green interference based symbiotic security scheme is proposed. Particularly, the co-channel interference induced by the spectrum sharing between satellite and terrestrial networks and the inter-beam interference due to frequency reuse among satellite multibeam serve as the green interference to assist the symbiotic secure transmission, where the secure transmissions of both satellite and terrestrial links are guaranteed simultaneously. Specifically, to realize the symbiotic security, we formulate a problem to maximize the sum secrecy rate of satellite users by cooperatively beamforming optimizing and a constraint of secrecy rate of each terrestrial user is guaranteed. Since the formulated problem is non-convex and intractable, the Taylor expansion and semi-definite relaxation (SDR) are adopted to further reformulate this problem, and the successive convex approximation (SCA) algorithm is designed to solve it. Finally, the tightness of the relaxation is proved. In addition, numerical results verify the efficiency of our proposed approach.

Index Terms—Satellite-terrestrial, green interference, symbiotic security, secrecy rate.

I. INTRODUCTION

In the emerging 6G, integrated satellite-terrestrial networks can provide a Scenario of Internet access with expanded coverage and seamless connectivity [1], [2]. The use cases of integrated satellite-terrestrial networks have attracted a lot of attention in applications such as Internet-of-things (IoT), vehicle-to-everything (V2X), holographic communications, etc [3]–[6]. With the increasing number of connective devices and abundant service requirements, the spectrum resource of space information networks is increasingly scarce [7]. To address this issue, the spectrum sharing within satellite-terrestrial networks and frequency reuse among multiple beams of satellite are widely adopted to improve the spectrum utilization [8]. However, the co-channel/inter-beam interference caused by the spectrum sharing and frequency reuse degrades the overall communication performance [9]–[11], and the security vulnerability is opportunistic to penetrate crossing satellite and terrestrial networks [12], [13]. Particularly, due to the openness of wireless channels and the broad broadcasting coverage, the integrated satellite-terrestrial communications are vulnerable to eavesdropping threats and the very large and complex geographical areas give harbour to attackers and eavesdroppers (Eves), which results in serious security issues.

To combat the eavesdropping threats, physical layer security has been widely investigated in conventional wireless communications and also actively explored in satellite and aerial networks recently. As a supplement of cryptography protocol in the upper layer, physical layer security approaches are aimed to ensure secrecy capacity by exploiting the randomness difference of wireless channels [14]. Particularly, several related works of physical layer security in satellite-terrestrial communications have been reported. To achieve the secure transmissions of satellite communications, additional communication facilities generally work as an assistance to enhance the main channel capacity or degrade the eavesdropping channel capacity. By exploiting terrestrial base stations (BSs) to serve as cooperative relays of satellite communications, an opportunistic user-relay selection criteria is proposed to improve the secrecy performance in hybrid satellite-terrestrial relay networks [12]. An unmanned aerial vehicle (UAV) relay and an aerial Eve are particularly considered in hybrid satellite-terrestrial networks, a 3D mobile UAV relaying strategy is designed and the secrecy capacity of satellite-terrestrial communications is analyzed in [15]. A multi-user cooperation scheme is proposed to improve the secrecy rate of satellite communications, where the inter-user-interference serves as the green interference to degrade the Eves [13]. In addition, the mutual interference between satellite and terrestrial networks generally degrades the system performance [4], however the green interference from terrestrial network can be designed by beamforming (BF) optimization to minimize the total transmission power while guaranteeing the secrecy rate constraint of satellite users and the common quality of service of terrestrial users [16]. However, aforementioned
related works in satellite-terrestrial networks only consider the security of satellite or terrestrial link independently and generally external resources are consumed to assist with the concerned secure link.

In this paper, we consider the downlink secure transmission in integrated satellite-terrestrial networks as shown in Fig. 1, where the multi-beam satellite shares spectrum resource with terrestrial networks and the full frequency reuse is considered among multi-beam. Specifically, a BS coexists in each satellite beam and an Eve is considered to wiretap the satellite and terrestrial link simultaneously. Particularly, the channel similarity between satellite links and limited resource at satellite challenges the implementation of physical layer security in integrated satellite-terrestrial communications. To address this issue and hold the security requirement of terrestrial segment, we conduct a work to guarantee secure transmissions in both satellite and terrestrial communications in this paper and the satellite-terrestrial symbiotic security is realized. The main contributions of this paper are as follows.

- A framework of satellite-terrestrial symbiotic secure transmission is first proposed, where the green interference from the internal system without additional assistance is considered to implement the symbiotic security, where the co-channel interference caused by the spectrum sharing within satellite-terrestrial networks and the inter-beam interference due to frequency reuse among satellite beams serve as the green interference. By carefully designing such green interference with BF optimization to confuse the wiretap channel, both satellite and terrestrial links can benefit from each other in achieving the secure transmission. Due to the inherent green interference in integrated satellite-terrestrial communications, the symbiotic security can be realized without consuming external resources.

- To realize the symbiotic security, we formulate a problem to maximize the sum secrecy rate of satellite users (SUs) in multiple beams by jointly optimizing BFs of satellite and all BSs, and meanwhile a predefined secrecy rate of terrestrial user (TU) in each beam is ensured. To solve this intractable non-convex problem, the Taylor expansion and semi-definite relaxation (SDR) are first adopted to reformulate this problem with constructing convex approximations, and secondly a successive convex approximation (SCA) algorithm is conduct to solve it.

- To prove the tightness of relaxation, we introduce an equivalent power minimization problem and by which the rank-one constraints of BF vectors of satellite and BSs are proved. In addition, we develop a reference benchmark which jointly optimizes satellite BF and the power allocation of BSs, where the BS can utilize partial power to create artificial noise (AN) for confusing Eve. Finally, simulations are carried out to verify the efficiency of our proposed approach.

The reminder of this work is organized as follows. In Section III, the system model of symbiotic secure transmission in integrated satellite-terrestrial downlink communications is presented and we formulate the problem to maximize the sum secrecy rate of SUs with constrained secrecy rate of TUs. Then a series of reformations and a cooperative BF optimization are conduct to solve this non-convex problem in Section IV. In Section V, for the reference propose, the joint optimization approach of the satellite BF and the power allocation of BSs is given, and simulation results are carried out to evaluate the secrecy performance of our proposed approaches. Finally, this paper is concluded in Section VI.

II. RELATED WORKS

By utilizing multi-antenna technology, spatial modulation based physical layer security approaches can be summarized as precoding, friendly jamming, and transmitting selection [17]–[19]. In terrestrial networks, abundant channel uncertainties can be utilized to distinguish with the main and wiretap channels, and recently intelligent reflecting surface (IRS) is introduced to enhance the physical layer security recently [20], [21]. Particularly, secure BF schemes in multiple-input–single-output (MISO) and multiple-input–multiple-output (MIMO) systems are widely investigated [22]–[24], and artificial noise (AN) aided secure BF approach is also generally adopted to confuse Eves [25], [26]. In addition, non-orthogonal multiple access (NOMA) based physical layer security approaches have also attracted some attentions [27], [28].

Whereas for satellite communications, a two-way physical layer security protocol is proposed in optical links and the random nature of Poisson channel is exploited to ensure secret communications [29], where a nano-satellite is particularly considered as the Eve in the uplink. A threshold-based user scheduling scheme is proposed to address a case of multiple eavesdroppers [30]. By jamming from satellite and full-duplex receiver, a joint BF and power allocation scheme is proposed to ensure the secrecy outage probability of multi-beam satellite communications [31]. Particularly, a comprehensive survey on physical layer security in satellite communications is conducted in [32]. However, the inherent difference between
satellite and terrestrial communications has not been clearly pointed out when executing physical layer security respectively. Few works highlight the resource limitation at satellite and the distinctive channel characteristic of satellite channels, i.e., channel similarity [18], [19], [33], [34].

Considering a coexistence of satellite and terrestrial networks, current investigations show that either the secure transmission of satellite communication or terrestrial communications is considered. To guarantee secure satellite communications, the signal-to-interference-plus-noise (SINR) of Eve for wiretapping satellite signals is decreased by terrestrial BS’s cooperative BF, and the SINR of legitimate satellite user is increased [35], where the quality of service (QoS) of terrestrial link is guaranteed. The BS provides interference resource to assist secure satellite link in cognitive satellite-terrestrial networks [37]. In addition, by exploiting the BS and a cooperative terminal as green communication in cognitive satellite-terrestrial communications [36]. A secrecy-energy efficiency is considered while constrains the cellular users’ rate requirements in a cognitive satellite-terrestrial network [37].

III. SYSTEM MODEL AND PROBLEM FORMULATION

We consider the downlink secure transmission in integrated satellite-terrestrial communications shown in Fig. 1, where a multi-beam satellite is assumed and a BS with terrestrial network exists in each beam. Full frequency reuse is adopted among satellite beams and the spectrum is shared with the BSs. Particularly, in each beam, we consider a legitimate satellite user (SU) and terrestrial user (TU) coexisting in the common coverage of satellite and the BS. Therefore, when a passive Eve hides in such common area, it could wiretap the SU or TU possibly.

In this section, the channel and signal models of satellite and terrestrial communications are first presented, where the imperfect channel state information (CSI) for the Eve is assumed. Based on the signal models, the received SINRs of SUs, TUs and Eves are given. Further, we conduct a symbiotic security problem that the secure transmissions of both satellite beams and the spectrum is shared with the BSs. Particularly, in each beam, we consider a legitimate satellite user (SU) and terrestrial user (TU) coexisting in the common coverage of satellite and the BS. Therefore, when a passive Eve hides in such common area, it could wiretap the SU or TU possibly.

In this section, the channel and signal models of satellite and terrestrial communications are first presented, where the imperfect channel state information (CSI) for the Eve is assumed. Based on the signal models, the received SINRs of SUs, TUs and Eves are given. Further, we conduct a symbiotic security problem that the secure transmissions of both satellite beams and the spectrum is shared with the BSs. Particularly, in each beam, we consider a legitimate satellite user (SU) and terrestrial user (TU) coexisting in the common coverage of satellite and the BS. Therefore, when a passive Eve hides in such common area, it could wiretap the SU or TU possibly.

A. Channel and Signal Models

For the satellite-to-ground channel, the free space path loss (FSPL), rain attenuation, and satellite beam gain are generally considered to construct the channel model [39], which is given by

\[ h = \sqrt{C_L b\beta \exp(-j\theta)}, \]  

where \( C_L \) denotes the FSPL, \( b \) denotes the beam gain, \( \beta \) denotes the channel gain due to rain attenuation, and \( \theta \) is the phase vector with uniform distribution over \([0, 2\pi]\). Specifically,

\[ C_L = \frac{(\lambda/4\pi)^2}{(d^2 + h^2)}, \]

where \( \lambda \) denotes signal wavelength, \( d \) denotes the distance from the beam center to the center of satellite coverage, and \( h \) accounts for the height of satellite. The beam gain is defined by

\[ b = G\left(\frac{J_1(u_0)}{2u_0} - 36\frac{J_3(u_0)}{u_0^2}\right)^2, \]

where \( G \) denotes the maximum satellite antenna gain, \( u_0 = 2.07123\frac{\sin(\alpha)}{\sin(\alpha_{\text{dB}})} \) with \( \alpha \) being the elevation angle between the beam center and SU and \( \alpha_{\text{dB}} \) being the 3 dB angle of satellite beam. Additionally, \( J_1(\cdot) \) and \( J_3(\cdot) \) are the first-kind Bessel functions of order 1 and 3, respectively. \( \beta \) is modeled as a log-normal random variable, i.e., \( \ln(\beta_{\text{dB}}) \sim N(u, \delta^2) \) with \( \beta_{\text{dB}} \) being the dB form of \( \beta \). Particularly, \( h_{\text{su}} \in \mathbb{C}^{N \times 1} \) and \( h_{\text{gu}} \in \mathbb{C}^{M \times 1} \) are assumed to be the channel vectors from satellite to SU, and Eve respectively.

Whereas, we adopt the channel model for terrestrial links as

\[ g = \sqrt{\alpha}g_0, \]

where \( \alpha \) denotes the large-scale fading, \( \alpha = C_0 r^{-\delta} \) with \( C_0 \) being the channel power gain at the reference distance of 1 m and \( r \) denoting the distance from BS to the destination, and \( g_0 \) denotes the small-scale fading which undergoes Nakagami-\( m \) fading with fading severity \( m \) and average power \( \Omega \). Particularly, \( g_{\text{su}} \in \mathbb{C}^{M \times 1} \), \( g_{\text{gu}} \in \mathbb{C}^{M \times 1} \), and \( g_{\text{e}} \in \mathbb{C}^{M \times 1} \) denote the channel vectors between BS and SU, TU, and Eve respectively.

In addition, the imperfect CSI of Eve is modeled as

\[ h_e = h_e + \Delta h_e \]

and

\[ g_e = g_e + \Delta g_e, \]

where \( h_e \) and \( g_e \) denote the estimations of eavesdropping channels by satellite and the BS, with \( \Delta h_e \) and \( \Delta g_e \) being the norm-bounded estimate errors.
correspondingly. To facilitate the easy, we assume \( \| \Delta h_k \| = \| \Delta g_k \| \leq \Delta \) in this work.

Assuming that \( x_{su,i} \) and \( x_{tu,k} \) denote the expected signal of SU and TU respectively. Without loss of generality, the signal received by SU \( k \) in the \( k^{th} \) beam can be represented as

\[
y_{su,k} = h_{su,k}^\dagger \sum_{i} w_i x_{su,i} + g_{su,k}^\dagger f_k x_{tu,k} + n_{su,k},
\]

where \( h_{su,k} \) denotes the channel vector from satellite to SU, \( g_{su,k} \) denotes the channel vector from the BS to TU, \( w_k, g_k \in \mathbb{C}^{N \times 1} \) and \( f_k \) denote the BF vectors of satellite and BS in the \( k^{th} \) beam, \( n_{su,k} \) is the noise received by SU. The signal received by TU \( k \) can be written as

\[
y_{tu,k} = g_{tu,k}^\dagger f_k x_{tu,k} + h_{tu,k}^\dagger \sum_{i} w_i x_{su,i} + n_{tu,k},
\]

where \( f_k \in \mathbb{C}^{M \times 1} \) denotes the BF at BS.

Besides, the received signal by the Eve in the \( k^{th} \) beam is given by

\[
y_{e,k} = h_{e,k}^\dagger \sum_{i} w_i x_{su,i} + g_{e,k}^\dagger f_k x_{tu,k} + n_{e,k},
\]

where \( f_k \) denote the BF at BS.

B. Problem Formulation

From (6), it can be see that the Eve wiretaps signals of SU and TU. However, (4) and (5) indicate that the SU and TU receive interference from BS and satellite respectively, which can be designed to unequally degrade the legitimate users and Eve in each beam. Since such interference can be regarded as the green interference to assist the implementation of physical layer security, the secrecy rate of SU and TU can be obtained as follows.

Based on (4) and (5), the SINR of SU \( k \) can be calculated as

\[
\gamma_{su,k} = \frac{\| h_{su,k}^\dagger w_i \|^2}{\sum_{i \neq k} \| h_{su,i}^\dagger w_i \|^2 + \| g_{su,k}^\dagger f_k \|^2 + \delta_{su,k}^2},
\]

and the SINR of TU \( k \) is obtained as

\[
\gamma_{tu,k} = \frac{\| g_{tu,k}^\dagger f_k \|^2}{\sum_{i=1}^{N} \| h_{tu,i}^\dagger w_i \|^2 + \| g_{su,k}^\dagger f_k \|^2 + \delta_{tu,k}^2},
\]

where \( \delta_{su,k}^2 \) and \( \delta_{tu,k}^2 \) denote the noise power received by SU \( k \) and TU \( k \).

Accordingly, the SINR of Eve for wiretapping SU \( k \) can be written as

\[
\gamma_{se,k} = \frac{\| h_{e,k}^\dagger w_i \|^2}{\sum_{i \neq k} \| h_{e,i}^\dagger w_i \|^2 + \| g_{e,k}^\dagger f_k \|^2 + \delta_{e,k}^2},
\]

and the SINR of Eve for wiretapping TU \( k \) is given by

\[
\gamma_{te,k} = \frac{\| g_{e,k}^\dagger f_k \|^2}{\sum_{i=1}^{N} \| h_{e,i}^\dagger w_i \|^2 + \delta_{e,k}^2},
\]

where \( \delta_{e,k}^2 \) denotes the noise power received by the Eve.

The secrecy rate of SU \( k \) and TU \( k \) can be respectively given by

\[
R_{su,k}^s = \log_2 \left( \frac{1}{\gamma_{su,k}} \right) - \log_2 \left( \frac{1}{\gamma_{se,k}} \right),
\]

\[
R_{tu,k}^t = \log_2 \left( \frac{1}{\gamma_{tu,k}} \right) - \log_2 \left( \frac{1}{\gamma_{te,k}} \right).
\]

From (9) and (10), we can see the SINR of Eve in each beam which targets SU is degraded by the green interference from BS, and meanwhile the SINR of Eve targeting TU is degraded by the green interference from satellite. Further, by using (13), the sum secrecy rate of legitimate SUs in satellite multi-beam is given in (15), shown at the bottom of the page.

To guarantee the secrecy performance of both satellite link and terrestrial link simultaneously, our focus is on optimizing
the BF of multi-beam satellite and BS to maximize the sum secrecy rate of legitimate SUs in satellite multi-beam and satisfy a predefined secrecy constraint of legitimate TU in each beam.

Thus, the problem can be mathematically formulated as

$$
P_1 : \max_{\{w_k, f_k\}_{k=1}^N} \sum_{k=1}^N R_s^u, k \quad \text{s.t.} \quad R_s^u \geq Q_{tu,k}, \ k = 1, 2, \ldots, N, \quad \sum_{k=1}^N \|w_k\|^2 \leq P_S, \quad \|f_k\|^2 \leq P_B, \ k = 1, 2, \ldots, N.
$$

In $P_1$, (16b) guarantees the secrecy requirements of TUs within satellite beams, where $Q_{tu,k}$ is a predefined secrecy rate threshold for TU in the $k^{th}$ beam; (16c) and (16d) represent the power constraints of satellite and BS, respectively.

Obviously, the problem $P_1$ has non-convex objective function and constraints. A series of reformulations are conducted in the following section to convert such intractable problem into a solvable alternative, and a joint satellite-terrestrial BF optimizing approach is proposed to solve this problem. To facilitate the simplification, the noise power is normalized, i.e., $\delta_{su,k} = \delta_{tu,k} = \delta_{e,k} = 1$.

### IV. Joint Satellite-Terrestrial BF Optimizing

In this section, we aim to solve the secrecy rate maximization problem by reformulating the objection function and its non-convex constraints simplify this problem as a solvable form. Particularly, a Taylor expansion and SDR are first adopted to reformulate the problem $P_1$ and then a successive convex approximation approach is carried out to solve the reformulated problem. Finally, the tightness of the relaxation is proved.

#### A. Taylor Expansion and SDR Reformulation

We introduce exponential variables to make the following changes.

$$e^{\alpha_k} = \sum_{i=1}^N \text{Tr}(H_{su,i}W_i) + \text{Tr}(G_{su,k}F_k) + 1, \quad \text{(17)}$$

$$e^{\tau_k} = \sum_{i \neq k}^N \text{Tr}(H_{su,i}W_i) + \text{Tr}(G_{su,k}F_k) + 1, \quad \text{(18)}$$

$$e^{\gamma_k} = \sum_{i=1}^N \text{Tr}(H_{e,i}W_i) + \text{Tr}(G_{e,k}F_k) + 1, \quad \text{(19)}$$

$$e^{\nu_k} = \sum_{i \neq k}^N \text{Tr}(H_{e,i}W_i) + \text{Tr}(G_{e,k}F_k) + 1. \quad \text{(20)}$$

By substituting (17–20) into (16a), the objection function in $P_1$ can be equivalently represented as

$$\max_{\{s_k, \mu_k, q_k, v_k\}_{k=1}^N} \sum_{i=1}^N \left(s_k - \mu_k - q_k + v_k\right), \quad \text{(21)}$$

which is a convex problem because the criterion is a sum of affine functions (composed with $s_k - \mu_k$ and $q_k - v_k$). Particularly, the constraints of $s_k - \mu_k, q_k, v_k$ in (21) hold the following bounds.

$$e^{\alpha_k} \leq \sum_{i=1}^N \text{Tr}(H_{su,i}W_i) + \text{Tr}(G_{su,k}F_k) + 1, \quad \text{(22)}$$

$$e^{\tau_k} \geq \sum_{i \neq k}^N \text{Tr}(H_{su,i}W_i) + \text{Tr}(G_{su,k}F_k) + 1, \quad \text{(23)}$$

$$e^{\gamma_k} \geq \sum_{i=1}^N \text{Tr}(H_{e,i}W_i) + \text{Tr}(G_{e,k}F_k) + 1, \quad \text{(24)}$$

$$e^{\nu_k} \leq \sum_{i \neq k}^N \text{Tr}(H_{e,i}W_i) + \text{Tr}(G_{e,k}F_k) + 1. \quad \text{(25)}$$

It can be verified that all the inequalities from (22) to (25) hold with equalities at the optimal points by the monotonicity of objective function. However, it can be observed that the constraints in (23) and (24) are still non-convex.

In addition, keeping (14) in mind, the constraint in (16b) is also non-convex due to the non-convex fractional program. Similarly, we make the following changes.

$$e^{\tau_k} = \sum_{i=1}^N \text{Tr}(H_{tu,i}W_i) + \text{Tr}(G_{tu,k}F_k) + 1, \quad \text{(26)}$$

$$e^{\gamma_k} = \sum_{i=1}^N \text{Tr}(H_{e,i}W_i) + 1, \quad \text{(27)}$$

$$e^{\nu_k} = \sum_{i=1}^N \text{Tr}(H_{e,i}W_i) + 1. \quad \text{(28)}$$

By substituting (26–28, 19) into (14), the secrecy constraint of TU in (16b) can be equivalently reformulated as

$$\eta_k + q_k - \tau_k - \alpha_k \leq \frac{Q_{tu,k}}{\log_2 e}, \quad \text{(29)}$$

with the successive constraints as follows

$$e^{\tau_k} \leq \sum_{i=1}^N \text{Tr}(H_{tu,i}W_i) + \text{Tr}(G_{tu,k}F_k) + 1, \quad \text{(30)}$$

$$e^{\gamma_k} \geq \sum_{i=1}^N \text{Tr}(H_{tu,i}W_i) + 1, \quad \text{(31)}$$

$$e^{\nu_k} \leq \sum_{i=1}^N \text{Tr}(H_{e,i}W_i) + 1, \quad \text{(32)}$$

and (24) is also satisfied, where (31) and (24) are non-convex. To address the non-convex constraints in (23), (24), (31), we adopt Taylor expansion to make these constraints conservatively convex approximating at $\{\{\mu_k\}, \{\tilde{q}_k\}, \{\tilde{\eta}_k\}\}$. By using the first-order Taylor expansion of $e^{\tau_k}, e^{\gamma_k}$, and $e^{\nu_k}$, the restrictive approximations for (23), (24), (31) can be given as

$$\sum_{i=1}^N \text{Tr}(H_{su,i}W_i) + \text{Tr}(G_{su,k}F_k) + 1 \leq e^{\tilde{\tau}_k} (\tilde{\mu}_k - \tilde{\mu}_k + 1), \quad \text{(33)}$$
\[ \sum_{i=1}^{N} \text{Tr}(H_{e,i}W_{i}) + \text{Tr}(G_{e,k}F_{k}) + 1 \leq e^{\tilde{\eta}_k} (q_k - \tilde{q}_k + 1), \]  

\[ \sum_{i=1}^{N} \text{Tr}(H_{tu,i}W_{i}) + 1 \leq e^{\tilde{\eta}_k} (\eta_k - \tilde{\eta}_k + 1), \]

where \( \tilde{\mu}_k, \tilde{q}_k, \) and \( \tilde{\eta}_k \) begin with an initial values.

### B. Successive Convex Approximation Approach

By defining the renewed optimization variables as a set, i.e.,

\[ \mathcal{Z} = \{ W_k, F_k, \{ s_k \}, \{ \mu_k \}, \{ q_k \}, \{ v_k \}, \{ \tau_k \}, \{ \eta_k \} \}, \]

thus the primal problem \( \mathcal{P}1 \) can be reformulated as

\[ \max_{\mathcal{Z}} \sum_{k=1}^{N} (s_k - \mu_k - q_k + v_k) \]

s.t.

\[ \sum_{k=1}^{N} \text{Tr}(W_k) \leq P_S, \quad k = 1, 2, \ldots, N, \]  

\[ \text{Tr}(F_k) \leq P_B, \quad k = 1, 2, \ldots, N, \]  

\[ F_k \succeq 0, \quad W_k \succeq 0, \]

(22), (25), (29-30), (32), (33-35).

To solve \( \mathcal{P}2 \), we adopt the cvx tool and carry out a SCA based approach, where \( \tilde{\mu}_k, \tilde{q}_k, \) and \( \tilde{\eta}_k \) can be updated by each iteration of SCA. Particularly, the details of SCA-based joint satellite-terrestrial BF optimization can be seen in algorithm table I. In addition, the main computational complexity is solved the convex approximation problem in each iteration. Considering the SDP for solving \( \mathcal{P}3 \), the rank-one of \( \{ W_k \} \) and \( \{ F_k \} \) can be calculated by \( O(\max\{m,n\}^4\eta^{1/2}) \), where \( m \) and \( n \) are the constraint order and the dimension of equality constraints for SDP, respectively. Thus, the total complexity can be calculated as \( t \cdot O((8N + 2)^4) + \log(1/e) \).

In addition, to analyze the tightness of SDR from \( \mathcal{P}1 \) to \( \mathcal{P}2 \), the rank-one of \( \{ W_k \} \) and \( \{ F_k \} \) is proved as follows.

**Proposition 1:** We consider a power minimization problem, which can be expressed as

\[ \min_{\mathcal{Z}} \sum_{i=1}^{N} \text{Tr}(W_i + F_i) \]

s.t.

\[ \sum_{k=1}^{N} (s_k - \mu_k - q_k + v_k) \geq \varphi^0, \]

(36b-36e),

where \( \varphi^0 \) denotes the optimal objective value of \( \mathcal{P}2 \). It can be obtained that any feasible solutions of \( \mathcal{P}3 \) is optimal for \( \mathcal{P}2 \).

### Algorithm I SCA-Based Joint Satellite-Terrestrial BF Optimization

**Input:** \( \{ Q_{tu,k}, \varepsilon, P_S, P_B \} \).

**Result:** \( \{ W_n^*, n = 1, \ldots, N \}, \{ F_n^*, k = 1, \ldots, N \} \).

1. **Initialization:** \( \{ \tilde{\eta}_k \}, \{ \tilde{\eta}_k^0 \}, \{ \tilde{\eta}_k \} \).
2. **Set step** \( t = 0 \).
3. **repeat**
4. **Using the CVX solver SDP to solve** \( \mathcal{P}2 \):
5. **Output:** \( \{ s_k^* \}, \{ \eta_k^* \}, \{ \mu_k^* \}, \{ q_k^* \}, \{ v_k^* \} \), \( \{ W_k^* \}, \{ F_k^* \} \).
6. **Obtain** \( R_{s,\text{sum}}^t = \sum_{k=1}^{N} s_k^* - \mu_k^* - q_k^* + v_k^* \).
7. **until** \( R_{s,\text{sum}}^t - R_{s,\text{sum}}^{t-1} < \varepsilon \).
8. **Obtain** \( \{ W_n^* \} \) and \( \{ F_n^* \} \) by the singular value decomposition (SVD) of \( \{ W_k^* \} \) and \( \{ F_k^* \} \).
9. **Procedure End**

**Proof:** Assuming that \( \mathcal{Z}^* \) is the optimal solution for solving \( \mathcal{P}3 \), then the following condition is restrictively satisfied

\[ \varphi^0 \leq \sum_{k=1}^{N} (s_k^* - \mu_k^* - q_k^* + v_k^*), \]

with \( W_k^* \) and \( F_k^* \) satisfying constraints in (36b-36e).

From (38), it can be found that the maximum \( \varphi^0 \) is reached when \( \sum_{k=1}^{N} (s_k^* - \mu_k^* - q_k^* + v_k^* \) has the optimal solution at \( \mathcal{Z}^* \).

Thus, \( \mathcal{Z}^* \) is the optimal solution for \( \mathcal{P}2 \) with objective value \( \varphi^0 \) and the proof is concluded.

Based on Proposition 1, we indirectly prove the rank-one condition in \( \mathcal{P}2 \) by proving that in \( \mathcal{P}3 \) by the following theorem.

**Theorem 1:** For any feasible solutions of \( \{ W_k, F_k \} \) from \( \mathcal{P}3 \), Rank(\( W_k \)) = 1 and Rank(\( F_k \)) = 1.

**Proof:** Please see the appendix.

### V. Joint Optimization of Satellite BF and BS PA

For the reference propose, an alternative approach that jointly optimizing satellite BF and the PA of BS is given in this section, which is as a benchmark in this paper.

We consider the BSs can use a partial transmission power to generate AN for confusing Eve deliberately. The SINRs of SU, TU, and Eve can be respectively rewritten as

\[ \gamma_{su,k} = \frac{\| h_{su,k}^H w_k \|^2}{\sum_{i \neq k} \| h_{su,i} w_i \|^2 + \ell_k P_B \| g_{su,k} f_{su,k} \|^2 + (1 - \ell_k) P_B \| g_{su,k} O_{kv} \|^2 + \delta_{su,k}^2} \]

\[ \gamma_{se,k} = \frac{\| h_{e,k}^H w_k \|^2}{\sum_{i \neq k} \| h_{e,i} w_i \|^2 + \ell_k P_B \| g_{e,k} f_{e,k} \|^2 + (1 - \ell_k) P_B \| g_{e,k} O_{kv} \|^2 + \delta_{se,k}^2} \]
\[ \gamma_{tu,k} = \ell_k P_B \left\| g_{tu,k}^\dagger \right\|^2 \left( \sum_{i=1}^{N} \left\| h_{tu,i}^\dagger w_i \right\|^2 + \delta_{tu,k}^2 \right) \]  
\[ \gamma_{te,k} = \frac{\ell_k P_B \left\| g_{te,k}^\dagger \right\|^2}{\sum_{i=1}^{N} \left\| h_{te,i}^\dagger w_i \right\|^2 + (1-\ell_k) P_B \left\| g_{te,k}^\dagger O_k v_k \right\|^2 + \delta_{te,k}^2} \]  

where \( \ell_k \) is the PA coefficient of BS, \( f_{\text{mrt}}^k = g_{tu,k}^\dagger \| g_{tu,k} \| \) denotes the MRT-based BF vector of BS for transmitting useful signal to TU, \( v_k \in \mathbb{C}^{(M-1)\times 1} \) is the AN vector, and \( O_k = \left( I - h h^H h \right)^{t} \) is the projection matrix into the null of two legitimate channels, i.e., \( g_{tu} \) and \( g_{su} \). In addition, we make \( A_k = O_k v_k v_k^\dagger O_k^\dagger \) and

\[ A_k = (1-\ell_k) P_B \text{Tr} (G_{e,k} A_k). \]  

Based on (39–43), the secrecy rate of SU and TU are obtained in (44) and (45), shown at the bottom of the page. Hence, another optimization problem targeting the primal objective and constraints in \( P1 \) can be formulated as

\[ \mathcal{P}4: \max_{\{w_k\}_{k=1}^{N}, \ell_k} \sum_{k=1}^{N} R_{s_{tu,k}} \] 
\[ \text{s.t.} \ R_{s_{tu,k}} \geq \gamma_{tu,k}, \ k = 1, 2, \ldots, N, \] 
\[ \sum_{k=1}^{N} \left\| w_k \right\|^2 \leq P_S, \] 
\[ 0 \leq \ell_k \leq 1. \]  

From (44–46d), it is observed that the problem \( \mathcal{P}4 \) is also intractable since its non-convex objective function and constraints. Similarly, the Taylor expansion is adopted to reformulate the problem \( \mathcal{P}4 \) and changes by the corresponding exponential variables are made as follows.

\[ e^{s_{tu,k}} = \sum_{i} \text{Tr} (H_{s,i} W_i) + \ell_k P_B \text{Tr} (G_{s,u,k} F_{k}^{\text{mrt}}) + 1, \]  
\[ e^{\nu_{tu,k}} = \sum_{i \neq k} \text{Tr} (H_{s,i} W_i) + \ell_k P_B \text{Tr} (G_{s,u,k} F_{k}^{\text{mrt}}) + 1, \]  
\[ e^{q_{tu,k}} = \sum_{i} \text{Tr} (H_{e,i} W_i) + \ell_k P_B \text{Tr} (G_{e,k} F_{k}^{\text{mrt}}) + A_k + 1, \]  
\[ e^{\nu_{tu,k}} = \sum_{i \neq k} \text{Tr} (H_{e,i} W_i) + \ell_k P_B \text{Tr} (G_{e,k} F_{k}^{\text{mrt}}) + A_k + 1, \]  

\[ e^{q_{tu,k}} = \ell_k P_B \text{Tr} (G_{tu,k} F_{k}^{\text{mrt}}) + \sum_{i=1}^{N} \text{Tr} (H_{tu,i} W_i) + 1, \]  
\[ e^{\nu_{tu,k}} = \ell_k P_B \text{Tr} (G_{tu,k} F_{k}^{\text{mrt}}) + \sum_{i=1}^{N} \text{Tr} (H_{tu,i} W_i) + 1, \]  

\[ e^{q_{tu,k}} = \sum_{i=1}^{N} \text{Tr} (H_{tu,i} W_i) + A_k + 1, \]  
\[ e^{\nu_{tu,k}} = \sum_{i=1}^{N} \text{Tr} (H_{tu,i} W_i) + A_k + 1, \]  

\[ e^{q_{tu,k}} = \ell_k P_B \text{Tr} (G_{tu,k} F_{k}^{\text{mrt}}) + \sum_{i=1}^{N} \text{Tr} (H_{tu,i} W_i) + 1, \]  
\[ e^{\nu_{tu,k}} = \ell_k P_B \text{Tr} (G_{tu,k} F_{k}^{\text{mrt}}) + \sum_{i=1}^{N} \text{Tr} (H_{tu,i} W_i) + 1, \]  

By defining the renewed optimization variables as a set, i.e., \( \mathcal{X}' = \{ \{ W_k \}, \ell_k, \{ s_{k}' \}, \{ \mu_{k}' \}, \{ q_{k}' \}, \{ v_{k}' \}, \{ r_{k}' \}, \{ \eta_{k}' \} \} \), and using the above replacements in (47–53), the problem \( \mathcal{P}4 \) can be reformulated as

\[ \mathcal{P}5: \max_{\{s_{k}'\}_{k=1}^{N}} \sum_{k=1}^{N} (s_{k}' - \mu_{k}' - q_{k}' + v_{k}') \] 
\[ \text{s.t.} \ \eta_{k}' + q_{k}' - r_{k}' - \alpha_k \leq - \frac{Q_{tu,k}}{\log_2 e}, \] 
\[ e^{s_{k}'} \leq \sum_{i} \text{Tr} (H_{s,i} W_i) + \ell_k P_B \text{Tr} (G_{s,u,k} F_{k}^{\text{mrt}}) + 1, \] 
\[ e^{\nu_{k}'} \leq \sum_{i \neq k} \text{Tr} (H_{s,i} W_i) + \ell_k P_B \text{Tr} (G_{s,u,k} F_{k}^{\text{mrt}}) + 1 \] 
\[ + A_k + 1, \] 
\[ e^{q_{k}'} \leq \ell_k P_B \text{Tr} (G_{tu,k} F_{k}^{\text{mrt}}) + \sum_{i=1}^{N} \text{Tr} (H_{tu,i} W_i) + 1, \] 
\[ e^{\nu_{k}'} \leq \ell_k P_B \text{Tr} (G_{tu,k} F_{k}^{\text{mrt}}) + \sum_{i=1}^{N} \text{Tr} (H_{tu,i} W_i) + 1, \] 
\[ e^{q_{k}'} \leq \ell_k P_B \text{Tr} (G_{tu,k} F_{k}^{\text{mrt}}) + \sum_{i=1}^{N} \text{Tr} (H_{tu,i} W_i) + 1 \] 
\[ + A_k + 1, \] 
\[ e^{\nu_{k}'} \leq \sum_{i=1}^{N} \text{Tr} (H_{tu,i} W_i) + A_k + 1, \] 
\[ e^{q_{k}'} \leq \sum_{i=1}^{N} \text{Tr} (H_{tu,i} W_i) + A_k + 1, \] 
\[ e^{\nu_{k}'} \leq \sum_{i=1}^{N} \text{Tr} (H_{tu,i} W_i) + A_k + 1, \] 
\[ e^{q_{k}'} \leq \ell_k P_B \text{Tr} (G_{tu,k} F_{k}^{\text{mrt}}) + \sum_{i=1}^{N} \text{Tr} (H_{tu,i} W_i) + 1, \] 
\[ e^{\nu_{k}'} \leq \ell_k P_B \text{Tr} (G_{tu,k} F_{k}^{\text{mrt}}) + \sum_{i=1}^{N} \text{Tr} (H_{tu,i} W_i) + 1, \]
VI. PERFORMANCE EVALUATION

In this section, we conduct extensive numerical simulations to evaluate the secrecy performance. The main system parameters are set in Table I. Specifically, the height of satellite orbit is 600 Km and the maximum beam gain $G_{\text{max}}$ is set to 46.6 dB. The 3 dB angles of all beams are set to $\alpha_{\text{3dB}} = 3.152$ and $\delta^2 = 1.6$. The carrier frequency of satellite downlink transmission is 2 GHz. The horizontal distance from BS to SU, TU, and Eve is 100 m, 100 m, 120 m, respectively. For convenience, the same secrecy rate constraint of TUs in different satellite beams is preset as $Q$ for the simulation. Particularly, the impact of BS transmission power ($P_B$), satellite transmission power ($P_S$), number of BS transmit antennas ($M$), and secrecy rate constraint of TUs ($Q$) on the maximum secrecy rate performance of SU are evaluated as follows.

Fig. 2 shows the impact of BS transmission power on the maximum sum secrecy rate of SUs. From Fig. 2, it can be seen that the maximum secrecy rate of SU is monotonically increasing as the BS transmission power increases. Particularly, it can be found that the objective value in (37a) increases as the BS transmission power ($Tr(F_i)$) increases. According to the Proposition 1, the objective function in the problem $P_2$ in (36a) has the same monotonicity as that in (37a), which indicates the maximum sum secrecy rate of SUs increases as the BS transmission power. In addition, our

\[
\begin{aligned}
&c_k^w \leq \sum_{i=1}^{N} \text{Tr}(H_{c_i}W_i) + A_k + 1, \\
&\sum_{k=1}^{N} \text{Tr}(W_k) \leq P_S, \\
&0 \leq \ell_k \leq 1.
\end{aligned}
\]

From (50), we can see that the problem $P_5$ can also be solved by a SCA-based optimization algorithm. Finally, we conduct the solving procedure in the algorithm table II.

**Algorithm 2 SCA-Based Joint Satellite BF and the PA of BS Optimization**

| System Parameters | Numerical Value |
|-------------------|-----------------|
| Satellite height  | 600 Km          |
| Carrier frequency | 2 GHz           |
| Maximum beam gain | 46.6 dB         |
| 3 dB angle (for all beams) | 0.4° |
| Rain attenuation parameters | $\mu_{\text{CS}} = -3.152$, $\delta^2 = 1.6$ |
| Terrestrial BS channel parameters |
| Channel power gain | -38.46 dB       |
| Nakagami$m$ channel parameters | $m = 2$, $\Omega = 1$ |

Fig. 2. Secrecy rate performance of SUs vs. satellite transmission power. ($P_S = 20$ dB, $Q = 0.5$ bit/s/Hz, $M = 4$.)

Fig. 3. Secrecy rate performance of SU vs. satellite transmission power. ($P_B = 30$ dB, $Q = 0.5$ bit/s/Hz, $M = 4$.)
proposed cooperative BF optimization approach outperforms these two benchmarks, e.g., the approach that jointly optimizes both satellite BF and the PA of BS, and the approach that optimizes satellite BF with ZF-based BS BF. This is because the BS power focuses more on the main channel of TU by MRT-based BF while the AN damages the Eve poorly. Whereas the ZF-based BS BF approach doesn’t concentrate the green interference and the AN from BS to damage the Eve, which improves the secrecy performance of SU slightly only by the satellite BF since the similarity of satellite channels.

In Fig. 3, the impact of satellite transmission power on the maximum sum secrecy rate of SUs is evaluated. From Fig. 3, it can be seen that the maximum sum secrecy rate of SUs is monotonically increasing of the satellite transmission power. This is because the more green interference from satellite degrades the eavesdropping of TU as the satellite transmission power increases, thus the more BS power resource can serve as the green interference for SU to degrade the Eve. Similarly, the objective value in (37a) increases as the satellite transmission power \( (\text{Tr}(\mathbf{W}_i)) \) increases. According to the Proposition 1, the maximum sum secrecy rate of SUs increases as the satellite transmission power. In addition, our proposed cooperative BF optimization approach outperforms the approach that jointly optimizes both satellite BF and the PA of BS and the approach that optimizes satellite BF with ZF-based BS BF. Particularly, the approach that optimizes satellite BF with ZF-based BS BF outperforms the approach that jointly optimizes both satellite BF in low transmission power region, which indicates that the main channel of TU is damaged slightly by satellite with low transmission power and the BS tends to suppress the Eve rather than to enhance the main channel of TU for guaranteeing the secrecy rate constraint.

In this paper, a symbiotic secure transmission scheme based on cooperative BF optimization in integrated satellite-terrestrial communications has been proposed. Particularly, the co-channel interference induced by spectrum sharing within satellite-terrestrial networks and the inter-beam interference due to frequency reuse among satellite beams serve as the green interference has been used to ensure secure transmissions of both satellite and terrestrial links simultaneously. Specifically, the problem to maximize the sum secrecy rate of SUs is formulated and the BF optimizing is conducted cooperatively, where the secrecy rate constraint of each TU is guaranteed. Furthermore, the Taylor expansion and SDR have been adopted to reformulate this problem, and a SCA based joint satellite-terrestrial BF optimization approach has been proposed to solve this problem. The tightness of the relaxation has also been proved. In addition, numerical results have verified the efficiency of our proposed cooperative BF optimization approach and revealed that the inherent green
interference from internal system without additional assistance can assist the implement of symbiotic secure transmissions in integrated satellite-terrestrial networks.

**Appendix**

**Proof of Theorem 1**

Proof: The Lagrangian function of Problem (P2) can be obtained as (55), shown at the bottom of the page.

Based on (55), we take the partial derivative of \( \mathcal{L}(\cdot) \) with respect to \( W_k \) and apply KKT conditions as follows

\[
D - H_{su,k} \sum_{k=1}^{N} \lambda_k - U_k = 0, \quad \text{(56)}
\]

\[
U_k W_k = 0, \quad \text{(57)}
\]

\[
W_k \succeq 0, \quad \text{(58)}
\]

where

\[
D = I_N \left( 1 + \sum_{i=1}^{N} \beta_i \right) + H_{e,k} \left( \sum_{i \neq k}^{N} \zeta_i - \sum_{i=1}^{N} \rho_i - \sum_{i=1}^{N} \varsigma_i \right) + H_{tu,k} \left( \sum_{i=1}^{N} v_i - \sum_{i=1}^{N} u_i \right) + H_{su,k} \sum_{i \neq k}^{N} \tau_i. \quad \text{(59)}
\]

By using (56–57), we have the reformulation as follows

\[
D W_k = H_{su,k} W_k \sum_{k=1}^{N} \lambda_k. \quad \text{(60)}
\]

From (59) and (60), we can find that

\[
N - 2 \leq \text{rank}(D) \leq N. \quad \text{(61)}
\]

By (56), we have \( E = D \) by denoting \( E = H_{su,k} \sum_{k=1}^{N} \lambda_k + U_k \), and thus \( \text{rank}(E) \geq N - 2 \). With (57), we have

\[
\text{rank}(EW_k) = \text{rank}(H_{su,k} W_k \sum_{k=1}^{N} \lambda_k) \leq \text{rank}(H_{su,k}) = 1 \quad \text{(62)}
\]

and \( \text{rank}(E) + \text{rank}(W_k) \leq \text{rank}(EW_k) + N. \)

If \( \text{rank}(EW_k) = 1 \), we have \( \text{rank}(W_k) = N \) and \( \text{rank}(E) \leq 1 \), which conflicts with the precondition \( \text{rank}(E) \geq N - 2 \). Consequently, the provision of \( \text{rank}(EW_k) = 0 \) should be satisfied. Then, \( \text{rank}(W_k) \leq 2 \)

is achieved.

Further, we reformulated (56) as

\[
\Theta - E - H_{e,k} \left( \sum_{i \neq k}^{N} \rho_i + \sum_{i=1}^{N} \varsigma_i \right) - \sum_{i=1}^{N} \theta_i H_{tu,k} = 0, \quad \text{(63)}
\]

where \( \Theta = I_N \left( 1 + \sum_{i=1}^{N} \beta_i \right) + H_{e,k} \sum_{i=1}^{N} \zeta_i + \sum_{i \neq k}^{N} \tau_i H_{su,k} + \sum_{i=1}^{N} v_i H_{tu,k} \), and it can be observed that \( \Theta > 0 \) due to \( \beta_i \geq 0, \zeta_i \geq 0, \tau_i \geq 0, \) and \( v_i \geq 0 \).

By post-multiplying \( W_k \) at both sides of (63) and using \( \text{rank}(EW_k) = 0 \), (63) can be rewritten as

\[
\Theta W_k = (E + H_{e,k} \left( \sum_{i \neq k}^{N} \rho_i + \sum_{i=1}^{N} \varsigma_i \right) + \sum_{i=1}^{N} \theta_i H_{tu,k}) W_k. \quad \text{(64)}
\]

In (64), since \( \Theta > 0 \), we have

\[
\text{rank}(\Theta W_k) = \text{rank}(W_k), \quad \text{(65)}
\]

and thus (66) is achieved.

\[
\text{rank}(W_k) = \text{rank}(H_{e,k} \left( \sum_{i \neq k}^{N} \rho_i + \sum_{i=1}^{N} \varsigma_i \right) + \sum_{i=1}^{N} \theta_i H_{tu,k}) W_k)
\]

\[
\leq \text{rank}(H_{e,k} W_k \left( \sum_{i \neq k}^{N} \rho_i + \sum_{i=1}^{N} \varsigma_i \right) + \sum_{i=1}^{N} \theta_i H_{tu,k}) W_k)
\]

\[
+ \text{rank}(H_{tu,k} W_k \sum_{i=1}^{N} u_i). \quad \text{(66)}
\]

\[
\mathcal{L}\left(\{\xi_k, \varsigma_k, \lambda_k, \rho_k, \tau_k, \zeta_k, v_k, \theta_k, \phi_k, \beta_k, \kappa_k, W_k, F_k, U_k, L_k\}\right)
\]

\[
= \sum_{i=1}^{N} \text{Tr}(W_i + F_i) - \sum_{k=1}^{N} \xi_k (s_k - \mu_k - q_k + \varphi_k - \varphi^0) + \sum_{k=1}^{N} \lambda_k \left( e^{\mu_k} - \sum_{i=1}^{N} \text{Tr}(H_{su,i} W_i) - \text{Tr}(G_{su,k} F_k) - 1 \right)
\]

\[
+ \sum_{k=1}^{N} \rho_k \left( e^{\mu_k} - \sum_{i \neq k}^{N} \text{Tr}(H_{e,i} W_i) - \text{Tr}(G_{e,k} F_k) - 1 \right) + \sum_{k=1}^{N} \tau_k \left( \sum_{i \neq k}^{N} \text{Tr}(H_{su,i} W_i) + \text{Tr}(G_{su,k} F_k) - e^{\mu_k} (\mu_k - \tilde{\mu}_k) \right)
\]

\[
+ \sum_{k=1}^{N} \zeta_k \left( \sum_{i=1}^{N} \text{Tr}(H_{e,i} W_i) + \text{Tr}(G_{e,k} F_k) - e^{\mu_k} (\mu_k - \tilde{\mu}_k) \right) + \sum_{k=1}^{N} \theta_k \left( \sum_{i=1}^{N} \text{Tr}(H_{tu,i} W_i) - e^{\mu_k} (\eta_k - \tilde{\eta}_k) \right)
\]

\[
+ \sum_{k=1}^{N} \phi_k \left( \sum_{i=1}^{N} \text{Tr}(H_{tu,i} W_i) - e^{\mu_k} (\mu_k - \tilde{\mu}_k) \right) + \sum_{k=1}^{N} \kappa_k \left( \text{Tr}(F_k) - P_{\beta} \right) - \sum_{k=1}^{N} \text{Tr}(L_k F_k) \quad \text{(55)}
\]
Particularly,
\[
\text{rank}(H_{e,k}W_k \sum_{i \neq k} \rho_i + \sum_{i=1}^N \chi_i)) \leq \text{rank}(H_{e,k}) = 1,
\]
(67)
\[
\text{rank}(H_{tu,k}W_k \sum_{i=1}^N \vartheta_{i,k}) \leq \text{rank}(H_{tu,k}) = 1.
\]
(68)

However, if \( \text{rank}(W_k) = 2 \), it can be observed from (67) that \( \text{rank}(H_{e,k}W_k \sum_{i \neq k} \rho_i + \sum_{i=1}^N \chi_i)) = 1 \) and
\[
\text{rank}(H_{tu,k}W_k \sum_{i=1}^N \vartheta_{i,k}) = 1,
\]
which indicates an incompatible result that \( \text{rank}(W_k) = N \).

Therefore, \( \text{rank}(W_k) \leq 1 \) is kept, and \( \text{rank}(W_k) = 0 \) cannot be a solution and which should be discarded. Finally,
\[
\text{rank}(W_k) = 1 \text{ is proved.}
\]

Similarly, for the proof of \( \text{Rank}(F_k) = 1 \), we take the partial derivative of \( \mathcal{L}(\cdot) \) with respect to \( F_k \) and apply KKT conditions as follows
\[
A - \vartheta_k G_{tu,k} - L_k = 0,
\]
(69)
\[
L_k F_k = 0,
\]
(70)
\[
L_k \geq 0,
\]
(71)
where
\[
A = [1 + \sum_{k=1}^N \kappa_k] I_N + (\tau_k - \lambda_k) G_{su,k} + (\zeta_k - \rho_k) G_{e,k}
\]
(72)
and it is observed that \( N - 2 \leq \text{rank}(A) \leq N \). Due to \( G_{tu,k} = h_{tu,k}h_{tu,k}^H \), \( \text{rank}(G_{tu,k}) = 1 \). Thus, similar to the way of proof \( \text{Rank}(W_k) = 1 \) above, \( \text{Rank}(F_k) = 1 \) can also be proved.

**REFERENCES**

[1] X. You et al., “Towards 6G wireless communication networks: Vision, enabling technologies, and new paradigm shifts,” Sci. China Inf. Sci., vol. 64, no. 1, pp. 1–74, 2021.

[2] H. Tataria, M. Shafi, A. F. Molisch, M. Dohler, H. Sjöland, and F. Tufvesson, “6G wireless systems: Vision, requirements, challenges, insights, and opportunities,” Proc. IEEE, vol. 109, no. 7, pp. 1–34, Mar. 2021.

[3] F. Lyu et al., “Service-oriented dynamic resource slicing and optimization for space-air-ground integrated vehicular networks,” IEEE Trans. Intell. Transp. Syst., early access, Apr. 15, 2021, doi: 10.1109/TITS.2021.3070542.

[4] Z. Lin, M. Lin, T. de Cola, J.-B. Wang, W.-P. Zhu, and J. Cheng, “Supporting IoT with rate-splitting multiple access in satellite and aerial-integrated networks,” IEEE Internet Things J., vol. 8, no. 14, pp. 11427–11439, Jan. 2021.

[5] Y. Liu et al., “Physical layer security assisted computation offloading in intelligently connected vehicle networks,” IEEE Trans. Wireless Commun., vol. 20, no. 6, pp. 3555–3570, Jun. 2021.

[6] Y. Hui et al., “Secure and personalized edge computing services in 6G heterogeneous vehicular networks,” IEEE Internet Things J., vol. 9, no. 8, pp. 5920–5931, Apr. 2021.

[7] Y. Xu, H. Zhou, T. Ma, J. Zhao, B. Qian, and S. Shen, “Leveraging multi-agent learning for automated vehicles scheduling at non-signalized intersections,” IEEE Internet Things J., vol. 8, no. 14, pp. 11427–11439, Jan. 2021.

[8] C. Zhang, C. Jiang, L. Kuang, J. Jin, Y. He, and Z. Han, “Spatial spectrum sharing for satellite and terrestrial communication networks,” IEEE Trans. Aerosp. Electron. Syst., vol. 55, no. 3, pp. 1075–1089, Jun. 2019.

[9] J. Yang, S. C. Draper, and R. Nowak, “Learning the interference graph of a wireless network,” IEEE Trans. Signal Inf. Process. Netw., vol. 3, no. 3, pp. 631–646, Sep. 2017.

[10] K. An, T. Liang, G. Zheng, X. Yan, Y. Li, and S. Chatzitofois, “Performance limits of cognitive-uplink FSS and terrestrial FS for Ka-band,” IEEE Trans. Aerosp. Electron. Syst., vol. 55, no. 5, pp. 2604–2611, Oct. 2019.

[11] Z. Lin et al., “Refactoring RIS aided hybrid satellite-terrestrial relay networks: Joint beamforming design and optimization,” IEEE Trans. Aerosp. Electron. Syst., early access, Mar. 3, 2022, doi: 10.1109/TAES.2022.3155711.

[12] V. Bankey and P. K. Upadhyay, “Physical layer security of multiuser multirelay hybrid satellite-terrestrial relay networks,” IEEE Trans. Veh. Technol., vol. 68, no. 3, pp. 2488–2501, Mar. 2019.

[13] Z. Yin et al., “Secrecy rate analysis of satellite communications with frequency domain NOMA,” IEEE Trans. Veh. Technol., vol. 68, no. 12, pp. 11847–11858, Dec. 2019.

[14] J. Zhang, H. Du, Q. Sun, and D. W. K. Ng, “Physical layer security enhancement with reconfigurable intelligent surface-aided networks,” IEEE Trans. Inf. Forensics Security, vol. 16, pp. 3480–3495, 2021.

[15] P. K. Sharma and D. I. Kim, “Secure 3D mobile UAV relaying for hybrid satellite-terrestrial networks,” IEEE Trans. Wireless Commun., vol. 19, no. 4, pp. 2770–2784, Apr. 2020.

[16] M. Lin, Z. Lin, W.-P. Zhu, and J.-B. Wang, “Joint beamforming for secure communication in cognitive satellite-terrestrial networks,” IEEE J. Sel. Areas Commun., vol. 36, no. 5, pp. 1017–1029, May 2018.

[17] E. Panayirci, A. Yesilkaya, T. Cogal, H. V. Poor, and H. Haas, “Physical-layer security with optical generalized space shift keying,” IEEE Trans. Commun., vol. 66, no. 5, pp. 3042–3056, May 2020.

[18] Z. Yin, N. Cheng, T. Luan, and P. Wang, “Physical layer security in cyber-physical enabled integrated satellite-terrestrial vehicle networks,” IEEE Trans. Veh. Technol., vol. 71, no. 5, pp. 4561–4572, May 2022.

[19] Z. Yin et al., “ UAV-assisted physical layer security in multi-beam satellite-enabled vehicle communications,” IEEE Trans. Intell. Transp. Syst., vol. 23, no. 3, pp. 2739–2751, Mar. 2022.

[20] K. Feng, X. Li, Y. Han, S. Jin, and Y. Chen, “Physical layer security enhancement exploiting intelligent reflecting surface,” IEEE Commun. Lett., vol. 25, no. 3, pp. 734–738, Mar. 2021.

[21] H. Yang, Z. Xiong, J. Zhao, D. Niyato, L. Xiao, and Q. Wu, “Deep reinforcement learning-based intelligent reflecting surface for secure wireless communications,” IEEE Trans. Wireless Commun., vol. 20, no. 1, pp. 375–388, Jan. 2021.

[22] S. Zhao, J. Liu, Y. Shen, X. Jiang, and N. Shiratori, “Secure beamforming for full-duplex MIMO two-way untrusted relay systems,” IEEE Trans. Inf. Forensics Security, vol. 15, pp. 3775–3790, 2020.

[23] Q. Li and L. Yang, “Beamforming for cooperative secure transmission in cognitive two-way relay networks,” IEEE Trans. Inf. Forensics Security, vol. 15, pp. 130–143, 2020.

[24] M. Tian, W. Sun, P. Zhang, L. Huang, and Q. Li, “Joint beamforming design and receive antenna selection for large-scale MIMO wiretap channels,” IEEE Trans. Veh. Technol., vol. 69, no. 3, pp. 2716–2730, Mar. 2020.

[25] S. Yin, J.-M. Kang, I.-M. Kim, and J. Ha, “Deep artificial noise: Deep learning-based precoding optimization for artificial noise schemes,” IEEE Trans. Veh. Technol., vol. 69, no. 3, pp. 3465–3469, Mar. 2020.

[26] L. Sun, R. Wang, Z. Tang, and V. C. M. Leung, “Artificial-noise-aided nonlinear secure transmission for multiuser multi-antenna systems with finite-rate feedback,” IEEE Trans. Commun., vol. 67, no. 3, pp. 2274–2293, Mar. 2019.

[27] Y. Liu, Z. Qin, M. Elkashty, Y. Gao, and L. Hanzo, “Enhancing the physical layer security of non-orthogonal multiple access in large-scale networks,” IEEE Trans. Wireless Commun., vol. 16, no. 3, pp. 1656–1672, Mar. 2017.

[28] Z. Xiang, W. Yang, Y. Cai, Z. Ding, and Y. Song, “Secure transmission design in HARQ assisted cognitive NOMA networks,” IEEE Trans. Inf. Forensics Security, vol. 15, pp. 2528–2541, 2020.

[29] M. Hayashi and A. Vazquez-Castro, “Physical layer security protocol for Poisson channels for passive man-in-the-middle attack,” IEEE Trans. Inf. Forensics Security, vol. 15, pp. 2295–2305, 2020.
Propagation Data and Prediction Methods Required for the Design [30] K. Guo et al., “Physical layer security for multiuser satellite communication systems with threshold-based scheduling scheme,” IEEE Trans. Veh. Technol., vol. 69, no. 5, pp. 5129–5141, May 2020.

[31] G. Cui, Q. Zhu, L. Xu, and W. Wang, “Secure beamforming and jamming for multibeam satellite systems with correlated wiretap channels,” IEEE Trans. Veh. Technol., vol. 69, no. 10, pp. 12348–12353, Oct. 2020.

[32] J. Li, Z. Fei, C. Zhou, and Y. Zhang, “Physical-layer security in space information networks: A survey,” IEEE Internet Things J., vol. 7, no. 1, pp. 33–52, Jan. 2020.

[33] M. Tropea, F. De Rango, and A. F. Santamaria, “Design of a two-stage scheduling scheme for DVB-S2/S2X satellite architecture,” IEEE Trans. Broadcast., vol. 67, no. 2, pp. 424–437, Jun. 2021.

[34] A. I. Perez-Neira, M. Caus, and M. A. Vazquez, “Non-orthogonal transmission techniques for multibeam satellite systems,” IEEE Commun. Mag., vol. 57, no. 12, pp. 58–63, Dec. 2019.

[35] J. Du, C. Jiang, H. Zhang, X. Wang, Y. Ren, and M. Debbah, “Secure satellite-terrestrial transmission over incumbent terrestrial networks via cooperative beamforming,” IEEE J. Sel. Areas Commun., vol. 36, no. 7, pp. 1367–1382, Jul. 2018.

[36] Y. Yan, W. Yang, D. Guo, S. Li, H. Niu, and B. Zhang, “Robust secure beamforming and power splitting for millimeter-wave cognitive Satellite–Terrestrial networks with SWIPT,” IEEE Syst. J., vol. 14, no. 3, pp. 3233–3244, Sep. 2020.

[37] Z. Lin, M. Lin, B. Champagne, W.-P. Zhu, and N. Al-Dhahir, “Secure and energy efficient transmission for RSMA-based cognitive satellite-terrestrial networks,” IEEE Wireless Commun. Lett., vol. 10, no. 2, pp. 251–255, Feb. 2021.

[38] Z. Lin, M. Lin, B. Champagne, W.-P. Zhu, and N. Al-Dhahir, “Secure beamforming for cognitive satellite-terrestrial networks with unknown eavesdroppers,” IEEE Syst. J., vol. 15, no. 2, pp. 2186–2189, Jun. 2021.

[39] Propagation Data and Prediction Methods Required for the Design of Earth-Space Telecommunication Systems, Recommendation ITU-R, document P.618–12, 2015.

Zhisheng Yin (Member, IEEE) received the B.E. degree from the Wuhan Institute of Technology, the B.B.A. degree from the Zhongnan University of Economics and Law, Wuhan, China, in 2012, the M.Sc. degree from the Civil Aviation University of China, Tianjin, China, in 2016, and the Ph.D. degree from the School of Electronics and Information Engineering, Harbin Institute of Technology, Harbin, China, in 2020. From September 2018 to September 2019, he has visited the BBCR Group, Department of Electrical and Computer Engineering, University of Waterloo, Canada. He is currently an Associate Professor with the School of Cyber Engineering, Xidian University, Xi’an, China. His research interests include space-air-ground integrated networks, wireless communications, digital twin, and physical layer security.

Nan Cheng (Member, IEEE) received the B.E. and M.S. degrees from the Department of Electronics and Information Engineering, Tongji University, Shanghai, China, in 2009 and 2012, respectively, and the Ph.D. degree from the Department of Electrical and Computer Engineering, University of Waterloo, in 2016. He has worked as a Post-Doctoral Fellow with the Department of Electrical and Computer Engineering, University of Toronto, from 2017 to 2019. He is currently a Professor with the State Key Laboratory of ISN and the School of Telecommunications Engineering, Xidian University, Shannxi, China. His current research focuses on 5G/6G, space-air-ground integrated networks, big data in vehicular networks, and self-driving systems. His research interests also include performance analysis, MAC, opportunistic communication, and application of AI for vehicular networks.

Wei Wang (Member, IEEE) received the B.Eng. degree in information countermeasure technology and the M.Eng. degree in signal and information processing from Xidian University in 2011 and 2014, respectively, and the Ph.D. degree in electrical and electronic engineering from Nanyang Technological University (NTU), Singapore, in 2018. From September 2018 to August 2019, he was a Post-Doctoral Fellow at the Department of Electrical and Computer Engineering, University of Waterloo, Canada. He is currently a Professor at the Nanjing University of Aeronautics and Astronautics. His research interests include wireless communications, space-air-ground integrated networks, wireless security, and blockchain. He was awarded the Chinese Government Award for outstanding self-financed students abroad in 2018 and the Young Elite Scientist Sponsorship Program, China Association for Science and Technology, in 2021.