

# An Introduction to Free-space Optical Communications

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**Abstract.** *Over the last two decades free-space optical communication (FSO) has become more and more interesting as an adjunct or alternative to radio frequency communication. This article gives an overview of the challenges a system designer has to consider while implementing an FSO system. Typical gains and losses along the path from the transmitter through the medium to the receiver are introduced in this article. Detailed discussions of these topics can be found in this special issue of the Radioengineering Journal.*

## Keywords

Free-space optical communications, link budget, turbulence, fading.

## 1. Introduction

Free-space optical communication (FSO) systems (in space and inside the atmosphere) have developed in response to a growing need for high-speed and tap-proof communication systems. Links involving satellites, deep-space probes, ground stations, unmanned aerial vehicles (UAVs), high altitude platforms (HAPs), aircraft, and other nomadic communication partners are of practical interest. Moreover, all links can be used in both military and civilian contexts. FSO is the next frontier for net-centric connectivity, as bandwidth, spectrum and security issues favor its adoption as an adjunct to radio frequency (RF) communications [1].

While fixed FSO links between buildings have long been established and today form a separate commercial product segment in local and metropolitan area networks [2], the mobile and long-range applications of this technology are aggravated by extreme requirements for pointing and tracking accuracy because of the small optical beam divergences involved. This challenge has to be addressed to fully exploit the benefits of optical links. Furthermore, long-haul optical links through the atmosphere suffer from strong fading as a result of index-of-refraction turbulence (IRT) and link blockage by obscuration such as clouds, snow and rain.

In this article an overview of the challenges a system designer has to respond to when implementing an FSO sys-

tem is provided. Typical gains and losses along the path from the transmitter through the medium, to the receiver are introduced in this article. Some results concerning the qualitative parameters of the links and statistical characteristics of the atmosphere are described.

A more detailed discussion and further information on these topics can be found in papers in this special issue of the Radioengineering Journal.

## 2. Discussion of Selected Modulation Schemes

The optical carrier can be modulated in its frequency, amplitude, phase, and polarization. The most commonly used schemes because of their relatively simple implementation are amplitude modulation with direct detection and phase modulation in combination with a (self-)homodyne or heterodyne receiver.

The technically simplest digital modulation scheme is amplitude-shift keying (2 ASK). In optical systems it is referred to as on-off keying (OOK). OOK is an intensity modulation scheme where the light source (carrier) is turned on to transmit a logic "one" and turned off to transmit a "zero". In its simplest form this modulation scheme is called NRZ (non-return-to-zero)-OOK. Besides NRZ also other codes exist. The most common one besides NRZ is RZ (return-to-zero) coding. The advantages of RZ compared to NRZ are its higher sensitivity [3] and the fact that the clock frequency lies within the modulation spectrum. Unfortunately, both NRZ and RZ can lead to loss of clock synchronization if long strings of ones or zeros are transmitted. This can be avoided with other coding systems such as Manchester coding, which is related to RZ but amounts to state changes at the beginning or in the middle of clock cycles - pulse position modulation. With such a variant of RZ the clock of the digital signal can easily be recovered. These advantages come at the cost of a requirement of twice the bandwidth of NRZ in order to fulfill the Nyquist-Shannon theorem. Nevertheless, it has been shown, for example in [4], [3], that RZ can also work when using the same bandwidth as for NRZ. In this case an increase in sensitivity of about 2 dB has been reported [4].

Furthermore, line codes are often used to guarantee that

the short time average of the signal (i.e., the "baseline") is constant. This is important because optical amplifiers need input signals with constant mean power if they work with control loops to guarantee constant mean output power. Further AC-coupling (high-pass filtering) of the electrical signal at the receiver will introduce a significant amount of inter-symbol interference if the average of the signal is not constant [5]. Therefore 8B10B coding on top of NRZ is commonly used in fiber systems and can also be applied to FSO systems. For 8B10B-NRZ the bandwidth requirement is only 25 percent more than for NRZ. An additional advantage 8B10B coding has is that this coding forces frequent level changes independent of the input stream. Therefore the clock of the signal can easily be recovered even if long strings of "ones" or "zeros" are transmitted.

For OOK, the exact wavelength of the carrier and its phase are irrelevant for the demodulation. The receiver just directly detects the currently incoming power and compares it against a certain level. OOK is sensitive to amplitude distortion (fading) and propagation through different routes, while the second one is negligible for clear-sky conditions. Atmospheric obscuration e.g. in clouds can lead to significant attenuation of the received signal but is less important for FSO systems operating under clear-sky conditions.

Coherent modulation systems are also used in optical communications. Usually, a binary coherent modulation scheme is used. For example binary phase shift keying (BPSK), where the phase of the coherent laser light is shifted between two states. Coherent receivers rely on the superposition of the received light with the light of a local oscillator. Instead of the local oscillator self-homodyne is also possible. This is used in differential phase shift keyed (DPSK) systems, which are less sensitive than BPSK systems. In BPSK systems typically some kind of optical phase-locked loop is required, which allows the local oscillator laser to be tuned exactly to the same frequency (or a frequency with a constant offset) and phase as the received carrier. The sensitivity of coherent receiver implementations is approximately one to two orders of magnitude better than the sensitivity of OOK systems [6], [7] but at the cost of higher system complexity and additional sensitivity to phase distortions of the received beam.

Generally, an OOK system is more robust with regard to atmospheric distortion than a coherent modulation system. This is because for OOK the information is only encoded in intensity whereas PSK uses intensity and phase coding. Both the intensity and the phase of a beam are disturbed in atmospheric propagation. Further, OOK has mainly been used in optical fiber communications due to its low complexity. Additionally, many reliable and cost effective components are available in the market, which is important for the development of FSO communication terminals. As a result, OOK systems have been preferred for optical links inside the atmosphere: they are the primary focus of this article.

Since the electrical signal in OOK receivers is propor-

tional to the received optical power, all further calculations can be carried out based on the statistics of the received optical power focused on the receiver photodetector.

### 3. The Optical Link Equation

The overall system performance of a link is quantified using a link margin derived from the link equation. The optical link equation is analogous to the link equation for any radio frequency (RF) communication link. Starting with the transmit power the designer identifies all link degradations and gains to determine the received signal level. The received signal level is then compared with the sensitivity of the receiver, thus giving the link margin.

#### 3.1 Channel Without Atmospheric Disturbance

In this section optical links unaffected by the atmosphere are discussed. In the basic free-space channel the optical field generated at the transmitter propagates only with an associated beam spreading loss. For this system the performance can be determined directly from the power flow. The signal power received  $P_{Rx}$  [W] depends on the transmit power  $P_{Tx}$  [W], transmit antenna gain  $G_{Tx}$ , receive antenna gain  $G_{Rx}$ , the range loss  $G_r$ , and system-dependent losses  $A_{system,lin}$ .

$$P_{Rx} = P_{Tx} \cdot G_{Tx} \cdot G_r \cdot G_{Rx} \cdot A_{system,lin}. \quad (1)$$

Assuming a Gaussian beam underfilling the transmit aperture, the transmit antenna gain  $G_{Tx}$  is ([8], page 99):

$$G_{Tx} = \frac{32}{\Theta^2} \quad (2)$$

where  $\Theta$  [rad] is the full-angle  $e^{-2}$  divergence of the transmit beam.

The range loss  $G_r$  depends on the link propagation distance  $L$  and is given by:

$$G_r = \left( \frac{\lambda}{4\pi \cdot L} \right)^2. \quad (3)$$

Further, the receive antenna gain, with telescope aperture diameter (antenna size)  $D$ , is given by [6]:

$$G_{Rx} = \left( \frac{\pi \cdot D}{\lambda} \right)^2. \quad (4)$$

The  $A_{system,lin}$  reflects all the other system-dependent losses. It includes losses due to link misalignment, telescope losses, losses due to splitting out light for tracking systems, etc.

Because of the absence of atmospheric effects the link margin  $M_{link}$  in dB is given by:

$$M_{link}[\text{dB}] = P_{Rx,dBm} - S_r \quad (5)$$

where received power  $P_{Rx,dBm}$  [dBm] must be given on a logarithmic scale.  $S_r$  [dBm] is the required power at the receiver to achieve an expected communication performance, also called receiver sensitivity. It depends on several constraints, for example data rate and the required bit error probability. Sensitivity depends on noise sources influencing the detection, such as ambient light and electronic noise. Similar power budget analyses of the link are described in prior publications [9], [10], [11], [12]. The power balance equation can be expressed with the help of the power level diagram [9].

To consider the effects disturbing a link propagating through the Earth's atmosphere the link equation (5) must be extended. The primary atmospheric processes that affect optical wave propagation are extinction and refractive index turbulence (IRT). The main problems of optical communication in the atmosphere are attenuation of optical intensity and fluctuations of received optical signal. An attenuation of optical intensity is caused by the absorption, scattering and refraction of optical waves by gas molecules and aerosols such as fog, snow and rain. Especially for short links heavy fog is the main factor that limits the link function. For link lengths exceeding several hundred meters fluctuations of received optical signal present a severe problem.

Signal fluctuations of the received signal  $P_{Rx}$  can in some time intervals fall below the receiver sensitivity  $S_r$ . In such time intervals a so-called "fade" of the signal occurs. The effects of atmospheric extinction, atmospheric turbulence and fades are introduced in the following two sections.

### 3.2 Atmospheric Extinction Effects

It is well known that clouds, rain, snow, fog, haze, pollution etc. are atmospheric factors that affect our viewing of distant objects. These same factors also affect the transmission of a laser beam through the atmosphere. As transmission through clouds or heavy fog or haze is normally not possible, because attenuation exceeds several tens of dB/km, this is not discussed in this paper. Nevertheless, the signal under clear-sky weather conditions is attenuated because of extinction caused by air molecules and aerosols. The transmittance  $T$  of laser radiation that has propagated over a distance  $L$  is described by the Beer's law:

$$T = \exp(-\alpha_e(\lambda) \cdot L[\text{km}]). \tag{6}$$

The positive extinction coefficient  $\alpha_e(\lambda)$  describes the extinction level of the medium. It is usually given in  $\text{km}^{-1}$  and is commonly available in databases like LOWTRAN [13] or others like FASCODE, MODTRAN, HITRAN, for example described in [14]. It turns out that the extinction is highly wavelength-dependent. Atmospheric trace gases lead to strong and broad absorption bands, each consisting of a multitude of fine absorption lines. Based on the spectral distribution of these bands, the so called atmospheric optical transmission windows with low signal losses of the propagating beam can be calculated by evaluating thousands

of absorption lines in the spectral range from 0.3  $\mu\text{m}$  to 14  $\mu\text{m}$ . A description of the atmospheric transmission windows based on extensive evaluation of various data-bases [15], [16], [17], is given in Tab. 1 and Fig. 1. It can be seen that typical terrestrial communication wavelengths like 808 nm (Si detectors), 1064 nm (Nd-YAG lasers) or 1550 nm (InGaAs detectors, erbium-doped fiber amplifiers) are applicable, whereas 950 nm and 1300 nm are not ideal for FSO systems.

I	II	III	IV	V	VI	VII	VIII
0.30	0.97	1.16	1.40	1.95	3.00	4.5	7.7
0.92	1.10	1.30	1.80	2.40	4.20	5.2	14

Tab. 1. Atmospheric Optical Transmission Windows (Window start- and stop-wavelength given in  $\mu\text{m}$ ).

In addition to absorption, scattering has also to be taken into account. This can be described by the Rayleigh scattering coefficient [18]. Generally, scattering effects decrease monotonically with wavelength and altitude.

Even in optical windows some extinction must be considered, e.g. due to Rayleigh scattering. A rough estimate for the clear-sky extinction is based on the meteorologic parameter visibility  $V$ . This can be given by the Kruse relation [19], [20]. The Kruse relation, which is modified to reflect the attenuation in decibel per kilometer, is given by:

$$A_e[\text{dB}/\text{km}] = \frac{17}{V[\text{km}]} \cdot \left( \frac{0.55}{\lambda[\mu\text{m}]} \right)^q \geq 0 \tag{7}$$

where the exponent  $q$  is given by

$$q = \begin{cases} 1.6, & \text{if } V > 50 \text{ km,} \\ 1.3, & \text{if } 6 \text{ km} \leq V \leq 50 \text{ km,} \\ 0.585 \cdot V^{\frac{1}{3}}, & \text{if } V < 6 \text{ km.} \end{cases} \tag{8}$$

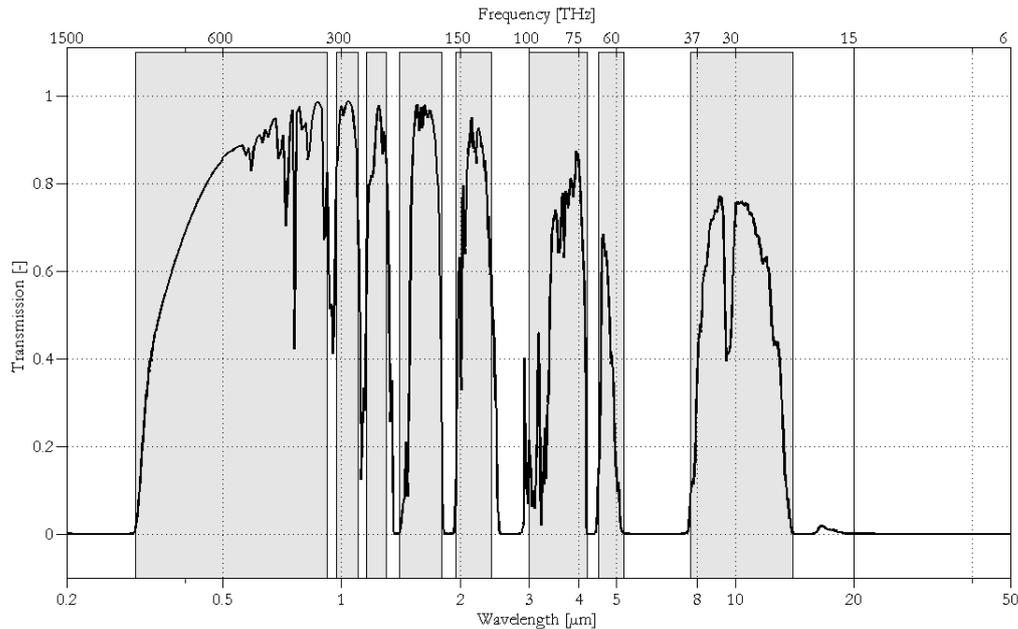
As well as the Kruse relation there are also other models, as for example presented by the papers in this issue of the Radioengineering Journal. Further, [21] proposed another expression for the parameter  $q$ , which was given by Kruse as defined in equation (8). Naboulsi et. al. in their work [22] developed relations using the atmospheric database FASCODE to evaluate the attenuation in the 690 nm to 1550 nm wavelength range.

Coming back to the link equation, (5) must be modified by  $A_e$  [dB/km] in order to consider extinction effects of the atmosphere:

$$M_{link}[\text{dB}] = P_{Rx,dBm} - S_r - L[\text{km}] \cdot A_e. \tag{9}$$

In the near-earth layer, rainfall and snow can also reduce the link margin and must be considered in the link equation (9). Several models exist to estimate the attenuation due to rainfall and snow. These models can be found for example in the standardization documents of the International Telecommunication Union [20].

In addition to extinction effects, fading effects produced by the atmosphere must also be considered. This is discussed in the following.



**Fig. 1.** Atmospheric transmittance based on absorption analysis using LOWTRAN [13]. A zenith path from 0 km to 120 km altitude as well as the *midlatitude summer* atmospheric model are assumed. Atmospheric transmission windows are highlighted in grey color.

### 3.3 Influence of Turbulence

This section is divided into two parts. First physical beam propagation is discussed. Second the reception process of a distorted wave is discussed and the impact on the communication system is given.

*Physical Effects of Optical Beam Propagation Through Random Media:* Random variations of the refractive index - also known as index-of-refraction turbulence (IRT) - of the Earth's atmosphere are responsible for wavefront distortion. Thus, if a beam with a longitudinal coherence length of at least several wavelengths propagates through IRT the intensity of the original beam profile is redistributed. For example, a Gaussian-shaped intensity profile is transformed into a random interference pattern, the so-called intensity speckle pattern. Cross-sections of the beam before and after propagation through the atmosphere are shown in Fig. 2. As the refractive index structure along the path is time dependent because of the turbulent mixing of refractive index cells, the spatial intensity distribution at the receiver plane varies. The temporal variation of intensity observed at an infinitely small point and the spatial variation of intensity within the receiver aperture are commonly described as "scintillation". The intensity scintillation-index  $\sigma_I^2$  is the normalized variance of the intensity and is used as a measure of scintillations. The scintillation-index is usually evaluated in terms of the  $\beta_0^2$ -

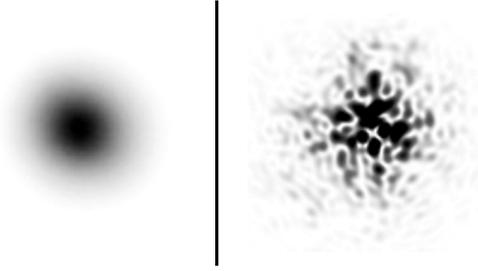
parameter, which is an analytical measure for the integrated amount of turbulence along the link path. It shall be noted that for weak fluctuations ( $\sigma_I^2 < 0.3$ ) the  $\beta_0^2$ -parameter equals the Rytov variance. Fig. 3 shows the intensity scintillation-index  $\sigma_I^2$  as a function of  $\beta_0^2$  of a spherical wave<sup>1</sup> under general irradiance fluctuation conditions<sup>2</sup>. In strong turbulence or along long paths the scintillation-index saturates. Saturation occurs because multiple scattering can cause the incident wave to become increasingly incoherent as it propagates through the medium. A single source of light can, therefore, appear as extended multiple sources scintillating with random phase. When these multiple apparent source fields are added, the resultant intensity scintillation is limited [24]. Thus, for a low level of turbulence single scattering, which deflects light from the main beam, causes weak scintillation. For an increasing amount of turbulence more multiple scattering occurs. Multiple scattering can deflect light from the main beam but as turbulence gets stronger it can actually deflect the light back into the main beam again. Therefore the scintillation saturates.

For a horizontal path (spherical wave)  $\beta_0^2$  is given by [25]:

$$\beta_0^2 = 0.496 \cdot C_n^2 \cdot k^{7/6} \cdot L^{11/6}. \quad (10)$$

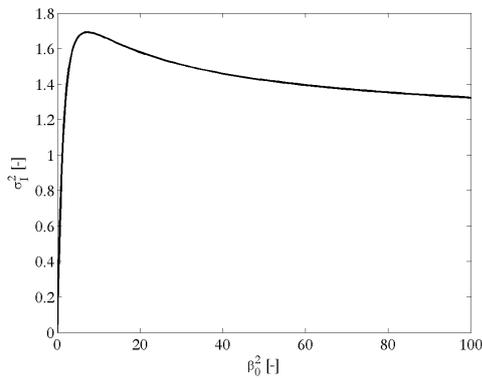
<sup>1</sup>In the case of mobile links or static links without active pointing and tracking inside the atmosphere we usually deal with spherical waves, because the transmit-beam divergence has to expand above the diffraction-limited value to ensure illumination of the partner terminal from an unstable moving platform. Spherical waves are therefore used as the examples here, but the theory presented is not limited to these kinds of waves. The classification of the transmitted beam as a spherical wave holds when the full  $e^{-2}$  divergence angle  $\Theta$  in radians is larger than  $7.1 \cdot \sqrt{\lambda/L}$ , as can be deduced from the theory given in [23], page 180, by using an arbitrarily chosen classification limit.

<sup>2</sup>The non general case is the case when the Rytov approximation holds. This approximation is only true for weak fluctuations. The Rytov approximation assumes that wave distortions caused by the turbulence encountered early on in the propagation path will not have any influence on the distortions caused by turbulence countered further on the propagation path.



**Fig. 2.** Laser beam propagation through turbulent atmosphere: intensity cross-section of the transmit beam (left), intensity cross-section at the receiver plane (right).

Here,  $k = \frac{2\pi}{\lambda}$  is the optical wave number,  $L$  [m] is again the propagation path length and  $C_n^2$  is the refractive index structure parameter.  $C_n^2$  is the structure constant of refractive index fluctuations and a measure of the turbulence strength, given in  $\text{m}^{-2/3}$ . It depends strongly on the height above ground  $h_a$ . Nevertheless, for applications involving propagation along a horizontal or quasi-horizontal path,  $C_n^2$  can be assumed to be constant, especially for near-ground links where the variance in altitude due to the Earth's curvature is negligible. At near ground level,  $C_n^2$  values will show a diurnal cycle, which peaks during midday hours, reaches near-constant values at night, and has minima near sunrise and sunset. This behavior is documented by measurements, which can be found for example in [6], [24], [26].



**Fig. 3.** Intensity scintillation-index  $\sigma_I^2$  as a function of  $\beta_0^2$  under general irradiance fluctuation conditions. According to equation found in [25], page 39.

The Hufnagel-Vally model [23] provides a model often used by researchers to describe the altitude dependence of  $C_n^2(h_a)$  in rural areas. The H-V<sub>5/7</sub> variant of the Hufnagel-Vally model is given by

$$C_n^2(h_a) = 0.00594 \left(\frac{21}{27}\right)^2 \cdot \left(\frac{h_a}{10^3 \text{ m}}\right)^{10} \text{ m}^{-2/3} \cdot \exp\left(-\frac{h_a}{1000 \text{ m}}\right) + 2.7 \cdot 10^{-16} \text{ m}^{-2/3} \cdot \exp\left(-\frac{h_a}{1500 \text{ m}}\right) + 1.7 \cdot 10^{-14} \text{ m}^{-2/3} \cdot \exp\left(-\frac{h_a}{100 \text{ m}}\right). \quad (11)$$

Height dependent values of  $C_n^2$  based on the H-V<sub>5/7</sub> model are given in Fig. 4. The Hufnagel-Valley model gives an averaged  $C_n^2$ -value for a certain altitude. In reality,  $C_n^2$  shows various small scale variations with altitude.  $C_n^2$  profiles have been studied extensively, and beside the Hufnagel-

Vally model various other theoretical models have been proposed in the past. They can be found for example in [24], [23].

IRT above water differs from that above soil due to the fact that energy exchange on the ground is controlled almost exclusively by molecular conduction. In water, however, there is an additional exchange of mass and heat transfer at the air-water interface by convection (vertical sensible heat flux), advection (horizontal heat flux) and evaporation (lateral heat flux) [27]. The potential rate of evaporation is determined by the air-sea temperature difference (ASTD) and the state of the air. Slight roughness of the water surface modifies the wind field above water and ocean waves enhance vertical mixing.

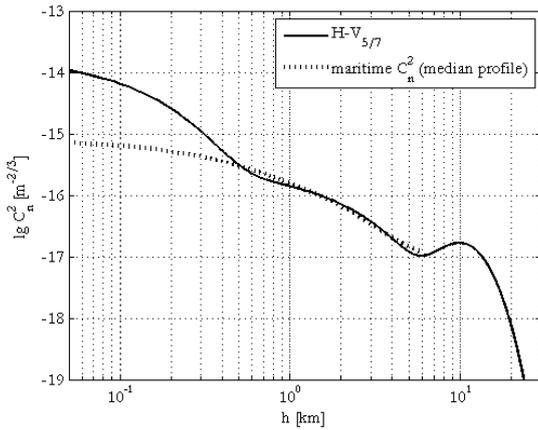
Because of the large thermal capacity of water, it requires much more energy to raise the temperature of a volume of water than for most soils. Therefore ASTD is smaller than the temperature difference between most other natural surfaces. Furthermore, the daily fluctuations of the water surface temperature will be small. In general, the  $C_n^2$  values above water are smaller than expected above land (compare Fig. 4) and diurnal variations are less pronounced, e.g. maximum  $C_n^2$  can not everytime be expected at midday. *Majumdar* provides in his work [6] a maritime turbulence profile model for altitudes up to 6000 m. Parameter sets for three cases are provided: *best*  $C_n^2(h = 0 \text{ m}) = 1 \cdot 10^{-16} \text{ m}^{-2/3}$ , *median*  $C_n^2(h = 0 \text{ m}) = 8 \cdot 10^{-16} \text{ m}^{-2/3}$ , and *worst*  $C_n^2(h = 0 \text{ m}) = 1 \cdot 10^{-14} \text{ m}^{-2/3}$ . These cases reflect the dependence of  $C_n^2$  on the condition of the air-sea interface. The model is in good agreement with the measured values given in [27]. The medium profile *maritime* -  $C_n^2$  model, which is valid for  $h_a < 6000 \text{ m}$  is given by [6] as

$$C_n^2(h_a) = 9.8583 \cdot 10^{-18} \text{ m}^{-2/3} + 4.9877 \cdot 10^{-16} \text{ m}^{-2/3} \cdot \exp\left(-\frac{h_a}{300 \text{ m}}\right) + 2.9228 \cdot 10^{-16} \text{ m}^{-2/3} \cdot \exp\left(-\frac{h_a}{1200 \text{ m}}\right). \quad (12)$$

This *maritime* -  $C_n^2$  profile is shown in Fig. 4 in comparison with the rural H-V<sub>5/7</sub>-model. It can be seen that above 500 m there is not much difference between the two models, because the influence of the boundary layer is negligible.

A strong and temporarily changing gradient in the index-of-refraction on the link can cause a deflection of an optical wave from a straight-line trajectory. Such a refraction causes very slow but relatively strong fluctuations in the angle of arrival of the beam at the receiving aperture. To eliminate this effect an active beam steering and tracking system is necessary, even for stationary links.

*Reception of Distorted Wavefront:* As given in the preceding section, atmospheric propagation disturbs the beam profile, which means that the wavefront of the optical beam is distorted. Receiving this distorted wavefront will cause signal fading. The fading effect and the necessary margin to



**Fig. 4.** Rural  $C_n^2$  as a function of height above ground  $h$  according to the Hufnagel-Valley  $H-V_{5/7}$ -model in comparison with a *maritime*  $-C_n^2$  model.

overcome it are discussed in this section.

In optical receiver systems the energy in the beam is collected by a receive aperture. We consider circular receiver apertures defined by the function:

$$f_{Rx}(r, D) = \begin{cases} 1, & \text{if } |r| \leq \frac{D}{2}, \\ 0, & \text{if } |r| > \frac{D}{2} \end{cases} \quad (13)$$

where  $D$  is the diameter of the receiver aperture. It is typically in the range of several centimeters to tens of centimeters.  $r$  is the radial distance from the optical axis. We assume long-range communication links, where the optical signal spot at the receiver plane is several times larger than the aperture diameter  $D$ . In this case the received signal amplitude equals the integral of optical intensity  $I(r, t)$  over area.

$$P_{Rx}(t) = \iint_{-\infty}^{\infty} f_{Rx}(r, D) \cdot I(r, t) d^2r. \quad (14)$$

The effect of integrating over the intensity reduces the deleterious effects of scintillation. This reduction is called aperture averaging. Qualitatively, we can regard the aperture as consisting of an array of nonoverlapping regions. Within each region the scintillations are perfectly correlated while between the regions there is no significant correlation. The regions are also called speckle. For horizontal paths a rough estimate for the speckle size at the receiver is given by the communication wavelength and the link distance:  $\sqrt{L \cdot \lambda}$  [6]. If the aperture is larger than the speckle size, then uncorrelated scintillations from many regions will be averaged together, thereby reducing the signal dynamics.

The variance of received power  $\sigma_P^2$  scaled by the square of the mean power  $\langle P_{Rx} \rangle$  is called the power scintillation-index. The ratio of the irradiance flux variance obtained by a finite-size receiver lens to that obtained by a point receiver is called the aperture-averaging factor  $f_{AA}$ :

<sup>3</sup> The (general) scintillation-index  $\sigma_{SI}^2$  can be replaced by the power scintillation-index  $\sigma_P^2$  if the signal  $H$  describes the received power  $P_{Rx}$  or by the intensity scintillation-index  $\sigma_I^2$  if the intensity PDF is given. The power equals the integrated intensity over the receiver aperture; compare (14).

<sup>4</sup> As the area below the probability density function must be equal to unity the equation must be normalized by the mean power after the substitution.

$$f_{AA} = \frac{\sigma_P^2}{\sigma_I^2}, \quad 0 < f_{AA} < 1. \quad (15)$$

The aperture-averaging factor quantifies the reduction of scintillation.

Amplitude fading, even if aperture-averaging is taken into consideration, can be described by statistical models showing the probability density function (PDF) of the received signal. Analysis presented in [28]-[33] shows that the log-normal (LN) statistical model generally adequately describes the amplitude-fading of the received signal. Beside the LN model several other models have been reported in the literature, e.g. gamma-gamma [31], [34], [35] or K-distribution [29], [36], [37], and may provide a better description in very strong turbulence, but their distribution functions are mathematically more complicated. Nevertheless, measurements with real existing systems presented in [32], [33] confirm, that the LN statistical model adequately describes the dynamics of the received power signal. Therefore, in the following LN-fading statistics are discussed. Generally, the PDF of the received analog signal  $H$  is modeled by the LN distribution:

$$f_{HLN}(h) = \frac{1}{h \cdot \sqrt{2\pi\sigma_{LD}^2}} \exp\left(-\frac{[\ln h - \mu_{LD}]^2}{2\sigma_{LD}^2}\right), \quad h > 0 \quad (16)$$

The parameters of the LN distribution  $\mu_{LD}$  and  $\sigma_{LD}^2$  are the mean value and the variance of the underlying normal distribution, respectively. The expectation value of the LN-PDF  $E[H]$  is also the expectation value of the received signal  $E[H]$ .

$$E[H] = \exp\left(\mu_{LD} + \frac{\sigma_{LD}^2}{2}\right) \quad (17)$$

The well known (general) scintillation-index  $\sigma_{SI}^2$ <sup>3</sup> is defined by

$$\sigma_{SI}^2 = \frac{\text{Var}[H]}{(E[H])^2}. \quad (18)$$

It directly depends on LN distribution parameter  $\sigma_{LD}^2$

$$\sigma_{SI}^2 = \frac{\exp(2\mu_{LD} + \sigma_{LD}^2)(\exp(\sigma_{LD}^2) - 1)}{(\exp(\mu_{LD} + \frac{1}{2}\sigma_{LD}^2))^2} = \exp(\sigma_{LD}^2) - 1 \quad (19)$$

and specifies the LN-PDF  $f_{HLN}(h)$ . If  $f_{HLN}(h)$  models the distribution of the received power the (general) scintillation-index  $\sigma_{SI}^2$  must be substituted by the power scintillation-index  $\sigma_P^2$ .

Further, it is operationally satisfactory to substitute in (16)  $h = P_{Rx}$  where  $P_{Rx} > 0$  and therefore (16) becomes<sup>4</sup>

$$f_{P_{Rx}LN}(P_{Rx}) = \frac{1}{P_{Rx} \cdot \sqrt{2\pi\sigma_{LD}^2}} \exp\left(-\frac{[\ln \frac{P_{Rx}}{\langle P_{Rx} \rangle} - \mu_{LD}]^2}{2\sigma_{LD}^2}\right) \quad (20)$$

In what follows, all received power values are assumed to be normalized to the mean value  $\langle P_{Rx} \rangle$ . In this case the parameters of the LN-distribution for the received power are given by:

$$\sigma_{LD}^2 = \ln(\sigma_p^2 + 1), \quad (21)$$

$$\mu_{LD} = -\frac{\sigma_{LD}^2}{2}. \quad (22)$$

In general, based on a knowledge of the received power distribution  $f_{P_{Rx}}$  a system outage probability  $p_B$  can be calculated. If the communication system is assumed to work properly when the receiving power is greater than the receiver sensitivity  $S_r$  the probability of system outage (fractional fade time) is a cumulative density function (CDF).

$$p_B(S_r) = \int_0^{S_r} f_{P_{Rx}}(P_{Rx}) \, dP_{Rx}. \quad (23)$$

The required power margin between the average reception power  $\langle P_{Rx} \rangle$  and  $S_r$  ( $S_r < \langle P_{Rx} \rangle$ ) must be regarded as an additional fading loss  $A_{fade}$  of the transmission system.

$$A_{fade}[\text{dB}] = 10 \cdot \lg \frac{\langle P_{Rx} \rangle}{S_r} \geq 0 \quad (24)$$

With this threshold approach it is assumed that during times with  $P_{Rx}$  below  $S_r$  no data reception is possible at all. This reflects a good-bad-state channel modeling and does not require a detailed investigation of the specific receiver performance; the latter would again depend on the modulation format and individual implementation performance. In connection with the good-bad-state channel model the fractional fade time  $p_B$  can also be called outage probability or bad-state probability.

If  $P_{Rx}$  is LN distributed one obtains the fractional fade time  $p_B$  based on equation (20) and in analogy to [30], [28], [23].

$$p_B(S_r) = \text{frac} [P \leq S_r] \quad (25)$$

$$= \frac{1}{2} \left( 1 + \text{erf} \left( \frac{\ln \frac{S_r}{\langle P_{Rx} \rangle} - \mu_{LD}}{\sqrt{2} \sigma_{LD}} \right) \right) \quad (26)$$

where  $\text{erf}(\cdot)$  denotes the error function. To calculate the fading loss the equation (26) must be solved for  $\frac{S_r}{\langle P_{Rx} \rangle}$ :

$$\frac{S_r}{\langle P_{Rx} \rangle} = \exp \left( \sqrt{2} \sigma_{LD} \cdot \text{erf}^{-1}(2p_B - 1) + \mu_{LD} \right). \quad (27)$$

The fading loss  $A_{fade}$  on a logarithmic scale is therefore given by

$$A_{fade}[\text{dB}] = -10 \lg e \cdot \left( \sqrt{2} \sigma_{LD} \cdot \text{erf}^{-1}(2p_B - 1) + \mu_{LD} \right). \quad (28)$$

With the assumption  $E[P_{Rx}] = 1$  and the approximation  $10 \lg e \simeq 4.343$ , (28) reduces to:

$$A_{fade}(\sigma_p^2, p_B)[\text{dB}] = -4.343 \left( \sqrt{2 \ln(\sigma_p^2 + 1)} \cdot \text{erf}^{-1}(2p_B - 1) - \frac{1}{2} \ln(\sigma_p^2 + 1) \right) \quad (29)$$

Therefore, the fading loss is determined by the power scintillation-index  $\sigma_p^2$  and allowed fractional fade time  $p_B(S_r)$ .

(29) describes the loss or margin which must be considered in link design in order to obtain a certain fractional fade time. Therefore, the link equation from (5), (9), respectively, must be extended by  $A_{fade}$  in order to consider IRT fading:

$$M_{link}[\text{dB}] = P_{Rx, \text{dBm}} - S_r - L[\text{km}] \cdot A_e - A_{fade}. \quad (30)$$

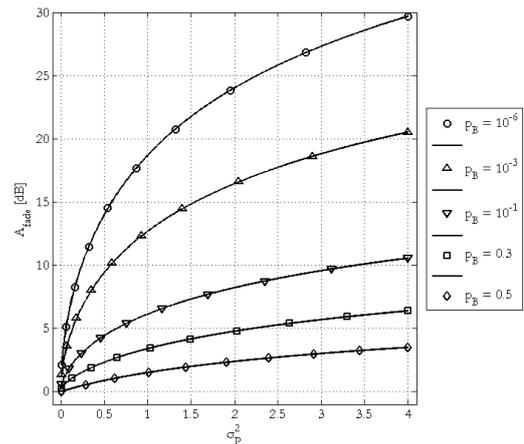


Fig. 5. Fading loss  $A_{fade}$  vs. power scintillation-index  $\sigma_p^2$  as a function of fractional fade time  $p_B$ .

As can be observed in Fig. 5 the fading loss according to (29) can easily exceed 20 dB with typical link requirements (e.g. with outage probabilities of  $10^{-6}$ ). Further, for moderate outage requirements ( $> 10^{-3}$ ) with turbulence saturation and aperture averaging the loss will rarely exceed 13 dB. Saturation means that for long distances the intensity scintillation index  $\sigma_I^2$  is saturated near or somewhat above unity while the power scintillation-index  $\sigma_p^2$  becomes less than unity because of aperture averaging [33], [28].

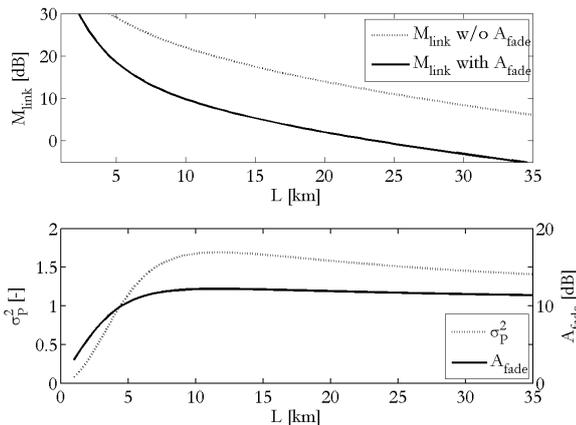
Finally, having introduced all the main factors disturbing a free-space optical link inside the atmosphere we can calculate link budget based on (30). An exemplary link budget for a 20 km horizontal link is shown in Fig. 6.

OLiBuT - Optical Link Budget Tool			
Version 1.3			
Transmit power (mean)	$P_{Tx}$		23,0 dBm
	$\theta$	1,00 mrad full 1/e2 div.	
	$L$	20,0 km link distance	
	$\lambda$	1550 nm wavelength	
System loss	$A_{system}$	0,5	-3,0 dB
Rx antenna	$D$	11,00 cm ant. diameter	
Received Power	$P_{Rx}$		-22,2 dBm 6036 nW
Atmos. extinction [Kruse-Mie, ITU-R P.1814]	$A_e$	25 km visibility 0,2 dB/km	3,5 dB
Fading loss	$A_{fade}$	1,5 pow. scintillatin index 1,00E-02 frac. fade time	10,7 dB
Receiver sensitivity (mean)	$S_r$	1,0E-07 BER	-36 dBm 251 nW
Margin of the link	$M_{link}$		0 dB

Fig. 6. Exemplary link budget base on link equation (30) [38].

Further we evaluate the influence of IRT induced fading-loss versus link range. Therefore we chose the fol-

lowing link parameter:  $C_n^2(h_a = \text{const.}) = 1 \cdot 10^{-14} \text{ m}^{-2/3}$ ,  $\lambda = 1550 \text{ nm}$ ,  $\Theta = 1 \text{ mrad}$ ,  $D = 5 \text{ cm}$ ,  $p_B = 10^{-2}$ ,  $P_{Tx} = 500 \text{ mW}$ ,  $A_{\text{system,lin}} = 0.5$ ,  $A_e = 0.2 \text{ dB/km}$ , and a typical receiver sensitivity for a 155 Mbit/s system of  $S_r = -43 \text{ dBm}$ . Fig. 6 shows the link margins according to (9) and (30). As described earlier, with increasing link length the integrated amount of turbulence increases. This first causes the scintillation-index to increase steadily, then a maximum is observed and finally it saturates. As shown in the lower plot in Fig. 6, the fading-loss according to (29) behaves in a way analogous to the scintillation-index. It first increases, peaks, and is then nearly constant for longer distances.



**Fig. 7.** Upper plot: Link margin including the effect of fading cause by IRT in comparison to a case without atmospheric fading. Lower plot: Scintillation-index and fading-loss versus link distance in comparison to the link margin of the upper plot.

If the basic parameters of the given link are known, it is possible to use (5) and obtain link margin  $M_{\text{link}}$  as a function of link propagation distance  $L$ . Such a relationship represents the steady state model of the given link. In addition, if the statistical character of the atmosphere at the chosen installation site of the link is known, it is possible to obtain the probability of atmospheric attenuation exceeding a given value that represents the statistical model of the chosen link installation site. With the help of synthesis of the steady state model of a given link and the statistical model of the chosen installation site we can obtain the so-called complex model of the link. Statistical characteristics of the atmosphere in some localities in Europe were published in [11].

### 3.4 Conclusion

A brief survey of the fundamentals of FSO has been presented in this introductory article. This brief survey has focused on outdoor FSO static optical links and describes some basic models of the link and some simple models of the atmosphere.

The advantages of FSO result from the basic characteristics of a laser beam, especially from its high frequency, coherency and low divergence, which lead to efficient deliv-

ery of power to a receiver and a high information-carrying capacity.

The basic characteristics of a laser beam provide the following additional advantages of FSO links:

- A narrow beam guarantees high spatial selectivity so there is no interference with other links.
- The high available bit rate allows them to be applied in all types of networks.
- The optical band lies outside the area of telecommunication regulation; therefore no license is needed for operation.
- The small size and small weight of optical terminals enables links to be easily integrated into mobile systems.

Nevertheless, challenges remain. The main problems of FSO links working outdoors in the atmosphere result from attenuation and fluctuation of optical signal at a receiver. To improve reliability, a number of new methods are being applied. For example, a hybrid FSO/RF system increases link availability by overcoming attenuation effects. RF transmission is affected more by rain and optical transmission is affected more by fog. Further, error protection schemes able to deal with the slow fading typical for FSO links are currently under development.

After considering all its advantages and disadvantages it is clear that FSO has good prospects for widespread implementation. FSO technology is ready for utilization as terrestrial links, mobile links and satellite links.

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