Outage Probability of Triple-Hop Mixed RF/FSO/RF Stratospheric Communication Systems

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***Abstract*—This paper proposes a triple-hop mixed Radio-Frequency/Free-Space-Optical/Radio-Frequency (RF/FSO/RF) communication system, which intends to support wireless long-range links between two terrestrial stations via two stratospheric relays. It is considered that these terrestrial stations communicate with the relays over RF links, whereas the relays communicate with each other over a FSO link. The RF channels experience Rician fading due to the Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) signal components. Besides, the optical channel is affected by atmospheric attenuation, atmospheric turbulence, and pointing errors. Mathematical expressions for the outage probability are derived, considering the beam wander effect. The results demonstrate the theoretical derivations.**

Keywords-Atmospheric turbulence; beam wander; Free-Space-Optical (FSO) communications; High-Altitude Platforms (HAPs); outage probability; pointing errors; Rician channels.

I. INTRODUCTION

The development of next-generation wireless broadband communications comprises the seamless integration of terrestrial and aerospace infrastructures over heterogeneous networks [1]. In recent years, the use of mobile airborne services via High-Altitude Platforms (HAPs) flying in the stratosphere has been suggested for civil and military applications [2]. To successfully fulfill the demands of future wireless communication services, shifting from the Radio-Frequency (RF) domain to the optical domain is indispensable [3] [4]. In Free-Space-Optical (FSO) systems, the data is transmitted at high data rates in the multigigabit regime using collimated highly directed laser beams with compact equipment and low power consumption. The FSO technology ensures privacy with low probability of interception, immunity to electromagnetic interference, and exemption from spectrum regulatory restrictions.

The stratosphere stands for a propagation medium well suited for FSO connections. Hopefully, the inter-HAP crosslink is above attenuating clouds, fog or significant aerosols. Hence, inter-HAP distances of up to 900 km are possible with 100% availability [5]. Nevertheless, stratospheric FSO links may experience substantial fluctuations in both the intensity and the phase of the received signal due to variations of the Index of Refraction Turbulence (IRT) along the propagation path resulting by the inhomogeneities in temperature and pressure fluctuations, especially for link distances of 1 km and above [6]. Moreover, beam pointing error effects are highly pronounced on the performance of a stratospheric network, which involves large distances and possible displacement of the platforms due to the winds or pressure variations of the stratosphere [7]. In addition, both mechanical vibrations and electronic noise may cause the received spots from the laser beams to wander on the detector planes. Hence, acquisition, pointing, and tracking errors should also be mitigated to achieve high directivity of the transmitted beam. To extend the network range, and effectively combat the effect of turbulence, the use of relay-aided transmission schemes has been suggested [8]. In [7], a full-FSO system with multiple stratospheric relays and fixed stations on the ground was proposed. However, FSO systems should operate under accurate pointing requirements. Hence, employing FSO techniques is highly challenging and insufficient as soon as the terrestrial stations are in motion.

Motivated by these observations, this paper investigates the use of two stratospheric relays acting as Decode-and-Forward (DF) relay nodes, in order to facilitate challenging triple-hop long-range wireless communication between two terrestrial mobile stations. Although the Amplify-and-Forward (AF) scheme is simple to implement, DF offers better performance and is a common assumption in multi-hop networks. A mixed RF/FSO/RF airborne communication scenario is considered, where an RF transmission scheme is adopted for the communication between the terrestrial stations and the stratospheric relays, whereas these relays are interconnected through an FSO link. A stratospheric communication channel is expected to be Rician in its general form [9]. Hence, the Rician distribution is adopted to model the channels for the RF links. To investigate the effect of atmospheric turbulence on the FSO link, a Kolmogorov power spectrum for refractive-index fluctuations is considered and the Gamma-Gamma (G-G) distribution is used, which matched data values obtained from measurements, under a variety of turbulence conditions [10]. Finally, the effects of pointing errors are described by the Rayleigh distribution [7]. Mathematical expressions are derived for the outage probability and numerical results are provided for different values of the system parameters.

The rest of the paper is organized as follows. Section II presents the system model. In Section III, the RF and FSO fading channels are modeled. In Section IV, the outage probability is mathematically derived. Results are provided in Section V. Finally, conclusions are drawn in Section VI.

II. SYSTEM MODEL

This paper considers a mixed RF/FSO/RF airborne communication system with slowly-varying and frequency-flat-fading channels. As shown in Figure 1, the transmitted signal from a source node propagates through two serial DF stratospheric relays of similar size and type before arriving at a destination node. It is considered that the direct link between the source and the destination is obstructed due to high attenuation. To aid our analysis, the subscripts *S*, *D*, and R_m, where $1 \le m \le 2$, are affiliated with the source, the destination, and the *m*-th relay, respectively. In this system, the S–R_1 and R_2–D links use RF technology, while the R_1–R_2 link is based on FSO technology. The communication is assumed to operate in a half-duplex mode and to be conducted over three phases: $S \rightarrow R_1$, $R_1 \rightarrow R_2$, and $R_2 \rightarrow D$. The source and the destination are equipped with single antennas. Besides, the relays not only include antennas, but also lasers and photo-detectors.

A. First RF Link

The received signal at the stratospheric relay R_1 can be expressed as [11]

$$y_{S,R_1} = \sqrt{P_S}\, h_{S,R_1} x_{S,R_1} + n_{R_1}, \tag{1}$$

where P_S is the transmit power, h_{S,R_1} is a non-zero-mean complex Gaussian random variable, x_{S,R_1} is the transmitted symbol from the source with $\mathrm{E}\left\{\left|x_{S,R_1}\right|^2\right\} = 1$, $\mathrm{E}\{\cdot\}$ is the statistical expectation operator, n_{R_1} represents the zero-mean complex Gaussian noise at R_1 with N_{o,R_1} noise Power Spectral Density (PSD). Using (1), the instantaneous Signal-to-Noise Ratio (SNR) at R_1 can be written, respectively, as

$$\gamma_{S,R_1} = \frac{P_S}{N_{o,R_1}} \left|h_{S,R_1}\right|^2. \tag{2}$$

B. FSO Inter-HAP Link

In the FSO link, the cost-effective Intensity Modulation Direct-Detection (IM/DD) is employed. The received RF signal at the R_1 is decoded and converted to optical signal by employing the Subcarrier Intensity Modulation (SIM) technique. In particular, after filtering by a Bandpass Filter (BPF), a Direct Current (DC) bias is added to the filtered RF signal to ensure that the optical signal is non-negative. Then, the biased signal is sent to a continuous wave laser driver. The retransmitted optical signal at R_1 is written as [12]

$$y_{R_1,opt} = \sqrt{P_{opt}}\left(1 + M y_{S,R_1}\right), \tag{3}$$

where P_{opt} denotes the average transmitted optical power and it is related to the relay electrical power P_{R_1} by the electrical-to-optical conversion efficiency η_1 as $P_{opt} = n_1 P_{R_1}$, and M denotes the modulation index.

The optical signal at R_2 received from R_1 can be expressed as

$$y_{R_1,R_2} = I\left[\sqrt{P_{opt}}\left(1 + M y_{S,R_1}\right)\right] + n_{R_2}, \tag{4}$$

where $I > 0$ is the received fading gain (irradiance) between the laser of R_1 and the photodetector of R_2 through the optical channel and n_{R_2} is the zero-mean complex Gaussian noise at R_2 with N_{o,R_2} noise PSD.

The DC component is filtered out at R_2 and an optical-to-electrical conversion is performed. Then, assuming that $M = 1$, the received signal can be expressed as

$$y_{R_1,R_2} = I\sqrt{P_{ele}}\left[\sqrt{P_{opt}}\, y_{S,R_1}\right] + n_{R_2}, \tag{5}$$

where $P_{ele} = n_2 P_{opt} = n_1 n_2 P_{R_1}$ is the electrical power received at R_2 and n_2 is the optical-to-electrical conversion efficiency.

The instantaneous SNR at R_2 can be approximated as [11]

$$\gamma_{R_2} \simeq \min\left\{\gamma_{S,R_1}, \gamma_{R_1,R_2}\right\}, \tag{6}$$

where $\gamma_{R_1,R_2} = \left(n_1 n_2 P_{R_1} I^2\right) / N_{o,R_2}$.

The performance of the FSO link is limited by background radiation and thermal noise, which can be modeled as independent and identically distributed (i.i.d.) AWGN, as an accurate approximation of the Poisson photon-counting detection model [13].

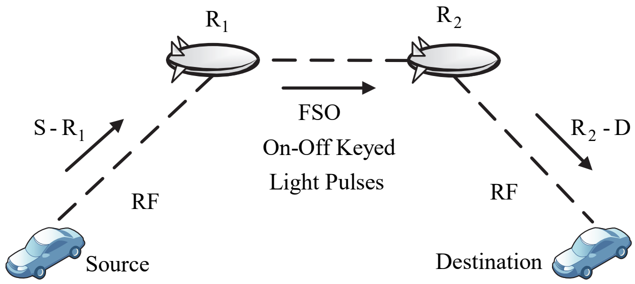

Figure 1. Simple representation of the triple-hop mixed RF/FSO/RF stratospheric communication system.

C. Second RF Link

The FSO signal at the R_2 is finally reconverted to an RF signal before being sent to the destination over the second RF link. The signal received at the destination is written as

$$y_D = \sqrt{P_{R_2}} h_{R_2,S} x_{R_2,S} + n_D, \quad (7)$$

where P_{R_2} is the transmit power, h_{R_2S} is a non-zero-mean complex Gaussian random variable (leading to a Rician distributed amplitude), $x_{R_2,S}$ is the signal transmitted by the R_2 with $\mathrm{E}\left\{\left|x_{R_2,S}\right|^2\right\} = 1$, and n_D is the zero-mean complex Gaussian noise at D with $N_{o,D}$ noise PSD. Using (7), the SNR at the destination can be written as

$$\gamma_{R_2,D} = \frac{P_{R_2}}{N_{o,D}} \left|h_{R_2,D}\right|^2. \quad (8)$$

The instantaneous end-to-end SNR at the destination can be approximated as [11]

$$\gamma_D \simeq \min\left\{\gamma_{S,R_1}, \gamma_{R_1,R_2}, \gamma_{R_2,D}\right\}. \quad (9)$$

III. Statistical Modeling of the Triple-Hop Mixed RF/FSO/RF Channel

In this paper, the Rician distribution is utilized to model the channels for the RF links. The Probability Density Function (PDF) of the instantaneous SNR received at R_1, denoted as γ_{S,R_1}, is given by [14]

$$f_{\gamma_{S,R_1}}\left(\gamma_{S,R_1}\right) = \frac{K_1+1}{\bar{\gamma}_{S,R_1}} \exp\left(-\left(K_1+1\right)\frac{\gamma_{S,R_1}}{\bar{\gamma}_{S,R_1}} - K_1\right) \times I_0\left(2\sqrt{K_1\left(K_1+1\right)\frac{\gamma_{S,R_1}}{\bar{\gamma}_{S,R_1}}}\right), \quad (10)$$

where K_1 is the Rician factor of the first RF link, i.e., the average power ratio of the Line-of-Sight (LoS) component to the Non-Line-of-Sight (NLoS) component, and $I_0(\cdot)$ is the modified Bessel function of the first kind and zero-th order. The Rician factor K_1 strongly depends on the elevation angle of the HAPs and the operating frequency [15]. The PDF $f_{\gamma_{R_2,D}}\left(\gamma_{R_2,D}\right)$ of the Rician distribution for the second RF link with Rician factor K_2 can be defined as in the first RF link by replacing the indices.

For the FSO link, a composite optical channel model is used [7]. In particular, the channel state I models the random attenuation of the propagation channel that arises due to the path loss I^l, the atmospheric turbulence I^a, and the pointing errors I^p. The combined optical channel model is defined as follows

$$I = I^l I^a I^p. \quad (11)$$

Since the time scales of these fading processes are of the order of 10^{-3} s to 10^{-2} s [16], which are far larger than the bit interval $\left(\approx 10^{-9}\text{ s for multi-Gbps systems}\right)$, I is constant over a large number of transmitted bits [17].

A. Effects of Atmospheric Attenuation

The atmospheric attenuation is deterministic and is defined by the exponential Beers–Lambert Law [18]

$$I^l(L) = \exp(-\sigma L), \quad (12)$$

where $I^l(L)$ is the atmospheric attenuation loss of the FSO link over a path of length L, i.e., the distance between the relays, and σ is the wavelength- and weather-dependent attenuation coefficient. The attenuation I^l is considered fixed during a long period of time.

B. Effects of Turbulence

In this paper, the effects of turbulence are modeled using the G-G distribution. Hence, the PDF of I^a is given by [19]

$$f_{I^a}\left(I^a\right) = \frac{2(ab)^{(a+b)/2}}{\Gamma(a)\Gamma(b)} \left(I^a\right)^{\frac{(a+b)}{2}-1} K_{a-b}\left(2\sqrt{abI^a}\right), \quad (13)$$

where $K_u(\cdot)$ is the u-th order modified Bessel function of the second kind. Note that (13) can be written in terms of the Meijer's G-function as $K_u(x) = 0.5G_{0,2}^{2,0}\left[x^2/4 \middle| u/2\ u/2\right]$ [20]. The parameters a and b are directly related to the atmosphere and can be adjusted to achieve a good agreement between $f_{I^a}\left(I^a\right)$ and measurement data. These parameters are determined by the Rytov scintillation model. However, for large distances, as those involved in the proposed system, this model is inappropriate due to the hot spot displacement of the beam caused by the beam wander, i.e., the deflection of the beam due to turbulence. By considering the beam wander effect, a and b can be modeled as [21]

$$a = \left[\frac{4.42\sigma_R^2 \Lambda_e^{5/6} \sigma_{pe}^2}{w_{LT}^2} + \exp\left(\frac{0.49\sigma_B^2}{\left(1+0.56(1+\Theta)\sigma_B^{12/5}\right)^{7/6}}\right) - 1\right]^{-1}, \quad (14)$$

$$b = \left[\exp\left(\frac{0.51\sigma_B^2}{\left(1+0.69\sigma_B^{12/5}\right)^{5/6}}\right) - 1\right]^{-1}, \quad (15)$$

where $\sigma_R^2 = 1.23 C_n^2 k^{7/6} L^{11/6}$ is the Rytov variance, C_n^2 is the index of refraction structure parameter, $\Lambda_e = 2L / k w_{LT}^2$,

$k = 2\pi / \lambda$ is the wave number, λ is the carrier wavelength, $w_{LT} = w\sqrt{1+1.33\sigma_R^2 \Lambda^{5/6}}$ is the long-term spot radius, w is the beam radius at the receiver, $\Lambda = 2L / kw^2$, σ_{pe}^2 is the variance of pointing error caused by beam wander ([22], p. 350), σ_B^2 is the Rytov variance with beam wander correction ([22], p. 351), $\Theta = \Theta_0 / \left(\Theta_0^2 + \Lambda_0^2\right)$, $\Theta_0 = 1 - L / F_0$, F_0 is the phase curvature parameter of the Gaussian beam at the transmitter, $\Lambda_0 = 2L / kw_0^2$, and w_0 is the transmitter beam radius. Using [23, eq. (3)], one can also obtain the Scintillation Index (SI) σ_I^2. The value of C_n^2 represents the turbulence condition of the atmosphere and can be estimated using the Hufnagel-Valley model, which is based on various empirical scintillation data of the atmosphere. This model defines the index of refraction structure parameter as a function of the wind speed and the altitude of the HAPs above the ground level as ([22], p. 481)

$$C_n^2(h) = 0.00594\left(\frac{u}{27}\right)^2 \left(10^{-5} h\right)^{10} \exp\left(-\frac{h}{1000}\right) +2.7\times10^{-16} \exp\left(-\frac{h}{1500}\right) + \hat{A}\exp\left(-\frac{h}{100}\right), \quad (16)$$

where $\hat{A}$ is the nominal value of the $C_n^2(0)$ at the ground, u is wind speed in m/s, and h is the altitude of the HAPs in meters. As C_n^2 increases, the turbulence becomes stronger. For applications involving propagation along a horizontal path, it is customary to assume that C_n^2 remains constant [22].

C. Effects of Pointing Errors

To ensure that the communication scenario is viable, proper LoS alignment between the relays via appropriate pointing and tracking mechanisms is required. In this paper, a model that incorporates geometric spreading in the pointing error PDF ([18], p. 1703) is used. Considering a Gaussian beam profile of beam waist w_z (at a distance z) and modeling the random radial displacement of the beam at the detector as Rayleigh distributed, the PDF of the pointing error I^p includes the random attenuation due to both geometric spreading and pointing errors and can be expressed as [18]

$$f_{I^p}\left(I^p\right) = \frac{\gamma^2}{(A)^{\gamma^2}}\left(I^p\right)^{\gamma^2-1}, \; 0 \le I^p \le A, \quad (17)$$

where $\gamma = w_{eq} / 2\sigma_s$, $w_{eq}^2 = w_z^2 \sqrt{\pi}\cdot \mathrm{erf}(u) / \left[2u\exp\left(-u^2\right)\right]$ is the equivalent beam width at the receiver, $u = \left(\sqrt{\pi}a_r\right)/\left(\sqrt{2}w_z\right)$, σ_s is the jitter standard deviation due to the pointing error at the detector determined by the degree of the misalignment between the apertures, $A = \left[\mathrm{erf}(u)\right]^2$, and a_r is the receiver aperture radius.

Using (12), (13), and (17), the PDF of the composite channel in (11) can be evaluated by writing the Bessel function $K_u(\cdot)$ in terms of the Meijer's G-function as [7]

$$f_I(I) = \frac{ab\gamma^2}{AI^l\Gamma(a)\Gamma(b)} G_{1,3}^{3,0}\left[\frac{ab}{AI^l} I \,\middle|\, \begin{matrix}\gamma^2\\ \gamma^2-1, a-1, b-1\end{matrix}\right]. \quad (18)$$

Using (18), the PDF of the instantaneous SNR received at R_2, denoted as γ_{R_1,R_2}, can be expressed as

$$f_{\gamma_{R_1,R_2}}\left(\gamma_{R_1,R_2}\right) = \frac{ab\gamma^2}{2AI^l\Gamma(a)\Gamma(b)}\sqrt{\frac{1}{\gamma_{R_1,R_2}\bar{\gamma}_{R_1,R_2}}} \times G_{1,3}^{3,0}\left[\frac{ab}{AI^l}\sqrt{\frac{\gamma_{R_1,R_2}}{\bar{\gamma}_{R_1,R_2}}} \,\middle|\, \begin{matrix}\gamma^2\\ \gamma^2-1, a-1, b-1\end{matrix}\right], \quad (19)$$

where $\bar{\gamma}_{R_1,R_2}$ is the average SNR received at R_2.

IV. Derivation of Outage Probability

The outage probability is defined as the probability that the SNR at the destination falls below a predetermined outage threshold γ_{out}, i.e., $P_{out} = \Pr\left[\gamma_D \le \gamma_{out}\right]$, where $\Pr[\cdot]$ is the probability operation. In this case, the communication system cannot achieve adequate reception. The outage probability can be obtained from the Cumulative Distribution Function (CDF) of the end-to-end SNR as $P_{out} = F_{\gamma D}(\gamma_{out})$. This CDF can be written in terms of the CDFs of the three hops' SNRs as [24]

$$F_{\gamma D}(\gamma_{out}) = 1 - \left[\left(1 - F_{\gamma S,R_1}(\gamma_{out})\right)\left(1 - F_{\gamma R_1,R_2}(\gamma_{out})\right)\left(1 - F_{\gamma R_1,D}(\gamma_{out})\right)\right], \quad (20)$$

where $F_{\gamma S,R_1}(\gamma_{out})$, $F_{\gamma R_1,R_2}(\gamma_{out})$, and $F_{\gamma R_1,D}(\gamma_{out})$ are the CDFs of the SNRs of the first, second, and third hop, respectively. One observes that the system falls in outage providing that at least one of the three hops gets in outage or, equivalently, the SNR of one hop becomes less than γ_{out}.

The CDF of the instantaneous SNR received at R_1 can be expressed as [25]

$$F_{\gamma_{S,R_1}}\left(\gamma_{S,R_1}\right) = 1 - Q_1\left[\sqrt{2K_1}, \sqrt{\frac{2(K_1+1)}{\bar{\gamma}_{S,R_1}}\gamma_{S,R_1}}\right], \quad (21)$$

where $Q_1[\cdot]$ is the first-order Marcum Q-function. The CDF $F_{\gamma_{R_2,D}}\left(\gamma_{R_2,D}\right)$ of the Rician distribution for the second RF link can be similarly defined by replacing the indices.

The CDF of the instantaneous SNR received at R_2 can be obtained as follows

$$F_{\gamma_{R_1 R_2}}\left(\gamma_{R_1,R_2}\right) = \int_0^{\gamma_{R_1,R_2}} f_{\gamma_{R_1,R_2}}\left(x\right)dx. \qquad (22)$$

Using (19) and [26, eq. (07.34.21.0003.01)], (22) becomes

$$F_{\gamma_{R_1,R_2}}\left(\gamma_{R_1,R_2}\right) = \frac{ab\gamma^2}{AI^l\Gamma(a)\Gamma(b)}\sqrt{\frac{\gamma_{R_1,R_2}}{\overline{\gamma}_{R_1,R_2}}} \times G_{2,4}^{3,1}\left[\frac{ab}{AI^l}\sqrt{\frac{\gamma_{R_1,R_2}}{\overline{\gamma}_{R_1,R_2}}}\middle| \begin{matrix} 0,\gamma^2 \\ \gamma^2-1,a-1,b-1,-1 \end{matrix}\right]. \qquad (23)$$

The expressions in (21) and (23) can be numerically evaluated using well-known software packages, e.g., Mathematica and MATLAB.

V. RESULTS

In this section, the performance of the proposed system is evaluated in terms of the outage probability. Unless indicated otherwise, the values of model parameters used are $\overline{\gamma}_{S,R_1} = \overline{\gamma}_{R_2,D} = 20$ dB, $\overline{\gamma}_{R_1,R_2} = 50$ dB, $\gamma_{out} = 0$ dB, $K_1 = K_2 = K = 10$ dB, L = 400 km, h = 20 km, $\sigma = 0.01$ dB/km (clear weather conditions), $w = w_0 = 2$ cm, Θ_0 = 0 (focus Gaussian beam), and $\sigma_s = 0.15$ m. Note that a laser aperture diameter of $2a_r = 0.3$ m is assumed. Then, $w_z = 1.38$ m [27]. A wavelength λ = 1550 nm is considered for the FSO link since it is widely used for most airborne optical communication scenarios. In addition, two values of the wind speed that determine C_n^2 are considered; $u_1 = 10$ m/s (best case) and $u_2 = 30$ m/s (worst case) [23]. For these values, we obtain $C_{n,u_1}^2 \approx 1.72\cdot 10^{-19}$ $\text{m}^{-2/3}$, $C_{n,u_2}^2 \approx 1.55\cdot 10^{-18}$ $\text{m}^{-2/3}$, $\sigma_{R,u_1}^2 \approx 0.2$, $\sigma_{R,u_2}^2 \approx 1.82$, $\sigma_{I,u_1}^2 \approx$ 0.08, and $\sigma_{I,u_2}^2 \approx 0.67$.

Figure 2 depicts the outage probability for different values of the Rician factor $K_1 = K_2 = K$ and u = 10 m/s. It is obvious that increasing the Rician factor improves the performance of the system. Note that a certain outage floor exists at high values of K due to the average SNR over the FSO link. Hence, all curves tend to the same saturation floor.

Figure 3 demonstrates the outage probability for both the best and worst case of turbulence conditions and different inter-HAP distance. As this distance decreases, a significant performance improvement can be achieved. However, the variation of the FSO propagation distance slightly affects the outage probability when the worst case of turbulence conditions is observed.

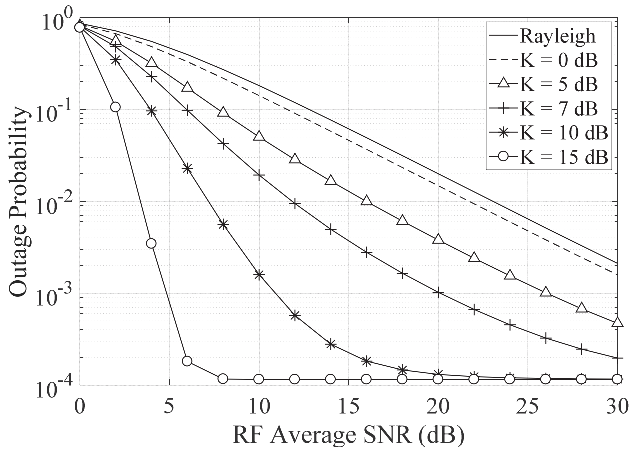

Figure 2. The outage probability in terms of the RF average SNR for different Rician factor of the RF links.

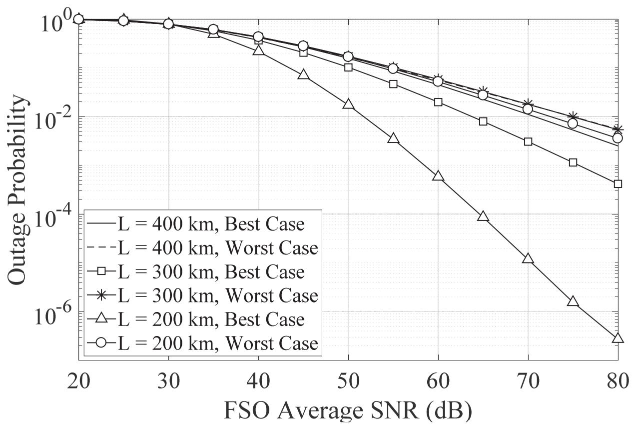

Figure 3. The outage probability in terms of the FSO average SNR for different turbulence conditions and different inter-HAP distance.

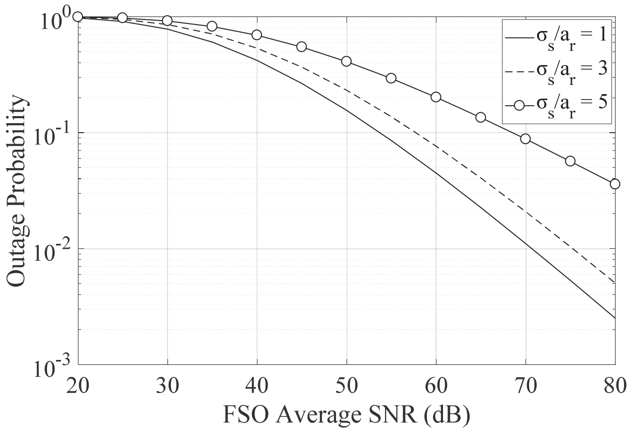

Figure 4. The outage probability in terms of the FSO average SNR for different normalized jitter standard deviation.

Finally, Figure 4 shows the effect of the normalized jitter standard deviation σ_s / a_r on the outage probability for u = 10 m/s. One observes that the performance significantly degrades and the pointing errors have a dominant effect on the system performance, as σ_s / a_r increases.

VI. CONCLUSION

In this paper, the performance of a triple-hop mixed RF/FSO/RF stratospheric communication system has been investigated. The results have depicted that the Rician factor significantly influences the system performance. These results have also underlined that the performance degrades, as the inter-HAP distance increases. However, for the worst turbulence case, this distance slightly affects the outage probability. Finally, the results have shown that the misalignment-induced fading has a severe effect on the system performance. Since there are no experimental data available in the literature to fully verify the theoretical results, future research efforts may be devoted to collecting measured channel data in real-world propagation conditions.

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