Outage Probability Analysis for Hybrid Satellite and Terrestrial Network with Different Combining Schemes

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Abstract. In this paper, we investigate the outage probability (OP) of a hybrid satellite and terrestrial cooperative network (HSTCN) with the terrestrial relay having multiple antennas. Here, it is assumed that the satellite channel undergoes the shadowed-Rician fading, while terrestrial channel follows correlated Rayleigh fading. By supposing that statistic channel state information (CSI) of relay-destination link is available at the relay, we first obtain the end-to-end output signal-to-noise ratio (SNR) expression of the HSTCN. Then, the closed-form expressions of the outage probability for the considered system are derived, where two combining schemes, namely, selection combing (SC) and maximal-ratio combining (MRC) protocols are utilized at the destination to combine signals form the satellite and relay. Finally, numerical results are given to validity of the OP analysis, and reveal the performance difference of the two combining schemes.

Keywords: Satellite communication · Correlated Rayleigh · Multi-antennas

1 Introduction

Satellite communication is known as its wide coverage and convenience for remote communication [1]. In order to extend the coverage of satellite and achieve high data transmission, especially when the line of sight link (LOS) is blocked by obstacles, the hybrid satellite-terrestrial cooperative networks were proposed [2].

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Since the potential value of HSTCNs, many researchers studied this issue. The authors in [3] addressed a problem of amplify-and-forward (AF) based HSTCN in which the MRC was applied at the destination, and the average symbol error rate (ASE) of this system was given. In [4], the authors studied the secrecy performance of a HSTCN in the presence of multiple eavesdroppers, furthermore, they also assumed that the perfect CSI was available at the relay and they considered different cooperative protocols at the relay, namely decode-and-forward (DF) and AF. The authors in [5] considered a HSTCN with AF based relay, in which the satellite node and destination node were equipped with multi-antenna while the relay node was equipped with single antenna, the outage probability of this system was evaluated. The authors in [6] analyzed the ergodic capacity of a best relay selection HSTCN, in which statistic CSI of relay-destination links was available at the relays. Furthermore, they considered two different cases that DF and AF were applied at the relay, respectively.

Although many researchers such as [3–6] have studied the performance form many angles, they haven't considered the situation that the relay-destination link follows correlated Rayleigh fading and the CSI of this link is statistical such as [7], especially when there are different combining protocols applied at the destination. To fill this gap, we consider a HSTCN with a multi-antenna DF relay where the satellite links undergo the shadowed-Rician fading and the terrestrial link undergoes the correlated Rayleigh fading. Moreover, in order to fully analyze the performance of this system, we assume that the destination applies SC and MRC protocols, respectively. Then, we analyze the outage probability of these two schemes and obtain the closed-form expressions, as far as the authors known, this is the first time that such expressions are obtained. Finally, the numerable results are provided to confirm the correctness of these expressions and show the different performance of the two combining protocols.

2 System Model

We consider a HSTCN in which the satellite source (S) communicates with a terrestrial destination (D) with the aid of a terrestrial relay (R), similar as [8]. We assume that the S-R and S-D links follow the shadowed-Rician fading and the R-D link undergoes the correlated Rayleigh fading. The satellite and the terrestrial user nodes are both installed a signal antenna, while the terrestrial relay node is equipped with N antennas.

The process of the communication in this HSTCN can be divided into two time slots. During the first time slot, S sends its signal $x_s(t)$ to R and D with the average power $\mathrm{E}\left[|x_s(t)|^2\right] = 1$, the received signal at R and D are expressed as [9]

$$y_{d1}(t) = \sqrt{P_s} h_{sd}(t) x_s(t) + n_{d1}(t), \tag{1}$$

$$y_r(t) = \sqrt{P_s} \mathbf{w}_{sr}^H \mathbf{h}_{sr} x_s(t) + n_r(t), \tag{2}$$

where P_s denotes the transmit power of S, h_{sd} and $\mathbf{h}_{sr} = [h_1, h_2, \cdots, h_N]^T$ the channel coefficient of S-D link and S-R link, respectively, $\mathbf{w}_{sr} \in \mathbf{C}^{N\times 1}$ the receive beamforming (BF) weight vector at R, $n_{d1(t)}$ and $n_r(t)$ represent the zero mean additive white Gaussian noise (AWGN) with variances σ_0^2 and σ_1^2 at D and R, respectively. Then, the signal-to-noise ratios (SNRs) at D and R during the first time phase are, respectively, given by

$$\gamma_{d1} = \frac{P_s}{\sigma_0^2}|h_{sd}|^2, \tag{3}$$

$$\gamma_r = \frac{P_s}{\sigma_1^2}\mathbf{h}_{sr}^H\mathbf{w}_{sr}\mathbf{w}_{sr}^H\mathbf{h}_{sr}. \tag{4}$$

During the second time phase, R processes the received signal $y_r(t)$ and employs the DF strategy and sends the re-encoded signal $x_r(t)$ with $\mathrm{E}\left[|x_r(t)|^2\right] = 1$ to D with weight vector $\mathbf{w}_{rd} \in \mathbf{C}^{N\times 1}$. Thus, the received signal at D from the relay can be modeled as

$$y_{d2}(t) = \sqrt{P_r}\mathbf{h}_{rd}^H\mathbf{w}_{rd}x_r(t) + n_{d2}(t), \tag{5}$$

with $n_{d2}(t)$ is the zero mean additive white Gaussian noise (AWGN) with $E\left[n_{d2}(t)^2\right] = \sigma_2^2$. When applying the DF protocol applied at R, the SNR of S-R-D link is given by [10,11]

$$\gamma_{df} = \min\{\gamma_r, \gamma_{d2}\}, \tag{6}$$

where

$$\gamma_{d2} = \frac{P_r}{\sigma_2^2}\mathbf{w}_{rd}^H\mathbf{h}_{rd}\mathbf{h}_{rd}^H\mathbf{w}_{rd}. \tag{7}$$

Since D receives signals both from S and R, we consider D applies two different combining protocols to combine the signal, namely, MRC and SC.

(1) By applying SC at D, the output SNR is given by

$$\gamma_{SC} = \max\{\gamma_{df}, \gamma_{d1}\} = max\{min\{\gamma_r, \gamma_{d2}\}, \gamma_{d1}\}, \tag{8}$$

(2) By applying MRC at D, the output SNR is given by

$$\gamma_{MRC} = \gamma_{df} + \gamma_{d1} = min\{\gamma_r, \gamma_{d2}\} + \gamma_{d1}. \tag{9}$$

3 Problem Formulation and Preliminary Results

We consider a optimization problem to maximize the end-to-end SNRs, namely, γ_{SC} and γ_{MRC} with the constrained of transmit BF weight vectors of this system.

$$\max_{\mathbf{w}_{sr},\mathbf{w}_{rd}} \gamma_i \quad s.t. \|\mathbf{w}_{sr}\| = 1, \|\mathbf{w}_{rd}\| = 1, \tag{10}$$

where $(i = SC, MRC)$. Since γ_{d1} is not affected by $\mathbf{w}_{sr}, \mathbf{w}_{rd}$, and according to (8) and (9), the optimization problem (10) can be reformulated as the following two optimization problem, namely

$$\max_{\mathbf{w}_{sr}} \gamma_r = \frac{P_s}{\sigma_1^2} \mathbf{w}_{sr}^H \mathbf{h}_{sr} \mathbf{h}_{sr}^H \mathbf{w}_{sr} \quad s.t. \, \|\mathbf{w}_{sr}\| = 1, \tag{11}$$

$$\max_{\mathbf{w}_{rd}} \gamma_{d2} = \frac{P_r}{\sigma_{d2}^2} \mathbf{w}_{rd}^H \mathbf{h}_{rd} \mathbf{h}_{rd}^H \mathbf{w}_{rd} \quad s.t. \, \|\mathbf{w}_{rd}\| = 1. \tag{12}$$

Then, we focus on the design of receive and transmit BF at R.

3.1 Satellite Downlink Channels

For the optimization problem (11), obviously, the solution is MRC [12], so we have $\mathbf{w}_{sr} = \mathbf{h}_{sr}/\|\mathbf{h}_{sr}\|$. Such that, the maximal value of γ_r is given by

$$\gamma_r = \overline{\gamma}_r |\mathbf{h}_{sr}|^2, \tag{13}$$

where $\overline{\gamma}_r = \frac{P_s}{\sigma_1^2}$ presents the average SNR at S, and $|\mathbf{h}_{sr}|^2 = \sum_{i=1}^{N} |h_i|^2$.

In this paper, we assume the satellite links undergo Shadowed-Rician fading, thus the probability density functions (PDFs) of $|h_i|^2$ $(i = 1, 2 \cdots N)$ can be expressed as [12,13]

$$f_{|h_i|^2}(x) = \alpha_i \exp(-\beta_i x) {}_1F_1(m_i; 1; c_i x), \tag{14}$$

where $\alpha_i = (2b_i m_i/(2b_i m_i + \Omega_i))^{m_i}/2b_i$, $\beta_i = 1/2b_i$,$c_i = (\Omega_i/(2b_i m_i + \Omega_i))/2b_i$, $(i = 1, \cdots N)$, Ω_i is the average power of the LOS component, $2b_i$ is the average power of the multi-path component and m_i the Nakagami-m parameter. We assume that S-R link is $ii.d$ fading channels, such that, we denote $\Omega_1 = \cdots = \Omega_N = \Omega b_1 = \cdots = b_N = b, m_1 = \cdots = m_N = m$, hence the subscript $i = 1, \cdots N$ can be dropped, meanwhile, we retain our focus in the case of Nakagami-m parameter taking integer values, $i.e.\, m \in \mathrm{N}$. With the help of [12], ${}_1F_1(m; 1; cx)$ becomes

$${}_1F_1(m; 1; cx) = \exp(cx) \times \sum_{k=0}^{m-1} \frac{(-1)^k (1-m)_k (cx)^k}{(k!)^2}, \tag{15}$$

with $(x)_n = x(x+1) \cdots (x+n-1)$. Then, by applying (15) to (14), the PDF of $|h_i|^2$ can be denoted as

$$f_{|h_i|^2}(x) = \sum_{k=0}^{m-1} \underbrace{\frac{(-1)^k (1-m)_k c^k}{(k!)^2}}_{\xi(k)} \times \alpha x^k \exp(-(\beta - c)\, x). \tag{16}$$

After some mathematical calculation, the PDF of $|\mathbf{h}_{sr}|^2$ is given by [12]

$$f_{|\mathbf{h}_{sr}|^2}(x) = \sum_{k_1=0}^{m-1} \cdots \sum_{k_N=0}^{m-1} \Xi(N) x^{\Lambda-1} \exp\left(-(\beta - c)\, x\right), \tag{17}$$

where $\Lambda \triangleq \sum_{i=1}^{N} k_N + N$ and

$$\Xi(N) = \prod_{i=1}^{N} \xi(k_i)\alpha^N \prod_{j=1}^{N-1} B(\sum_{l=1}^{j} k_l + j, k_{j+1} + 1), \tag{18}$$

with $B(\cdot,\cdot)$ denoting the beta function [14]. Thus the PDF of γ_r can be obtained as

$$f_{\gamma_r}(x) = \sum_{k_1=0}^{m-1} \cdots \sum_{k_N=0}^{m-1} \frac{\Xi(N)x^{\Lambda-1}}{\overline{\gamma}_s{}^{\Lambda}} \exp\left(-\frac{\beta-c}{\overline{\gamma}_s}x\right). \tag{19}$$

Meanwhile, S-D link also undergoes the shadowed-Rician fading with the parameters (m_0, b_0, Ω_0), such that, the PDF of γ_{d1} can be expressed as

$$f_{\gamma_{d1}}(x) = \sum_{k=0}^{m_0-1} \frac{\xi(k)}{\overline{\gamma}_s^{k+1}} \alpha_0 x^k \exp\left(\frac{-(\beta_0 - c_0)}{\overline{\gamma}_s}x\right). \tag{20}$$

3.2 Terrestrial Downlink Channel

We assume the R-D link follows correlated Rayleigh fading, such as the related work [15], thus $\mathbf{h}_{rd}(N \times 1)$ can be modeled as [15,16]

$$\mathbf{h}_{rd}(t) = \frac{1}{\sqrt{L}} \sum_{l=1}^{L} \rho_l(t)\,\mathbf{a}(\theta_l), \tag{21}$$

where $\theta_l \in \left[\overline{\theta}_l - \Delta\theta_l/2, \overline{\theta}_l + \Delta\theta_l/2\right]$ is the angle-of-departure (AOD) of the l-th path signal with $\overline{\theta}_l$ being the mean cluster AOD and $\Delta\theta_l$ the angular spread, respectively, $\rho_l\ \left(0, \sigma^2\right)$ denote the fading coefficient of the path signal, respectively. Without loss of generality, $\rho_l(t)$ in (21) is modeled as a complex Gaussian random variable with zero mean and unit variance. If uniform linear array (ULA) is employed at the transmitter, the downlink array steering vector $\mathbf{a}(\theta_l)$ is given by

$$\mathbf{a}(\theta_l) = \left[1, exp\left(j\kappa d_a \cos\theta_l\right), \ldots, exp\left(j\left(N-1\right)\kappa d_a \cos\theta_l\right)\right]^T, \tag{22}$$

with $\kappa = \frac{2\pi}{\lambda_{rd}}$ being the wavenumber, λ_{rd} the carrier wavelength and d_a the inter-element spacing. Then, we put our attention on the optimization problem (12) to maximize the received SNR at D for R-D link. Specifically, the statistical CSI of R-D link is available at R as our assumption. In this case, R only know the matrix of $\mathbf{h}_{rd}$, that is, $R = E\left[\mathbf{h}_{rd}\mathbf{h}_{rd}^H\right]$. Such that, the optimization problem (12) can be denoted as

$$\begin{aligned} \max_{\mathbf{w}_{rd}} \gamma_{d2} &= \bar{\gamma}_r \mathbf{w}_{rd}^H \underbrace{E\left[\mathbf{h}_{rd}\mathbf{h}_{rd}^H\right]}_{R} \mathbf{w}_{rd}, \\ s.t. \quad & \|\mathbf{w}_{rd}\| = 1. \end{aligned} \tag{23}$$

Then, with the help of singular value decomposition (SVD) to R [17], we have that

$$\mathbf{R} = \mathbf{V}\mathbf{\Phi}\mathbf{V}^H, \quad \mathbf{\Phi} = \ \text{diag}\left(\lambda_1, \ldots, \lambda_N\right), \quad \mathbf{V} = \left[\mathbf{v}_1, \ldots, \mathbf{v}_N\right], \tag{24}$$

where $\mathbf{V}$ is the unitary matrix with $\mathbf{v}_j\,(j=1,\ldots,N)$ being the corresponding eigenvectors, $\mathbf{\Phi}$ the eigenvalue matrix with eigenvalues $\lambda_j\,(j=1,\ldots,N)$ which are arranged in decreasing order. With the aid of Generalized Rayleigh entropy formula, we have that

$$\mathbf{w}_{rd}^H\mathbf{R}\mathbf{w}_{rd} \le \lambda_{\max}(\mathbf{R}) = \lambda_1, \tag{25}$$

with the equality sign holding when $\mathbf{w}_{rd}$ equals to the eigenvector corresponding to λ_1. Such that, the solution of optimization (12) is $\mathbf{w}_{rd}=\mathbf{v}_1$. Meanwhile, by using the Kronecker model, $\mathbf{h}_{rd}$ can be denoted as

$$\mathbf{h}_{rd} = \mathbf{R}^{\frac{1}{2}}\tilde{\mathbf{h}}_{rd}, \tag{26}$$

where $\tilde{\mathbf{h}}_{rd} = \left[\tilde{h}_{rd,1},\ldots,\tilde{h}_{rd,N}\right]^T$ with $\tilde{h}_{rd,i} \sim CN(0,1)$ being i.i.d random variables. Such that, γ_{d2} can be rewritten as

$$\begin{aligned}\gamma_{d2} &= \bar{\gamma}_r\left|\mathbf{w}_{rd}^H\mathbf{h}_{rd}\right|^2 = \bar{\gamma}_r\left|\mathbf{v}_1^H\mathbf{R}^{\frac{1}{2}}\tilde{\mathbf{h}}_{rd}\right|^2\\ &= \bar{\gamma}_r\tilde{\mathbf{h}}_{rd}^H\mathbf{R}^H\mathbf{v}_1\mathbf{v}_1^H\mathbf{R}^{\frac{1}{2}}\tilde{\mathbf{h}}_{rd}\\ &= \bar{\gamma}_r\lambda_1\left|\tilde{h}_{rd,1}\right|^2.\end{aligned} \tag{27}$$

Then, after some mathematical calculation, the PDF of γ_{d2} is given by

$$f_{\gamma_{d2}}(x) = \frac{1}{\lambda_1\bar{\gamma}_r}e^{-\frac{x}{\lambda_1\bar{\gamma}_r}}. \tag{28}$$

4 Outage Probability

Outage probability is defined as the probability that the SNR falls below a certain threshold γ_{th}, thus the OPs of this system when SC and MRC are applied at D, namely, P_{SC}^{out} and P_{MRC}^{out} are given by

$$\begin{aligned}P_{SC}^{out} &\triangleq \Pr\{\gamma_{SC} < \gamma_{th}\} = \Pr\{\max\{\gamma_{df},\gamma_{d1}\} < \gamma_{th}\}\\ &= F_{\gamma_{df}}(\gamma_{th}) \times F_{\gamma_{d1}}(\gamma_{th})\\ P_{MRC}^{out} &\triangleq \Pr\{\gamma_{MRC} < \gamma_{th}\} = \Pr\{(\gamma_{df}+\gamma_{d1}) < \gamma_{th}\}\\ &= \int_0^x F_{\gamma_{df}}(x-\tau) \times f_{\gamma_{d1}}(\tau)d\tau,\end{aligned} \tag{29}$$

with $F_{\gamma_{df}}(\gamma_{th}) = 1-(1-F_{\gamma_r}(\gamma_{th}))\times(1-F_{\gamma_{d2}}(\gamma_{th}))$, $F_{\gamma_i}(x)$, $(i \triangleq r, d1, d2)$ being the cumulative distribution function (CDF) of γ_i. with the help of [14], the CDF of γ_{d1} can be written as

$$F_{\gamma_{d1}} = \sum_{k=0}^{m_0-1}\frac{k!\xi(k)\alpha_0}{(\beta_0-c_0)^{k+1}}\left(1-\sum_{l=0}^{k}\frac{(\beta_0-c_0)^l{\gamma_{th}}^l}{l!\bar{\gamma}_s^t}\times\exp\left(\frac{-(\beta_0-c_0)\gamma_{th}}{\bar{\gamma}_s}\right)\right). \tag{30}$$

Such that, the CDF of γ_{df} can be obtained as

$$F_{\gamma_{df}} = \left[1-\sum_{k_1=0}^{m-1}\cdots\sum_{k_N=0}^{m-1}\sum_{r=0}^{\Lambda-1}\frac{(\Lambda-1)!\Xi(N){\gamma_{th}}^r}{r!\bar{\gamma}_s^r(\beta-c)^{\Lambda-r}}\exp\left(-\left(\frac{\beta-c}{\bar{\gamma}_s}+\frac{1}{\lambda_1\bar{\gamma}_r}\right)\gamma_{th}\right)\right], \tag{31}$$

(1) In the case of SC applied at D, with the help of Eqs. (29) - (31), P_{SC}^{out} can be written as (32)

$$\begin{aligned} P_{SC}^{out} &= F_{\gamma_{df}}(\gamma_{th}) \times F_{\gamma_{d1}}(\gamma_{th}) \\ &= \sum_{k=0}^{m_0-1} \frac{k!\xi(k)\alpha}{(\beta_0-c_0)^{k+1}} \left(1 - \sum_{l=0}^{k} \frac{(\beta_0-c_0)^l {\gamma_{th}}^l}{l!\bar{\gamma}_s^t} \exp(\frac{-(\beta_0-c_0)\gamma_{th}}{\bar{\gamma}_s})\right) \\ &\times \left[1 - \sum_{k_1=0}^{m-1} \cdots \sum_{k_N=0}^{m-1} \sum_{r=0}^{\Lambda-1} \frac{(\Lambda-1)!\Xi(N){\gamma_{th}}^r}{r!\bar{\gamma}_s^r(\beta-c)^{\Lambda-r}} \exp\left(-\left(\frac{\beta-c}{\bar{\gamma}_s} + \frac{1}{\lambda_1\bar{\gamma}_r}\right)\gamma_{th}\right)\right]. \end{aligned} \tag{32}$$

(2) In the case of MRC applied at D, the OP is given by (32)

$$\begin{aligned} P_{MRC}^{out} &= \sum_{k=0}^{m_0-1} \frac{k!\xi(k)\alpha_0}{(\beta_0-c_0)^{k+1}} \left(1 - \sum_{l=0}^{k} \frac{(\beta_0-c_0)^l {\gamma_{th}}^l}{l!\bar{\gamma}_s^t} \exp\left(\frac{-(\beta_0-c_0)\gamma_{th}}{\bar{\gamma}_s}\right)\right) \\ &- \sum_{k=0}^{m_0-1} \sum_{k_1=0}^{m-1} \cdots \sum_{k_N=0}^{m-1} \sum_{r=0}^{\Lambda-1} \frac{(\Lambda-1)!\Xi(N)\alpha_0\xi(k){\gamma_{th}}^{(k+r+1)}}{r!\bar{\gamma}_s^{(r+k+1)}(\beta-c)^{\Lambda-r}} \exp\left(-\left(\frac{\beta-c}{\bar{\gamma}_s} + \frac{1}{\lambda_1\bar{\gamma}_r}\right)\gamma_{th}\right) \\ &\times B(r+1,k+1)\,{}_1F_1\left(k+1, r+k+2, \left(\frac{1}{\lambda_1\bar{\gamma}_r} + \frac{(\beta-c)-(\beta_0-c_0)}{\bar{\gamma}_s}\right)\gamma_{th}\right) \end{aligned} \tag{33}$$

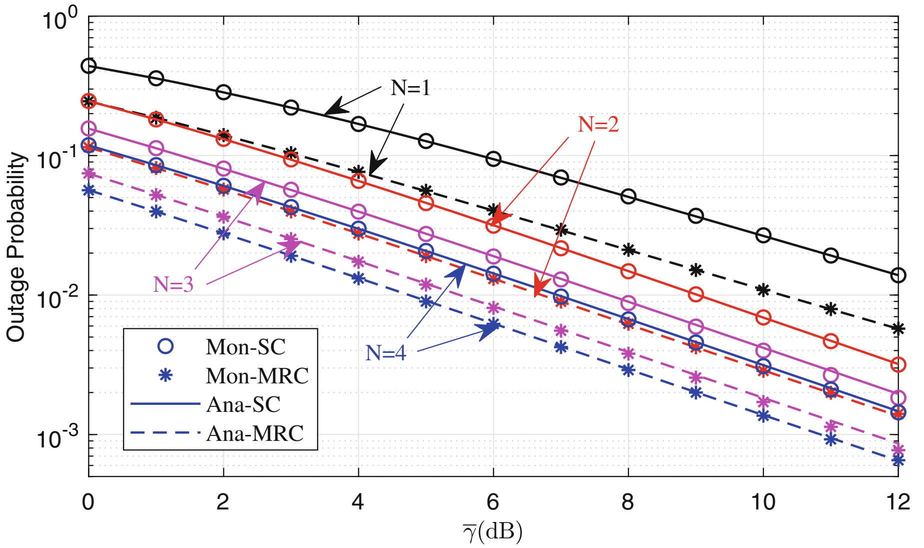

Fig. 1. Outage probability of the system

5 Simulation Results

In this section, we provide the simulation results to testify the validity of expressions of OP in the last section, the results also shows the influence of the antennas' number and different combining protocol to the OP of this system. The simulation results are obtained with 10^7 channel realizations, and we assume that $\overline{\gamma} = \overline{\gamma}_r = 2\overline{\gamma}_s$, $\gamma_{th} = 0\,\text{dB}$ for both the satellite and terrestrial links.

Figure 1 shows the OP of the system in the case that different protocols applied at D and different antennas' number equipped at R. We assume that $b = 0.251$, $m = 5$, $\Omega = 0.278$ and $\theta = 5°, L = 10$. It can be clearly observed that the OP curves are corresponding ti the analysis curves, while the performance gets better with the increase of antennas' number at relay no matter in any scheme. And we find that the performance of the system when MRC applied at D is better than the case that SC applied at D, which means MRC is more efficient than SC for combining.

6 Conclusion

In this paper, we analyze the performance of a HSTCN with a DF based terrestrial relay which is equipped with multi-antennas. We consider MRC and SC combing schemes at D for this system to detail the analysis, the expressions of OP are obtained. According to the numerical results, we find that the performance of this system gets better with these reasons: the increase of antennas' number at terrestrial relay and the enhancing of combining protocol at the destination.

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