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Model of Beam Interruptions for Free-Space Optical Systems

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Abstract: - The paper deals with a statistical model of beam interruptions for free-space optical (FSO) systems. The model is based on the probability density function of random attenuations and the probability density function of interruption durations.

Key-Words: - Free Space Optics, Communications, Atmospheric transmission channel

1 Introduction

The statistical model of FSO links is based on the analysis of random attenuations and their fluctuations of the atmospheric transmission channel. With respect to requirements of network services it takes into account not only the random changes of power levels and attenuation but also the random fade durations. It is well known that a general data transmission using the Internet protocol (IP) is almost insensitive to link interruptions for hundreds of milliseconds while real-time video services will be badly affected.

2 Staistical Model of FSO Links

The statistical model of FSO links serves for estimation of probability of the link interruption P_I and distribution of durations of individual fades. The total time of link interruptions T_I is defined as a time interval during which the link is not functional (bit error rate exceeds acceptable level) because of fades. The probability of such a state is

$$P_I \approx \frac{T_I}{T_M}, \quad (1)$$

where T_M is the length of period under consideration. The individual link interruption occurs when received optical power falls below the sensitivity of the receiver or when it exceeds its saturation level. The total time T_I is given as the sum of individual fade durations. With regard to the considerable difference between usual transmission rates and the processes in the atmosphere it is possible to regard the environmental influences as a slow modulation of bit error rate.

The fades are caused by many factors [4]. Long-term fades are caused by the growth of aerosol concentration in the atmosphere, in particular during autumn months when fogs are likely to occur. Other factors include thermal deformation of transceiver consoles during sunshine. Short-term fades are usually put down to birds flying through the laser beam or to atmospheric turbulences that can cause fast fluctuations (scintillations) of received power whose dynamic range exceeds the dynamic range of receiver. The random character of received power $P_{m,RXA}$ for a link with fades is depicted in Fig. 1 [5].

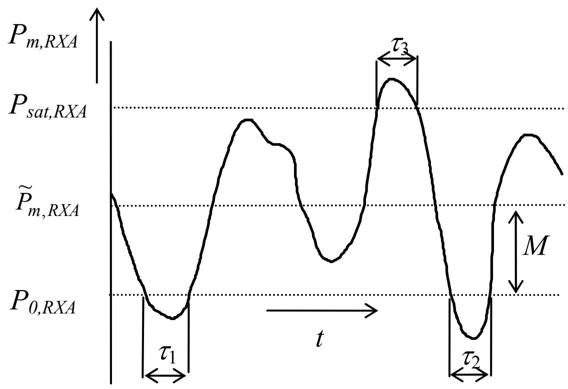

Fig. 1 Random character of received optical power for a link with fades (τ_1, τ_2 and τ_3 - intervals where optical power on RXA exceeds receiver dynamical range).

The influence of random losses on the link power budget can be shown on the power level diagram (Fig. 2). It is convenient to measure the optical power on apertures TXA and RXA. The mean radiated power on TXA is denoted as $P_{m,TXA}$ and the power levels on RXA are denoted as follows: level of receiver saturation $P_{sat,RXA}$, received power level for standard clear atmosphere $\widetilde{P}_{m,RXA}$, and level corresponding to receiver sensitivity $P_{0,RXA}$. The mean optical power on RXA is equal to $\widetilde{P}_{m,RXA}$ when additional atmospheric random attenuation α_{atm} is zero.

The largest positive value of α_{atm} that does not make the received power fall below $P_{0,RXA}$ is equal to M (link margin). The lowest negative value of α_{atm} that does not make the received power exceed saturation level $P_{sat,RXA}$ is equal to $-\delta$. Negative values of attenuation α_{atm} (a kind of *gain of turbulences*) can theoretically occur due to the constructive interference of waves in the turbulent atmosphere. However, the probability of this phenomenon is very low.

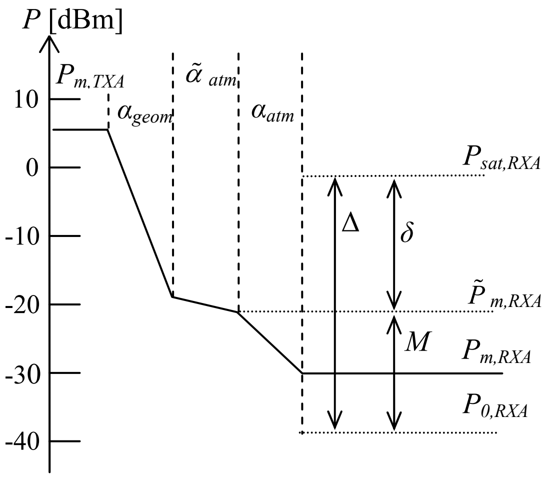

Fig. 2 Influence of random attenuation on link power budget (α_{geom} – geometrical attenuation [3], $\tilde{\alpha}_{atm}$ - attenuation of standard clear atmosphere, α_{atm} - additional random attenuation of real atmosphere).

The random atmospheric attenuation causes variations in the received optical power. Fig. 3 shows an example of $P_{m,RXA}$ during several days in October and November 1999. The test site was equipped with a single-beam FSO link. The path length was L_{12} = 750 m and the link margin was M = 17 dB.

Probability density function pdf_α of random additional attenuation α_{atm} corresponds to that of received optical power. Fig. 4(*a*) shows a theoretical estimation of the shape of typical probability density function pdf_α including both long-term and short-term fades [1]. A histogram obtained from our test site is shown in Fig. 4(*b*). A particular empirically obtained characteristic of α_{atm} depends, of course, on the geographical location of the link, path length and total period of observation.

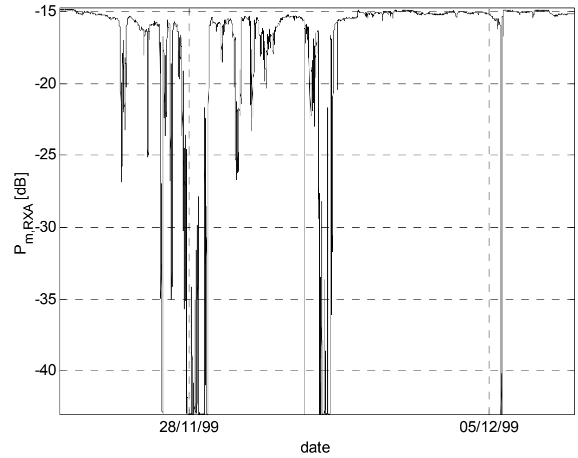

Fig. 3 Typical behavior of received power measured during period of heavy fogs.

Fig. 5 shows exceedance probability E_α [2]. This quantity determines the probability P that random attenuation exceeds the given value, i.e. $E_\alpha(\alpha_i) = P(\alpha_{atm} \geq \alpha_i)$. Its relation to classical cumulative distribution function D_α is obvious, $E_\alpha(\alpha_i) = 1 - P(\alpha_{atm} < \alpha_i) = 1 - D_\alpha(\alpha_i)$.

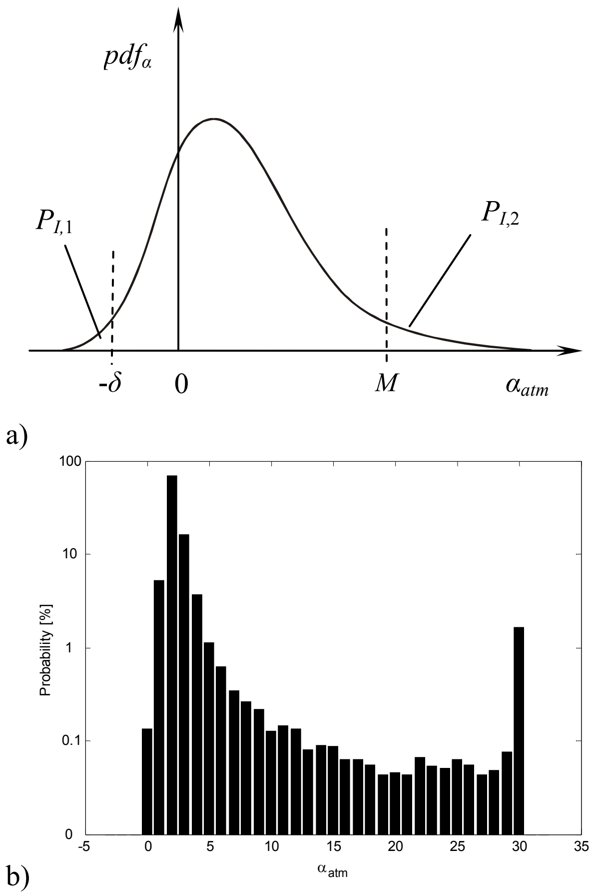

Fig. 4 (*a*) Theoretical shape of pdf_α [1].
(*b*) Estimation of pdf_α from our test site.

The link is interrupted when the received optical power exceeds the dynamic range of receiver. This event occurs with the probability (Fig. 4(*a*))

$$P_I = P_{I,1} + P_{I,2} = 1 - \int_{-\delta}^{M} pdf_\alpha(\alpha_i) d\alpha_i = \\ = 1 + E_\alpha(M) - E_\alpha(-\delta) \approx \frac{T_I}{T_M} \quad . \quad (2)$$

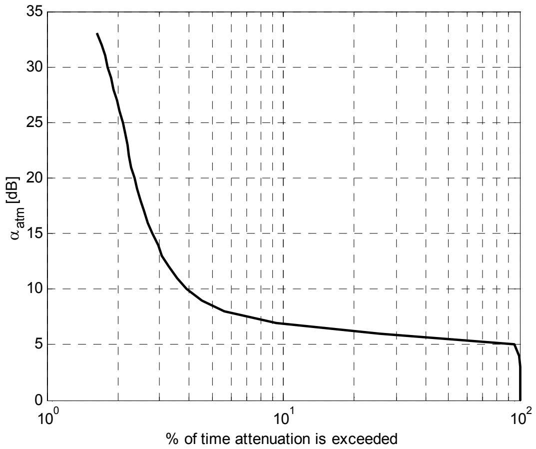

Fig. 5 Cumulative exceedance probability of random attenuation α_{atm} .

It is obvious that fade durations can be very different. They can practically span several orders of magnitude and their effect depends on a particular network service. Short fades (of millisecond duration) contribute to the link bit error rate and may not be even noticed by users (for a general Internet connection using the IP protocol). The longer events contribute to the link unavailability time.

It is therefore necessary to evaluate the distribution of fade durations. The events form a time series. Our measuring equipment was able to capture events longer than 1ms. Fig. 6 shows an estimation of the probability density function of fade durations pdf_τ. It has turned out that pdf_τ is not very sensitive to the link margin for $M > 10$dB because the fades are usually deep.

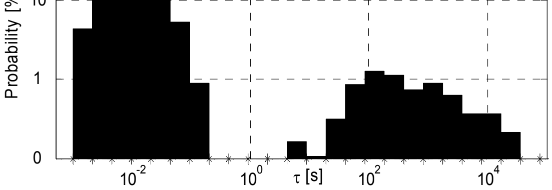

Fig. 6. Estimation of probability density function of fade durations pdf_τ ($M = 17$dB).

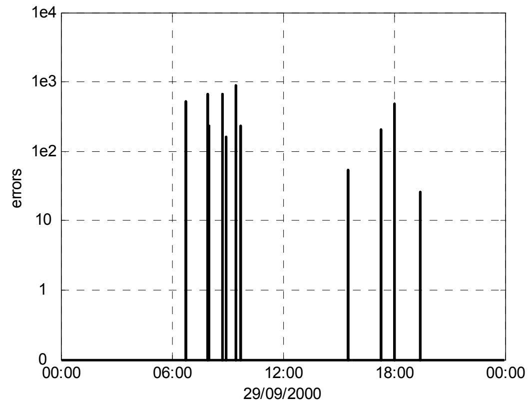

Fig. 7 Example of short events registered on September 29th 2000.

The short-term events correspond to the effect of birds flying through the beam, atmospheric turbulence, console vibrations, etc. The long-term events are caused by weather, namely by fog.

Fig. 8. A bird flying through the beam (the transceiver is located on the 7th floor; captured from a distance of 750m).

The distribution in Fig. 6 shows surprisingly that very short fades were more frequent than longer ones. It was caused by birds whose *density* depends, of course, on the particular locality. Practical measurements showed their influence should not be neglected, especially in suburb areas with green vegetation. Fig. 7 shows a typical record of short-term interruptions caused by birds while Fig. 8 shows such an event.

3 Link Unavailability

Let us consider a period of link observation T_M. The sum of durations of all individual fades gives the total time of link interruption T_I. It can be approximated by

$$T_I \doteq \sum_i n_i \tau_i \quad , \tag{3}$$

where n_i is the number of events whose duration lies in $\left\langle \tau_i - \Delta\tau/2 ; \tau_i + \Delta\tau/2 \right\rangle$, where $\Delta\tau$ is the class interval. Let N be the total number of link interruptions, and P_i the class probability. Then the number of events n_i can be expressed as

$$n_i = NP_i \quad , \tag{4}$$

and for the total interruption time we obtain

$$T_I = N \sum_i P_i \tau_i = N\bar{\tau} \quad , \tag{5}$$

where $\sum_i P_i \tau_i$ expresses the mean value of $\bar{\tau}$.

Reduced time of link interruption T'_{ab} caused only by events whose duration lies in $\tau_i \in \left\langle \tau_a ; \tau_b \right\rangle$ can be expressed as

$$T'_{ab} = N \sum_a^b P_i \tau_i = N\bar{\tau}_{ab} \quad . \tag{6}$$

After substitution of (5) into (6) and some rearrangements it is possible to express the reduced interruption time T'_{ab} as

$$T'_{ab} = T_I \frac{\bar{\tau}_{ab}}{\bar{\tau}} \quad . \tag{7}$$

After transition to infinitesimal calculus ($\Delta\tau \to d\tau$) the reduced time T'_{ab} can be expressed with respect to (2) in the integral form as

$$P_{I,ab} = \left[1 - \int_{-\delta}^{M} pdf_\alpha(\alpha_i) d\alpha_i \right] \frac{\int_{\tau_a}^{\tau_b} \tau_i \, pdf_\tau(\tau_i) d\tau_i}{\int_0^\infty \tau_i \, pdf_\tau(\tau_i) d\tau_i} \approx \frac{T'_{ab}}{T_M} , \tag{8}$$

where pdf_τ is the probability density function of fade durations. Equation (8) allows the estimation of link unavailability caused by events with a defined duration period based on the knowledge of two probability density functions pdf_τ and pdf_α.

5 Conclusions

Statistical models of free-space optical (FSO) data link that take into account the duration of individual fade events were presented. It allows an estimation of unavailability of the link caused by events with a defined duration based on the knowledge of two probability density functions. Influence of atmospheric effects to various network services can be easily modeled.

6 Acknowledgements

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