Outage Analysis of Optical ISL-Assisted End-to-End LEO Satellite Communication Systems

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Abstract

In advanced sixth-generation (6G) networks, free-space optical (FSO) enabled inter-satellite links (ISLs), also known as inter-satellite optical communication (ISOC) links, are expected to be the crucial technology for high-speed and long-distance communication in integrated satellite–terrestrial networks. This study investigates the outage performance of the end-to-end (E2E) optical ISL-assisted low-Earth-orbit (LEO) satellite communication systems. The inter-satellite communication is performed over an optical link and is subject to various space channel impairments, including Hoyt distributed vibrations and perturbations-induced pointing errors, as well as plasma absorption. Besides, the gateway-to-satellite and satellite-to-user channels are considered as radio frequency (RF) links following the Nakagami-*m* distribution. Based on this, we calculate the cumulative distribution function (CDF) and probability density function (PDF) of E2E signal-to-noise ratio (SNR). Then, utilizing PDF and CDF, we derive a series-based expression for probability (OP) employing both heterodyne detection (HD) and intensity modulation with direct detection (IM/DD) techniques under a decode and forward (DF) relaying scheme of the considered system. Additionally, to gain further insights, we demonstrate the impact of all considered channel parameters through numerical results.

I. Introduction.

In sixth-generation (6G) communication networks, integrated satellite–terrestrial networks (ISTNs) will be significant for providing extensive coverage through both terrestrial and non-terrestrial infrastructures [1]. Free-space optical (FSO)-aided inter-satellite links (ISLs), also known as inter-satellite optical ISLs are anticipated to be the promising technology for ISTNs to offer high-speed, long-distance communications with extensive coverage, enabling both deep-space missions and global coverage. Additionally, optical ISLs have numerous advantages as compared to radio frequency (RF)-based ISLs. These benefits include higher data rates, smaller antenna sizes, lighter and more compact terminals, narrower beams, minimal interference, enhanced security, greater directivity, lower transmit power, and operation in unlicensed spectrum. In recent years, extensive research has been carried out by academic and industrial researchers on ISOC [1]. Motivated by the existed literature, we examine the outage performance of end-to-end (E2E) optical ISL-assisted low-Earth-orbit (LEO) satellite communication systems.

II. System and Channel Models

Figure 1 illustrates the system model of E2E optical ISL-assisted LEO satellite communication system. In this model, the gateway (G) communicates with users (U) via three sequential hops: a radio frequency (RF) feeder link (G–S), an optical ISL (S–R), and an RF user link (R–U). The satellites S and R are presumed to orbit in a LEO co-orbital configuration, utilizing a decode-and-forward (DF) relay for the entirety of the connection.

A. G–S Link

The received signal at S is expressed as

$$r_{\mathrm{GS}} = \sqrt{P_{T_1} T_G S_G} F_{L_1} h_{\mathrm{GS}} \tau_1 + n_{\mathrm{GS}}, \tag{1}$$

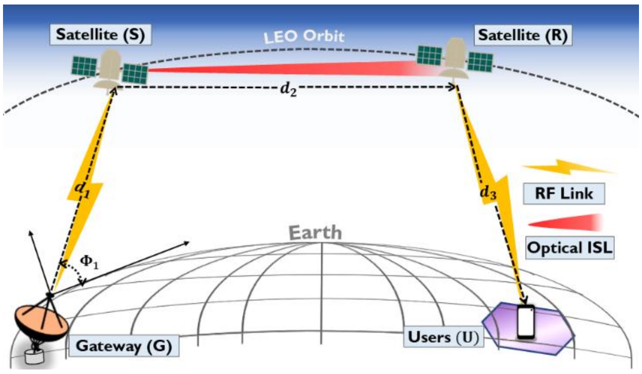

Fig. 1. System model of the E2E optical ISL-assisted LEO satellite communication system.

where P_{T_1} is the transmitted power by G, T_G shows the transmitter antenna gain, S_G indicates the receiver antenna gain, and F_{L_1} denotes the free-space path loss (FSPL) of GS link. Further, h_{GS} characterizes the G-S link channel fading coefficient. Moreover, n_{GS} refers to the additive white Gaussian noise (AWGN) with zero mean and variance σ_{GS}^2.

B. S-R Link

The optical signal received at R is expressed as

$$r_{\mathrm{SR}} = \sqrt{P_{T_2}}\, h_{\mathrm{SR}}\, \tau_2 + n_{\mathrm{SR}}, \tag{2}$$

where $h_{\mathrm{SR}} = h_p\, h_a$, h_p and $h_a = \exp(-L d_2)$ represent the fading channel coefficient corresponding to vibrations and perturbation-induced pointing errors and plasma absorption, respectively. The optical link length and attenuation coefficient denoted by d_2 and L, respectively. In Eq. (2), $\sqrt{P_{T_2}}$ denotes transmitted power, τ_2 is modulated signal, and n_{SR} shows AWGN with zero mean and variance σ_{SR}^2. The combined probability density function (PDF) of h_{SR} is derived as follows:

$$f_{h_{\mathrm{SR}}}(h) = \frac{w_{zeq}^2\sqrt{\eta}}{4\sigma_2^2 h}\left(\frac{h}{h_a A_0}\right)^{\frac{(1+\eta)w_{zeq}^2}{8\sigma_2^2}} I_0\left[\frac{(1-\eta)w_{zeq}^2)}{8\sigma_2^2}\ln\left(\frac{h_a A_0}{h}\right)\right]. \tag{3}$$

In Eq. (3), $0 \le h \le h_a A_0$, w_{zeq} denotes equivalent beam waist, and A_0 indicates the amount of the collected power. Further $\eta = \frac{\sigma_2^2}{\sigma_1^2+\sigma_2^2}$ where σ_1^2 and σ_2^2 are variances of radial displacement resulting from perturbations and vibrations. Moreover, $I_0(\cdot)$ symbolizes modified Bessel function of the first kind of zero order.

C. R–U Link

The received signal at U can be expressed as

$$r_{\mathrm{RU}} = \sqrt{P_{T_3} R_G U_G} F_{L_2}\, h_{\mathrm{RU}}\, \tau_3 + n_{\mathrm{RU}}, \tag{4}$$

where P_{T_3} is transmitted power by R, R_G represents the transmitter antenna gain of R, U_G shows the receiver antenna gain of the user, F_{L_2} denotes FSPL pathloss between R and U. Further, h_{RU} characterizes the RF link channel fading coefficient. Moreover, n_{RU} is the AWGN with zero mean and variance σ_{RU}^2.

III. End-to-End Statistical Characterization

In this section, we evaluate the PDF and cumulative distribution function (CDF) of the end-to-end SNR of the considered system for the DF relaying protocol. Utilizing Eq. (1), the instantaneous SNR of S-R link can be written as follows:

$$\gamma_{\mathrm{SR}} = h_{\mathrm{SR}}^t \bar{\gamma}_{\mathrm{SR}}. \tag{5}$$

In Eq. (5), when t=1 indicates HD technique and t=2 shows IM/DD technique. The average SNR of the S-R link is shown by $\bar{\gamma}_{\mathrm{SR}}$. Further, the CDF of γ_{SR} can be computed as

$$F_{\gamma_{\mathrm{SR}}}(\gamma) = \Pr[h_{\mathrm{SR}}^t \bar{\gamma}_{SR} \le \gamma] = \int_0^{\left(\frac{\gamma}{\bar{\gamma}_{\mathrm{SR}}}\right)^{\frac{1}{t}}} f_{h_{\mathrm{SR}}}(h)dh. \tag{6}$$

Then, utilizing Eq. (6) the series-based expression for CDF of γ_{SR} can be calculated as

$$F_{\gamma_{\mathrm{SR}}}(\gamma) = \frac{w_{zeq}^2\sqrt{\eta}}{4\sigma_2^2}\sum_{n=0}^{\infty}\left(\frac{(\eta-1)w_{zeq}^2}{8\sigma_2^2}\right)^{2n}\left(\frac{(1+\eta)w_{zeq}^2}{8\sigma_2^2}\right)^{-(2n+1)}$$

$$\times \frac{1}{2^{2n}(n!)^{2n}}\Gamma\left(2n+1, \left(\frac{(1+\eta)w_{zeq}^2}{8\sigma_2^2}\right)\ln\left(\frac{h_a A_0}{(\gamma/\bar{\gamma}_{\mathrm{SR}})^{1/t}}\right)\right). \tag{7}$$

In Eq. (7), $\Gamma(\cdot,\cdot)$ represents the upper incomplete Gama function. Likewise, using Eq. (3), the PDF of γ_{SR} is computed as

$$f_{\gamma_{\mathrm{SR}}}(\gamma) = \frac{\gamma^{\left(\frac{1}{t}-1\right)}}{t\,(\bar{\gamma}_{\mathrm{SR}})^{\frac{1}{t}}} f_{h_{\mathrm{SR}}}\left(\left(\frac{\gamma}{\bar{\gamma}_{\mathrm{SR}}}\right)^{\frac{1}{t}}\right). \tag{8}$$

In case of the G-S and R-U links, we exploit the Nakagami-*m* distribution which aptly characterizes the multipath behavior of the RF signal. Thus, the PDF and CDF of the instantaneous SNR of the G-S and R-U links can be expressed as, respectively

$$f_{\gamma_i}(\gamma) = \frac{1}{\Gamma(m)}\left(\frac{m}{\bar{\gamma}_i}\right)^m \gamma^{m-1} \exp\left(\frac{m}{\bar{\gamma}_i}\gamma\right), \tag{9}$$

$$F_{\gamma_i}(\gamma) = 1 - \frac{1}{\Gamma(m)}\Gamma\left(m, \frac{m}{\bar{\gamma}_i}\gamma\right). \tag{10}$$

In eqs. (9)-(10), $i \in \{1,2\}$, 1 indicates the G-S link and 2 shows the R-U link. Further, $\bar{\gamma}_i = \Omega\hat{\gamma}_i$, m shows fading severity, and Ω average power. Here, $\Gamma(\cdot)$ symbolizes the complete gamma function.

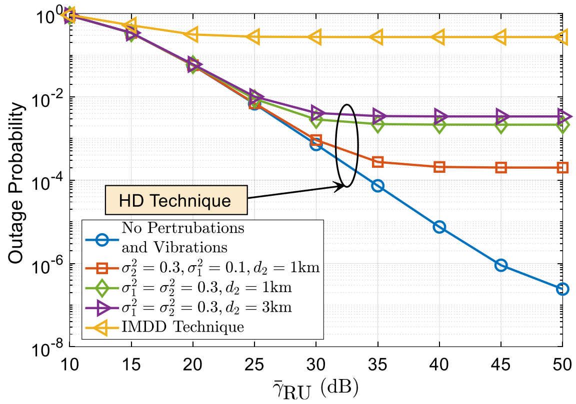

Fig. 2. Outage probability versus average SNR of user for different system parameters.

The E2E CDF of instantaneous SNR of the considered system for the DF relay can be expressed as

$$F_{\gamma_{\mathrm{DF}}}(\gamma) = \Pr[\min(\gamma_{\mathrm{GS}}, \gamma_{\mathrm{SR}}, \gamma_{\mathrm{RU}}) < \gamma]\ ,$$

$$= 1 - (1 - F_{\gamma_{\mathrm{GS}}}(\gamma)) \times (1 - F_{\gamma_{\mathrm{SR}}}(\gamma)) \times (1 - F_{\gamma_{\mathrm{RU}}}(\gamma)). \tag{11}$$

IV. Outage Probability Analysis

In this section, we derive the novel series-based expression of the outage probability ($P_{\mathrm{out}}^{\mathrm{DF}}$) of the considered system model. It is the probability of communication link failure when E2E instantaneous SNR falls below a threshold SNR value γ_{th}. Thus, the outage probability of the considered system can be obtained by setting $\gamma = \gamma_{\mathrm{th}}$ in Eq. (11) as follows:

$$P_{\mathrm{out}}^{\mathrm{DF}} = 1 - \left(\frac{1}{\Gamma(m)}\Gamma\left(m, \frac{m}{\bar{\gamma}_{GS}}\gamma_{\mathrm{th}}\right)\right)\left(1\, \frac{w_{zeq}^2\sqrt{\eta}}{4\sigma_2^2}\sum_{n=0}^{\infty}\left(\frac{(\eta-1)w_{zeq}^2}{8\sigma_2^2}\right)^{2n}\frac{1}{2^{2n}(n!)^{2n}}\Gamma\left(2n+1, \left(\frac{(1+\eta)w_{zeq}^2}{8\sigma_2^2}\right)\ln\left(\frac{h_a A_0}{(\gamma_{\mathrm{th}}/\bar{\gamma}_{\mathrm{SR}})^{1/t}}\right)\right).\right) \times \left(\frac{1}{\Gamma(m)}\Gamma\left(m, \frac{m}{\bar{\gamma}_{RU}}\gamma_{\mathrm{th}}\right)\right). \tag{12}$$

V. Numerical Result

Figure 2 shows the impact of different system parameters on the outage probability when the average SNR of the user varies. It is observed that outage probability performance worsens with the presence of perturbations and vibrations, increasing the length of optical ISL, and when the IM/DD technique is utilized.

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References

[1] G. Wang, *et. al.*, “Free Space Optical Communication for Inter-Satellite Link: Architecture, Potentials and Trends,” *IEEE Commun. Mag.*, vol. 62, no. 3, pp. 110-116, Mar. 2024,