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Reliability of Digital FSO Links in Europe

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Abstract**—**The paper deals with an analysis of visibility records collected from 210 European airports to obtain a realistic estimation of the availability of Free Space Optical (FSO) data links. Commercially available optical links usually operate in the 850nm waveband. Thus the influence of the atmosphere on the optical beam and on the visible light is similar. Long-term visibility records represent an invaluable source of data for the estimation of the quality of service of FSO links. The model used characterizes both the statistical properties of fade depths and the statistical properties of individual fade durations. Results are presented for Italy, France, and Germany.

Keywords**—**Computer networks, free-space optical links, meteorology, quality of service.

I. Introduction

THE model of Free Space Optical (FSO) digital link is based on the power budget analysis. If the received optical power falls below the receiver sensitivity threshold, a fade occurs. In modern high-speed packet switching networks the fade duration is always longer (in the order of several magnitudes) than packets transmitted. This assumption significantly simplifies the channel description.

Long fades are caused by precipitation, in particular by fog, heavy rain, and snow. Short fades of the order of tens of milliseconds are due to atmospheric turbulences and birds. Long fades contribute to the digital link unavailability while short fades interfere with the communication protocols used [2].

The availability of links spanning distances of hundreds of meters is influenced mainly by fog and low clouds. Kilometre links are influenced additionally by heavy rain and snow.

II. FSO Link Budget

With respect to the simplified power level diagram shown in Fig. 1 it is possible to write the power balance equation in the form of

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

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where $P_{m,RXA}$ is the mean optical power on the receiving aperture, $P_{m,TXA}$ is the mean optical power on the transmitting aperture. All quantities are in decibels. The system attenuation α_{sys} includes all constant losses and gains that depend only on transceiver design and link length L_{12}

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

where D_{RXA} is the diameter of receiving aperture, and φ_T is the beam divergence full angle. For the Gaussian beam and sufficiently long link ($L_{12}\varphi_t >> D_{RXA}$) the additional gain is γ_{add} = 3.7 dB. Attenuation α_{atm} represents all random losses caused by atmospheric phenomena.

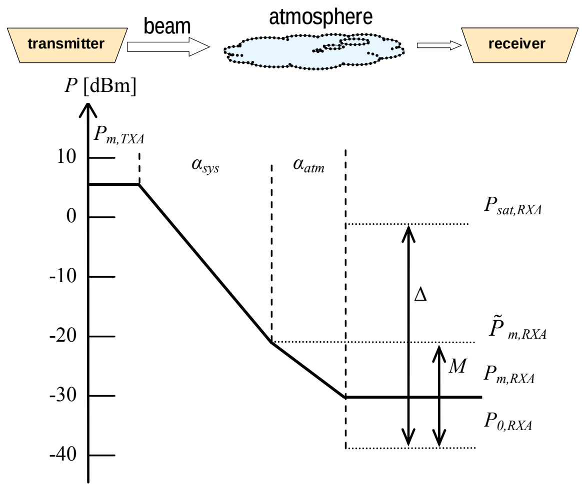

Fig. 1 Power level diagram for typical link

Link margin M is the difference between the mean received optical power without atmospheric effects $\tilde{P}_{m,RXA}$ and the receiver sensitivity threshold, Fig. 1

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

The upper bound for M is determined by the dynamical range of receiver Δ. Typically, the value of Δ is more than 40dB.

The total atmospheric attenuation of the link α_{atm} is divided into attenuation caused by particles α_{part} and attenuation caused by turbulence α_{turb}

$$\alpha_{atm} = \alpha_{1,part}L_{12} + \alpha_{turb} \ \text{[dB]} \tag{4}$$

where $\alpha_{1,part}$ is the specific attenuation due to scattering and absorption on particles.

The attenuation which corresponds to atmospheric turbulences can be expressed only approximately. Using the model of a weakly turbulent atmosphere we have

$$\alpha_{turb} \approx \left|10\log\left(1-\sqrt{\sigma_{r,I}^2}\right)\right| \text{, [dB]} \qquad (5)$$

where $\sigma_{r,I}^2$ is the relative variance of optical intensity in the plane of the receiver, which can be expressed as [1]

$$\sigma_{r,I}^2 = 0{,}5C_n^2\left(\frac{2\pi}{\lambda}\right)^{7/6} L_{12}^{11/6} . \qquad (6)$$

For the spherical wave ($\lambda = 850$ nm) propagating in conditions of the standard clear atmosphere ($\alpha_{1,part} \approx 0.5$ dB/km; $C_n^2 = 10^{-14}$ m$^{-2/3}$) the dependence of attenuation α_{turb} on distance L_{12} is illustrated in Fig. 2.

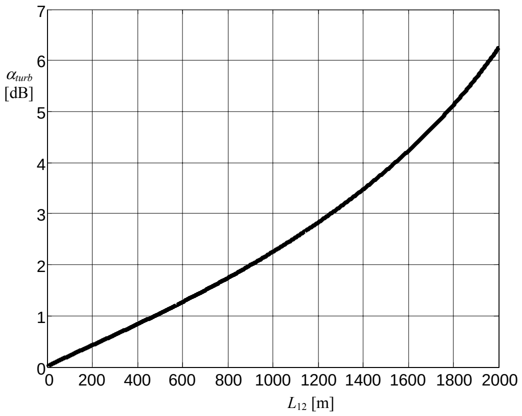

Fig. 2 Dependence of attenuations α_{turb} of the clear atmosphere on mutual distance L_{12} of the transceivers

Fig. 2 shows that atmospheric turbulences affect multikilometre links. The value of α_{turb} describes how optical intensity (in log scale) fluctuates around the mean value. The result is "fast" fades, whose duration ranges from one to tens of milliseconds. These fades interfere with network protocols.

The specific attenuation $\alpha_{1,part}$ is 0.5dB/km for the *clear* atmosphere. It increases substantially during fog, snowfall and rain. Values of 400dB/km have been observed [6].

The predominant process for light attenuation by fog is the Mie scattering [6]. The fog density is measured indirectly as the Meteorological Optical Range (MOR). The visibility range V_M is given by the Koschmieder law as

$$V_M = \frac{10\log_{10}(1/\eta)}{\alpha_{1,\lambda=550nm}} , \qquad (7)$$

where η is 0.05 (older definition used the value of 0.02) [7]. The attenuation is measured at 550nm with the spectral band of 250nm.

The relation between $\alpha_{1,part}$ and the visibility range for other wavelengths is a subject of discussions [3], [4] as it depends on fog density and particle size distribution. Some investigations indicate no wavelength dependence for visibilities below 500 metres. An empirical formula was proposed by I. Kim [3]

$$\alpha_{1,part} = \frac{13}{V_M}\left(\frac{\lambda}{550}\right)^{q} \text{ [dB/km]} \qquad (8)$$

where V_M is the meteorological visibility in km for η = 0.05, 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.

Other formulae were proposed by Al Naboulsi [4] for *radiation* and *advection* fog for $\lambda = 690 \div 1550$nm. *Radiation fog* is related to the ground cooling by radiation. It appears when the air is sufficiently cool and becomes saturated. This is a fog which generally appears during the night and at the end of the day. *Advection* fog is formed by the movements of wet and warm air masses above colder maritime or terrestrial surfaces [6]. Fig. 3 shows a comparison of the formulae for low visibility conditions. A further study of dense fog is needed as few practical measurements have been done so far [6]. We will use (8) for all subsequent analyses. Al Naboulsi's formula seem to be derived for η = 0.02.

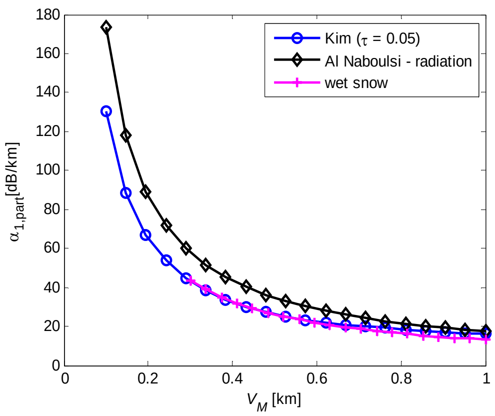

Fig. 3 Comparison of formulae for $\alpha_{1,part}$ for λ=850nm

In the case of rain, attenuation is caused by geometric scattering due to raindrops. Independent of the wavelength, this attenuation is theoretically related to the raindrop size distribution [4]

$$\alpha_{1,rain} = aR^b \text{, [dB/km]} \qquad (9)$$

where R is the rain intensity in mm/h, and a and b are empirical constants (a=1.076, b=0.67 [4]). It gives an attenuation of 8dB/km for a rain intensity of 20mm/h.

Attenuation due to snow is a function of the wavelength and precipitation intensity S (mm/h) according to the following relations [4]:

$$\alpha_{1,snow} = (0.0001023\lambda_{nm} + 3.79)S^{0.72}\text{, [dB/km]} \quad (10a)$$

$$\alpha_{1,snow} = (0.0000542\lambda_{nm} + 5.50)S^{1.38}. \quad (10b)$$

Formula (10a) is for wet snow, while (10b) is for dry snow. For S = 40mm/h we obtain an attenuation of 55dB/km.

Knowing V_M it is easy to obtain the specific attenuation of rain or snowfall for other wavelengths using (7), (9) and (10), Fig. 3. The relation between $\alpha_{1,part}$ and V_M exhibits uncertainty of the order of ±20dB/km for V_M≈100m for practical observations [6].

III. Statistical Model of Slow Fades

Fig. 4 shows the time behavior of received optical power at RXA [2]. A fade occurs when the total atmospheric attenuation exceeds the link margin M.

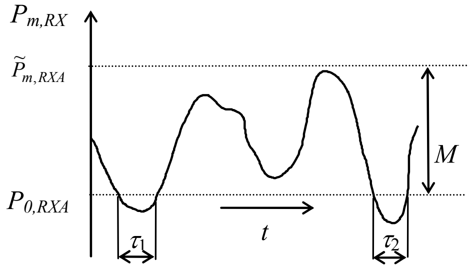

Fig. 4 Random character of received optical power for a link with fades

The visibility data are available from airport reports. We analyzed records for 210 airports in Italy, France, and Germany for the years 2002 to 2005 with the sampling period from 15 minutes to 1 hour. Thus it is possible to estimate only long-term outages of FSO links. The visibility resolution was 100m, which gives the largest recorded attenuation of about 130dB/km. A certain preprocessing was necessary since some records were incomplete or contained errors.

Regarding the coefficient of atmospheric attenuation $\alpha_{1,atm}$ as a random variable the probability of link unavailability can be expressed as

$$P_{un} = P(\alpha_{1,atm} \geq M_1) = E_\alpha(M_1)\ , \quad (11)$$

where M_1 is the specific link margin $M_1 = M / L_{12}$, and E_α is the cumulative exceedance probability of atmospheric attenuation. For a reasonably long observation period T (years) the total time of link unavailability will be

$$T_{un} \approx P_{un}T\ . \quad (12)$$

Fig. 5 shows empirical exceedance probability E_α for several airports. The curves for all the sites exhibit an evident knee between 10 dB/km – 20 dB/km. The exceedance probability above the knee is roughly linear in semilogarithmic coordinates, which corresponds to an exponential-tail distribution. Fig. 7 shows P_{un} for all airports for M_1 = 80dB/km.

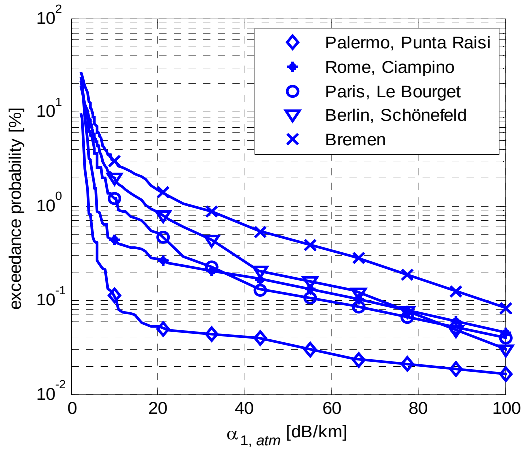

Fig. 5 Empirical E_α (unavailability) for selected sites

If a fixed value of normalized link margin M_1 is considered, the increase of atmospheric attenuation causes fades. The fade durations form a random time series $\{\tau_i\}$, which can be characterized by the conditional exceedance probability [5]

$$P(\tau \geq \tau^* \mid \alpha_{1,atm} \geq M_1) = E_{\tau|\alpha}(\tau^* \mid M_1)\ , \quad (13)$$

i.e. the probability that the fade duration is longer than τ^* in the case of a fade deeper than M_1. $E_{\tau|\alpha}$ can be estimated from

$$E_{\tau|\alpha}(\tau^* \mid M_1) \approx \frac{n_{\tau_i \geq \tau^*}}{N}\ , \quad (14)$$

where $n_{\tau_i \geq \tau^*}$ is the number of fades longer than τ^*, and N is the total number of fades during a sufficiently long period, Fig. 6. Typically, the fades are deep. Thus $E_{\tau|\alpha}$ does not change dramatically with M_1.

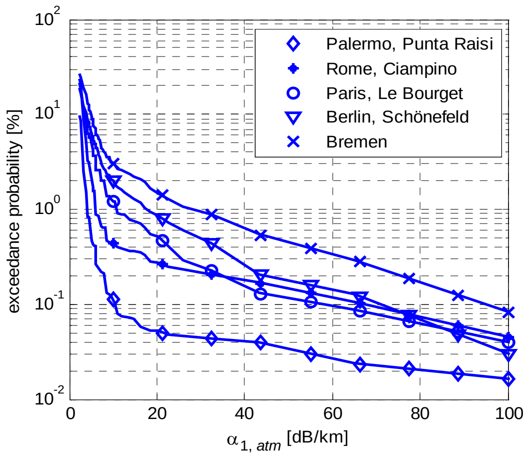

Fig. 6 Cumulative conditional exceedance probability of fade durations for different values of M_1 for Bremen airport

Table I shows link unavailability for selected sites estimated from four-year records. These figures represent a realistic performance that can be expected for FSO links in Europe.

TABLE I
LINK UNAVAILABILITY IN % FOR SELECTED SITES

M_1 [dB/km]	Palermo	Rome	Paris	Berlin	Bremen
40	0.041	0.18	0.16	0.26	0.62
60	0.027	0.12	0.096	0.14	0.34
80	0.016	0.073	0.06	0.07	0.17

IV. CONCLUSION

An analysis of four-year records provided realistic figures for European areas. For a typical link the unavailability will be between 0.1 – 1%, i.e. a total of one or two days during a year.

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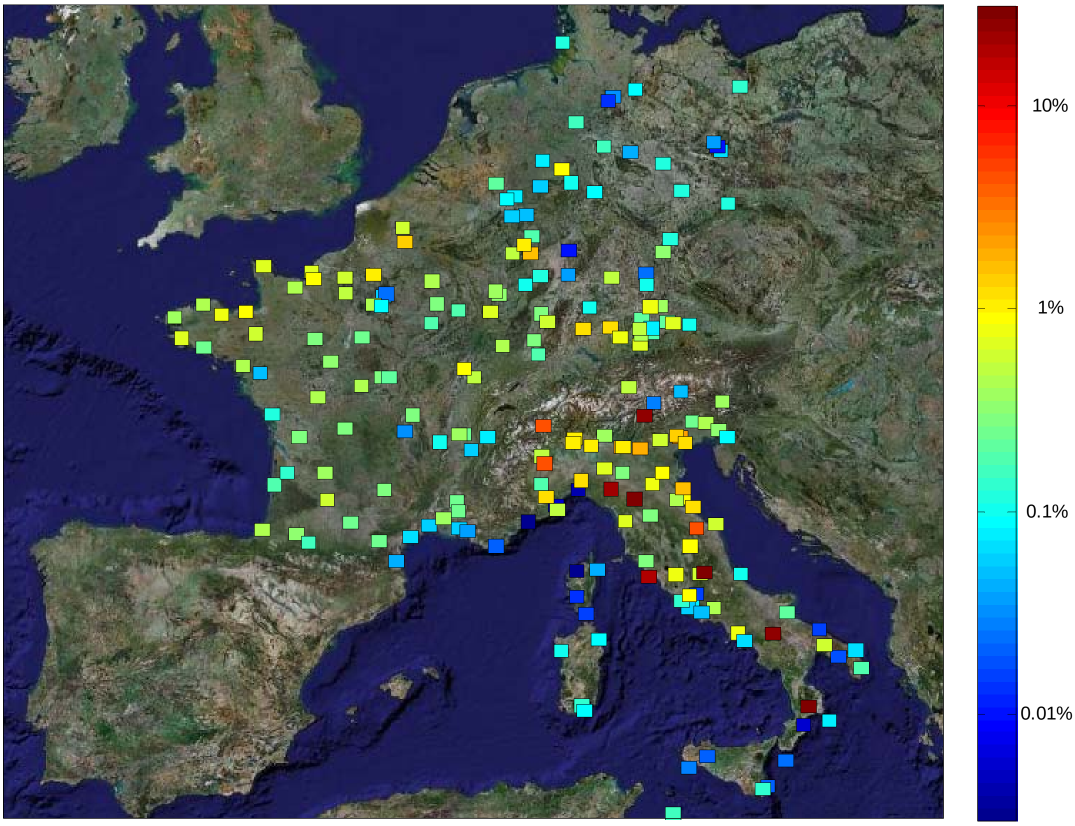

Fig. 7 Long-term unavailability for M_1 = 80dB/km