Statistical Analysis of Fade Events on FSO Systems

ZDENEK KOLKA[1], VIERA BIOLKOVA[1], DALIBOR BIOLEK[2]
[1]Department of Radio Electronics, [2]Department of Microelectronics
Brno University of Technology
Purkyňova 118, 612 00 Brno
CZECH REPUBLIC
kolka@feec.vutbr.cz, biolkova@feec.vutbr.cz, dalibor.biolek@unob.cz

Abstract: The paper deals with the time-domain characteristics of fade events on Free-Space Optical (FSO) systems caused by atmospheric attenuation. Commercially available optical links operate mostly in the 850 nm and 1550 nm wavebands, where the dominating atmospheric phenomenon is fog. Based on the analysis of meteorological visibility records, typical empirical characteristics of fade event durations were obtained. The studies published so far are focused, in the majority of cases, on determining the total availability of FSO links, neglecting the properties of individual fade events. The model presented in this paper is based on the cumulative distribution function for the occurrence of fade events, and the conditional cumulative distribution function for fade durations.

Key-Words: Free-space optical links, atmospheric attenuation, link availability, power budget

1 Introduction

The development of municipal network infrastructure is characterized by an ever-increasing demand on broadband connectivity, specifically in the Last-Mile networks [1]. This trend will continue in next decades.

The main attraction of FSO technology is the bandwidth comparable to optical fibers since both systems operate on the same physical principle. In addition, the optical band used for communication is still license-free.

The optical band available for atmospheric wireless links ranges theoretically from 0.7 μm to 10 μm [2]. Components for the 850 nm window are cheap, but wavelengths up to 1400 nm are critical from the point of view of eye safety. The 1550 nm window is preferable because of the higher permissible eye-safe power and the possibility of using the WDM technology to increase the bandwidth. Atmospheric attenuation due to scattering is lower at 1550 nm in comparison with 850nm. A significantly lower attenuation was demonstrated for the 10 μm band. However, this rather expensive technology is still in the development phase.

The attenuation of atmospheric channel is time- and space-varying due to scattering on hydrometeors during fog, snow, and heavy rain. Studies have shown that optical attenuations can reach values of up to 120 dB/km in moderate continental fog environments in the winter season, and 480 dB/km in dense maritime fog environments [3]. If this slowly-varying attenuation is greater than the link margin, the communication is completely cut-off for hours or even days.

The other effects include misalignment of relatively narrow beams caused by building swaying, wind and vibration [4] and atmospheric turbulence causing received-power fluctuations on a millisecond time scale. The effect of turbulence is often modeled on a sufficiently long time scale by introducing a power penalty [5].

The overall availability of FSO links is influenced by the occurrence of fog events. A significant increase in link availability can be achieved by combining the FSO link with a radio-frequency (RF) link. The main environmental factor influencing RF links is the scattering and absorption on rain droplets whereas attenuation due to fog is not significant [3].

The deployment of FSO or hybrid technology depends on a realistic estimation of attainable parameters. Several studies have been published on the availability performance, e.g. [3], [6], [7], [8]. But most of them deal with the availability of FSO links, neglecting the properties of individual fade events.

This paper presents a study on the time-domain properties of fade events for European climatic conditions. Section 2 of the paper presents a model of the FSO atmospheric channel used for the analysis, and Section 3 provides statistical results.

2 Model of terrestrial FSO system

2.1 Power budget

The mean optical power $P_{m,RXA}$ on the receiving aperture of an FSO terminal is in decibels as [9]

$$P_{m,RXA} = P_{m,TXA} - \alpha_{sys} - \alpha_{atm} \ , \tag{1}$$

where $P_{m,TXA}$ is the mean optical power on the transmitting aperture. The system attenuation α_{sys} includes all constant losses and gains between both apertures. For $L_{12}\varphi_t \gg D_{RXA}$ it can be expressed as

$$\alpha_{sys} = 20\log\frac{L_{12}\varphi_T}{D_{RXA}} - \gamma_{add} \, , \tag{2}$$

where L_{12} is the path length, D_{RXA} is the diameter of receiving aperture, and φ_T is the full angle of beam divergence (for a drop to $1/e^2$). For the Gaussian beam an additional gain stemming from the definition of φ_T is $\gamma_{add} = 3.7$ dB. Attenuation α_{atm} represents all random losses caused by atmospheric phenomena.

Link margin M is the difference between the mean received optical power without atmospheric effects and the receiver sensitivity threshold $P_{0,RXA}$ defined for a chosen BER performance, i.e.

$$M = P_{m,TXA} - \alpha_{sys} - P_{0,RXA} \ . \tag{3}$$

For an easy-to-build 100 Mb/s system whose parameters are: $P_{m,TXA} = 10$dBm, $\varphi_T = 3$ mrad, $L_{12} = 500$ m, $D_{RXA} = 0.2$ m, $P_{0,RXA} = -30$ dBm we obtain $\alpha_{sys} = 13.8$ dB, and $M = 26.2$ dB.

2.2 Atmospheric effects

Atmospheric attenuation can be expressed as a sum of absorption on atmospheric gases α_{ab} and scattering on hydrometeors α_{sc}

$$\alpha_{atm} = (\alpha_{1,sc} + \alpha_{1,ab})L_{12} \ , \tag{4}$$

where $\alpha_{1,sc}$ and $\alpha_{1,ab}$ are the specific attenuation coefficients.

The atmospheric attenuation due to molecular absorption is negligible for both the 850 nm and the 1550 nm bands. The scattering attenuation increases substantially during fog, whose density is measured indirectly as the visibility range V_M [10]

$$V_M = \frac{10\log_{10}(0.05)}{\alpha_{1,\lambda=550nm}} \, . \tag{5}$$

The attenuation is measured at 550 nm. The relation between $\alpha_{1,sc}$ and the visibility range V_M for other wavelengths has been discussed in many studies [6], [7] as it depends on the density and size distribution of water droplets. Kim's formula [6] was used in this paper:

$$\alpha_{1,part} = \frac{13}{V_M}\left(\frac{\lambda}{550}\right)^{-q} \ \text{[dB/km]} \, , \tag{6}$$

where λ is the wavelength in nm, and q depends on V_M:

$q =$ 1.6 for $V_M > 50$ km;
1.3 for 6 km $< V_M \le 50$ km;
$0.16\, V_M + 0.34$ for 1 km $< V_M \le 6$ km;
$V_M - 0.5$ for 0.5 km $< V_M \le 1$ km;
0 for $V_M \le 0.5$ km.

The validity of (6) should not be overestimated as it was derived empirically. Experimental results for the 10 μm band revealed a significant deviation from the values predicted by (6) [2].

2.3 Statistics

A fade event occurs when the total atmospheric attenuation exceeds the link margin M, see Fig. 1.

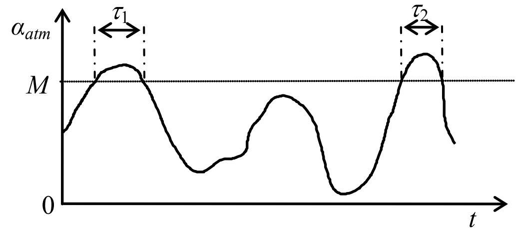

Fig. 1 Fade events on FSO link.

The probability of a fade event can be expressed as

$$P(\alpha_{1,atm} \ge M_1) = E_\alpha(M_1) \ , \tag{7}$$

where $M_1 = M/L_{12}$ is the specific link margin, and E_α is the cumulative exceedance probability of atmospheric attenuation.

If a fixed value of normalized link margin M_1 is considered, the fade-event durations form a random time series $\{\tau_i\}$, which can be characterized by the conditional exceedance probability

$$P(\tau \ge \tau^* \,|\, \alpha_{1,atm} \ge M_1) = E_{\tau|\alpha}(\tau^*, M_1) \ , \tag{8}$$

i.e. the probability that the fade duration is longer than τ^* in the case of a fade event deeper than M_1.

Then the probability of a fade event deeper than M_1 and longer than τ^* is simply

$$P(\tau \ge \tau^* \wedge \alpha_{1,atm} \ge M_1) = E_{\tau|\alpha}(\tau^*, M_1)E_\alpha(M_1) \, . \tag{9}$$

3 Fade-event analysis

The analysis is based on visibility observations carried out at 210 airports in Italy, France, and Germany for the years 2002 to 2005 with the sampling period ranging from 15 minutes to 1 hour.

All calculations were done for the 850 nm optical band. The largest recorded attenuation was 130 dB/km.

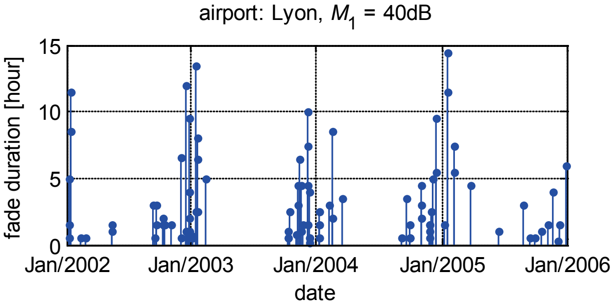

Fig. 2 Record of fade events for M_1 = 40 dB/km

As could be expected, the occurrence of fog events has an apparent one-year period, Fig. 2. The majority of events occur between November and February.

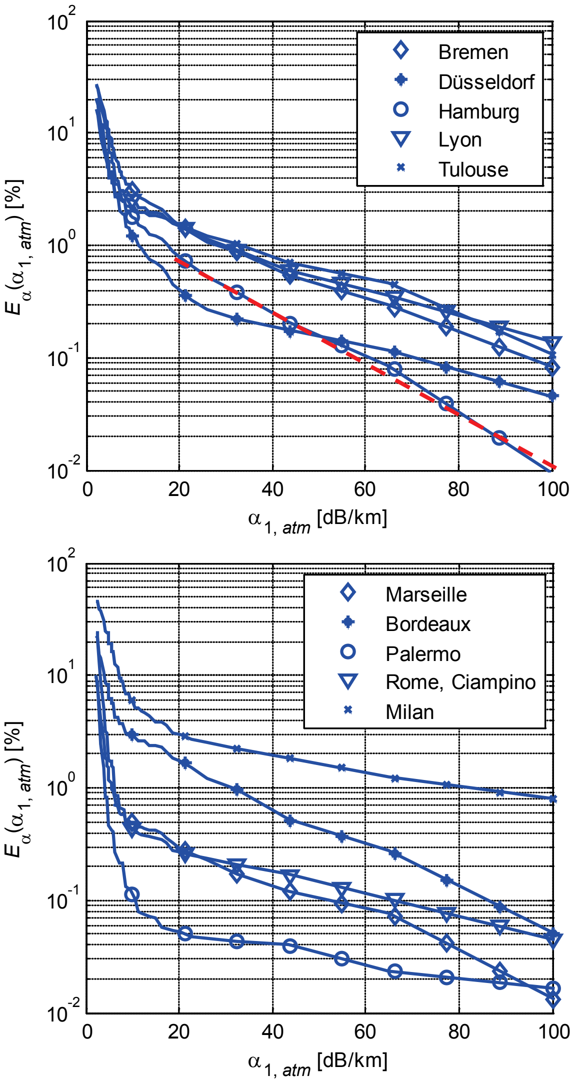

Fig. 3 Empirical E_α for selected sites (approximation- dashed).

Figure 3 shows empirical exceedance probability E_α for some selected sites. The curves exhibit an evident knee below 20 dB/km. The exceedance probability above the knee is roughly linear in the semilogarithmic coordinates up to 100 dB/km, which corresponds to an exponential-tail distribution. The tail can be approximated by the linear function

$$\log(E_\alpha(\alpha_1)) \approx \log(E_\alpha(20)) - a(\alpha_1 - 20), \qquad (10)$$

which leads to

$$E_\alpha(\alpha_1)\Big|_{\alpha_1 > 20dB/km} \approx E_\alpha(20)\,10^{-a(\alpha_1 - 20)}, \qquad (11)$$

where a is an empirical coefficient, see Table I.

Table I Tail CDF parameters fitted for selected sites

Site	E_α(20) [%]	a
Dresden	0.6229	0.0120
Cologne	0.3709	0.0161
Hamburg	0.7276	0.0213
Nurnberg	0.3576	0.0177
Leipzig	0.9090	0.0166
Grenoble	0.4908	0.0152
Strasbourg	2.1488	0.0154
Avignon	0.8051	0.0082
Cherbourg	1.8504	0.0069
Bordeaux	1.6240	0.0179
Naples	0.1528	0.0066
Milano	2.4017	0.0079
Torino	1.5913	0.0081
Bologna	2.7348	0.0096
Firenze	1.0227	0.0092

Figure 4 shows the cumulative conditional exceedance probability of fade durations for selected sites. As can be seen, the curves do not change dramatically with M_1. The conclusion is illustrated in Fig. 5, which shows $E_{\tau|\alpha}(\tau^*, M_1)$ as a function of M_1. The figure reveals a certain similarity among different sites. For example, the conditional probability of a fade event longer than 2 hours is between 40% and 70% for all sites, irrespective of M_1 being between 20 dB/km and 80 dB/km.

4 Conclusions

The paper presents realistic results for estimating FSO performance in Europe. The analysis showed an apparent similarity among statistical results for sites across Europe.

First, the cumulative exceedance probability of fades deeper than 20 dB/km exhibits approximately exponential behavior, which can be characterized by two parameters. The typical values of exponential coefficients suggest that the increase of availability by one decade requires a prohibitively expensive increase of the equivalent transmitted power by 6 to 8 orders of magnitude (60 to 80 dB).

Second, the cumulative conditional exceedance probability of shorter fade durations depends little on the normalized link margin and is similar for the sites monitored.

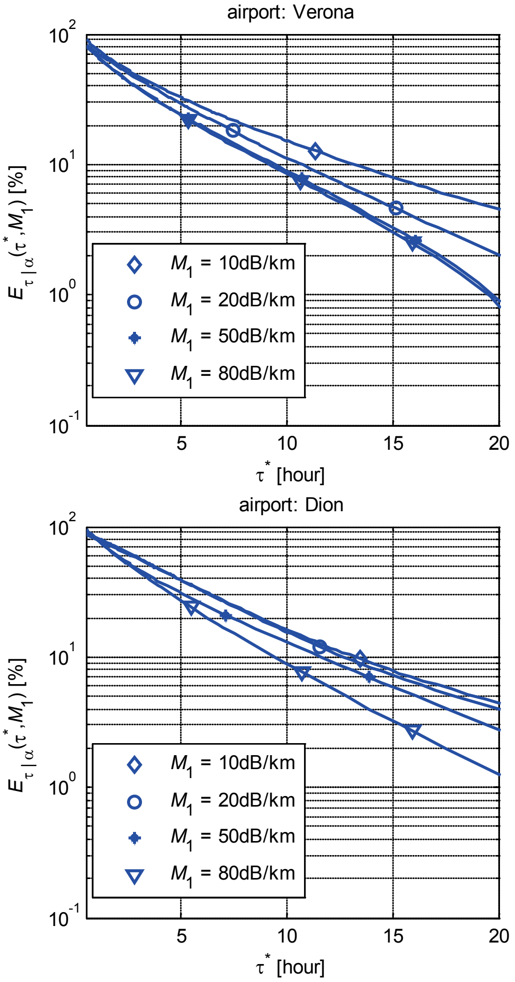

Fig. 4 Cumulative conditional exceedance probability of fade durations.

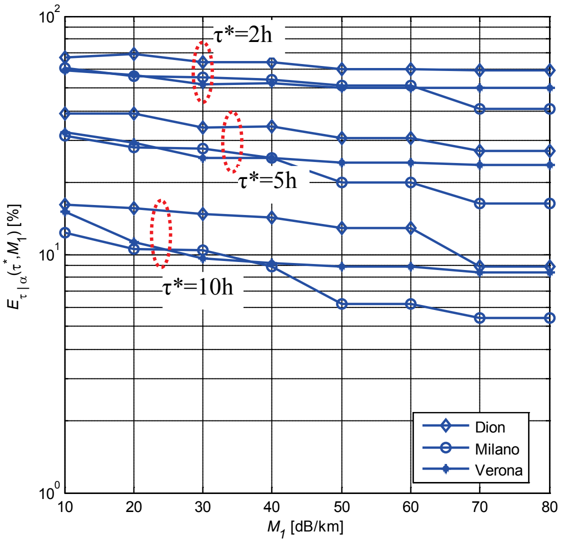

Fig. 5 Conditional probability for selected τ* as function of M_1.

Acknowledgements

This work has been supported by the Czech Science Foundation under grant No. P102/11/1376, by the Czech Ministry of Industry and Trade under grant agreement No. FR-TI4/148, by the project CZ.1.07/2.3.00/20.0007 WICOMT of the operational programme Education for competitiveness, and Project for the development of K217 Department, UD Brno – Modern electrical elements and systems.

References:

[1] S. Wright, H. Fahmy, A. J. Vernon, Deployment Challenges for Access/Metro Optical Networks and Services, *IEEE J. Lightwave Techn.*, vol. 22, Nov. 2004, pp. 2606-2616.

[2] T. Plank, M. Czaputa, E. Leitgeb, S.S. Muhammad, N. Djaja, B. Hillbrand, P. Mandl, M. Schönhuber, Wavelength Selection on FSO-Links, In *Proc. of the 5th European Conference on Antennas and Propagation (EUCAP'2011)*, Rome 2011, pp. 2508 – 2512.

[3] F. Nadeem, V. Kvicera, M. S. Awan, E. Leitgeb, S. S. Muhammad, G. Kandus, Weather Effects on Hybrid FSO/RF Communication Link, *IEEE J. Sel. Areas in Comm.*, vol.27, no.9,Dec. 2009.

[4] S. Arnon, Optimization of optical wireless communication systems, *IEEE Trans. Wireless Comm.*, vol. 2, July 2003, pp. 626-629.

[5] D. Giggenbach, H. Henniger, Fading-loss assessment in atmospheric freespace optical communication links with on-off keying, *Optical Engineering*, vol. 47, April 2008, pp. 046001-1 - 046001-6.

[6] I. Kim, B. Mc Arthur, E. Korevaar, Comparison of laser beam propagation at 785 nm and 1550 nm in fog and haze for optical wireless communications, in *Proc. of SPIE*, vol. 4214, 2001, pp. 26-37.

[7] M. Al Naboulsi, H. Sizun, F. de Fornel, Fog attenuation prediction for optical and infrared waves, *Optical Engineering*, vol. 43, 2004, pp. 319-329.

[8] O. Wilfert, V. Kvicera, Z. Kolka, M. Grabner, O. Fiser, Propagation study of 850nm/58 GHz hybrid municipal system, in *Proc. of SPIE*, vol. 7814, 2010, DOI: 10.1117/12.860508.

[9] S. G. Lambert, W. L. Casey, *Communication in Space*, London: Artech House, 1995.

[10] *Guide to Meteorological Instruments and Methods of Observation*. World Meteorological Organization, Geneva, Switzerland, 2006.