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Performance evaluation of optical channel transmission between UAVs and Ground Stations

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Abstract. Free space optical (FSO) communications links is a promising solution for the provision of high data rate point to point communications. In particular deploying FSO technology for mobile links between Unmanned Aerial Vehicles (UAVs) and fixed Ground Stations (GS) introduces several interesting challenges. In this paper, we investigate the ability of a mobile FSO system to operate in different atmospheric conditions. Specifically, we characterize the quality of the optical channel with a proper model in terms of Bit Error Rate (BER) and average Signal to Noise Ratio (SNR) and we report a detailed optical amplification model able to support a constant Quality of Service for different distances from 1 km up to 35 km at 10 Gbps with 1550 nm wavelength. An extensive comparative analysis among different FSO configurations links considering the altitude of the UAV, the wavelength and the atmospheric conditions is provided. The results show that there is degradation at the BER over a slanted path compared to a horizontal path at the same conditions.

1. Introduction

In recent years, there has been a renewed interest in understanding and exploiting FSO communications, mainly because of the large potential bandwidth available compared to radio frequency and its flexibility compared to optical fibers. Currently FSO technology is being researched for applications involving ground to ground (terrestrial links) and air to ground terminal [1]. However, the FSO systems are vulnerable to adverse weather conditions. They suffer from atmospheric absorption, scattering and signal fading as a result of turbulence. A critical factor for the quality of a FSO link is the mitigation of the adverse impact of different weather conditions that a light beam experiences through the optical path.

Deploying FSO technology for mobile links introduces several interesting challenges. Scintillation could result in high-error-rate FSO performance and is more considerable in long-distance transmissions. Especially when the communicating parties are in rapid motion, the variation of the distance combined with the different levels of refractive index that the optical beam meets, results in a constantly varying level of the received optical power. In the literature, many techniques have been reported for the improvement of BER in a fixed and mobile version of a FSO link. Diversity of wavelength, utilization of multiples transmitters and receivers and implementation of optical amplifiers has been adopted by many researchers [2]. In case of IM/DD OOK modulation format, BER performance versus SNR and horizontal distances has been presented, considering plane wave model, spherical wave model and Gaussian wave model [3].

In this paper we propose an alternative approach to evaluate the quality performance of a FSO link addressing the issue of calculating an average SNR and the BER along a mobile slanted path communication optical link between a UAV and a fixed ground station. In this approach we take into account simultaneously changing parameters affecting the average SNR, separating the slanted path into small intervals. Moreover in order to improve the BER, the present study is also concerned with the design of the Erbium Doped Fiber Amplifiers (EDFAs) in order to increase the output power, limiting at the same time the Amplified Spontaneous Emission (ASE) noise. Various parameters of EDFA such as Erbium ion density, doped fiber length, pumping power and doping radius can affect on ASE noise which in turn affects on the value of BER. The proposed system is based on the optimization of the parameters of the booster amplifier and of the low noise amplifier at the transmitter and receiver respectively in order to increase the overall system performance.

2. System model

A FSO transceiver is placed on either side of the transmission path. The optical part of the transmitter involves a light source and a telescope assembly. The receivers detect light through a telescope by using appropriate semiconductor photodiodes. An Avalanche Photo Diode (APD) which is used in the model has internal gain which increases the responsivity when compared to PN photodetectors, as shown in the Figure 1.

The optical signal power received at the photodetector for variable distance can be written using the range equation as:

$$P_{r,i} = P_t \cdot G_t \cdot L_{P_t} \cdot L_{s,i} \cdot L_{o,i} \cdot L_{P_r} \cdot G_r \qquad (1)$$

The structure of the proposed booster optical amplifier is shown in Figure 2. It consists of two stages of amplification which provides at the end up to 1.986 W total

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average signal power with less than 6 uW noise and 2.9 mW remaining pump power. The first stage is a low noise pre-amplifier based on high power forward pumping at 980 nm to provide lower Noise Figure (NF). The second stage consists of four booster amplifiers co- & counter-propagating that are coupled together through 3 dB couplers and a phase shifter. The length of the Erbium fibers, the bandwidth of the optical filters and the pump power have been optimized for the best performance.

The structure of the proposed low noise optical amplifier is shown in Figure 3. It consists of two stages co-propagating EDFAs separated by a 0.3 nm optical filter and a variable optical attenuator to control the output power.

This system is implemented and simulated using Optiwave software Optisystem 7 & Matlab.

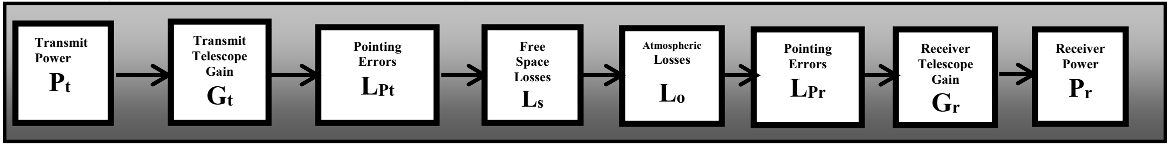

Figure 1. FSO link calculations.

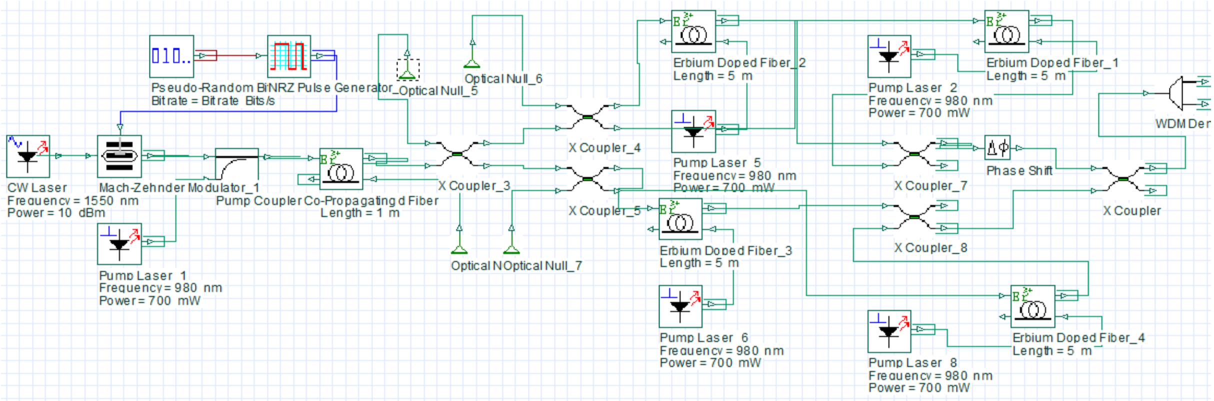

Figure 2. Booster amplifier

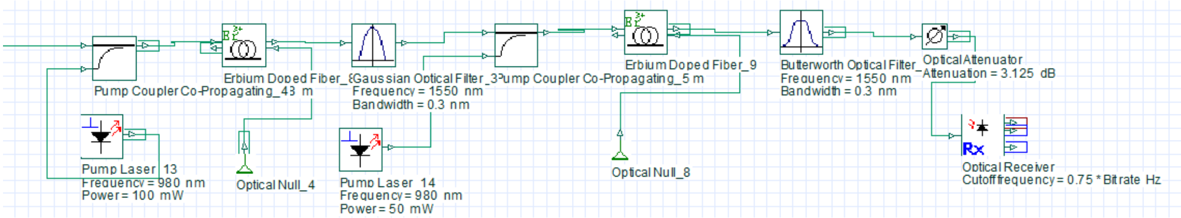

Figure. 3. Low noise amplifier

3. Theory analysis

3.1 Turbulence modelling along a slanted path

We consider the propagation in free space of a lowest-order Transverse Electro-Magnetic (TEM) Gaussian beam wave. Initially we divide the slanted path into small intervals and consider Rytov variance (σ_R^2) and the corresponding Rytov variance for a Gaussian beam for each interval:

$$\sigma_{R,ij}^2 = 1.23 c_{n,i}^2 k^{7/6} L_j^{11/6} \tag{2}$$

$$\sigma_{B,ij}^2 \simeq 3.86 \sigma_{R,ij}^2 \left\{ \begin{aligned} & 0.4\left[\left(1+2\Theta_i\right)^2 + 4\Lambda_i^2\right]^{5/12} \\ & \cdot \cos\left[\frac{5}{6}\tan^{-1}\left(\frac{1+2\Theta_i}{2\Lambda_i}\right)\right] - \frac{11}{16}\Lambda_i^{5/6} \end{aligned} \right\} \tag{3}$$

where k is the wave number, L is the propagation distance, Θ_i and Λ_i are the output plane beam parameters. Using the modified Rytov theory for a slanted path and assuming zero inner and infinite outer scale, the longitudinal component for the large-scale and small-scale log-irradiance variations can be modified as:

$$\sigma_{I,ij}^2 = \exp\left[\frac{0.49\sigma_{\mathrm{B},ij}^2}{\left(1+0.56\sigma_{\mathrm{B},ij}^{12/5}\right)^{7/6}} + \frac{0.51\sigma_{\mathrm{B},ij}^2}{\left(1+0.69\sigma_{\mathrm{B},ij}^{12/5}\right)^{5/6}}\right] - 1 \qquad (4)$$

In our study, the c_n^2 profile is changing along the slanted path taking into account for computational purposes the Hufnagel-Valley (H/V) model, where the ground turbulence level $A' = c_n^2(0) = 1.7 \cdot 10^{-14} m^{-2/3}$ and $u_{rms} = 21 \ m/s$ is the rms wind speed. The propagation distance due to the mobility of the flight terminal (UAV) is changing perpetually. Assuming that UAV is cruising at fixed altitude h and the ground station is located at the origin of the inertial coordinates, the propagation distance can be expressed $L_i = h / \sin\theta_i$ where θ is the time-varying angle between the transmitter and the receiver evaluating for the scenario from 90° to 10°.

3.2 Average SNR – BER expressions

Once we have characterized the noise level at the input of a receiver, it is possible to analyze the SNR in the absence of turbulence. Assuming that all of the noise sources described previously are uncorrelated, the signal-noise ratio of the link at the single photo-detector can be expressed by $SNR_{0,i} = i_{s,i}^2 / \sigma_{N,i}^2$. In presence of turbulence the averaged signal power to noise power ratio is a fluctuating term and the average value of the SNR has to be taken. The mean value $< SNR >$ can be expressed by the equation :

$$\left\langle SNR_{ij} \right\rangle = \frac{SNR_{0,i}}{1 + 1.63\sigma_{R,ij}^{12/5} \cdot \Lambda_i + A \cdot \sigma_{I,ij}^2 \cdot SNR_{0,i}} \qquad (5)$$

where A is the aperture averaging factor for Gaussian beam. Assuming uncorrelated mean values of $< SNR >$ for each interval along the slanted path, the total average BER can be calculated by

$$< BER > = \frac{1}{2} erfc\left(\frac{1}{2\sqrt{2}\sqrt{\sum_{ij} 1/ < SNR_{ij} >}} \right) \qquad (6)$$

4. Results and discussions

Based on the analytical study presented in sections 2 & 3, simulation of ground-to-UAV FSO communication link, were performed, considering the effects of several parameters. Optical losses L_{pt} and L_{pr}, which are set at 3 dB, are presented in the system due to pointing errors and imperfections in lenses respectively. Atmospheric losses L_o are calculated through Beer's law in relation to the wavelengths (0.85 um, 1.55 um and 10 um) and the visibility (2 Km - haze and 10 Km - clear sky). We consider the transmitter laser power to be 100 mW initially, the beam waist radius 2cm and the receiver aperture diameter 10 cm, which are defined in order to eliminate atmospheric path losses through turbulence effects.

Figures 4 & 5 illustrate the received optical power as a function of the distance between the ground station and the UAV for three wavelengths and two different conditions of visibility. It is seen that if the visibility becomes worse and for a distance greater than 3 Km, the 10 um is the appropriate choice. On the other hand in clear sky conditions, it seems that both 0.85 um and 1.55 um are the best choices for short or long range communication. Fig. 6 illustrates the SNR against the distance at clear sky, altitude 3 Km, wavelength 1.55 um, comparing horizontal and slanted paths communication. At the horizontal path, it is seen that when the distance is greater than 9 Km, the average SNR due to the turbulence matches the SNR without turbulence, due to the increase of the scintillation index factor. Along the slanted path, at the same time there is a variation both of the measure of the strength of the fluctuations in the refractive index and of the distance, presenting as a result a difference of almost 16 dB among slanted and horizontal average SNR. Fig. 7 illustrates the average SNR as a function of the distance for different values of the aperture averaging factor at two different conditions of visibility. For distances less than 4 Km with haze, the contribution of the averaging factor at the SNR improvement is important. However, for distances greater than 4 Km conditions the aforementioned improvement still exists only at clear sky.

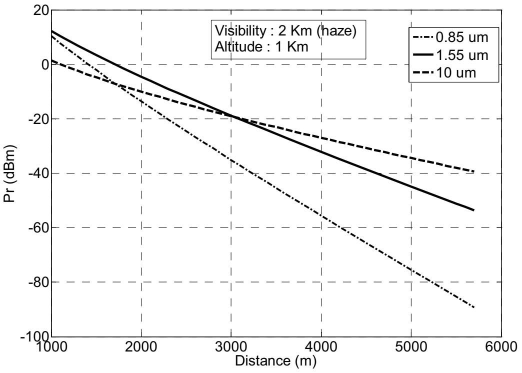

Figure 4. Pr vs distance for haze conditions.

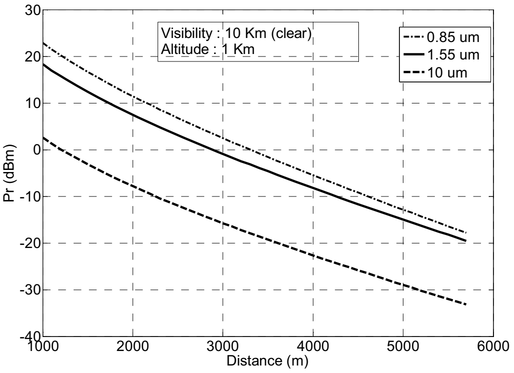

Figure 5. Pr vs distance for clear sky conditions.

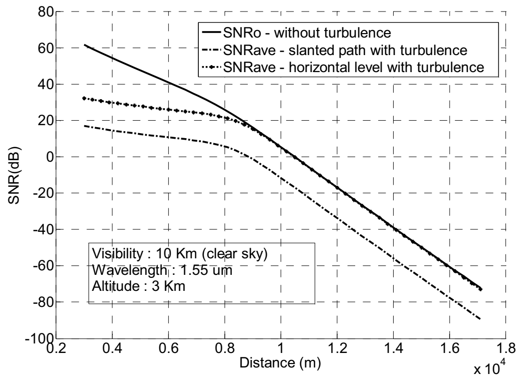

Figure 6. SNR vs distance for different paths.

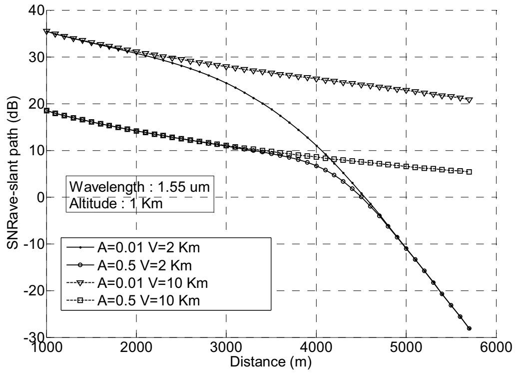

Figure 7. SNRave vs distance for different values of A.

Figures 8 & 9 illustrate the results of the average BER & Q factor according to the range between the UAV and the GS for clear sky and haze conditions, respectively. The numerical results show that with the proposed amplification scheme, we achieve a reliable link for distances up to 43.2 km for clear sky conditions where BER and Q factor are better than 1.5e-13 and 7.2, respectively. At haze conditions, the corresponding parameters are a distance up to 8.7 km where BER and Q factor are better than 6.3e-15 and 7.6, respectively.

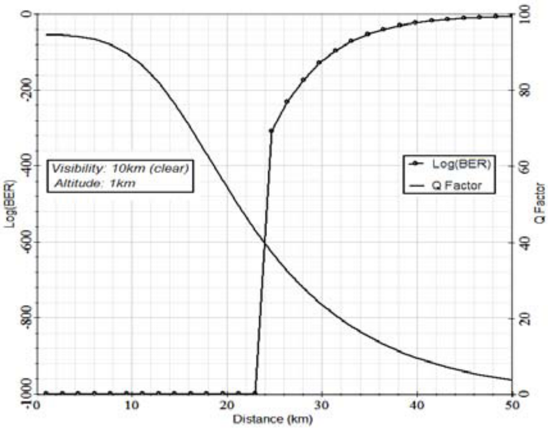

Figure 8. BER & Q factor vs Range for clear sky conditions

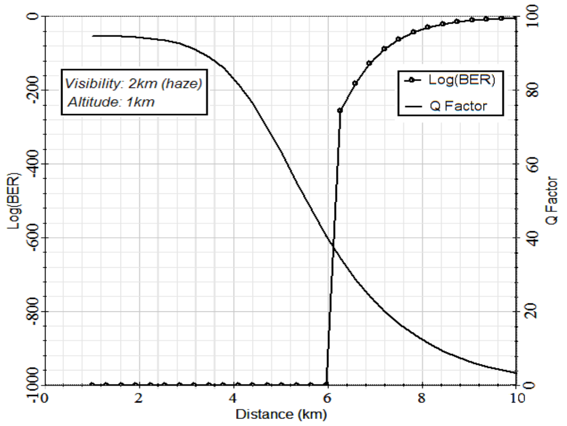

Figure 9. BER & Q factor vs Range for haze conditions.

5. Conclusions

In this paper, we have investigated the SNR and the BER performance of FSO links between UAV and ground stations over slanted paths. A detailed simulation analysis took place in order to calculate the Rytov variance and the scintillation index by separating the slanted path into small intervals. The system was evaluated in clear sky and haze atmospheric conditions calculating the BER & Q factor taking also into consideration amplifiers noise and as well as the shot and the thermal noise of the APD diode. The results show that there is degradation at the BER over a slanted path compare to a horizontal path at the same conditions. This variation requires the appropriate selection of the wavelength, the amplification scheme and the aperture averaging factor to maximize the quality of the transmission. The proposed system can provide a reliable communication link for variable ranges from 1 km up to 35 km at clear sky conditions.

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