

Bit Error Rate analysis along a slanted path link 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. The FSO links due to their huge bandwidth and license free spectrum provide a viable communication solution between Unmanned Aerial Vehicles (UAVs) and fixed Ground Stations (GS). It of great importance to characterize the quality of the optical channel with a proper model, taking into consideration the interesting challenges of the mobility and the slanted path of the optical beam in order to design a high performance communication link. In this paper we investigate the performance of a mobile link between a fixed GS and an UAV in terms of Bit Error Rate (BER) and average Signal to Noise Ratio (SNR). It deals with modelling the influence of the scintillation index and the received optical power with noise on link performance, separating the slanted path into small intervals assuming a Gaussian-beam wave. 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.

Keywords: FSO, UAV, atmospheric turbulence, scintillation, Gaussian beam, slanted path.

1. INTRODUCTION

A Free Space Optical communication system (FSO) is an interesting alternative for the, nowadays, enormous telecom demands and it has a number of advantages compared to conventional free space radio frequency (RF) based systems. Currently FSO technology is being researched for applications involving ground to ground (terrestrial links), air to ground terminal [1], and satellite uplink/downlink. However, the FSO systems are vulnerable to adverse weather conditions. They suffer from atmospheric absorption, scattering and signal fading as a result of turbulence. 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 changing 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. Through slanted paths between UAV and fixed ground terminals, a critical factor for the quality of the link is the mitigation of the adverse impacts of turbulence due to the different levels of the atmosphere that spread the light beam.

The standard measurement performance of a FSO that has been adopted by most manufacturers is the BER that depends on the modulation format and the Signal to Noise Ratio (SNR). In literature, BER performance for a fixed FSO link has been estimated in many studies. 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 [2]-[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 two simultaneously changing parameters affecting the average SNR. First, we derive an expression of an average SNR calculating the Rytov variance, the scintillation index and the received optical power and noise separating the slanted path into small intervals. Then, we derive the average BER expressions for an intensity-modulation/direct detection (IM/DD) FSO system with on-off keying (OOK) using the ideal Gaussian intensity profile corresponding to the theoretical TEM₀₀ Mode. BER expressions, for the specific environment with and without turbulence taking into consideration all possible sources of noises, are proposed and an extensive comparative analysis among different FSO configurations links considering the altitude of the UAV, the wavelength and the atmospheric conditions is provided. Additionally simulation results demonstrate the difference between horizontal and slanted path optical propagation.

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. The system link calculation which combines attenuation and geometrical aspects is carried out as shown in the Fig. 1.

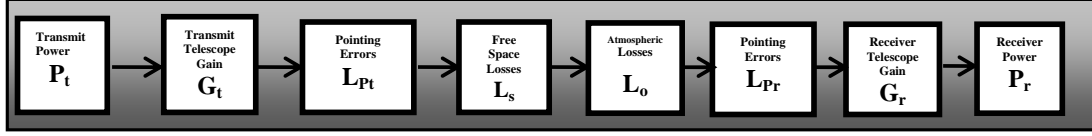


Fig. 1. FSO link calculations.

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

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

A laser beam propagating through the atmosphere combined absorption and scattering is attenuated due to the presence of aerosols, dust, smoke, fog, clouds, rain, snow and atmospheric molecules. Another parameter of signal fading is the turbulence induced scintillation. Initially we evaluate the noise that comes from the background power (sun radiation) and the inherent detector noise. The photocurrent at the output of the detector induced by the received optical signal and the total rms noise are given by [4]:

$$i_{s,i} = G \cdot R \cdot P_{r,i} = G \frac{q_e \cdot \eta \cdot \lambda}{h \cdot c} P_{r,i} \quad (2)$$

$$\sigma_{N,i} = \sqrt{2q_e R G^2 F B_w (P_{r,i} + P_{bg}) + F_n \frac{4K_B T B_w}{R_L} + 2q_e B_w (G^2 F I_{bl} + I_{sl})} \quad (3)$$

where G is the APD gain, R is the responsivity of the detector, q_e is the electron charge, η is the detector quantum efficiency, λ is the wavelength of the carrier, h is the Planck constant, c is the velocity of light in vacuum, F is the excess noise factor, B_w is the bandwidth of the detector filter, F_n is the amplifier coefficient, K_B is the Boltzmann constant, T is the effective noise temperature, R_L is the effective input resistance of detector and I_{bl} and I_{sl} are the bulk and surface leakage currents respectively.

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:

$$\sigma_{R,ij}^2 = 1.23 \sigma_{n,i}^2 k^{7/6} L_j^{11/6} \quad (4)$$

$$\sigma_{B,ij}^2 \approx 3.86 \sigma_{R,ij}^2 \left\{ 0.4 \left[(1 + 2\Theta_i)^2 + 4\Lambda_i^2 \right]^{5/12} \cdot \cos \left[\frac{5}{6} \tan^{-1} \left(\frac{1 + 2\Theta_i}{2\Lambda_i} \right) \right] - \frac{11}{16} \Lambda_i^{5/6} \right\} \quad (5)$$

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:

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

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 [5], 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 $\langle SNR \rangle$ can be expressed by the equation [5]:

$$\langle SNR_{ij} \rangle = \frac{SNR_{0,i}}{1 + 1.63\sigma_{R,ij}^{12/5} \cdot \Lambda_i + A \cdot \sigma_{I,ij}^2 \cdot SNR_{0,i}} \quad (7)$$

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

$$\langle BER \rangle = \frac{1}{2} \operatorname{erfc} \left(\frac{1}{2\sqrt{2} \sqrt{\sum_{ij} 1/\langle SNR_{ij} \rangle}} \right) \quad (8)$$

4. RESULTS AND DISCUSSIONS

Based on the analytical study presented in sections 2 & 3, simulation of ground-to-UAV FSO communication link, were performed in the MATLAB environment, 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 μm , 1.55 μm and 10 μm) and the visibility (2 Km - haze and 10 Km - clear sky). We consider the transmitter laser power to be 100 mW, 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.

Fig. 2 & fig. 3 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 μm is the appropriate choice. On the other hand in clear sky conditions, it seems that both 0.85 μm and 1.55 μm are the best choices for short or long range communication. Fig. 4 illustrates the SNR against the distance at clear sky, altitude 3 Km, wavelength 1.55 μm , 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. 5 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. Fig. 6 illustrates the average BER versus distance for horizontal and slanted path. It is observed that for a mobile FSO link the BER degradations begins above 3 Km distance for a slanted path instead of 9 Km for a horizontal path. Fig. 7 illustrates the average BER for a slanted path versus distance for three different wavelengths. The 10 μm wavelength result in the transmission of sufficient power to establish an average BER better than 10^{-9} for less than 4 Km distance with an altitude of 3 km in clear sky.

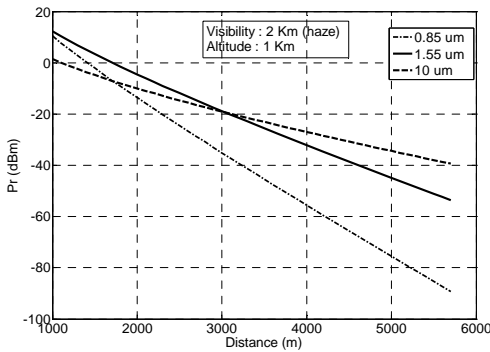


Fig. 2. P_r vs distance for haze conditions.

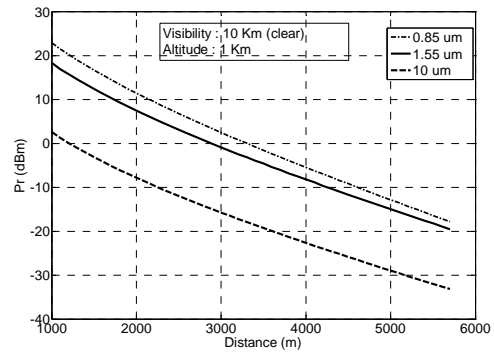


Fig. 3. P_r vs distance for clear sky conditions.

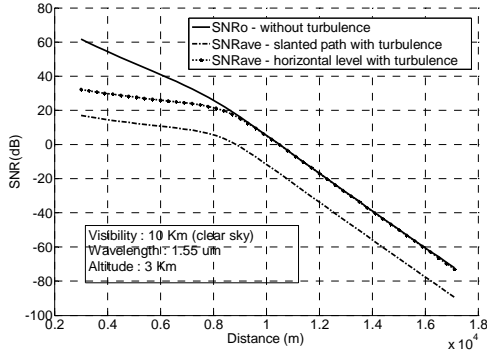


Fig. 4. SNR vs distance for different paths.

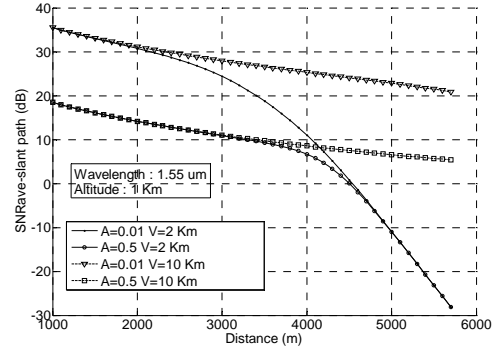


Fig. 5. SNRave vs distance for different values of A .

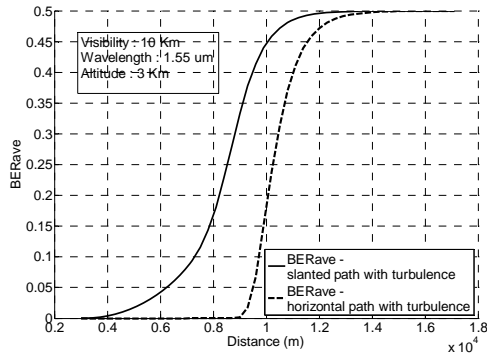


Fig. 6. BER vs distance for different paths.

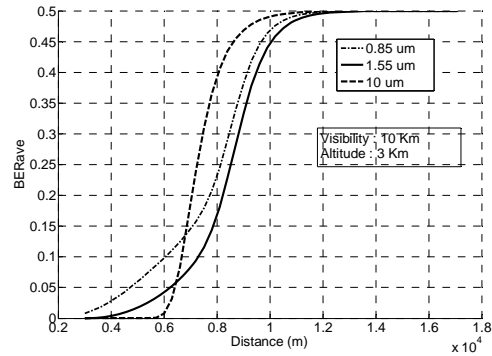


Fig. 7. BERave vs distance for different values of λ .

From the results presented in this paper, it is evident that the quality of the optical communication between a control GS and a UAV which flies at specific altitudes, introduces challenges with regard to the calculation of the variation of the scintillation index due to the slanted path.

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 average SNR and the corresponding average BER was calculated using the proposed scheme. 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 and the aperture averaging factor to maximize the quality of the transmission.

ACKNOWLEDGEMENTS

This research has been co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) - Research Funding Program: ARCHIMEDES III, "Massive" project. Investing in knowledge society through the European Social Fund.

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