Outage Performance of Cooperative Deep-Space Downlink with Backbone Relaying in SBINs

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Abstract. In this paper, we investigate the performance of cooperative deep-space downlink with an amplify-and-forward (AF) backbone relaying in Space-based Information Networks (SBINs). In this SBINs communication scenario, we assume both the source-destination and relay-destination links undergo the shadowed-Rician fading, and the source-relay link follows the Rician fading distributions, respectively. Moreover, the effect of satellite perturbation of backbone relaying satellite is considered, and the maximum ratio combining is implemented at the terrestrial destination. Based on this setup, we first derive the approximate statistical distributions of signal-to-noise ratio of the system, then the closed-form expressions are obtained to efficiently evaluate the outage probability (OP) of the system. Finally, some simulation results are provided to verify our analysis.

Keywords: Space-based Information Networks
Amplify-and-forward relaying · Shadowed-Rician fading
Dual-hop cooperative · Satellite perturbation

1 Introduction

Ideally, two geostationary Earth orbit (GEO) satellites can form a space-based constellation to gain an overall visual field for deep-space exploration observation to realize 24-h continuous information acquisition and data relaying. And three GEO satellites which are 120° apart in the Space-based Information Network (SBIN) backbone networks can provide global coverage of the space between Earth ground and GEO orbit.

Nowadays, with the development of high throughput satellites (HTS), several GEO HTS and geosynchronous Earth orbit (GSO) HTS can be connected to form the SBIN backbone networks, which can provide a global seamless broadband

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transmission by developing the inter-satellite links, and enhance the satellite-ground station communication capacity. People believe that SBINs will be a significant enabling factor as well as an important component of the upcoming 5th generation (5G) networks [1].

At present, the research works of the channel models in future SBINs are mainly focus on the hybrid satellite-terrestrial cooperative networks (HSTCNs). For example, the outage probability (OP) of HSTCNs using AF or decode-and-forward (DF) relaying was analyzed in [2], the OP of HSTCNs was investigated in [3] using multi-antenna source/relay/destination. The actual satellite communication system also need consider other factors, such as co-channel interference (CCI) [4], antenna tracking error [5], and so on.

Moreover, the SBINs backbone GEO satellites are subjected to various satellite perturbation forces (such as, Earths perturbation, third-body gravitational perturbation, solar perturbation, etc.), which leads to position drift and the beam center of the ground station antenna can not focus [6], and cause the satellite elevation error. The satellite elevation error will reduce antenna pointing accuracy, lossing of link margin, signal-to-noise ratio E_b/N_0 decrease and bit error rate (BER) increase, etc. [7]. Thus, this paper is the first work to study the effect of GEO satellite perturbation in cooperative deep-space downlink with an AF backbone relaying in SBINs.

In this paper, by applying maximal ratio combining (MRC) at the destination, the relay node employ AF protocol, every node is equipped with single antenna, and the equivalent end-to-end output signal-to-noise ratio (SNR) of the system is obtained. Then, analytical expressions are derived to evaluate the system performance. The detailed contributions of this paper are outlined as follows:

(1) The system model of deep-space downlink cooperative transmission system with relay GEO satellite is first built, and analytical expression for the end-to-end OP is given. Moreover, simulation results prove the rationality of this model.
(2) The effect of satellite perturbation in deep-space downlink cooperative transmission system with relay GEO satellite is considered for the first time. The cumulative perturbation error of antenna elevation affected by satellite perturbation is analyzed, and the relationship between satellite perturbation and the system OP is presented.

Notations: X-Y describes the link from node X to node Y. X-Y-Z represents the link from node X to node Z through relay node Y. $N(\mu, \sigma^2)$ denotes a complex Gaussian distribution with mean μ and variance σ^2.

2 System Model

2.1 Signal Model

We consider a deep-space downlink cooperative transmission system with relay GEO satellite, as shown in Fig. 1, consisting of a source (S), i.e., the space node, a GEO satellite relay (R) and a terrestrial destination (D). AF protocol is adopted at node. h_0, h_1 and h_2 are the channel gains of S-R, S-D and R-D links, respectively. And, h_0 undergoes Rician fading because of the affect of solar scintillation, h_1 and h_2 links experience Shadowed-Rician fading generally.

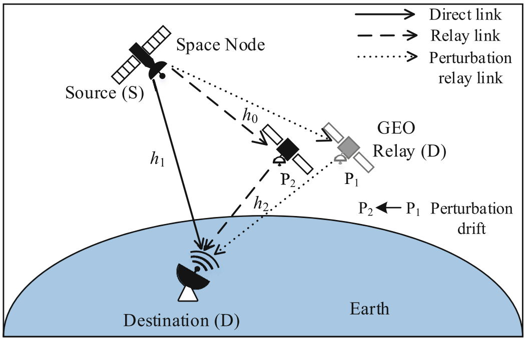

Fig. 1. Proposed deep-space downlink cooperative transmission system with relay GEO satellite, where every node is equipped with single antenna. "Perturbation drift" means that the position P_1 of satellite drifts position P_2 affected by satellite perturbation.

As illustrated in Fig. 1, we assume that all the channel state information (CSI) is perfectly known at node D but not available at node S, and S-R channel is known to node R. For such a system, the total transmission consist of two orthogonal time slots. In the first phase, the space node broadcasts its signal to the relay and the destination, the received signals at the relay and destination from the source are given by

$$y_0 = \sqrt{E_1} h_0 x + n_0 \tag{1}$$

$$y_1 = \sqrt{E_1} h_1 x + n_1 \tag{2}$$

where x is the transmitted signal with unit power, E_1 is the transmitted power at the source node. n_1 and n_0 are the independent complex additive white Gaussian noise (AWGN), they are the noise of S-D link and S-R link, and follow distribution $N(0, \sigma_1^2)$ and $N(0, \sigma_0^2)$, respectively.

During the second time slot, the GEO satellite relay processes its received signal and employs the AF strategy to normalize y_0 and then forward it to the destination. Then, the relay uses the amplifying factor G ($G > 0$) to multiply y_0 and the received signal at the destination is given by

$$y_2 = \sqrt{E_2} G h_2 y_0 + n_2 = G\sqrt{E_1 E_2} h_2 h_0 x + \sqrt{E_2} G h_2 n_0 + n_2 \tag{3}$$

where E_2 is assumed the transmit power of the second phase, n_2 is the noise of R-D link, it is the AWGN with distribution $N(0, \sigma_2^2)$. Assuming MRC is employed at destination, we can obtain the end-to-end SNR as

$$\gamma_{e2e} = \gamma_1 + \gamma_{02} \tag{4}$$

where γ_1 is the SNR of S-D link, γ_{02} is the SNR of S-R-D link. γ_1 and γ_{02} can be expressed as

$$\gamma_1 = \frac{E_1|h_1|^2}{\sigma_1^2} = \rho_1|h_1|^2 \tag{5}$$

$$\gamma_{02} = \frac{\frac{E_1|h_0|^2}{\sigma_0^2} \cdot \frac{E_2|h_2|^2}{\sigma_2^2}}{\frac{E_2|h_2|^2}{\sigma_2^2} + \frac{1}{G^2\sigma_0^2}} = \frac{\gamma_0\gamma_2}{\gamma_2 + C} \tag{6}$$

where $C = \frac{1}{G^2\sigma_0^2}, \gamma_0 = \frac{E_1|h_0|^2}{\sigma_0^2} = \rho_0|h_0|^2, \gamma_2 = \frac{E_2|h_2|^2}{\sigma_2^2} = \rho_2|h_2|^2$.

2.2 Channel Model

The S-R link is modeled as Rician fading, and its PDF of SNR γ_0 writes as

$$f_{\gamma_0}(x) = \frac{(K+1)}{\rho_0\Omega}\exp\left(-\frac{x(K+1)}{\rho_0\Omega} - K\right) \cdot I_0\left(2\sqrt{\frac{K(K+1)x}{\rho_0\Omega}}\right) \tag{7}$$

where $\Omega = (A^2 + 2\sigma^2)/2, \Omega$ is the average power of received signal at node $R, K = \frac{A^2}{2\sigma^2}$ is known as Rician factor, A is the amplitude of LOS signal, σ^2 is average power of multipath component, $I_0(\cdot)$ is the zeroth order modified Bessel function of the first kind. By integrating (7), the CDF can be calculated as

$$F_{\gamma_0}(x) = 1 - Q_1\left(\sqrt{2K}, \sqrt{\frac{2(K+1)x}{\rho_0\Omega}}\right), \tag{8}$$

where $Q_M(\cdot,\cdot)$ is Marcum Q function. For the Rician factor of (7), considering the effect of satellite perturbation, the empirical formula between Rician factor and elevation ($\theta_c \in [10°, 90°]$) can be rewritten as

$$K(\theta_c, \theta_e, t) = 2.731 - 1.074 \times 10^{-1}(\theta_c + \theta_e(\text{sin}t)) + 2.771 \times 10^{-3}(\theta_c + \theta_e(\text{sin}t)) \tag{9}$$

where $\theta_e(\sin t)$ is a function about "$\sin t$", and indicates the elevation error affected by satellite perturbation, θ_e represents the elevation error, θ_c is satellite elevation when satellite is located in ideal position.

Meanwhile, The S-D and R-D links experience Shadowed-Rician fading, their SNR of receiving signal are γ_1 and γ_2, respectively. The PDF of γ_i $(i = 1, 2)$ can be written as

$$f_{\gamma_i(x)} = \frac{\alpha_i}{\rho_i}e^{-\frac{\beta_i}{\rho_i}x} \cdot {}_1F_1\left(m_i; 1; \frac{\delta_i}{\rho_i}x\right) \tag{10}$$

where $\alpha_i = (2b_im_i/(2b_im_i + \Omega_i))^{m_i}/2b_i, \beta_i = 1/2b_i, \delta_i = 0.5\Omega_i/(2b_i^2m_i + b_i\Omega_i)$, Ω_i and $2b_i$ is the average power of LOS and multipath components, respectively, and m_i is the fading severity parameter, $m_i \in (0, \infty)$. ${}_1F_1(\cdot;\cdot;\cdot)$ represents the confluent hypergeometric function of first kind [8, Eq. (9.210.1)]. For analytical tractability, we retain our focus in case when the channel severity parameter take integer values, i.e., $m_i \in \mathrm{N}$. Hence, with the aid of [9, Eq. (07.20.03.0009.01), Eq. (07.02.03.0014.01)], the confluent hypergeometric function of first kind in (10) becomes

$$ {}_1F_1\left(m_i;1;\frac{\delta_i}{\rho_i}x\right)=\exp\left(\frac{\delta_i}{\rho_i}x\right)\sum_{n=0}^{m_i-1}\frac{(-1)^n(1-m_i)_n}{(n!)^2}\left(\frac{\delta_i}{\rho_i}x\right)^n \tag{11}$$

where $(\cdot)_n$ is the Pochhammer symbol with $n \in \mathrm{N}$.

We assume θ_{ci} is the elevation of transmitter (T_X) when the center line of receiving antenna beam in different link aims at the T_X. $\theta_{ci}(\sin t)$ is the elevation error affected satellite perturbation. When $\theta_{ci} \in (20^\circ, 80^\circ)$, Ω_i, b_i and m_i can be calculated by empirical formulas [10, Eq. (19)]. After considering the effect of satellite perturbation, the expressions of Ω_i, b_i and m_i can be transformed into

$$\begin{cases} b_i(\theta_{ci},\theta_{ei},t)=-4.7943\times10^{-8}(\theta_{ci}+\theta_{ci}(\sin t))^3+5.5784\times10^{-6}(\theta_{ci}\\ \;+\theta_{ci}(\sin t))^2-2.1344\times10^{-4}(\theta_{ci}+\theta_{ci}(\sin t))+3.2710\times10^{-2}\\ m_i(\theta_{ci},\theta_{ei},t)=6.3739\times10^{-5}(\theta_{ci}+\theta_{ci}(\sin t))^3+5.8533\times10^{-4}(\theta_{ci}\\ \;+\theta_{ci}(\sin t))^2-1.5973\times10^{-4}(\theta_{ci}+\theta_{ci}(\sin t))+3.5156\\ \Omega_i(\theta_{ci},\theta_{ei},t)=1.4428\times10^{-5}(\theta_{ci}+\theta_{ci}(\sin t))^3-2.3798\times10^{-3}(\theta_{ci}\\ \;+\theta_{ci}(\sin t))^2+1.2702\times10^{-1}(\theta_{ci}+\theta_{ci}(\sin t))-1.4864 \end{cases} \tag{12}$$

where $b_i(\theta_{ci},\theta_{ei},t)$, $m_i(\theta_{ci},\theta_{ei},t)$ and $\Omega_i(\theta_{ci},\theta_{ei},t)$ are the function of θ_{ci}, θ_{ei} and t.

3 Performance Analysis of Outage Probability

In order to analyze exactly the effect of satellite perturbation on deep-space downlink cooperative transmission system with relay GEO satellite, and OP is important quality-of-service (QoS) performance metric in wireless systems. Thus, in this section, the close-form expressions for the OP is derived. The OP is defined as the probability that the output instantaneous SNR γ_{e2e} falls below an acceptable SNR threshold γ_{th}. Combining (4), OP can be written as

$$P_{out}(\gamma_{th})=\Pr\{\gamma_{e2e}\le\gamma_{th}\}=F_{\gamma_1}(\gamma_{th})F_{\gamma_{02}}(\gamma_{th}) \tag{13}$$

where $F_{\gamma_1}(\cdot)$ is the CDF of S-D link, and $F_{\gamma_{02}}(\cdot)$ is the CDF of S-R-D link. From (10), when m_1 is integer values, the CDF of S-D link can be shown to be given by

$$F_{\gamma_1(x)}=\alpha_1\sum_{w=0}^{m_1-1}\frac{(-1)^w(1-m_1)_w}{(w!)^2}\frac{\delta_1^w}{(\beta_1-\delta_1)^{w+1}}\Upsilon\left(w+1,\frac{\beta_1-\delta_1}{\rho_1}x\right) \tag{14}$$

where $\Upsilon(\cdot,\cdot)$ is the incomplete gamma function.

Meanwhile, From (6) and (13), after some algebraic manipulations, the OP of S-R-D link can be written as

$$F_{\gamma_{02}}(\gamma_{th})=\int_0^\infty F_{\gamma_0}\left(\frac{\gamma_{th}(z+C)}{z}\right)f_{\gamma_2}(z)dz \tag{15}$$

Substituting (8) and (10) into (15), by integrating (15) over z, the result of (15) can be obtained. Combining with (14) and after performing some straightforward manipulations, $P_{out}(\gamma_{th})$ of a deep-space downlink cooperative transmission system with relay GEO satellite can be obtained, as presented in (16).

$$\begin{aligned} P_{out}(\gamma_{th}) \approx & \frac{\alpha_2\alpha_1}{\rho_2}\sum_{w=0}^{m_1-1}\frac{(-1)^w(1-m_1)_w}{(w!)^2}\frac{\delta_1^w}{(\beta_1-\delta_1)^{w+1}}\Upsilon\left(w+1,\frac{\beta_1-\delta_1}{\rho_1}\gamma_{th}\right) \\ & \cdot\left[\frac{\rho_2}{\beta_2}F\left(m_2,1;1;\frac{\delta_2}{\beta_2}\right)-2e^{-K-\frac{(K+1)\gamma_{th}}{\rho_0\Omega}}\sum_{l=0}^{k}\frac{\Gamma(k+l)k^{1-2l}K^l}{l!\Gamma(k-l+1)}\right. \\ & \cdot\sum_{q=0}^{l}\left(\frac{(K+1)\gamma_{th}}{\rho_0\Omega}\right)^q\frac{1}{q!}\sum_{p=0}^{q}C^p\sum_{n=0}^{m_2-1}\frac{(-1)^n(1-m_2)_n}{(n!)^2}\left(\frac{\delta_2}{\rho_2}\right)^n \\ & \left.\cdot\left(\frac{\rho_2(K+1)C\gamma_{th}}{\rho_0\Omega(\beta_2-\delta_2)}\right)^{\frac{n-p+1}{2}}K_{n-p+1}\left(\sqrt{\frac{(\beta_2-\delta_2)(K+1)C\gamma_{th}}{\rho_2\rho_2\Omega}}\right)\right] \end{aligned} \quad (16)$$

where $F(\cdot,\cdot;\cdot;\cdot)$ is Hypergeometric functions [8, Eq.(9.100)], $K_n(\cdot)$ represents the modified Bessel function of the second kind with order n [8, Eq. (8.446)], and $k = 50\sqrt{2K}$.

4 Numerical Results

This section gives numerical results to demonstrate the validity of the theoretical analysis and the effect of satellite perturbation on the lunar downlink cooperative transmission system with relay GEO satellite. We assume the node S is a detector on the Moon, its position is lat = 10°N, lon = 0°W. The node R is GEO satellite and the node D is the Qingdao station. The initial position (X, Y, Z) and velocity vector (Vx, Vy, Vz) of GEO satellite in the Cartesian coordinate system, their initial value are (X, Y, Z) = (−32299.6, −27102.6, 0) km and (Vx, Vy, Vz)= (1.97635, −2.35533, 0) km/sec. And the parameters of the various perturbations are shown as follow:

- The Earth gravity model: WGS84_EGM96.grv.
- Satellite mass: 1000 kg, mass-area ratio of satellite: 0.1 m^2/kg.
- Reflection coefficients of spacecraft is 1.2.
- Solar radiation pressure model: Spherical, Solar gravity: $1.327122 * 10^{11}\,\mathrm{km}^3/\mathrm{s}^2$.
- Lunar gravity: $4.902801076 * 10^3\,\mathrm{km}^3/\mathrm{s}^2$.

As we assume the noise power of three nodes is equal to 1, $\mathrm{E}_1 = \mathrm{E}_2, \rho_0 = \rho_1 = \rho_2 = \rho$. In S-R and R-D links, the elevation of T_X ignoring satellite perturbation at node R and D is equal, i.e., $\theta_{c0} = \theta_{c2} = \theta_0$. In order to obtain elevation error of every link, the data in Fig. 2 are sampled at intervals of 12 h.

Figure 2 shows the elevation error caused by satellite perturbation accumulates is about 1°, the simulation time is one month, the step is 60 s. In Moon-satellite link, the maximum of fluctuation is about 0.1°.

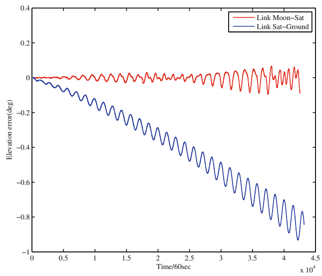

Fig. 2. Elevation error caused by perturbation.

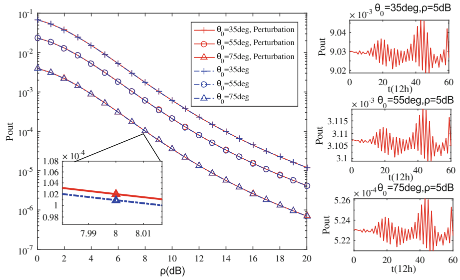

Fig. 3. OP with satellite perturbation versus various ρ regions.

In addition, we assume $\theta_{c1} = 60°$. The multiplier at node R is $G = 30\,\text{dB}$. When the elevation error accumulates in a lunar period, simulation results of OP with satellite perturbation are shown in Fig. 3. "t(12h)" in the x-axis represents an interval of 12 h in Fig. 3, and subfigures on the right show the fluctuation and error accumulation process of outage probability with satellite perturbation over time when $\rho = 5\,\text{dB}$, under different elevation (θ_0) of T_X at node R and D in cooperative link and assuming $\Omega = 5\,\text{W}$, $\gamma_{th} = 0\,\text{dB}$.

It is clear that OP performance is improving as increased receiving SNR ρ. Similarly, elevation of T_X in S-R and R-D links are growing, OP performance also is better. Moreover, comparing with the case ignoring the effect of satellite perturbation, the OP curve considering the effect of satellite perturbation is moved up. Three subfigures in Fig. 3 show the fluctuation and error accumulation process of OP with satellite perturbation over time in case of $\rho = 5\,\text{dB}$, under different θ_0, respectively. When θ_0 is 35°, 55° and 75°, the fluctuation of OP is same, and the fluctuation range are 2.7887e−5, 2.0846e−5 and 5.1451e−6 respectively, which means the fluctuation range is smaller with the increase of θ_0.

5 Conclusion

In deep-space downlink cooperative transmission system with relay GEO satellite, this paper assume the S-D and R-D links experience Shadowed-Rician fading while the S-R link undergoes Rician fading. The close-form expressions for the OP in considered system have been derived, and the impact of satellite perturbation on system performance is considered and analyzed. The simulation results show that the increase of receiving SNR in each node can improve the performance of OP, and satellite perturbation degrades the OP performance and leads to the fluctuation and error accumulation. In addition, growing elevation of T_X in S-R and R-D links improves system OP performance and reduce fluctuation range. Satellites in the orbit are always subjected to a variety of perturbation forces in space environment. Therefore, this paper considers the influence of satellite perturbation in deep-space downlink cooperative transmission system with relay GEO satellite, which is more reasonable and practical.

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