Cognitive Non-ideal NOMA Satellite-Terrestrial Networks with Channel and Hardware Imperfections

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Abstract—This paper investigates a non-orthogonal multiple access (NOMA) assisted cognitive satellite-terrestrial network which is practically limited by interference noises, transceiver hardware impairments, imperfect successive interference cancellation, and channel state information mismatch. Generalized outage probability expressions for NOMA users in both primary and secondary networks are derived considering the impact of interference temperature constraint. Finally, obtained results are corroborated by Monte Carlo simulations and compared with the orthogonal multiple access to show the superior performance of the proposed network model.

Index Terms—Cognitive radio (CR), non-orthogonal multiple access (NOMA), outage probability, satellite-terrestrial network (STN).

I. INTRODUCTION

Satellite-terrestrial networks (STNs) have received significant attention from research and industry due to their capability of providing a connection to rural and distant areas, where the deployment of terrestrial infrastructure is uneconomical/difficult. Moreover, the STNs are considered as a promising enabler of future fifth-generation (5G) networks that expect a 1000-fold data traffic increase [1]. This leads to a critical issue of spectrum scarcity [2]. It can be resolved by deploying cognitive radio (CR) in the STNs to enable spectrum sharing between the satellite and terrestrial networks [3].

Another criteria for the successful implementation of 5G is massive connectivity. Traditionally, satellite-terrestrial systems principally exploit an orthogonal multiple access (OMA) scheme to deliver services; however, it is considered as one of the bottlenecks since there is a limitation in the number of servable devices due to their orthogonality. Therefore, the non-orthogonal multiple access (NOMA) technique has been recently proposed as a promising technology for the future wireless networks because of its ability to maintain resource sharing (i.e., time, code and frequency) and, at the same time, differentiate the end-users with respect to different power levels [4]–[8]. In [6]–[8], the underlay CR and NOMA were jointly studied aiming at reducing the interference and more effective spectrum utilization. For example, in [6], the authors evaluated the outage performance of CR-NOMA by considering an amplify-and-forward relaying scheme while a similar system

model was examined for the detect-and-forward scheme over generalized $\alpha - \mu$ fading channels [7], [8].

Until now, very few papers studied the performance of NOMA in cognitive STNs [9]–[11]. For instance, the authors in [9] derived the closed-form outage probability (OP) and approximated ergodic capacity expressions for the primary and secondary users for a decode-and-forward relaying protocol. In [10], the authors examined the NOMA-assisted overlay multi-user cognitive STN and revealed its superiority over traditional benchmark schemes. Furthermore, in [11], the authors derived the analytical expression using Meijer-G functions for the ergodic capacity of NOMA-assisted cognitive STNs and confirmed its advantages.

In contrast to [9]–[11], this paper examines the cognitive NOMA-based STN considering the aggregate transceiver distortions, channel and successive interference cancellation (SIC) imperfections, hardware impairment (HI) as well as interference temperature constraint (ITC). Hence, the key contributions of this paper are as follows. First, closed-form analytical OP expressions are derived for both primary and secondary users in the considered cognitive NOMA-assisted STN. Second, the influence of several system parameters on the network performance is investigated using derived analytical results, and, by comparing the NOMA users' OP performance with a benchmark OMA scheme, the advantage of NOMA is verified. Finally, the correctness of derived analytical findings are validated by the Monte Carlo simulations and, therefore, the correctness of analytical results are verified.

II. SYSTEM MODEL

Consider a downlink underlay multi-user CR-assisted STN model consisting of secondary and primary networks as illustrated in Fig. 1. The primary network (PN) includes the satellite transmitter (T) which intends to directly communicate with multiple primary users (PUs), indicated by R_n , $n \in \{1, 2, \dots, N\}$. At the same time, the secondary network (SN) consists of a base station (S), which can access the licensed band spectrum of PUs and communicate with the secondary users (SUs), denoted by U_k , $k \in \{1, 2, \dots, K\}$. In this case, the PUs can suffer from the aggregate interference from S while T will interfere with the SUs.

Fig. 1. Cognitive NOMA-assisted STN model.

A. Channel Models

We model the communication links using linear minimum mean square error channel estimator as [12] $\chi = \tilde{\chi} + \epsilon$, where χ denotes the observed mismatched channel, while $\tilde{\chi}$ is a real channel estimate and ϵ indicates its estimation error, with $\mathcal{CN}(0, \lambda)$, where λ can be described considering the nominal transmit SNR ω , as $\lambda = \Phi\omega^{-\eta}$ [13]. The perfect CSI can be obtained if $\eta \rightarrow \infty$ for $\omega > 0$. Moreover, the additive white Gaussian noise (AWGN), with mean zero and variance σ^2 , exposes all the receiving nodes.

1) *Satellite Direct and Interference Channels:* The channels corresponding to the satellite links given by $\mathbf{g}_{TU} = [g_{T1}, g_{T2}, \dots, g_{TK}]$ and $\mathbf{h}_{TR} = [h_{T1}, h_{T2}, \dots, h_{TN}]$ follow shadowed-Rician fading. Thus, the corresponding probability density function (PDF) is given by [14]

$$f_{|\chi_n|^2}(x) = \sum_{\ell=0}^{m_n-1} \Upsilon x^\ell e^{-\partial_n x}, \quad x \geq 0, \quad (1)$$

with $\Upsilon = \frac{1}{2b_n} \left(\frac{2b_n m_n}{2b_n m_n + \Omega_n} \right)^{m_n} \frac{(1-m_n)^\ell (-\delta_n)^\ell}{(\ell!)^2}$ and $\partial_n = \varrho_n - \delta_n$, where $\delta_n = \frac{\Omega_n}{2b_n(2b_n m_n + \Omega_n)}$, $\varrho_n = \frac{1}{2b_n}$. Here, $2b_n$ is the average power of a multi-path component, Ω_n denotes the average power of a line-of-sight (LoS) component, and m_n represents the Nakagami parameter. Furthermore, as the Friis' law for free-space propagation states, the path-loss for satellite communication links has linear dependence with logarithmic distance as in [15] and can be expressed by $L(D) = \frac{1}{\mathcal{K}_B \mathcal{T} \mathcal{W}} \left(\frac{c}{4\pi f_c D} \right)^2$, where D represents the distance between T and the user of interest¹, while c and f_c denote the light speed and carrier frequency, respectively. $\frac{1}{\mathcal{K}_B \mathcal{T} \mathcal{W}}$ is a scale factor, where $\mathcal{K}_B$, $\mathcal{T}$ and $\mathcal{W}$ denote the Boltzmann's constant, receiver noise temperature and carrier bandwidth, respectively.

We denote the antenna gain at T as G_T , with φ representing the angle between the i -th user's location and the beam center

with respect to the satellite. Hence, the beam gain $G_i(\varphi)$ is expressed as [16]

$$G_i(\varphi) = G_{i,\max} \left(\frac{J_1(u)}{2u} + 36 \frac{J_3(u)}{u^3} \right)^2, \quad (2)$$

where $u = 2.07123 \frac{\sin \varphi}{\sin \varphi_{3\text{dB}}}$, $\varphi_{3\text{dB}}$ is the constant 3-dB angle for the beam and $J_l(\cdot)$ expresses the first-kind Bessel function of order l .

2) *Terrestrial Direct and Interference Channels:* The terrestrial links given by $\mathbf{g}_{SU} = [g_{S1}, g_{S2}, \dots, g_{SK}]$ and $\mathbf{h}_{SR} = [h_{S1}, h_{S2}, \dots, h_{SN}]$ are presumed to abide the Nakagami- m fading. Therefore, the corresponding channel gains (i.e., squared values) are Gamma random variables (RVs) with the PDF given by

$$f_{|\chi_k|^2}(y) = \frac{y^{m_k-1} e^{-\frac{y}{\nu}}}{\Gamma(m_k) \nu^{m_k}}, \quad (3)$$

where m_k and ν stand for the shape and scale parameters.

In addition, the sectored antenna pattern has been used to model analog beamforming between communicating nodes as $G(\theta) = G_m$, when $\theta \leq \theta_b$; otherwise, $G(\theta) = G_s$, where G_m and G_s denote the main and side lobe gains², respectively. θ is the angle of a boresight direction, while θ_b indicates the antenna beamwidth. For convenience, we assume that the terrestrial station interferes the PUs with side lobe gain, while a main lobe gain is exploited in the terrestrial direct links.

B. Signal and SINR Models

1) *Satellite Primary Network:* The satellite T and N terrestrial end-users ($R_n, n \in \{1, \dots, N\}$) comprise the downlink satellite PN that employs the NOMA concept by broadcasting a superposed signal $x = \sum_{n=1}^N \sqrt{\alpha_n} x_n$, where x_n and α_n denote the message devoted for the n -th user and the corresponding power allocation (PA) coefficient (with $\alpha_1 > \alpha_2 > \dots > \alpha_N$ s.t. $\sum_{n=1}^N \alpha_n = 1$).

Hence, considering the CSI imperfections, the received signal at R_i , for $i \in \{1, \dots, N\}$, can be written as

$$y_i = (\tilde{h}_i + \epsilon_i) \sqrt{P_T G_T G_i(\varphi) L} \left(\sum_{n=1}^N \sqrt{\alpha_n} x_n + \mu_i \right) + h_{Si} \sqrt{P_S G_S \bar{G}_i d_{Si}^{-\tau}} (s_k + \bar{\mu}_i) + n_i, \quad (4)$$

where $n_i \sim \mathcal{CN}(0, \sigma_i^2)$ denotes the AWGN term. $\mu_i \sim \mathcal{CN}(0, \kappa_i^2)$ and $\bar{\mu}_i \sim \mathcal{CN}(0, \bar{\kappa}_i^2)$ represent the impact of residual HIs by the aggregate distortion noises, where κ_i and $\bar{\kappa}_i$ denote the compound HI levels observed in the communication links of corresponding transmitter-receiver pairs.

Then, considering imperfect SIC, the corresponding signal-to-interference-noise-distortion ratio (SINDR) to decode message x_n , for $n \leq i$, can be written, by arranging $\rho_i =$

¹Without loss of generality, it is assumed that the distances between the satellite and terrestrial users are equal.

²It is assumed that an antenna gain has a constant value in the frame of given main or side lobe sectors.

$P_T G_T G_i(\varphi) L$, $\bar{\rho}_i = P_S G_S G_i d_{SRi}^{-\tau}$, $X_i = |\tilde{h}_{TRi}|^2$, $Y_i = |h_{SRi}|^2$, and $a = \alpha_n \rho_i$, as follows

$$\gamma_{i \rightarrow n} = \frac{a X_i}{b X_i + \Sigma_i + c Y_i}, \quad (5)$$

where $\Sigma_i = \rho_i (1 + \kappa_i^2) \sigma_\epsilon^2 + \sigma_i^2$ stands for the power of channel error and AWGN noise. The interference received from S is given by $c = (1 + \bar{\kappa}_{SRi}^2) \bar{\rho}_i$. $b = \rho_i \mathcal{A}$ represents the SIC-based interference, with $\mathcal{A} = (\Psi_n + \tilde{\Psi}_n + \kappa_i^2)$, where $\Psi_n = \sum_{t=n+1}^N \alpha_t$, and $\tilde{\Psi}_n = \sum_{l=1}^{n-1} \xi_l \alpha_l$, with $0 \leq \xi \leq 1$ [17]. Note that R_1 detects its own message by regarding the other signals as noise and setting $\Psi_1 = \sum_{t=2}^N \alpha_t$ and $\tilde{\Psi}_1 = 0$, while message x_N is decoded only at R_N , subject to $\Psi_N = 0$ and perfect/imperfect SIC realizations given by $\tilde{\Psi}_n = \sum_{l=1}^{n-1} \xi_l \alpha_l$.

2) *Terrestrial Secondary Network*: On the other hand, the terrestrial SN consists of the base station S and K NOMA end-users (U_k , $k \in \{1, \dots, K\}$), when the superimposed signal $s = \sum_{k=1}^K \sqrt{\beta_k} s_k$ is sent to all intended SUs, where s_k and β_k indicate the message dedicated for the k -th SU and the corresponding PA coefficient (with $\beta_1 > \beta_2 > \dots > \beta_K$ s.t. $\sum_{k=1}^K \beta_k = 1$). G_S is the antenna gain at S . In the same manner, the received signal at U_j can be written as

$$r_j = (\tilde{g}_j + \epsilon) \sqrt{P_S G_S G_{Dj} d_j^{-\tau}} \left(\sum_{k=1}^K \sqrt{\beta_k} s_k + \bar{\mu}_i \right) + g_{PD} \sqrt{P_T G_T G_D(\varphi) L} (x_n + \mu_j) + w_j, \quad (6)$$

Hence, the SINDR of U_j to detect message s_k from S is as

$$\psi_{j \rightarrow k} = \frac{W_1 Z_j P_S}{P_S (W_2 Z_j + E) + C Q_j + \sigma_j^2}, \quad (7)$$

where $Z_j = |\tilde{g}_j|^2$, $Q_j = |g_{Tj}|^2$, and $W_1 = \beta_k G_S G_{Dj} d_j^{-\tau}$. The power of channel error and AWGN noise is denoted by $E = G_S G_{Dj} d_j^{-\tau} (1 + \bar{\kappa}_i^2) \sigma_\epsilon^2$. $W_2 = G_S G_{Dj} d_j^{-\tau} \mathcal{A}$ stands for the SIC-based interference, with $\mathcal{A} = (\Psi_j + \tilde{\Psi}_j + \kappa_i^2)$, whereas $C = (1 + \kappa_{Tj}^2) P_T G_T G_D(\varphi) L$ is the interference from T .

III. OUTAGE PROBABILITY

A. Satellite Primary Network

By definition, the outage is defined as the probability that the SINDR value falls below a predefined signal-to-noise ratio (SNR) associated rate threshold, which can be expressed as $v = 2^{\mathcal{R}} - 1$, where $\mathcal{R}$ is the data rate threshold [18].

Thus, using Eq. (5), the OP of decoding message x_n by R_i can be determined as

$$\mathbb{P}_{\text{out},i}(v) = \Pr[\gamma_{i \rightarrow n} < v], 0 < n \leq i. \quad (8)$$

Proposition 1: Considering imperfect SIC/CSI and HI, we can express the closed-form expression of OP for the primary user of interest as in Eq. (9).

Proof: The full derivation is drawn in Appendix A. ■

Fig. 2. The OP comparison of the NOMA and OMA for the SN with different $\xi = \{0, 0.05, 0.1\}$.

B. Terrestrial Secondary Network

The OP for U_K can be expressed using Eq. (7) and considering ITC as in Eq. (10), where $S_i = \frac{I_{\text{ITC}}^{[i]}}{Y_i}$ and $P_S = \min(\bar{P}_S, S^*)$ by assuming $S^* = \min(S_1, S_2, \dots, S_N)$. Further, we denote $I_{\text{ITC}}^{[i]} = I_{\text{ITC}} d_{SRi}^{-\tau}$ and $Y_i = |h_{SRi}|^2$.

For the convenience, we simplify the expression by using the following definitions: $T_1 = \frac{v(E P_S + \sigma_j^2)}{P_S (W_1 - v W_2)}$, $T_2 = \frac{v C}{P_S (W_1 - v W_2)}$, $R_1 = \frac{v \sigma_j^2}{I_{\text{ITC}}^{[i]} (W_1 - v W_2)}$, $R_2 = \frac{v C}{I_{\text{ITC}}^{[i]} (W_1 - v W_2)}$, $R_3 = \frac{v I_{\text{ITC}}^{[i]} E}{I_{\text{ITC}}^{[i]} (W_1 - v W_2)}$, and $\Lambda = \frac{I_{\text{ITC}}^{[i]}}{P_S}$.

Proposition 2: The OP in the SN given by Eq. (10) can be expressed in closed form considering the ITC as sum of Eqs. (12) and (11), where, for the sake of brevity, the terms A and B are demonstrated separately.

$$A = \left(\sum_{\ell=0}^{m_n-1} \Upsilon \ell! \partial_n^{-\ell-1} - e^{-\frac{T_1}{\nu_0}} M_A T_2^n \sum_{\ell=0}^{m_n-1} \Upsilon(n+\ell)! \left(\frac{T_2}{\nu_0} + \partial_n \right)^{-n-\ell-1} \right) \frac{\gamma(m_k, \frac{\Lambda}{\nu})}{\Gamma(m_k)}. \quad (12)$$

Proof: The full derivation can be found in Appendix B. ■

IV. NUMERICAL RESULTS

This section provides the numerical results on the outage performance for the system model under consideration designated by the simulation framework drawn in Table I which mainly follows the parameters listed in [15], [16]. We also verify our derived analytical expressions through Monte Carlo simulations. For the sake of simplicity, we consider only two PUs and two SUs³.

³In the real-time communication, the use of multiple NOMA users may not be achievable because the processing complexity of the SIC at receivers raises in a non-linear manner by the increased number of users [21]. Moreover, when the SIC error propagates, this complexity gets to be more vital [7].

$$\mathbb{P}_{\text{out},i}^{\text{PN}}(v) = \sum_{\ell=0}^{m_n-1} \frac{\Upsilon \ell!}{\partial_n^{\ell+1}} - \sum_{\ell=0}^{m_n-1} \sum_{p=0}^{\ell} \frac{\ell!}{p!} \frac{\Upsilon e^{-I(i)\Sigma_i(\partial_n)}}{\partial_n^{\ell-p+1}} \sum_{t=0}^p \frac{(I(i))^p p! (\Sigma_i)^{p-t} c^t}{t!(p-t)!} \frac{\Gamma(t+m_k)}{\Gamma(m_k) \nu^{m_k}} \left(\frac{1}{\nu} + I(i) \partial_n c \right)^{-t-m_k} \quad (9)$$

$$\begin{aligned} \mathbb{P}_{\text{out},j}^{\text{SN}}(v) &= \Pr \left(\frac{W_1 Z_j P_S}{P_S (W_2 Z_j + E) + C Q_j + \sigma_j^2} < v, \bar{P}_s < S_i \right) + \Pr \left(\frac{W_1 Z_j S_i}{S_i (W_2 Z_j + E) + C Q_j + \sigma_j^2} < v, \bar{P}_s > S_i \right) \\ &= \underbrace{\Pr(Z_j < (T_1 + T_2 Q_j), Y_i < \Lambda)}_A + \underbrace{\Pr(Z_j < (R_1 Y_i + R_2 Q_j Y_i + R_3), Y_i > \Lambda)}_B. \end{aligned} \quad (10)$$

$$\begin{aligned} B &= \frac{\Gamma(m, \frac{\Lambda}{\nu})}{\Gamma(m)} \sum_{\ell=0}^{m_n-1} \Upsilon \ell! \partial_n^{-\ell-1} - e^{-\frac{R_3}{\nu_0}} M_B \sum_{i=0}^t \binom{t}{i} R_1^{t-i} R_2^i \frac{\Gamma(t+m)}{\Gamma(m) \nu^m} e^{-\left(\frac{1}{\nu} + \frac{R_1}{\nu_0}\right) \Lambda} \sum_{j=0}^{t+m-1} \sum_{\ell=0}^{m_n-1} \frac{\Lambda^j \Upsilon}{j!} \\ &\quad \times \frac{V_2 \Omega^{-(i+\ell+1)}}{\Gamma(-j+t+m)} G_{1,2}^{2,1} \left(\frac{\frac{R_2 \Lambda}{\nu_0} + \partial_n}{\Omega} \middle| \begin{matrix} 1 - (i+\ell+1) \\ 0, -(i+\ell+1) + (-j+t+m) \end{matrix} \right) \end{aligned} \quad (11)$$

(a) The OP performance for the SN with perfect CSI and SNR-independent CSI mismatches $\{0, 0.05\}$ and $\{0, 0.1\}$. (b) The OP performance for the SN with perfect CSI and SNR-dependent CSI mismatches $\{1, 10\}$, $\{0.5, 10\}$ and $\{0.5, 15\}$.

Fig. 3. The OP versus the transmit SNR for the terrestrial SN for different CSI scenarios.

Table I. Simulation parameters.

Parameter	Value
Terrestrial channel parameter, m_0	2
Satellite channel parameters, $\{m_i, b_i, \Omega_i\}$	$\{5, 0.251, 0.279\}$
Terrestrial antenna gains, $\{G_m, G_s\}$	$\{12, -1.1092\}$ dB
Satellite antenna gains, $\{G_T, G_{i,max}\}$	$\{4.8, 54\}$ dB
Threshold, $\{\zeta_{NOMA}, \zeta_{OMA}\}$	$\{3, 12\}$ dB
PA factors, $\{\alpha_1, \alpha_2\}$	$\{0.7, 0.3\}$
Path-loss exponent, τ	2
Orbit height, D	35786 km
S -to- R_N distance, $\{d_{R1}, d_{R2}\}$	$\{150, 75\}$ m
S -to- U_K distance, $\{d_{U1}, d_{U2}\}$	$\{100, 50\}$ m
3dB angle, φ_{3dB}	0.4°
Carrier frequency, f_c	2 GHz
Interference noise power	10 dB
Temperature, $\mathcal{T}$	300 K
Carrier bandwidth, $\mathcal{W}$	15 MHz

In Fig. 2, the OP comparison of the analytical results for a NOMA network with the simulated results for a OMA scheme is demonstrated for both SUs with $ITC = 10$ dB. Here, to ensure comparison fairness, the data rate requirements of OMA are set as two-fold for NOMA, and transmit power at S is set to $0.5P$. In addition, the asymptotic case with no ITC, i.e., $ITC \rightarrow \infty$, is plotted and it demonstrates the best performance without saturation. Moreover, it is clearly seen that the NOMA-based network outperforms the OMA in terms of OP. However, one can observe the outage of U_1 in the NOMA-assisted network starts saturating at lower levels of the transmit SNR compared to the OMA network. It can be explained by the ITC equation, where the transmit power of $0.5P_s$ rises the values of the ITC at S ; therefore, the level of transmit SNR, where the OP curves start saturating, increases. Additionally, the influence of various SIC scenarios is investigated for U_2

only, since U_1 is independent of SIC. According to the results, SIC-enabled end-user U_2 performs better than U_1 within the system model. Although, subject to the flawed SIC, the outage of U_2 deteriorates when ξ increases, as expected. It is worth mentioning that, at lower levels of the transmit SNR, imperfect SIC has a low impact on the performance.

Fig. 3 shows the impact of CSI mismatch for two users in the terrestrial SN. Moreover, it considers the SNR-independent/dependent CSI scenarios. When $\eta = 0$, meaning that the channel error variance is independent of the transmit SNR, it is observed that Φ significantly affects the system performance. Noticeably, Φ does not have any effect on the OP performance at low SNR values. Particularly, it starts influencing U_1 at 35 dB and U_2 at 25 dB, approximately. It happens due to the fact that when Φ approaches 0, the CSI quality tends to become perfect. Therefore, the small mismatch in CSI does not affect the performance at low SNR. Contrarily, when $\eta \neq 0$, CSI becomes SNR-dependent and achieves saturation only at a greater rate of the transmit SNR in comparison with the SNR-independent CSI. From Fig. 3(b), one can clearly observe that the increase of η leads to the improvement of system performance. Similarly, in the case of equal η values, the growth of Φ also results in a slight improvement of the OP performance. However, it is apparent that η has much more influence on the performance than Φ . It is worth mentioning that, despite the overall system improvement, all curves level out on the same OP rate in the high-SNR region.

V. CONCLUSION

In this paper, we have evaluated the performance of cognitive NOMA-assisted STNs wherein terrestrial SUs enjoy the access to spectrum with the satellite PN limited only by interference temperature constraint. Different from existing works, we have applied NOMA to both primary and secondary networks and obtained the closed-form OP expressions taking into account the hardware, SIC and CSI imperfections along with the interference noises. Particularly, we have shown the deteriorative effects of imperfect CSI and SIC. Furthermore, a comparison with the OMA network, which is considered as a benchmark scheme, revealed that the proposed NOMA-based STN demonstrates outstanding performance advancement while utilizing the spectrum resource in an efficient manner. Finally, derived analytical findings were verified by Monte Carlo simulations.

VI. ACKNOWLEDGMENT

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APPENDIX A SATELLITE PRIMARY NETWORK

In this section, we present the derivation steps for appraising the outage metric of primary NOMA users.

Hence, the OP can be evaluated using Eq. (5) as

$$\mathbb{P}_{\text{out},i}(v) = \Pr[X_i \leq I(i)(\Sigma_i + cY_i)] \\ = \int_0^\infty \underbrace{\left(\int_0^{I(i)(\Sigma_i + cY_i)} f_{X_i}(x) dx \right)}_{A_1} f_Y(y) dy, \quad (\text{A.1})$$

where $I(i) = \frac{v}{a_i - b_i v}$. Here A_1 can be solved by integrating Eq. (1) with the aid of [19, Eq. (3.351.1)] as

$$A_1 = \int_0^{I(i)(\Sigma_i + cY_i)} \sum_{\ell=0}^{m_n-1} \Upsilon x^\ell e^{-\partial_n x} dx = \sum_{\ell=0}^{m_n-1} \Upsilon \left(\frac{\ell!}{\partial_n^{\ell+1}} \right. \\ \left. - e^{-I(i)(\Sigma_i + cY_i)\partial_n} \times \sum_{p=0}^{\ell} \frac{\ell!}{p!} \frac{(I(i)(\Sigma_i + cY_i))^p}{\partial_n^{\ell-p+1}} \right). \quad (\text{A.2})$$

Further, by denoting $\Delta = I(i)(\Sigma_i + cY_i)$, Δ^p can be expanded using a binomial theorem as $\Delta^p = (I(i))^p \sum_{t=0}^p \binom{p}{t} (\Sigma_i)^{p-t} (cY_i)^t$. Now, for the terrestrial interference link, the i.n.i.d. Gamma RVs with shape m_k and scale ν parameters are generated using the PDF in Eq. (3). Substituting Eq. (A.2) into Eq. (A.1) and by using Δ^p , the outage can be rewritten as

$$\mathbb{P}_{\text{out},i}(v) = \sum_{\ell=0}^{m_n-1} \Upsilon \frac{\ell!}{\partial_n^{\ell+1}} \int_0^\infty \frac{y^{m_k-1} e^{-\frac{y}{\nu}}}{\Gamma(m_k) \nu^{m_k}} dy \\ - \sum_{\ell=0}^{m_n-1} \sum_{p=0}^{\ell} \frac{\ell!}{p!} \frac{\Upsilon e^{-I(i)\Sigma_i \partial_n}}{\partial_n^{\ell-p+1}} (I(i))^p \sum_{t=0}^p \binom{p}{t} \\ \times \frac{(\Sigma_i)^{p-t} c^t}{\Gamma(m_k) \nu^{m_k}} \int_0^\infty (y_i)^{t+m_k-1} e^{-y(\frac{1}{\nu} + I(i)\partial_n c)} dy. \quad (\text{A.3})$$

Finally, we can express the exact OP with the aid of [19, Eq. (8.310.1)] in its closed form as Eq. (9). ■

APPENDIX B TERRESTRIAL SECONDARY NETWORK

The term A in (10) can be rewritten as

$$A = \underbrace{\int_{q=0}^\infty f_Q(q) \underbrace{\int_{z=0}^{T_1+T_2Q_j} f_Z(z) dz}_{A_1}}_{A_2} \underbrace{\int_{y=0}^\Lambda f_Y(y) dy}_{A_3}. \quad (\text{B.1})$$

The PDFs of Z and Y abide by Nakagami- m statistical model and Q term follow Shadowed-Rician distribution. Therefore, by using the PDF in Eq. (3), we obtain $A_1 = 1 - e^{-\frac{T_1-T_2Q_j}{\nu_0}} M_A(T_2Q_j)^n$, where $M_A = \sum_{p=0}^{m_0-1} \frac{1}{\nu_0^p \Gamma(p+1)} \sum_{n=0}^p \binom{p}{n} T_1^{p-n}$. Now, using A_1 , the PDF in Eq. (1) and [19, Eq. (3.351.3)], we can calculate A_2 as

$$A_2 = \left(1 - e^{-\frac{T_1-T_2Q_j}{\nu_0}} M_A(T_2Q_j)^n \right) \sum_{\ell=0}^{m_n-1} \Upsilon \int_0^\infty q^\ell e^{-\partial_n q} dq$$

$$\begin{aligned}
&= \sum_{\ell=0}^{m_n-1} \Upsilon \left(\int_0^\infty q^\ell e^{-\partial_n q} dq - e^{-\frac{T_1}{\nu_0}} M_A T_2^n \int_0^\infty q^n q^\ell e^{-\left(\frac{T_2}{\nu_0} + \partial_n\right)q} dq \right) \\
&= \sum_{\ell=0}^{m_n-1} \Upsilon \left(\ell! \partial_n^{\ell-1} - e^{-\frac{T_1}{\nu_0}} M_A T_2^n (n+\ell)! \left(\frac{T_2}{\nu_0} + \partial_n \right)^{-n-\ell-1} \right), \quad (\text{B.2})
\end{aligned}$$

and the CDF of A_3 can be obtained independently as $\frac{\gamma(m_k, \frac{\Lambda}{\nu})}{\Gamma(m_k)}$. Finally, by inserting A_2 and A_3 into Eq. (B.1), we express the term A in closed-form as Eq. (12).

The term B in Eq. (10) can be determined as

$$B = \int_{q=0}^\infty f_Q(q) \underbrace{\int_{y=\Lambda}^\infty f_Y(y) \int_0^{R_1 Y + R_2 Y Q_j + R_3} f_Z(z) dz dy}_{B_1} dq. \quad (\text{B.3})$$

Here, using Eq. (3), B_1 can be calculated as

$$\begin{aligned}
B_1 &= \left(1 - e^{-\frac{R_1 Y - R_2 Y Q_j - R_3}{\nu_0}} \sum_{p=0}^{m_0-1} \frac{(R_3 + Y(R_1 + R_2 Q_j))^p}{\nu_0^p \Gamma(p+1)} \right) \\
&\times \int_\Lambda^\infty \frac{y^{m-1} e^{-\frac{y}{\nu}}}{\Gamma(m) \nu^m} dy = \frac{\Gamma(m, \frac{\Lambda}{\nu})}{\Gamma(m)} - e^{-\frac{R_3}{\nu_0}} M_B (R_1 + R_2 Q_j)^t \\
&\times \int_\Lambda^\infty \frac{y^t y^{m-1} e^{-y(\frac{1}{\nu} + V_1 Q_j)}}{\Gamma(m) \nu^m} dy = \frac{\Gamma(m, \frac{\Lambda}{\nu})}{\Gamma(m)} - e^{-\frac{R_3}{\nu_0}} M_B \\
&\times \underbrace{(R_1 + R_2 Q_j)^t \frac{\Gamma(t+m, (\frac{1+\nu V_1 Q_j}{\nu}) \Lambda)}{\Gamma(m) \nu^m} \left(\frac{1+\nu V_1 Q_j}{\nu} \right)^{-t-m}}_{B_2}, \quad (\text{B.4})
\end{aligned}$$

where $M_B = \sum_{p=0}^{m_0-1} \frac{1}{\nu_0^p \Gamma(p+1)} \sum_{t=0}^p \binom{p}{t} (R_3)^{p-t}$, $V_1 = \frac{R_1 + R_2}{\nu_0}$.

Now, we need to apply the series representation of the upper incomplete Gamma function given by [19] as $\Gamma(b, c) = \Gamma(b) e^{-c} \sum_{i=0}^{b-1} \frac{c^i}{i!}$ and binomial theorem in order to expand B_2 in Eq. (B.4). Then, by using the aforementioned methods and after some mathematical manipulations, we rewrite B_2 as

$$\begin{aligned}
B_2 &= \sum_{i=0}^t \binom{t}{i} R_1^{t-i} (R_2 Q_j)^i \sum_{j=0}^{t+m-1} \frac{\Gamma(t+m) \Lambda^j V_2}{\Gamma(m) \nu^m j!} \\
&\times e^{-\left(\frac{1}{\nu} + \frac{R_1 + R_2 Q_j}{\nu_0}\right) \Lambda} (1 + \Omega Q_j)^{j-t-m}, \quad (\text{B.5})
\end{aligned}$$

where $V_2 = \left(\frac{\nu_0 + \nu R_1}{\nu_0 \nu} \right)^{j-t-m}$ and $\Omega = \frac{\nu R_2}{\nu_0 + \nu R_1}$. Thus, the term B can be rewritten as

$$\begin{aligned}
B &= \frac{\Gamma(m, \frac{\Lambda}{\nu})}{\Gamma(m)} \sum_{\ell=0}^{m_n-1} \Upsilon \int_0^\infty q^\ell e^{-\partial_n q} dq - e^{-\frac{R_3}{\nu_0}} M_B \sum_{i=0}^t \binom{t}{i} \\
&\times R_1^{t-i} R_2^i \frac{\Gamma(t+m)}{\Gamma(m) \nu^m} e^{-\left(\frac{1}{\nu} + \frac{R_1}{\nu_0}\right) \Lambda} \sum_{j=0}^{t+m-1} \frac{\Lambda^j}{j!} V_2 \sum_{\ell=0}^{m_n-1} \Upsilon \\
&\times \int_0^\infty (1 + \Omega Q_j)^{-(t+m-j)} q^{i+\ell+1-1} e^{-\left(\frac{R_2 \Lambda}{\nu_0} + \partial_n\right)q} dq. \quad (\text{B.6})
\end{aligned}$$

Finally, by using the Meijer-G function represented with the aid of [20, Eqs. (7.34.3.46.1) and (7.34.3.271.1)], where $e^{-b\gamma} =$

$G_{0,1}^{1,0}(b\gamma|_0^-)$ and $(1+c\gamma)^{-d} = \frac{1}{\Gamma(d)} G_{1,1}^{1,1}(c\gamma|_0^{1-d})$, and after some mathematical manipulations with the additional aid of [19, Eq. (3.351.3)], we obtain the closed-form expression of term B as in Eq. (11). ■

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