Paper

Laser Beam Attenuation Determined by the Method of Available Optical Power in Turbulent Atmosphere

Lucie Dordová and Otakar Wilfert

Abstract—This work is focused on the atmospheric turbulence effect and a new method for determining optical signal attenuation caused by turbulence is presented here. A new method of power budget of optical links comes from optical intensity distribution in a laser beam after the beam passed through turbulent atmosphere. Results given by this method are compared with Rytov approximation which is nowadays the most frequently used method for determining turbulent attenuation. Results for communication wavelength of 850 nm and 1550 nm are presented as well as the results for a wavelength of 633 nm.

***Keywords—* method of available power, optical wireless link, Rytov approximation, turbulent atmosphere.**

1. Introduction

Nowadays the information is a valuable element in industry, science, education, medical sphere, banking system or in common household. Requirements for transmission rate increase every day. It is necessary to ensure not only high bit rate, but high quality signal as well. In the past metallic cables were adequate but with increasing demands on transmitted volume of information new communication systems were developed and existing communication systems were modified. Currently optical links occur as the best solution for high speed communication links with high reliability [1].

Several years ago optical fiber links became very popular and wide spread in the telecommunication industry. This technology is placed in the backbones networks as well as in local area networks (LANs). One of few disadvantages of optical fibers is cable laying, because it is necessary to build cable infrastructure. When quick installation demanded optical wireless links (OWL) are suitable. Scheme of optical wireless link is depicted in Fig. 1.

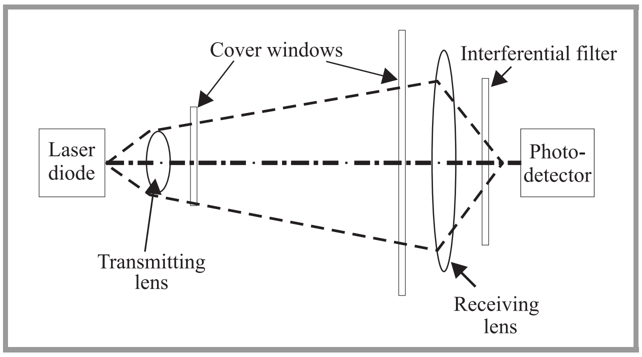

Fig. 1. Optical wireless link with laser diode, photodetector, cover window, interferential filter, transmitting and receiving lenses.

As a transmitter laser diode or light emitting diode is used. The second one is placed in optical links with limited short range (up to about 100 m) or in indoor communication systems. Laser diodes are applied in optical links with longer range (more than 100 m, up to 10 km). Laser beam divergence is set by transmitting lens. Typical values of divergence in free space optics (FSO) are 3–8 mrad. Cover windows are installed to avoid debasement of transmitter and receiver optical components. In receiving optical head receiving lens (most frequently Fresnel lens) is placed to focus laser beam on the active area of photodetector. Photodetector PIN is commonly used, but in special application avalanche photodiode is placed. Interferential filter serves to transmit useful wavelength only.

We consider link budget as stationary parameter in optical wireless link as well as transmission rate, bit error rate or link range. Atmospheric transmission media characteristics have statistical nature. The most significant statistical effects in free space optics are atmospheric attenuation caused by molecules and aerosols and of course atmospheric turbulences. Importance of the turbulence phenomena will be specified in this paper later.

2. Horizontal and Vertical Optical Wireless Links

Nowadays we differentiate between horizontal and vertical optical wireless links. Model of the horizontal links is shown in Fig. 2.

These links occur in most cases in the urban centers, so typical phenomena influence their operation. Smog, dust, fog, snow or rain are typical events affecting horizontal OWL in towns as well as laser the beam interruption caused by flying birds. Turbulent atmosphere hampers optical beam in the whole path length.

Vertical OWLs are still under development. Communication proceeds between the ground station and the high altitude platform (HAP), which can be placed a few tens of kilometers over the ground level (Fig. 3) [2]. In this case optical beam path is about tens of kilometers long, so it is

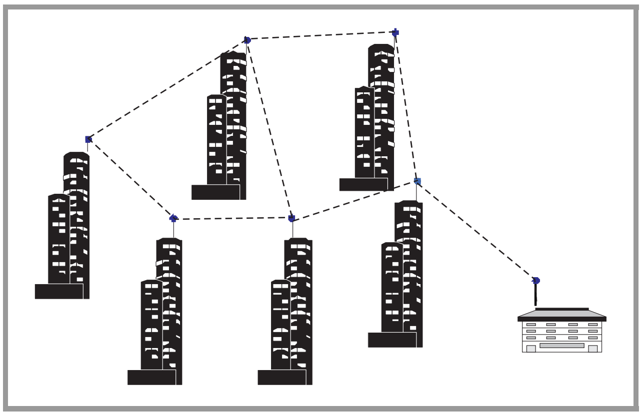

Fig. 2. Model of the horizontal optical wireless links.

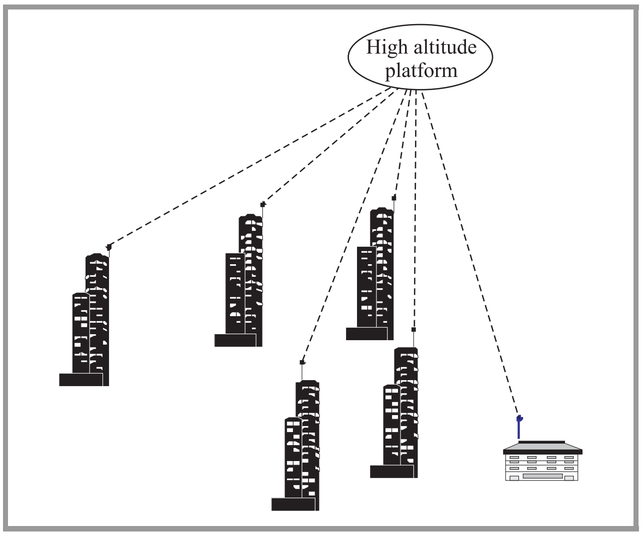

Fig. 3. Model of the vertical optical wireless links.

necessary to design precision tracking system for the signal detection, laser beam divergence should be set in the order of microradians.

3. Atmospheric Turbulence Theory

Atmospheric turbulence, generated by a temperature differential between the Earth's surface and the atmosphere, causes effects on optical waves which have been of great interest to scientists for many years. During daytime, the Earth is hotter than the air, causing the air nearest the ground to be hotter than that above. This negative temperature gradient causes light rays parallel to the earth to bend upwards. If the negative temperature gradient is sufficiently strong, it can result in an inverted image known as a mirage. Temperature gradients are positive during nighttime hours, resulting in downward bending of light rays. In addition, atmospheric turbulence disrupts the coherence of laser radiation and optical wave. Wave front distortions in the optical wave induced by atmospheric turbulence result in a broadening of the beam, random variations of the position of the beam centroid called beam wander, and redistribution of the beam energy within a cross section of the beam leading to irradiance fluctuations [3].

Atmospheric temperature variations and wind speed fluctuations create local unstable air masses, causing them eventually to break up into turbulent eddies or cells of many different scale sizes. These inhomogeneities range in size from a microscale to a macroscale, and hence, in effect form a continuum of decreasing "eddy" size [3].

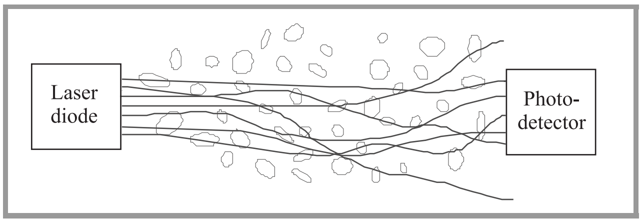

Fig. 4. Turbulent cells through the whole optical path.

Turbulent cells can occur in the whole path length (Fig. 4) or just in the few sections (Fig. 5). Variance in the refraction index is characteristic for atmospheric transmission media with atmospheric turbulences. Refraction index value depends on the local temperature, atmospheric pressure or particle density at specific location. Statistical character of refraction index is measured as refraction index structure function D_n [4]:

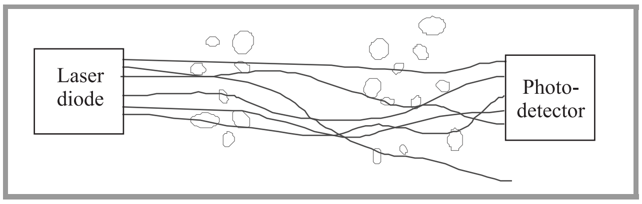

Fig. 5. Turbulent cells in some section of optical path.

$$D_n = \left\langle \left[n(A,t) - n(B,t) \right]^2 \right\rangle , \tag{1}$$

where $n(A,t)$ and $n(B,t)$ are refractive indexes in the points A, B and in time t. Refraction index structure parameter is in the relation with the distance r between points A and B according to Kolmogorov model [4]:

$$D_n = \begin{cases} C_n^2 \cdot r^{2/3} & l_0 \ll r \ll L_0 \\ C_n^2 \cdot l_0^{-4/3} r^2 & r \ll l_0 \end{cases} , \tag{2}$$

where C_n^2 is refractive index structure parameter [m$^{-2/3}$], l_0 presents inner scale of the turbulent cell [m] and L_0 signifies turbulent cell outer scale [m]. There exists relationship between C_n^2 and volume of atmospheric turbulences, which is shown in Table 1.

It is clear that volume of atmospheric turbulences increases with the rising refractive index structure parameter.

Table 1
Refractive index structure parameter influence on the atmosphere

C_n^2 [m$^{-2/3}$]	Atmospheric turbulences
10^{-16}	Weak
10^{-15}	Mean
10^{-14}	Strong
10^{-13}	Very strong

Atmospheric turbulences approves also by the variance of optical intensity in detected signal. Relative variation of optical intensity σ_{Ir}^2 can be expressed as [1]

$$\sigma_{Ir}^2 = \frac{\langle I^2\rangle - \langle I\rangle^2}{\langle I\rangle^2} = \frac{\langle I^2\rangle}{\langle I\rangle^2} - 1\,, \tag{3}$$

when I is optical intensity of the received signal and $\langle\,\rangle$ signifies mean value.

When $\sigma_{Ir}^2 \ll 1$, then we can use Rytov approximation which ties relative variation of optical intensity and refractive index structure parameter [5]:

$$\sigma_{Ir}^2 = K \cdot C_n^2 \cdot k^{7/6} \cdot L^{11/6}\,, \tag{4}$$

where K represents constant for plane wave 1.23 or 0.5 for spherical wave, k is wave number and L means distance between transmitter and receiver. This relation is valid only for homogenous distribution of atmospheric turbulences.

Optical signal attenuation is caused not only by scattering and absorption on particles, molecules and hydrometeors but also by turbulent atmosphere. Rytov relationship deals with this attenuation due to relation [6]:

$$\alpha_t = 2 \cdot \sqrt{23.17 \cdot k^{7/6} \cdot C_n^2 \cdot L^{11/6}}\,. \tag{5}$$

Optical signal attenuation and atmospheric turbulences are stronger during sunny days.

4. Available Optical Power

All theories work with the idea that atmospheric turbulences are homogenous and don't take into account laser beam geometric profile. Designed theory of available power looks at optical intensity distribution and there is not necessary to regard homogenous refractive index structure parameter through the laser beam path. We count with mean C_n^2 in the optical path of the laser beam. We also consider Gaussian beam only in this work (Fig. 6).

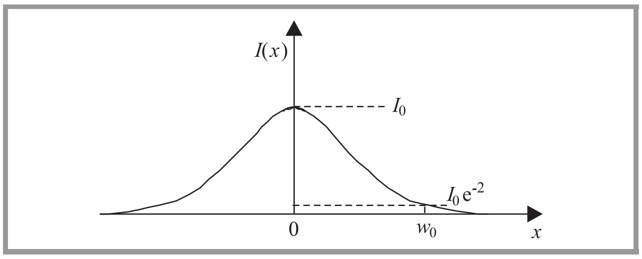

Fig. 6. Gaussian beam distribution.

In case of turbulent atmospheric transmission media there occurs optical intensity level fluctuation through the laser beam profile as shown in Fig. 7.

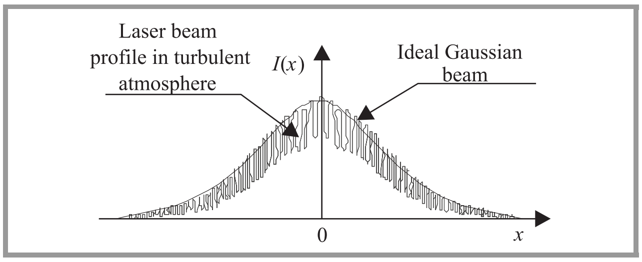

Fig. 7. Affected laser beam by turbulent atmosphere.

It is evident, that turbulent atmosphere debases optical signal properties, and optical intensity level is unstable in the time. This fluctuation has its limits for concrete refractive index structure parameter. We specified turbulent envelope (see Fig. 8) as limits for optical intensity fluctuation.

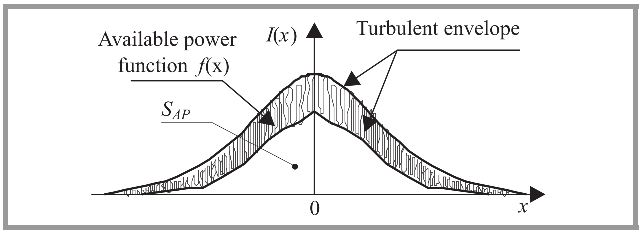

Fig. 8. Turbulent envelope and available power function of Gaussian laser beam.

Available power function $f(x)$ is defined as lower limit of turbulent envelope. We suppose decreasing available power function with increasing volume of turbulences. According to Fig. 8 we determine area of available power S_{AP} by following relation:

$$S_{AP} = \int_x f(x)\mathrm{d}x\,. \tag{6}$$

Upper limit of S_{AP} is defined as available power function $f(x)$ and as lower limit we consider x-axis (zero). In fact laser beam is 3 dimensional $(x, y, I(x,y))$ so we set up the volume of available power, for short available power by relation:

$$V_{AP} = \int_x\int_y f(x,y)\mathrm{d}x\,\mathrm{d}y\,. \tag{7}$$

In non-turbulent area we suppose that available power function is identical to Gaussian optical intensity distribution so we express available power as

$$V_{AP0} = \int_x\int_y f_0(x,y)\mathrm{d}x\,\mathrm{d}y. \tag{8}$$

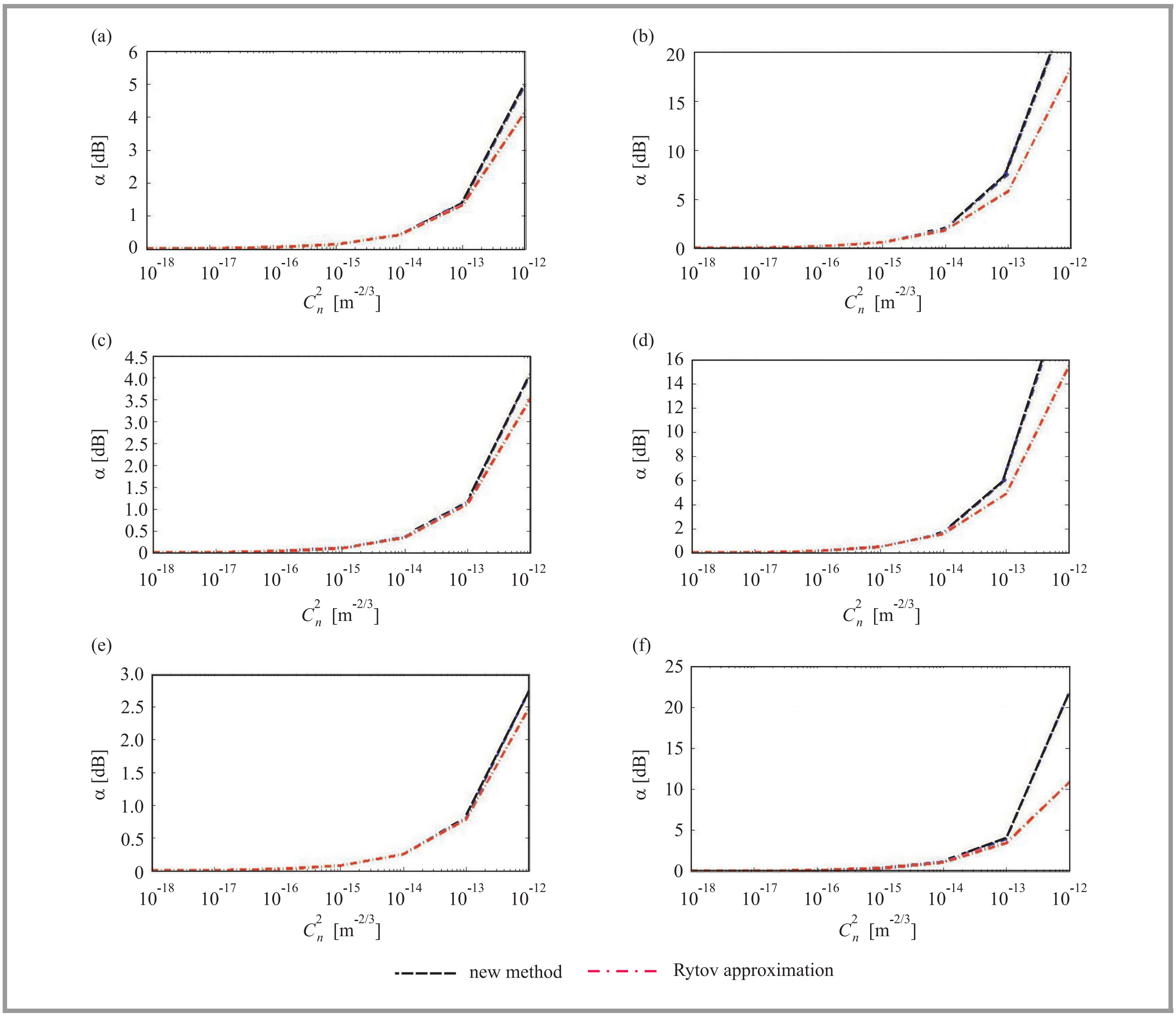

Fig. 9. Comparison results obtained by new method of available power with results given by Rytov approximation for: (a) $\lambda = 633$ nm, $L = 50$ m; (b) $\lambda = 633$ nm, $L = 250$ m; (c) $\lambda = 850$ nm, $L = 50$ m; (d) $\lambda = 850$ nm, $L = 250$ m; (e) $\lambda = 1550$ nm, $L = 50$ m; (f) $\lambda = 1550$ nm, $L = 250$ m.

In case of very high turbulences we consider that available power function is equal to x, y plane so available power is

$$V_{AP\max} = \int\limits_{x}\int\limits_{y} f_{\max}(x, y)\mathrm{d}x\,\mathrm{d}y = 0\,. \tag{9}$$

To simplify the situation we introduce relative available power V_{APr} by equation:

$$V_{APr} = \frac{V_{AP}}{V_{AP0}}\,, \tag{10}$$

where we divide general available power by "non-turbulent" available power. It is evident that relative available power for non-turbulent atmosphere is evaluated by number 1, which goes from the following relation:

$$V_{AP0r} = \frac{V_{AP0}}{V_{AP0}} = 1 \tag{11}$$

and the value of relative available power is equal to 0 for very high volume of turbulences

$$V_{AP\max r} = \frac{V_{AP\max}}{V_{AP0}} = 0\,. \tag{12}$$

Volume of atmospheric turbulences can be evaluated by the parameter of $V_{AP,r}$ from interval $< 0; 1 >$. Finally, we want to express atmospheric turbulence attenuation by method of available area. The next equation is adequate to quantify wanted magnitude:

$$\alpha_{AP} = 10 \cdot \log V_{APr}\,. \tag{13}$$

We are able to determine turbulence attenuation when the laser beam profile is available at the receiver side.

5. Results

We compared results obtained by new method of available power with the results given by Rytov approximation. Available power represents the worst case of turbulent atmospheric attenuation. Characteristics (Fig. 9) show that results for available power and Rytov approximation don't vary much for C_n^2 values smaller than 10^{-14}. The results became different for very strong turbulences. According to the method of available power we can't calculate optical signal attenuation for wavelength 633 nm and $L = 250$ m as well as for 850 nm and $L = 250$ m, because relative available powers have value 0, so attenuation is theoretically infinite. This means that there isn't guaranteed detection of the optical signal for this link parameter. Method of available power also says that turbulence attenuation is smaller for higher wavelength.

6. Conclusion

A new method of available power is presented in the paper. This method arises from a laser beam optical intensity profile, which is original in atmospheric turbulence phenomena study. On the basis of this method it will be possible to design an appropriate laser beam shape to maximally eliminate negative effect of turbulent atmosphere. For the present, basic theoretical analysis and initiative experiments with Gaussian beam have been provided. According to obtained results, the method of available power is the perspective method for determining optical signal attenuation which is due to turbulence in the atmosphere.

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