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Capacity of wander and spread beams in log-normal distribution non-Kolmogorov turbulence optical links

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ABSTRACT

We model the average channel capacity of optical wireless communication systems in weak turbulence horizontal channels, using the log-normal distribution models. The effects of beam wander and spread, pointing errors, turbulence inner scale, turbulence outer scale and the spectral index of non-Kolmogorov turbulence on system's performance are included. The model can evaluate the influence of the atmospheric turbulence conditions in the performance of a ground-to-train optical wireless communication system.

1. Introduction

Recently, optical wireless communication has increasingly attracted much attention for the first mile access environment [1]. The main drawback of optical wireless communication is the effect of the atmosphere on a propagating light beam. The atmospheric turbulence normally leads to refractive index fluctuations along the optical path and results in effects such as signal scintillation, beam broadening, and beam wander [2], thus affecting the capacity of the optical channel. In the weak atmospheric turbulence channels or the short propagating paths, the log-normal distribution is generally used to model the channel capacity [3–12]. Many models proposed to describe the turbulence impact on the capacity of the wireless optical communication channel. The accurate estimation [3] and approximate expressions [4,5] of the ergodic capacity of a single-input single-output system operating in a log-normal environment are modeled. The performance metrics affected by the atmospheric conditions and other parameters such as the length of the link and the receiver's aperture diameter are developed [6]. The ergodic capacity and capacity-versus-outage probability of direct-detection optical communication through a turbulent atmosphere using multiple transmit and receive apertures are modeled on account of shot-noise-limited operation in which detector outputs are doubly stochastic Poisson processes, scaled by lognormal random fades, plus a background noise. In the high and low signal-to-background ratio regimes, it is shows that the ergodic capacity of a fading channel equals or exceeds that for a channel with deterministic path gains [7]. The error performance of terrestrial free-space optics links modeled as Poisson channels in turbulent atmosphere is assessed by considering pulse-position modulation [8]. The impact of pointing error has bee investigated for the outage capacity optimization [9], capacity and the bit-error-rate performance [10] of the on-off keying system. A closed form mathematical expression for the evaluation of the ergodic capacity of optical wireless communication system is extracted, using the log-normal distribution [11]. The effects of log-normal amplitude fluctuations and Gaussian phase fluctuations on the ergodic capacity and ε-outage capacity of coherent optical links in the turbulent atmosphere [12] and information-bearing signal transmitted over two or more statistically independent fading channels [13] are analyzed. Taking into account the pulse broadening, the all effects of atmospheric turbulence on channel capacity are studied in [14]. The methods of the use of multiple lasers and multiple apertures with Q-ary pulse position modulation and transmit repetition [15], and multiple-pulse-position-modulation [16] to mitigate the effects of scintillation are presented.

In this paper, we model the average capacity by using the log-normal distributions of the non-Kolmogorov turbulent optical links with the combined effect of the beam wander and spread, and the pointing errors.

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2. Average channel capacity

The performance of an optical wireless communication system using intensity modulation/direct detection is studied [17]. In the study, the laser beams propagate along a horizontal path near ground through a turbulence channel with additive white Gaussian noise. The channel is assumed to be memoryless, stationary and ergodic, with independent and identically distributed intensity fast fading statistics. We also consider that the channel state information is available at both transmitter and receiver. In this case, the statistical channel model is given by

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

where y is the signal at the receiver, η is the instantaneous intensity gain, x is the modulated signal, and n is the additive white Gaussian noise with zero mean and variance $N_0/2$.

In this paper, it is supposed that $\eta = \eta_a \eta_p$, where η_a is the fading due to atmospheric turbulence with the effects of scintillation that arise from beam wander, η_p is the pointing errors because of building sway.

An optical wireless channel is a randomly time-variant channel and the received instantaneous electrical signal-to-noise ratio is a random variable $\mu = \eta^2/N_0$ [17], $\bar{\mu} = \bar{\eta}^2/N_0$ is the average electronic SNR. Thus, the channel capacity is a random variable, and its average value, known as average capacity, $\langle C \rangle$, indicates the average (practical) best rate for error-free transmission [17].

On representing the probability density function (pdf) of η as $p_\eta(\eta, w_{LT})$, the average channel capacity of an optical wireless channel due to signal intensity fluctuations caused by atmospheric turbulence is given by

$$\langle C \rangle = B \int_0^\infty \log_2 \left(\frac{1+\eta^2}{N_0} \right) p_\eta(\eta, w_{LT}) d\eta \tag{2}$$

where B is the channel's bandwidth.

3. Optical channel fading model

3.1. Atmospheric statistical model

Under weak turbulence, the log-normal distribution has been found to be a good model for η_a [2]. Under this model, we write

$$p_{\eta_a}(\eta_a) = \frac{1}{2\eta_a \delta_I \sqrt{2\pi}} \exp\left[-\frac{(\ln \eta_a + \delta_I^2/2)^2}{2\delta_I^2} \right] \tag{3}$$

where $\eta_a = I/I_0$ is the ratio of the faded light intensity to the intensity without turbulence, it is also called as normalized irradiance, δ_I is the irradiance scintillation index for Gaussian-beam wave propagation in the log-normal channel, which contains the effects of beam wander and spreading, and is given by [18]

$$\delta_I^2(r,\alpha,z) = \delta_{I,r}^2(r,\alpha,z) + \delta_{I,l}^2(r,\alpha,z) \tag{4}$$

where $\delta_{I,r}^2(r,\alpha,z)$ and $\delta_{I,l}^2(r,\alpha,z)$ represent the radial component and longitudinal component of the irradiance scintillation index, respectively

$$\begin{aligned} \delta_{I,r}^2(r,\alpha,z) = & -\frac{\alpha \delta^2(\alpha) \Lambda^{\alpha/2-1}}{3\Gamma(1-\alpha/2)\sin(\alpha\pi/4)} \frac{r^2}{w^2} \left[\Gamma\left(2-\frac{\alpha}{2}\right) \left(\frac{\Lambda z \kappa_l^2}{k} \right)^{2-\alpha/2} \right. \\ & \left. \times {}_2F_1\left(2-\frac{\alpha}{2}, \frac{3}{2}; \frac{5}{2}; -\frac{\Lambda z \kappa_l^2}{k}\right) + \frac{\Gamma(-2+\alpha/2)}{\Gamma(\alpha/2)} \left(\frac{\Lambda z \kappa_0^2}{k} \right)^{2-\alpha/2} \right] \end{aligned} \tag{5}$$

$$\begin{aligned} \delta_{I,l}^2(r,\alpha,z) = & \frac{\delta^2(\alpha)}{\sin(\alpha\pi/4)} \left\{ \frac{\left[(1+2\Theta)^2 + (2\Lambda + 3k/z\kappa_l^2)^2\right]^{\alpha/4}}{3^{\alpha/2-1}\left[(1+2\Theta)^2 + 4\Lambda^2\right]^{1/2}} \sin\left(\frac{\alpha}{2}\varphi_l + \varphi_0 \right) \right. \\ & \left. - \frac{6\Lambda}{(z\kappa_l^2/k)^{\alpha/2}\left[(1+2\Theta)^2 + 4\Lambda^2\right]} - \frac{\alpha}{2} \left(\frac{z\kappa_l^2}{k} \right)^{1-\alpha/2} {}_2F_1\left(1-\frac{\alpha}{2}, \frac{1}{2}; \frac{3}{2}; -\frac{\Lambda z \kappa_l^2}{k}\right) \right\} \end{aligned} \tag{6}$$

where z is the distance between the transmitter and receiver, $\Gamma(x)$ being the Gamma function, α is the spectral index of non-Kolmogorov turbulence; $\Lambda = (2z/kw_0^2)[(1-z/F_0)^2 + (2z/kw_0^2)^2]^{-1}$, $k = 2\pi/\lambda$ is the optical wavenumber and λ is the operational wavelength, w_0 is the phase front radius of curvature at the transmitter and F_0 is the phase front radius of curvature at the exit aperture; $\kappa_l = c(\alpha)/l_0$, l_0 is the turbulence inner scale, $c(\alpha) = [2\Gamma((5-\alpha)/2)A(\alpha)\pi/3]$ and $A(\alpha) = \Gamma(\alpha-1)\cos(\alpha\pi/2)/4\pi^2$; ${}_2F_1(a,b;c;x)$ is the hypergeometric function; $\kappa_0 = 4\pi/L_0$, L_0 is the turbulence outer scale; $\varphi_l = \tan^{-1}[(1+2\Theta)Q_l/(3+2\Lambda Q_l)]$ and $\varphi_0 = \tan^{-1}[2\Lambda/(1+2\Theta)]$; $\Theta = (1-z/F_0)/[(1-z/F_0)^2 + (2z/kw_0^2)^2]$; $\delta^2(\alpha)$ is the irradiance scintillation index for plane wave propagating through weak non-Kolmogorov turbulence

$$\delta^2 = -\frac{8\pi^2 A(\alpha)}{\alpha} \Gamma\left(1-\frac{\alpha}{2}\right) \sin\left(\frac{\pi\alpha}{4}\right) \tilde{C}_n^2(\alpha) k^{3-\alpha/2} z^{\alpha/2} \tag{7}$$