# Estimation of Outage Capacity for Free Space Optical Links over I-K and K Turbulent Channels

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**Abstract.** *The free space optical communication systems are attracting great research and commercial interest due to their capability of transferring data over short distances, with high rate and security, low cost demands and without licensing fees. However, their performance depends strongly on the atmospheric conditions in the link's area. In this work, we investigate the influence of turbulence on the outage capacity of such a system, for weak to strong turbulence channels, modeled by the I-K and the K-distribution and we derive closed-form expressions for its estimation. Finally, using these expressions we present numerical results for various link cases with different turbulence conditions.*

## Keywords

Atmospheric turbulence, outage capacity, I-K distribution, K-distribution, free space optical channels.

## 1. Introduction

The wireless optical communication systems, which are using the atmosphere as a propagation medium, attract much research and commercial interest over the last few years. The free space optical (FSO) communication systems achieve secure and efficient communication with low installation and operational cost [1], [2]. On the other hand, a very considerable problem that these systems face, is that for an outdoor line-of-sight, point-to-point wireless optical link, the atmospheric conditions play a very significant role on system's performance, [3]-[14]. In this work, we concentrate on one of the most important factors, the atmospheric turbulence that causes signal intensity fluctuations and fading to the received optical [15], [16]. Thus, the channel appears to have randomly time-varying characteristics due to the so called scintillation, [17], [18].

Depending on the signal's fading statistics, it could be assumed either as fast or slow [19]-[21]. When the fluctuations of the signal intensity are supposed to be very rapid, and thus there is a difference from one symbol to another, the channel can be characterized as fast fading, while, when these fluctuations are very slow compared to the bit rate of the link, as slow. For the cases of high bit rate transmission, the channel can be characterized as slow fading. For these cases, (i.e. quasi-static channels) [19], the link's performance can be described by the outage capacity [20], [22], [23].

In this work, we extract closed form mathematical expressions for the estimation of the outage capacity of an FSO link with additive white Gaussian noise (AWGN), over atmospheric turbulence-induced, slow fading channels, as modeled either by the I-K [24], [25] or the K distribution [26]. The latter is appropriate for the cases of strong atmospheric turbulence conditions while the former for weak to strong turbulence conditions and it is a very significant distribution model for the FSO links [23], [24], [27], due to the fact that is suitable for the most cases of turbulence conditions. From the mathematical expressions of the two models' capacities, the performance of the FSO link can be estimated for every system's parameter. Finally, we present some typical numerical results for both outage capacities models.

The remaining of the paper is organized as follows. In section 2, we present the derivation procedure of the mathematical expression for the estimation of the outage capacity for slow fading channels. In section 3, we present the considered optical channel modeled with the I-K distribution and the mathematical expression for its achievable outage capacity. In section 4, we present the closed form mathematical expression for the estimation of the outage capacity of a K-distribution modeled turbulent channel. Finally, the obtained numerical results are presented and discussed in section 5. Concluding remarks are outlined in section 6.

## 2. Outage Capacity

We study an FSO communication system using intensity modulation/direct detection (IM/DD). The laser beams propagate along a horizontal path through a turbulence channel with AWGN. The channel is assumed to be memoryless, stationary, with independent, identically distributed (i.i.d.) intensity slow fading statistics. The statistical channel model is [26], [28]-[30]:

$$y = sx + n = \eta I x + n \tag{1}$$

where $y$ is the signal at the receiver, $s = \eta I$ is the instantaneous intensity gain, $\eta$ is the effective photo-current conversion ratio of the receiver, $I$ is the normalized irradiance, $x$ is the modulated signal (and takes values "0" or "1"), and $n$ is the AWGN with zero mean and variance $N_0/2$ [31].

Due to the fact that the laser beam propagates through the atmosphere, which is a randomly varying channel that induces random intensity fluctuations, the instantaneous electrical SNR at the receiver $\gamma=s^2/N_0$ [26], and the instantaneous channel capacity $C$, are random variables too. Due to the fact that $C$ represents the channel's capacity only for a specific moment, we estimate the outage capacity, $C_{out}$, which is the capacity guaranteed for a probability (1-$r$) of the channel realizations [22]:

$$\Pr\left[C < C_{out}\right] = r. \tag{2}$$

If the pdf of $C$ is represented as $p_C(C)$, the above probability, (2), can be estimated as [20]:

$$r = \int_0^{C_{out}} p_C(C)\,dC\,. \tag{3}$$

By evaluating the integral of equation (3), it is feasible to evaluate the outage capacity of an FSO link due to slow varying signal intensity at the receiver caused by the atmospheric turbulence conditions.

# 3. The I-K Distribution Channel Model

The pdf of the I-K modeled normalized signal irradiance $I$, is given by [24], [25],

$$p_I(I) = \begin{cases} 2\alpha(1+\rho)\left(\frac{1+\rho}{\rho} I\right)^{\frac{\alpha-1}{2}} K_{\alpha-1}\left(2\sqrt{\alpha\rho}\right) I_{\alpha-1}\left(2\sqrt{\alpha(1+\rho)I}\right) \\ for\ I < \frac{\rho}{1+\rho} \\ \\ 2\alpha(1+\rho)\left(\frac{1+\rho}{\rho} I\right)^{\frac{\alpha-1}{2}} I_{\alpha-1}\left(2\sqrt{\alpha\rho}\right) K_{\alpha-1}\left(2\sqrt{\alpha(1+\rho)I}\right) \\ for\ I > \frac{\rho}{1+\rho} \end{cases} \tag{4}$$

where $I_v(.)$is the modified Bessel function of the first kind of order $v$, $K_v(.)$ is the modified Bessel function of the second kind of order $v$, while $\alpha$ and $\rho$ are the distribution's parameters and represent the effective number of scatters and a coherence parameter, respectively [24], [25], [27].

From (4), we obtain the following pdf for the instantaneous electrical SNR, $\gamma$, at the receiver,

$$p_\gamma(\gamma) = \begin{cases} 2\alpha(1+\rho)\left(\frac{1+\rho}{\rho}\right)^{\frac{\alpha-1}{2}} \frac{\gamma^{\frac{\alpha-3}{4}}}{\xi^{\frac{\alpha+1}{4}}} K_{\alpha-1}\left(2\sqrt{\alpha\rho}\right)\times \\ \times I_{\alpha-1}\left(2\sqrt{\alpha(1+\rho)}\sqrt{\frac{\gamma}{\xi}}\right) \quad for\ \gamma < \frac{\rho^2\xi}{(1+\rho)^2} \\ \\ 2\alpha(1+\rho)\left(\frac{1+\rho}{\rho}\right)^{\frac{\alpha-1}{2}} \frac{\gamma^{\frac{\alpha-3}{4}}}{\xi^{\frac{\alpha+1}{4}}} I_{\alpha-1}\left(2\sqrt{\alpha\rho}\right)\times \\ \times K_{\alpha-1}\left(2\sqrt{\alpha(1+\rho)}\sqrt{\frac{\gamma}{\xi}}\right) \quad for\ \gamma > \frac{\rho^2\xi}{(1+\rho)^2} \end{cases} \tag{5}$$

where $\xi$ is the average electrical SNR at the receiver, given by $\xi = \left(\eta E[I]\right)^2/N_0$, and $E$[.] is the expected value [26], [28], [32].

In order to evaluate the outage capacity of an optical channel modelled with the I-K distribution we should first estimate the corresponding pdf of the capacity, $C$.

This can be done from equation (5) and the well-known equation for the capacity, $C = Blog_2(1+\gamma)$ and has the following form,

$$p_C(C) = \begin{cases} \frac{2^{C/B+1}\ln(2)}{B\alpha^{-1}}(1+\rho)\left(\frac{1+\rho}{\rho}\right)^{\frac{\alpha-1}{2}} \frac{\left(2^{C/B}-1\right)^{\frac{\alpha-3}{4}}}{\xi^{\frac{\alpha+1}{4}}}\times \\ \times K_{\alpha-1}\left(2\sqrt{\alpha\rho}\right) I_{\alpha-1}\left(\sqrt{4\alpha(1+\rho)}\sqrt{\frac{2^{C/B}-1}{\xi}}\right), C < C_{cr} \\ \\ \frac{2^{C/B+1}\ln(2)}{B\alpha^{-1}}(1+\rho)\left(\frac{1+\rho}{\rho}\right)^{\frac{\alpha-1}{2}} \frac{\left(2^{C/B}-1\right)^{\frac{\alpha-3}{4}}}{\xi^{\frac{\alpha+1}{4}}}\times \\ \times I_{\alpha-1}\left(2\sqrt{\alpha\rho}\right) K_{\alpha-1}\left(\sqrt{4\alpha(1+\rho)}\sqrt{\frac{2^{C/B}-1}{\xi}}\right), C > C_{cr} \end{cases} \tag{6}$$

where $C_{cr}=Blog_2(1+\rho^2\xi/(1+\rho)^2)$.

By substituting (6) into (3) we obtain the following, two branch closed mathematical expression for the estimation of the outage capacity:

$$r = \begin{cases} 2\sqrt{\alpha\rho}\left(\frac{1+\rho}{\rho}\right)^{\frac{\alpha}{2}}\left(\frac{2^{\widetilde{C}_{out}}-1}{\xi}\right)^{\frac{\alpha}{4}} K_{\alpha-1}\left(2\sqrt{\alpha\rho}\right)\times \\ \times I_\alpha\left(2\sqrt{\alpha(1+\rho)}\sqrt{\frac{2^{\widetilde{C}_{out}}-1}{\xi}}\right), \widetilde{C}_{out} < \widetilde{C}_{cr} \\ \\ 1-2\sqrt{a(1+\rho)}\left(\frac{1+\rho}{\rho}\right)^{\frac{\alpha-1}{2}}\left(\frac{2^{\widetilde{C}_{out}}-1}{\xi}\right)^{\frac{\alpha}{4}}\times \\ \times I_{\alpha-1}\left(2\sqrt{\alpha\rho}\right) K_{-\alpha}\left(2\sqrt{\alpha(1+\rho)}\sqrt{\frac{2^{\widetilde{C}_{out}}-1}{\xi}}\right), \widetilde{C}_{out} > \widetilde{C}_{cr} \end{cases} \tag{7}$$

where $\tilde{C}_{out} = C_{out}/B$ and $\tilde{C}_{cr} = C_{cr}/B$. Equation (7) which gives the value of the probability $r$ as a function of the outage capacity $C_{out}$, is a strictly increasing function of $C_{out}$. Thus, it is easy from (7), to obtain the estimation of the outage capacity for every value of the probability $r$.

# 4. The K Distribution Channel Model

The pdf of the K-modeled signal irradiance $I$, is given by [26], [33],

$$p_I(I) = \frac{2\beta^{\frac{\beta+1}{2}}}{\Gamma(\beta)} I^{\frac{\beta-1}{2}} K_{\beta-1}\left(2\sqrt{\beta I}\right) \qquad (8)$$

where $\Gamma(.)$ is the gamma function, while the parameter $\beta$ is related to the effective number of discrete scatterers [26].

From (8), with a simple transformation, the following pdf for the instantaneous electrical SNR, $\gamma$, at the receiver, is obtained [26],

$$p_\gamma(\gamma) = \frac{\beta^{\frac{\beta+1}{2}}}{\Gamma(\beta)} \frac{\gamma^{\frac{\beta-3}{4}}}{\xi^{\frac{\beta+1}{4}}} K_{\beta-1}\left(2\sqrt{\beta\sqrt{\frac{\gamma}{\xi}}}\right). \qquad (9)$$

As in the case of I-K distribution, in order to evaluate the outage capacity of a slow fading optical channel modeled with the K-distribution we should first estimate the corresponding pdf for the instantaneous channel capacity, $C$. This can be done from the capacity's equation and (9) and is taking the following closed form expression [34],

$$p_C(C) = \frac{\ln(2)\beta^{\frac{\beta+1}{2}}}{2^{-C/B}\Gamma(\beta)} \frac{\left(2^{C/B}-1\right)^{\frac{\beta-3}{4}}}{\xi^{\frac{\beta+1}{4}}} K_{\beta-1}\left(2\sqrt{\beta\sqrt{\frac{2^{C/B}-1}{\xi}}}\right). \qquad (10)$$

From (3), (10), the following closed form mathematical expression for the estimation of the outage capacity of a K-distribution modeled optical channel, is obtained, [34]:

$$r = \frac{\left(2^{\tilde{C}_{out}}-1\right)^{\frac{\beta+1}{4}}}{\left(\sqrt{\xi}/\beta\right)^{\frac{\beta+1}{2}}\Gamma(\beta)} G^{2,1}_{1,3}\left(\beta\sqrt{\frac{2^{\tilde{C}_{out}}-1}{\xi}}\left|\begin{matrix}\frac{1-\beta}{2}\\ \frac{\beta-1}{2},\frac{1-\beta}{2},-\frac{\beta+1}{2}\end{matrix}\right.\right) \qquad (11)$$

where $G^{p,q}_{m,n}[\cdot]$is the Meijer$G$-function, [35], which is a standard built-in function in many of the well-known mathematical software packages. Taking into account that $r$, in equation (10), is a strictly increasing function of $C_{out}$, this expression can be used for the estimation of the outage capacity for every value of the probability $r$.

# 5. Numerical Results

Using the closed form mathematical expressions obtained in (7) and (10) the estimation of the outage channel capacity of slow fading free space optical links is feasible.

From (7) we can evaluate the outage capacity of a I-K modeled turbulence wireless optical channel, as a function of the average electrical SNR, $\xi$, for different values of the probability $r$ and the distribution parameters $\rho$ and $\alpha$ which are directly "connected" to the atmospheric turbulence conditions of the atmosphere. In this work, we present results for two different values of $r$, (i.e. 0.1 and 0.01) which are the most common in practical communication systems [22]. Moreover, we investigate two different values for $\rho$ (i.e. 0.1 and 10) and three for $\alpha$ (i.e. 1, 2, and 3). The parameter $\alpha$, as mentioned above represents the effective number of scatterers in the path between the transmitter and the receiver. Thus, this parameter is a measure of the atmospheric turbulence conditions and increases its value as the turbulence is getting weaker. It is clear that equation (7) can give results for any other case and for any other value of the above mentioned parameters.

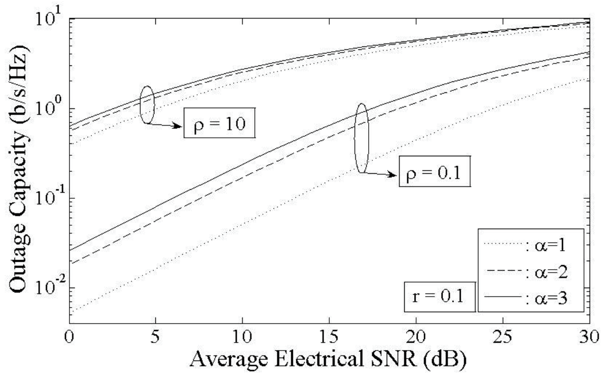


**Fig. 1.** Outage channel capacity $C_{out}/B$ for $r = 0.1$, of an FSO channel modeled with the I-K distribution, versus the average electrical SNR, $\xi$, for $\rho = 0.1$ and 10, and $\alpha = 1$, 2 and 3.

Thus, in Fig. 1, we present the obtained results for $r = 0.1$, for the two different values of $\rho$ and the respective three values for $\alpha$, while in Fig. 2 we show the corresponding results for $r = 0.01$.

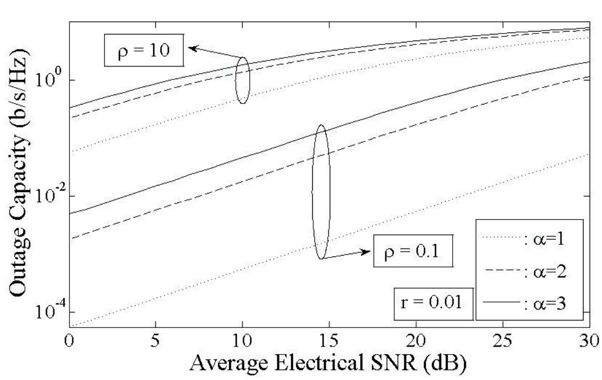


**Fig. 2.** Outage channel capacity $C_{out}/B$ for $r = 0.01$, of an FSO channel modeled with the I-K distribution, versus the average electrical SNR, $\xi$, for $\rho = 0.1$ and 10, and $\alpha = 1$, 2 and 3.

In Fig. (3) we present the corresponding results (i.e. $r = 0.1$ and $r = 0.01$) for the case of K-distribution modeled optical channel, for three different values of the parameter

$\beta$, (i.e. $\beta = 1$, $\beta = 2$ and $\beta = 3$), which is related to the atmospheric turbulence conditions. Thus, the value of $\beta$ is getting smaller as the atmospheric turbulence is getting stronger [26]. For larger values of $\beta$, the obtained results are slightly different from those with $\beta = 3$.

These results show that the atmospheric turbulence conditions affect the outage capacity of the FSO communication channels. More specifically, it is clear, that this influence is getting stronger as turbulence is getting stronger and as the probability $r$ is requested to be smaller.

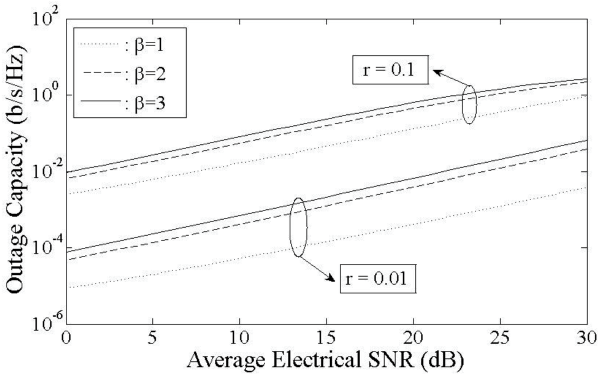


**Fig. 3.** Outage channel capacity $C_{out}/B$ for $r = 0.1$ and 0.01, of an FSO channel modeled with the K distribution, versus the average electrical SNR, $\xi$, for $\beta = 1$, 2 and 3.

# 6. Conclusions

In this work, we derive two closed form mathematical expressions for the estimation of the outage capacity of FSO channels with slow fading statistics, modeled with both the I-K and the K-distribution. Using these two expressions, the practical outage channel capacity can be estimated for different values of the outage capacity probability and circumstances of the atmospheric turbulence conditions. This is feasible due to the fact that the I-K distribution model describes accurately the links under weak to strong turbulence conditions, while the K distribution model is suitable for strong to very strong turbulence conditions. Thus, we investigate the influence of the turbulence, through the parameters $\alpha$, $\rho$ and $\beta$, of the I-K and the K distribution model, respectively, on the performance of the optical link. These results, and others that can be obtained from the two closed form mathematical expressions, can help in the design of effective FSO communication systems, due to the fact that the channel capacity is a very significant magnitude for the evaluation of link's performance.

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