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On the Availability of Negative Exponential Turbulent FSO Links with Time Dispersion

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ON THE AVAILABILITY OF NEGATIVE EXPONENTIAL TURBULENT FSO LINKS WITH TIME DISPERSION

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Keywords: Terrestrial Free Space Optical Communication System, Longitudinal Gaussian Pulses, Negative Exponential Distribution, Time Dispersion, Atmospheric Turbulence, Probability of Fade.

Abstract. *In this work, we investigate the influence of the group velocity dispersion effect along with the atmospheric turbulence on the performance of a terrestrial free space optical communication system which is using the atmosphere as propagation path. We assume that the examined wireless optical link employs longitudinal Gaussian pulses in order to transmit the information signal from the nonlinear laser diode of the transmitter to receiver's photo detector. The atmospheric conditions are modelled through the negative exponential distribution model, which is a very accurate model for the signal's irradiance estimation over strong turbulence conditions. Thus, taking into account these effects we obtain closed form mathematical expressions of the probability of fade of the link. Additionally, we evaluate specific parameters, such as the chirp, which can reduce the probability of fade and as a result they can improve the optical system's characteristics. The influence of the time dispersion effect on chirped pulse's propagation is further investigated. Finally, by using the derived mathematical expressions, we present several numerical results which demonstrate our suggestions for the improvement of the system's performance.*

1 INTRODUCTION

Free space optical (FSO) communication systems present a growing commercial and research interest during the last few years. This is mainly due to the very high and secure data transmission they provide. Indeed, by using an optical carrier whose frequency is extremely high, these systems provide a very high data bandwidth which corresponds to a very high information capacity. On the other hand, the fact that the optical radiation is transmitted by a very narrow laser beam guarantees the spatial isolation of the information signal and thus the lack of any possible external interference. Other significant advantages of these wireless systems are their low power consumption, their relatively low operational cost, their unlicensed optical spectrum and their simplicity for deployment and redeployment, [1]-[7].

It is also notable that in recent years, by transmitting more powerful and narrower optical pulses, both the optimal bit rate and the reliable link length of these systems have been significantly increased. However, for narrow pulses and long propagation distances the time dispersion ceases to be a negligible effect. More specifically, this effect alters the shape of the transmitted optical pulses which carry the information bits. Thus, depending on the link's characteristics, the time dispersion effect can either downgrade or even sometimes upgrade the overall system's performance and availability [8], [9].

On the other hand, FSO system's performance and availability depends strongly on the atmospheric turbulence effect .This effect arises from the random fluctuations of the refractive index of the atmosphere, due to the variable atmospheric temperature and pressure conditions. In general, atmospheric turbulence attenuates the propagating signal and causes the scintillation effect which results in random fluctuations of the signal's intensity at the receiver's side [2]-[5]. Therefore, under strong atmospheric turbulent conditions which means under deep signal fades, we observe a significant degradation in the system's performance and availability [1]-[5].

Motivated from these facts, in this work our goal is to achieve a beneficial impact of the time dispersion effect, in order to counterbalance the detrimental impact of the strong atmospheric turbulence on the link's performance. It is highlighted that the sign of the chirp parameter of the transmitted Gaussian pulses contributes strongly to this end. Furthermore, it is shown that such factors are also the peak power of the Gaussian pulses, their initial pulsewidth, the link length and the sensitivity limit of the receiver.

2 THE NEGATIVE EXPONENTIAL DISTRIBUTION MODEL FOR THE ATMOSPHERIC TURBULENT CHANNEL

Atmospheric turbulence is a very complex effect, since atmosphere is not a propagation medium whose refractive index remains constant. Therefore, atmosphere is a variable turbulent channel. According to the weather conditions, the atmospheric composition, the solar radiation and the area characteristics the atmospheric turbulence can be characterized as weak, moderate or strong. It is clear that in case of strong atmospheric turbulence, the induced scintillation effect should also be stronger. Thus, the performance degradation of the system should be more important, under strong turbulent conditions.

For this reason, we need to investigate the strong atmospheric turbulence effect. It is widely accepted that the Negative Exponential (NE) distribution model is accurate for the strong turbulent atmospheric channel. Additionally, it is a mathematically simple distribution model, while all the other models for strong atmospheric turbulence conditions can be reduced to this one [10]. Thus, under the assumption that the propagating Gaussian signal scatters in discrete scattering regions which are sufficiently large, the probability density function (PDF) of the NE model, as a function of the normalized received irradiance I_r, is given as, [10]-[13]:

$$f_{NE,I_r}(I_r) = \exp(-I_r) \quad (1)$$

The normalized received irradiance I_r is defined as [9]:

$$I_r = \frac{I}{I_n} \quad (2)$$

where I and I_n, denote the instantaneous and the average irradiance at the receiver, respectively.

Additionally, by integrating (1), we obtain the corresponding cumulative distribution function (CDF):

$$F_{NE,I_r}(I_r) = 1 - \exp(-I_r) \quad (3)$$

3 THE TIME DISPERSION EFFECT IN GAUSSIAN PULSE'S PROPAGATION THROUGH THE ATMOSPHERE

In case of On-Off Keying (OOK) and other incoherent ways of modulation, the transmitted Gaussian pulse-envelope consists of many and different spectral components. According to the time dispersion effect, these optical components are not propagating with the same speed through the variable atmospheric channel and as a result we observe distortions in the pulse's shape [14]. These distortions concern both the maximum amplitude of pulse, which affects the probability of fade of the link and the pulse's width, which affects the probability of crosstalk [8], [9], [14], [15]. It is also notable that the time dispersion effect is very important for the new generation's wireless links which employ narrow pulses (high bit rates) and they support long propagation distances [8], [9].

In order to investigate the time dispersion effect due to the atmosphere, the first step is to estimate the variable atmospheric refractive index. More specifically, since the terrestrial free space optical links operate inside troposphere (at heights of less than 10km above the Earth's surface), the refractive index of our dispersive media can be estimated through the following expression [8], [16]-[17]:

$$n(\lambda) = 1 + 77.6\left(1 + 7.52\times10^{-3}\lambda^{-2}\right)\frac{P}{\Theta}10^{-6} \tag{4}$$

where P stands for the atmospheric pressure in millibars, Θ is the atmospheric temperature in Kelvin degrees and λ represents the optical wavelength in μm. It is clear that as mentioned in the previous section, the value of the atmospheric refractive index depends on the variable values of P and Θ, which for the same heights can be accurately calculated as follows, [10]:

$$\begin{bmatrix}\Theta(h)\\ P(h)\end{bmatrix} = \begin{bmatrix}288.19 - 6.49h\times10^{-3}\\ 2.23\times10^{-6}\left(44.41 - h\times10^{-3}\right)^{5.256}\end{bmatrix} \tag{5}$$

where h is the link's height above the Earth's surface expressed in meters.

Therefore, from equations (4), (5) we conclude that for a specific link's height h we can calculate the refractive index of the atmosphere n(λ) for the transmission of a specific optical component with wavelength λ. Alternatively, we can express the refractive index as a function of the corresponding component's angular frequency ω. Indeed, by using the equations (4), (5) and the expression $\omega = v/\lambda$, where v represents the speed of the specific transmitted component with wavelength λ, we obtain:

$$n(\omega) = 1 + 2.74\left[1 + 7.52\times10^{-15}\left(\frac{\omega}{2\pi v}\right)^2\right]\left[1 - 22.5h\times10^{-6}\right]^{4.256}10^{-4} \tag{6}$$

where v is expressed in meters/sec while ω in rad/sec.

Then, by substituting the propagation constant, $\beta(\omega) = \omega n(\omega)c^{-1}$ in equation (6), we obtain:

$$\beta(\omega) = \frac{\omega}{c}\left[1 + 2.74\left(1 + 7.52\times10^{-15}\left(\frac{\omega}{2\pi v}\right)^2\right)\left(1 - 22.5h\times10^{-6}\right)^{4.256}10^{-4}\right] \tag{7}$$

where c stands for the speed of light in vacuum, expressed in m/sec.

Next, by expanding the propagation constant in Taylor series around the carrier angular frequency, ω_0, the following summation is obtained [14]:

$$\beta(\omega) = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2}\beta_2(\omega - \omega_0)^2 + \ldots \tag{8}$$

where $\beta_q = \left(\frac{d^q\beta}{d\omega^q}\right)_{\omega=\omega_0}$ for q=1, 2, ..., while β_1^{-1} and β_2, represent the optical pulse's group velocity and the time dispersion parameter, respectively. Thus, from the latter expression, equation (7) and (8), the time dispersion parameter β_2 can be expressed in ps^2/km, through the following form:

$$\beta_2 = \frac{1.97\times10^{15}}{c^2\lambda}\left(1-22.5h\times10^{-6}\right)^{4.256}\times \\ \times\left[1+2.74\left(1+7.52\times10^{-3}\lambda^{-2}\right)\left(1-22.5h\times10^{-6}\right)^{4.256}10^{-4}\right] \tag{9}$$

The normalized irradiance arriving at the receiver's side is obtained from (2) and (9) as:

$$I_r = \frac{\left|u(z,T)\right|^2}{\left|U(z,T)\right|^2} \tag{10}$$

where T denotes the retarded time in ps, [14], z represents the propagation distance in km, while the norms $|U(z,T)|^2$ and $|u(z,T)|^2$, stand for the expected and the instantaneous normalized and dimensionless intensities of the pulses at the receiver's side. For a Gaussian chirped pulse-envelope which propagates inside atmosphere we obtain [14]:

$$\left|U(z,T)\right|^2 = (1+2T_0^{-2}\beta_2 zC + T_0^{-4}\beta_2^{\,2}z^2(C^2+1))^{-1/2}\times \\ \times\exp\left(-\frac{T^2}{T_0^{\,2}+2\beta_2 zC+T_0^{-2}\beta_2^{\,2}z^2\left(C^2+1\right)}\right) \tag{11}$$

where T_0 and C represent the half width at e^{-1} of maximum intensity and the chirp parameter, respectively, [9], [14]. From equation (11), by setting T=0, we can calculate $|U(z,0)|^2$, i.e. the normalized intensity of the pulse, under time dispersion conditions. Due to the fact that the time dispersion parameter is positive, from the same equation it is clear that in case of upshifted chirped pulses, i.e. C>0, the normalized intensity, $|U(z,0)|^2$, decreases by the propagation distance. On the other hand, in case of downshifted chirped pulses, i.e. C<0, we observe that until a specific value of the propagation distance, z_{th}, the normalized intensity increases and after that starts to decreasing and the pulse's peak power will be equal to the initial one for z = z_{max}, [9]. After z_{max}, its peak power will be smaller than its initial one, but larger than the one of the corresponding pulse with positive chirp, for the same propagation distance [9].

Hence, by assuming that the pulse's detection is realized at its larger amplitude value, i.e. at the center of the pulse (T=0ps), [9], and by substituting (11) into (10), the normalized irradiance at the center of the longitudinal Gaussian pulse at the receiver of the FSO link is given as:

$$I_r = |u(z,T=0)|^2\sqrt{1+2T_0^{-2}\beta_2 zC+T_0^{-4}\beta_2^2 z^2\left(C^2+1\right)} \tag{12}$$

It is clear, that equation (12) highlights the influence of the time dispersion effect at the received irradiance, i.e. at the system's performance. Namely, we observe that for small values of T_0 and large values of C and z, the time dispersion effect reduces significantly the received irradiance. However, since the modern needs for communication demand small values of T_0 and large values of z, we should pay particular attention to the choice of the parameter C.

4 THE PROBABILITY OF FADE

The probability of fade is one of the most useful metrics for the estimation of the wireless link's performance and availability. This metric expresses the probability that the normalized irradiance, arriving at the receiver, I_r, falls below the critical threshold, $I_{r,th}$, which corresponds to the receiver's sensitivity limit, [9], [15]. Hence, the probability of fade represents the probability that the FSO system cannot operate properly and it is given as, [15]:

$$P_F = \Pr\left(I_r \le I_{r,th}\right) = F_{I_r}(I_{r,th}) \tag{13}$$

Therefore, for the strong atmospheric turbulent negative exponential channel, by substituting (3) into (13), we obtain the following expression for the probability of fade:

$$P_{F,NE}\left(I_{r,th}\right) = F_{I_r}\left(I_{r,th}\right) = 1 - \exp\left(-I_{r,th}\right) \tag{14}$$

Moreover, under the assumption that the pulse detection ideally happens at the centre of the received pulse (i.e. T=0ps), by substituting the expression (12) for the normalized irradiance, I_r, into (13) and (14) we finally obtain:

$$P_{F,NE}\left(|u(z,0)|_{th}\right) = 1 - \exp\left[-|u(z,0)|_{th}^2 \sqrt{1 + 2T_0^{-2}\beta_2 zC + T_0^{-4}\beta_2^2 z^2\left(C^2+1\right)}\right] \tag{15}$$

Thus, using expression (15), the probability of fade of the FSO link is estimated taking into account both the strong atmospheric turbulence and the time dispersion effect.

5 NUMERICAL RESULTS

In order to demonstrate the impact of the strong turbulent atmospheric channel along with the time dispersion effect on the FSO system's availability a common horizontal FSO link is assumed. This specific link employs longitudinal Gaussian pulses and it is established at an altitude of h=30m above the earth's surface, while the strong turbulent conditions are modeled through the negative exponential distribution. For a link length z=10km, operational wavelength λ=1.55μm, longitudinal pulsewidths T_0=5psec and T_0=8psec, chirp parameters C=-20, C=0 or C=20 and dimensionless receiver's threshold $|u(z,T)|^2$ varying between 0.01 and 0.1, the probability of fade of the link is estimated through the above derived expressions.

Figure 1 illustrates the availability results for the negative exponential model with longitudinal Gaussian pulsewidth T_0=5psec for three different chirp parameter's values. These results show that the probability of fade increases significantly by the increment of the receiver's threshold, which equivalently means, that the availability of the link reduces significantly by the propagation distance and the turbulence strength increment. It is also notable that for positive chirped pulses with parameter C=20, the probability of fade is significantly greater than its corresponding in the case of negative chirped pulses with parameter C=-20.Indeed, in the first case, due to the pulse's broadening with the propagating distance, the time dispersion effect is destructive for the link's availability. Conversely, due to pulse's narrowing with the propagating distance in the latter case, the time dispersion acts beneficial for the link's availability and that's why we obtain improved results. Finally the case of unchirped pulses, i.e. C=0 consists an intermediate case, since the pulsewidth remains practically invariable by the propagation distance.

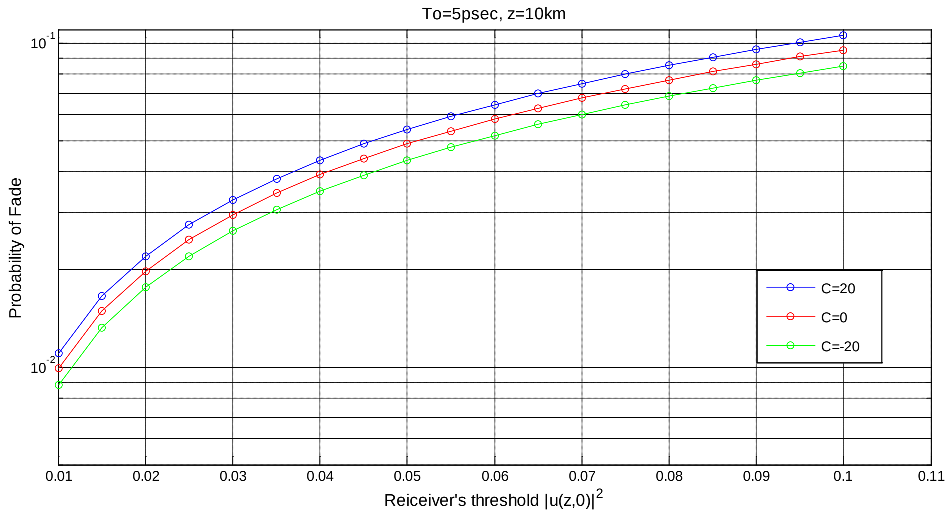

Figure 1. Probability of fade estimation versus intensity threshold for the N.E. distribution model, in the case of longitudinal Gaussian pulses with T_0=5psec and chirp parameters C=20, C=0 and C=-20.

Next, for the same link's characteristics, but by employing pulses with greater longitudinal Gaussian pulsewidth this time, i.e. T_0=8psec, figure 2 illustrates the obtained availability results. We observe again that in presence of stronger turbulence, which as mentioned above corresponds to higher receiver's threshold values, the link's availability heavily degrades. On the other hand, time dispersion effect acts in a similar way to the previous case. However, due to the fact that the initial pulsewidth is larger this time, the time dispersion effect affects less the propagated pulse's shape. As a result, in comparison with the case of T_0=5psec, for C=20 we obtain now slightly reduced probability of fade values. However, for the desirable case of C=-20 the probability of fade obtains now slightly increased values.

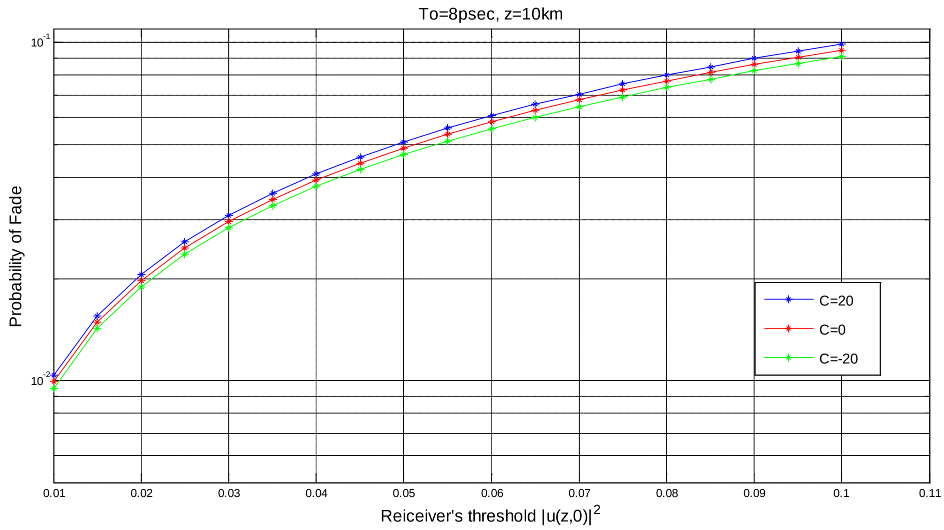

Figure 2. Probability of fade estimation versus intensity threshold for the N.E. distribution model, in the case of longitudinal Gaussian pulses with T_0=8psec and chirp parameters C=20, C=0 and C=-20.

6 CONCLUSIONS

In this work we investigated the influence of the time dispersion effect on the FSO system's availability over a strong turbulent atmospheric channel, modeled by the negative exponential distribution. For this end and in the case of longitudinal Gaussian pulse's transmission, we derived a closed form expression for the probability of fade of the system, which is a very accurate metric for its availability and performance. We showed that the strong atmospheric turbulence degrades significantly the system's performance and availability by the propagation distance. On the other hand, we demonstrated that the time dispersion effect acts beneficial in case of negative chirped pulses, while for positive chirped pulses the time dispersion acts as a destructive effect for the system's performance and availability too. We also proved that the impact of time dispersion is more significant for narrower pulses and long propagation distances. Thus, for long propagation distances through a strong turbulent atmospheric channel, we conclude that in order to improve the FSO system's performance and availability we should transmit narrower and negative chirped longitudinal Gaussian pulses.

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