BER and Availability Measured on FSO Link

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Abstract. *The BER and the availability belong among the basic qualitative parameters of free space optical (FSO) links. The BER parameter is usually mentioned by FSO manufacturers, but it is not defined what conditions a certain value of BER stands for. This article deals with problems of measuring the BER of free space optical link and with questions how to determine the probability of unavailability of a certain link. The implementation of bit error rate tester with the E1 interface system is presented. In the article the statistics of the meteorological optical range for the year 2006 are shown. Using these data one can determine the probability of a certain value of atmospheric attenuation that influences the link unavailability.*

Keywords

Free space optical link, quality of service, meteorological optical range, link unavailability, bit error rate.

1. Introduction

The quality of FSO link communication, expressed by the availability and bit error rate, is determined by the parameters of the link and the statistical properties of the atmosphere. The FSO link parameters are given by the manufacturer. Determination of the statistical parameters of the atmosphere for the selected link installation site is still problematic.

2. Mathematical Model and Power Budget of FSO Link

The mathematical model of FSO link includes the power balance equation and the power level diagram. The quantities used in the power balance equation and power level diagram are applied as their mean values. The basic link structure is shown in Fig. 1. The power level diagram shows the power values at different points along FSO path. The main parameters for a commercially available link are summarized in Tab. 1.

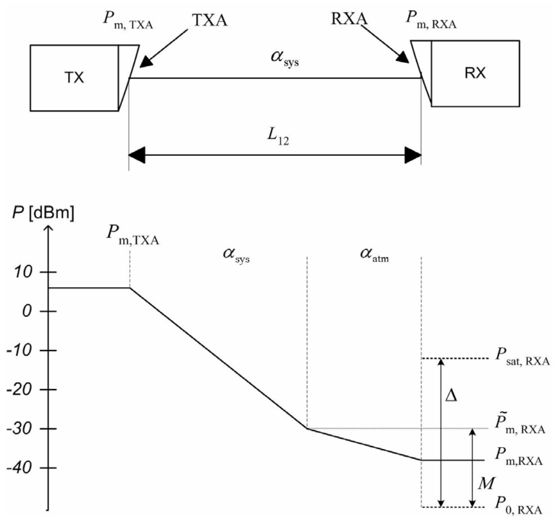

Fig. 1. FSO link model, power level diagram.

$P_{m,TXA}$ is the mean power on the transmitting aperture (TXA), $P_{m,RXA}$ is the mean power on the receiving aperture (RXA), α_{sys} is the system attenuation caused by propagation of the beam, α_{atm} represents all random losses caused by atmospheric phenomena, L_{12} is the distance between RXA and TXA. The highest permissible value of α_{atm}, defines the link margin M, which is upper limited with the dynamical range Δ of the receiver.

Technical data of CBL LaserLink 4E1/800	
Wavelength	850 nm
$P_{m,TXA}$	4x10 mW
$P_{0,RXA}$	-45 dBm @ *BER* -6
Beam divergence	< 10 mrad
RXA	diameter 257 mm
TXA	diameter 4 x 60 mm
Dynamic range	48 dB
L_{12}	850 m
Fade margin at distance 850 m	20 dB
Minimum visibility at installed distance	470 m at 800 m

Tab. 1. Parameters of the tested link.

3. Model of Installation Site

The characteristic of the atmosphere, in which the light beam propagates, significantly affects the quality of transmission. Generally, the atmosphere is non-stationary and inhomogeneous; the index of refraction varies depending on place and time. While the beam propagates through the atmosphere it is attenuated. The attenuation depends, of course, on the wavelength applied. Among the main atmospheric phenomena that affect the link function are:

- Extinction of optical intensity caused by scattering and absorption on molecules and aerosols.
- Fluctuation of received optical power caused by atmospheric turbulence.
- Disturbances caused by the interruption of beam (e.g. flying birds).

3.1 Atmospheric Attenuation

The atmospheric transmission T is described by Beer's law

$$T\left(L_{12}\right) = e^{-\alpha_{\mathrm{e}} \cdot L_{12}} \tag{1}$$

where L_{12} is the link distance (the distance between the transceivers of the link) and α_{e} is the atmospheric extinction coefficient.

The lowest level of T for resolving a black object in daylight is defined by WMO (World Meteorological Organization) and ICAO (International Civil Aviation Organization) as 0.05 at the wavelength of 550 nm where the human eye has the highest sensitivity. The meteorological optical range V_{M} (also called the *visibility*) is the distance for which $T = 0.05$

$$T\left(V_{\mathrm{M}}\right) = e^{-\alpha_{\mathrm{e}} \cdot V_{\mathrm{M}}} = 0.05\,. \tag{2}$$

The extinction coefficient α_{e} is then

$$\alpha_{\mathrm{e}} = \frac{-\ln(0.05)}{V_{\mathrm{M}}} \doteq \frac{3}{V_{\mathrm{M}}} \ [\mathrm{km}^{-1}]. \tag{3}$$

The main phenomenon influencing α_{e} in atmospheric optical communication windows (e.g. 850 nm) is the Mie scattering on particles ($\alpha_{\mathrm{e,part}}$). Its wavelength dependency can be taken into account by modifying α_{e} with a λ selective term, so that it finally reads [1], [2]

$$\alpha_{\mathrm{e,part}}(\lambda) \approx \frac{3}{V_{\mathrm{M}}} \left(\frac{\lambda}{550}\right)^{-0.585\sqrt[3]{V_{\mathrm{M}}}} \ [\mathrm{km}^{-1}]. \tag{4}$$

It is more convenient to express the atmospheric attenuation in the dB scale. Using

$$e^{-\alpha_{\mathrm{e,part}} \cdot L_{12}} = 10^{-\frac{\alpha_{\mathrm{1,part}}}{10} L_{12}}\,, \tag{5}$$

we obtain

$$\alpha_{\mathrm{e,part}} = 0.23 \cdot \alpha_{\mathrm{1,part}} \tag{6}$$

where $[\alpha_{\mathrm{e,part}}] = 1/\mathrm{km}$ and the specific attenuation $[\alpha_{\mathrm{1,part}}] = \mathrm{dB/km}$.

For a wavelength of 850 nm the weather condition and the atmospheric specific attenuation are summarized in Tab. 2.

V_{M} [km]	$\alpha_{\mathrm{1,part}}$ [dB/km]	Weather condition
< 0.08	> 146	Dense fog
0.08 up to 1	10 up to 146	Moderate fog
1 up to 26	0.23 up to 10	Thin fog or heavy rain
26 up to 63	0.08 up to 0.23	Haze
> 63	< 0.08	Clear

Tab. 2. Meteorological visibility and atmospheric attenuation (wavelength 850 nm).

Fog is one of the most significant factors influencing the range and reliability of optical links. Fog events usually persist from minutes to several hours. This phenomenon can be regarded as changing relatively slowly in comparison with atmospheric turbulences.

3.2 Atmospheric Turbulence and Beam Interruptions

In the air the areas with different temperatures and pressures create zones with different refraction indices. Various inhomogeneities in the atmosphere affect the beam distortion.

It is possible to evaluate the turbulence extent with the help of the structural parameter of the index of refraction. The relative optical variance at RXA is [3]

$$\sigma_{\mathrm{I,rel}}^2 = K C_{\mathrm{n}}^2 \left(\frac{2\pi}{\lambda}\right)^{\frac{7}{6}} L_{12}^{\frac{11}{6}} \tag{7}$$

where K is the constant, 1.23 for the plane wave and 0.5 for the spherical wave.

It is possible to use an approximate formula for a weakly turbulent atmosphere (relative variance of the optical intensity at RXA is less than 1) to estimate the attenuation α_{turb}, which is caused just by the turbulence

$$\alpha_{\mathrm{turb}} \approx \left| 10 \log\left(1 - \sqrt{\sigma_{\mathrm{I,rel}}^2}\right) \right|. \tag{8}$$

Attenuation α_{turb} caused by weak turbulence is summarized in Tab.3. The characteristic time period of the turbulence effect is of about several milliseconds. This phenomenon can be regarded as changing relatively fast.

The links operating in suburban localities with areas of green vegetation have problems with the presence of birds that can disturb the beam.

C_n^2 [$m^{-2/3}$]	α_{turb} [dB]	Turbulence
10^{-14}	3.2	Weak
10^{-15}	0.82	Very weak
10^{-16}	0.25	Calm

Tab. 3. Attenuation caused by turbulence, L_{12} = 850 m.

3.3 Atmospheric Attenuation Data

Long-term atmospheric attenuation records represent the fundamental data needed to determine the statistics of atmospheric attenuation. The specific attenuation $\alpha_{1,\mathrm{part}}$ can be obtained from meteorological visibility or directly from the RSSI (Receive Signal Strength Indicator) of an optical receiver.

A 850 m test link has been established between the Institute of Atmospheric Physics, Academy of Sciences of the Czech Republic (IAP) and TESTCOM in Prague. The values of meteorological visibility V_M are recorded at IAP automatically every 15 minutes. The visibility meter works within the range 10 m < $V_M \leq$ 2000 m. The minimal specific attenuation value 9 dB/km corresponds to the maximum range of the system which results from (4) and (6). Fig. 2 shows the atmospheric specific attenuation $\alpha_{1,\mathrm{part}}$ from January 1, 2006 till June 30, 2006. The exceedance cumulative distribution function of atmospheric attenuation is shown in Fig. 3.

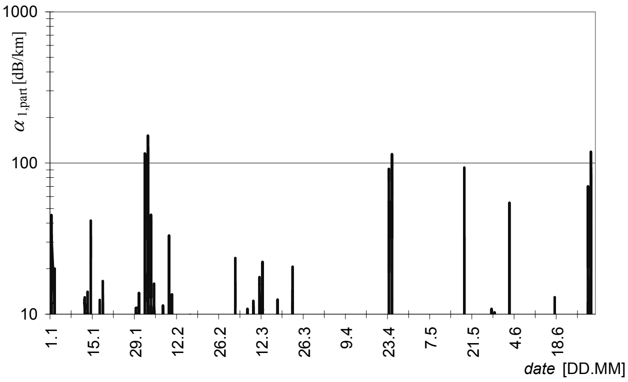

Fig. 2. Atmospheric attenuation on particles.

To determine the impact of turbulence, the atmospheric total attenuation α_{atm} was simultaneously monitored using the RSSI output of the optical receiver. Under the assumption of fog homogeneity the atmospheric total attenuation is

$$\alpha_{\mathrm{atm}} = \alpha_{1,\mathrm{part}} \cdot L_{12} + \alpha_{\mathrm{turb}} \tag{9}$$

and the atmospheric specific attenuation in dB/km

$$\alpha_{1,\mathrm{atm}} = \frac{\alpha_{\mathrm{atm}}}{L_{12}} \; . \tag{10}$$

The first part of the characteristic ($\alpha_{1,\mathrm{part}}$ in Fig. 3) is obtained from measuring the meteorological visibility, the second one ($\alpha_{1,\mathrm{atm}}$) is determined from the RSSI values.

Both characteristics are limited by the parameters of measuring devices. The visibility meter can measure a minimum atmospheric attenuation coefficient of 9 dB/km. The RSSI is limited by the dynamic range of the optical receiver up to 22 dB/km.

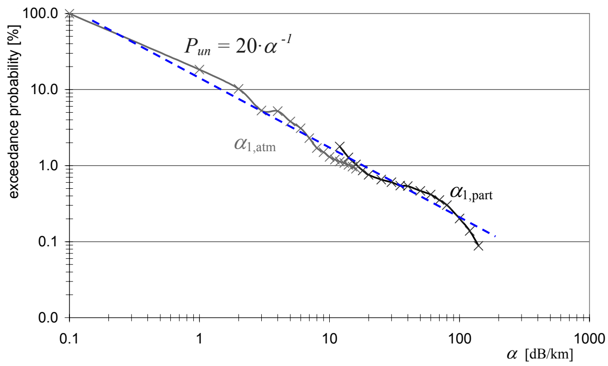

Fig. 3. Exceedance probability of atmospheric attenuation.

Observing the characteristics the difference that is caused by the measurement method can be seen. The characteristic obtained using the V_M value involves the scattering and absorption on particles. The characteristic obtained using the RSSI value corresponds with the total attenuation, including the attenuation caused by turbulences. The characteristic obtained using the RSSI would be more accurate. To obtain it, however, an appropriate network of measuring stations should be built first. Therefore, the characteristic using the V_M value can be used for modeling the place of installation with the result that the characteristic involves only the dispersion on particles. On the other hand, the values of V_M are available at many places, mainly at airports.

The manufacturer gives the minimum visibility of 470 m for L_{12} = 800 m. According to (4) it corresponds to $\alpha_{1,\mathrm{part}}$ = 22 dB/km, which gives 99,2% optical link availability (see Fig. 3).

4. Measuring *BER* and FSO Availability

4.1 Definition of *BER* and FSO Availability

Bit error rate *BER* can be estimated as

$$BER \approx \frac{n_e}{N_B} \tag{11}$$

where n_e indicates the number of the received error bits, and N_B is the number of all transmitted bits for a sufficiently long period.

A period of unavailable time begins at the onset of 10 consecutive Severely Errored Seconds (SES) [4]. These 10 seconds are considered to be part of unavailable time. A new period of available time begins at the onset of 10 consecutive non-SESs. These 10 seconds are considered to be part of available time. The Severely Errored Second is a one-second period whose *BER* exceeds a given value. The Errored Second (ES) is a one-second period with one or more errors [4]. The total unavailability time t_{un} is the sum of partial time intervals when the link is not accessible during the observation period t_{total}. Consequently the percentage of link unavailability P_{un} can be determined as

$$P_{un} = \frac{t_{un}}{t_{total}} \cdot 100 \,. \tag{12}$$

For commercially available FSO links, certain *BER* and P_{un} values are often specified, but the measurement time period is not mentioned. The measuring time must be specified, because all parameters mentioned above may significantly change during the year.

4.2 Bit Error Rate Tester Design and Implementation

The Bit Error Rate Tester (BERT) operates according to the following method: PRBS (Pseudo Random Bit Sequence) is transmitted one-way through the optical link. The clock signal is recovered at the receiver and the BERT compares the received data with the locally generated sequence. Error bits are recorded in a format that includes the time index and other important data. These data are transmitted through the RS232 interface into the computer (see Fig. 4).

Bit error rate depends on the method of receiver synchronization. The tester uses the same method of clock recovery (the identical chips) as commercially available data link interfaces.

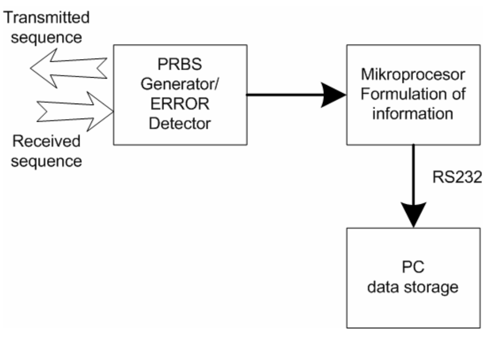

Fig. 4. BERT block diagram.

The tester for the error rate measurement was designed and assembled for the E1 interface systems. It generates PRBS data sequences of the 2^{15-1} length according to the ITU-T O.151 standard. The data transfer rate is 2.048 Mbps. The error detector is synchronized with the received sequence. After the reception of a correct 64 bit sequence, the receiver is designated as synchronized and ready to monitor the error rate. If there are six or more differences in the received sequence of 64 bits ($BER > 0.094$) the synchronization is broken and the process of synchronization starts again.

According to ITU-T O.151 the tester divides data stream into 2048b blocks. It reports the number of errored blocks, the number of out of synchronization blocks, and the total number of bit errors during 1 s period.

4.3 The Determination of *BER* and the Probability of FSO Unavailability P_{UN}

The algorithm for determining the unavailability time t_{un} [s] in an interval monitored for N seconds is shown in Fig. 5. The input data is the number of errored blocks e_i in the i-th second interval including the out of synchronization blocks. The output of the algorithm is the total time of unavailability t_{un} [s] over the selected period of N seconds.

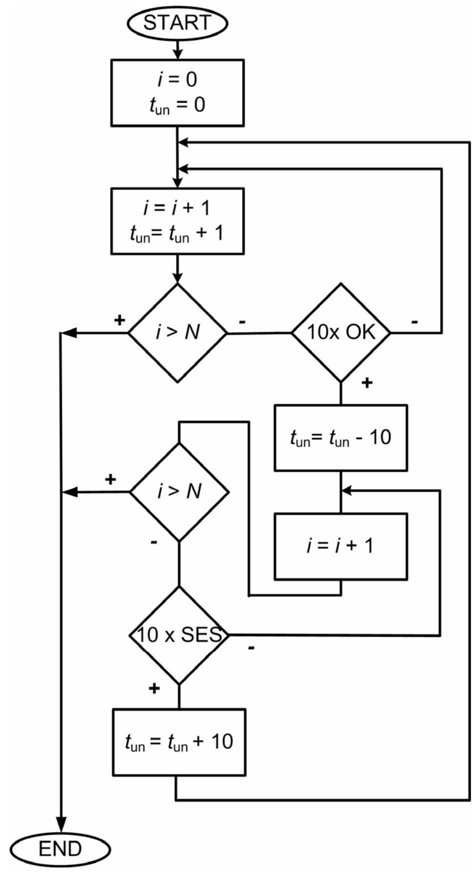

Fig. 5. Algorithm for t_{un} computation.

The percentage of link unavailability P_{un} [%] is

$$P_{un} = \frac{t_{un}}{N} \cdot 100 \,. \tag{13}$$

The total error-free time in seconds is

$$t_{ef} = N - \frac{1}{1000} \cdot \sum_{i=1}^{N} e_i \tag{14}$$

where e_i is the number of 1 ms error blocks in the i-th second. The percentage of the error free seconds is P_{ef} [%]

$$P_{ef} = \frac{t_{ef}}{N} \cdot 100 \,. \tag{15}$$

The BER for the chosen interval can be calculated as

$$BER = \frac{\sum_{i \notin \{UN\}} b_i}{2.048 \cdot 10^6 \cdot \left(N - t_{\mathrm{un}}\right)} \tag{16}$$

where b_i is the total number of errors in the i-th second and $\{UN\}$ is the set of seconds where the link was unavailable.

5. Measured Data of BER over the Year 2006

Fig. 6 shows the exceedance probability of BER. Data were measured from January 1, 2006 till November 30, 2006. Fig. 7 shows the exceedance probability of duration of individual unavailability intervals.

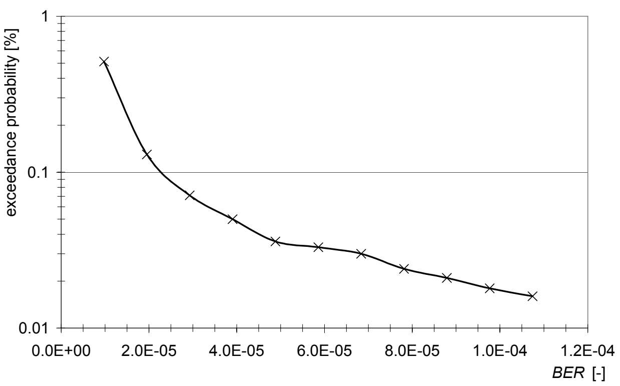

Fig. 6. Exceedance probability of BER (from 2006-01-01 till 2006-11-30).

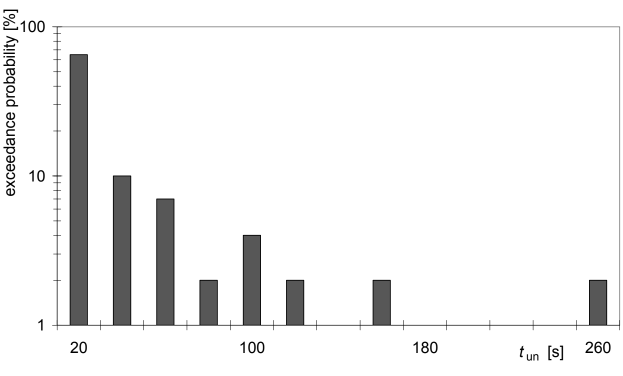

Fig. 7. Exceedance probability of duration of unavailability (from 2006-01-01 till 2006-11-30).

It is possible to show the percentage of blocks out of the synchronization from 2006-01-01 till 2006-11-30, Fig. 8. The complement of the time period including error blocks is the time interval when the FSO works properly.

The total time of unavailability t_{un} takes the value of 364207 s from 2006-01-01 till 2006-11-30. The total time of link operation during the interval mentioned N is $2885.76 \cdot 10^4$ s. From these values the total percentage time of link unavailability P_{un} can be calculated

$$P_{\mathrm{un}} = \frac{t_{\mathrm{un}}}{N} = \frac{364207.9}{2088.576 \cdot 10^4} = 1.74\% \,. \tag{17}$$

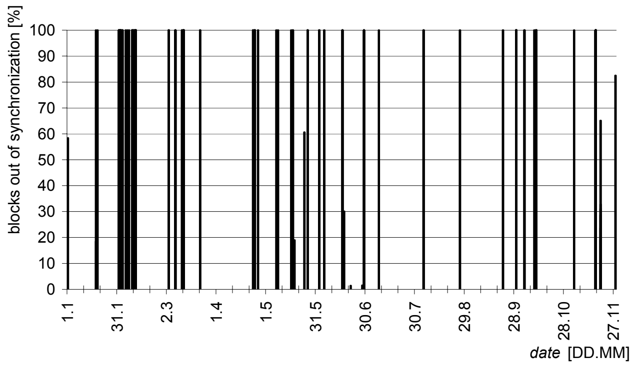

Fig. 8. Percentage of blocks out of synchronization (in a time interval of 60 s) from 2006-01-01 till 2006-11-30.

6. Conclusion

The measured value of the free space optical link unavailability by the BERT obtains the value of 1.7 percent. The value calculated using the optical link parameters and the determined probability of exceedance atmospheric attenuation corresponds to the optical link unavailability of 0.8 percent.

The values of atmospheric attenuation obtained from measuring the meteorological visibility V_{M} corresponds to the values obtained from the received powers (see Fig. 3). For determination of the FSO link availability it is possible to use the meteorological visibility data. The great advantage is the availability of these data; the meteorological visibility is now measured in many places all over the world.

The time of link unavailability monitored can be statistically evaluated from the measured data collected during the year (Fig. 7). Further the probability can be determined when a certain BER value occurs during the period of the optical link availability (Fig. 6).

The above data concerning BER allow us to determine the link distance for which a sufficient link margin with respect to a required BER is obtained. The transmission properties of FSO links can be further enhanced by the utilization of the Forward Error Correction algorithms.

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