

Simulation of Atmospheric Optical Channel with ISI

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Abstract: The paper deals with the simulation of transmission properties of atmospheric optical channel and with the analysis of receiver with equalizer for terrestrial Free-Space Optical links. During clear weather condition the optical channel is almost band-unlimited. Multipath propagation during fog events decreases the channel bandwidth, which results in intersymbol interference. Based on the Monte-Carlo simulations the application of a simple zero-forcing equalizer is evaluated.

Key-Words: Free-space optical links, Atmospheric scattering, ISI, Equalizer

1 Introduction

The dominantly fiber infrastructure of modern municipal networks can be completed with broadband wireless technology whose bandwidth is comparable to optical fibers [1]. Many propagation studies showed that carrier-grade availability can be obtained by combining Free-Space Optical (FSO) links with a matched-rate millimeter radio-frequency (RF) links [2]. Phenomena that degrade RF link performance and FSO link performance are (almost) mutually exclusive near the ground.

Municipal FSO systems operating at 850 nm or 1550 nm windows with rates up to 1.25 Gb/s have been commercially available for several years. 10 Gb/s links are being developed now. RF links operating at 1Gb/s are now available and future systems will be able to transmit up to 10Gb/s. They typically operate in 60GHz to 100GHz bands with the prospective utilization of frequencies of up to 300GHz in future.

While the propagation of RF waves in the atmosphere has been studied extensively and many proven models are available from ITU-R, similar support for FSO link design has not been fully established yet. Theoretical information capacity of the optical channel for different scintillation models was analyzed in [3]. The occurrence of fog events can cut-off the communication completely for hours or even days. Fog also imposes multiple propagation paths, which causes temporal broadening (dispersion) of transmitted pulses resulting in intersymbol interference (ISI) for high-bandwidth links. The significant effect of dispersion has been studied for ground-to-air/satellite communication through clouds [5], but only few papers deal with fog whose physical properties are different. Rather

complex digital detection techniques have been proposed to mitigate ISI [8], but no chips are available at the moment.

The paper deals with the evaluation of optical channel properties during fog and evaluates a simple analog equalizer for On-Off Keying (OOK). Section 2 describes a model of the atmospheric channel. Section 3 analyzes the receiver and Section 4 deals with simulation results.

2 Channel model

Let us consider the OOK FSO terrestrial link in Fig. 1. The mean optical power $P_{m,RXA}$ on the receiving aperture is given by the power budget equation (in decibels)

$$P_{m,RXA} = P_{m,TXA} - \alpha_{sys} - \alpha_{atm} \quad (1)$$

where $P_{m,TXA}$ is the mean optical power on the transmitting aperture. The system attenuation α_{sys} includes all constant losses and gains, which depend only on transceiver design and path length L_{12} .

Attenuation α_{atm} represents all random losses caused by atmospheric phenomena.

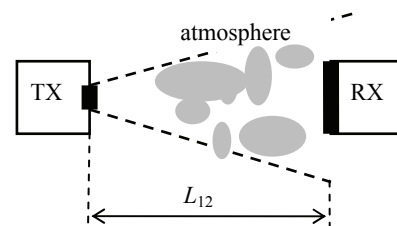


Fig. 1 FSO link configuration.

If the mean received optical power (1) decreases below the receiver threshold due to increased

attenuation, the link is considered to be in outage.

The dominant part of atmospheric attenuation can be expressed as a sum of scattering on hydrometeors (fog) α_{sc} and power penalties of turbulence α_{turb} and ISI α_{ISI} at the receiver

$$\alpha_{atm} \approx \alpha_{1,sc} L_{12} + \alpha_{turb} + \alpha_{ISI} \quad (2)$$

where $\alpha_{1,sc}$ is the specific attenuation coefficient, which is 0.5dB/km for the standard *clear* atmosphere and might reach 400dB/km during fog [4].

The effect of turbulence and ISI is modeled on a sufficiently long time scale by introducing an additional attenuation α_{turb} and α_{ISI} representing how the transmitted power should be increased to get an error performance similar to the ideal environment [9].

Light propagating through fog is scattered on water droplets. As the droplet diameter is comparable to wavelength the process is described by the Mie theory [4]. The type of fog is characterized by particle size distribution, which is usually approximated by the modified gamma distribution [4]

$$n(r) = ar^\alpha \exp(-br) \quad (3)$$

where r is the particle radius and a , b , and α are coefficients, Table I. Radiation fog generally appears during the night and at the end of the day, particularly in valleys. Advection fog is formed by the movement of wet and warm air masses above the colder maritime or terrestrial surfaces.

Table I Fog model parameters

Type	a	b	α
Heavy Advection Fog	0.027	0.3	3
Moderate Radiation Fog	607.5	3	6

The optical pulse consists of a number of photons that interact with water droplets of fog. The particle density is characterized by the mean distance $\bar{d}$ between two interactions. The optical density of fog is then

$$\tau = L_{12} / \bar{d} \quad (4)$$

The attenuation for unscattered light (i.e. for photons that reach the receiver aperture without being scattered) is

$$\alpha_{uns} = \tau 10 \log e = 4.34 \tau \text{ [dB]} \quad (5)$$

which is known as the Beer-Lambert law.

The distance between scatterings is a random variable with exponential PDF

$$p(d) = \exp(-d / \bar{d}) / \bar{d} \quad (6)$$

When a photon interacts with a droplet it is absorbed with probability P_{abs} or is scattered at a random angle θ with arbitrary rotation ϑ , Fig. 2. The values of P_{abs} and PDF of θ can be obtained using the Mie equations [7].

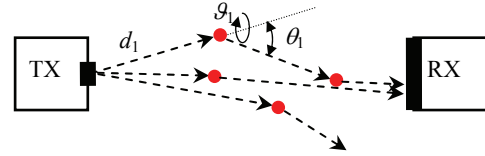


Fig. 2 Monte Carlo simulation of scattering.

As there is no closed model of light propagation in scattering media the results should be obtained via the Monte-Carlo analysis, i.e. by tracing each photon from a sufficiently large set.

Each photon is represented by coordinates of the next collision $\mathbf{c}$ and the velocity vector $\mathbf{v}$. The simulation algorithm is as follows:

1. Generate initial vectors $\mathbf{v}$ and $\mathbf{c}$.
2. Generate random distance $\mathbf{d}$ to the next collision using exponential PDF (6). Update coordinates $\mathbf{c}$.
3. Delete photons whose next collision position is behind the receiver plane or too far from the beam center from further simulation. Photons that reach the receiving aperture within the field of view contribute to the output pulse.
4. Delete photons that will be absorbed. Generate new random rotations ϑ (uniform on $0..2\pi$) and deflections θ (Mie phase function) for remaining photons.
5. Repeat steps 2 to 4 until no photon remains.

Typical Matlab simulation of 1 million photons takes approximately 120s on Intel Core Duo, 2.13 GHz.

The energy of received pulse is represented by photons that reach the receiving aperture in direction within the field of view. Due to the different paths of photon propagation the output pulse is dispersed in the time domain. As all photons are “transmitted” at the same time during the simulation the pulse obtained at the output is statistical approximation of the impulse response. Several approximations of the pulse have been proposed [8]. The simplest one is the gamma function

$$h(t) = k_1 \exp(-k_2 t) \text{ for } t \geq 0 \quad (7)$$

with coefficients k_1 and k_2 obtained by curve fitting. The time origin of (7) corresponds to the propagation

delay along the line of sight, i.e. to L_{12}/c . It is convenient to normalize the impulse response to

$$h_N(t) = h(t) / \int_0^\infty h(t) dt = k_2^2 \exp(-k_2 t) \text{ for } t \geq 0. \quad (8)$$

The normalized frequency response of the channel is then

$$H_N(\omega) = \frac{1}{(1 + j\omega/k_2)^2} \quad (9)$$

which has a double pole $p_{1,2} = -k_2$ and the 3dB bandwidth

$$f_{-3dB} = k_2 \sqrt{\sqrt{2} - 1} / 2\pi \quad (10)$$

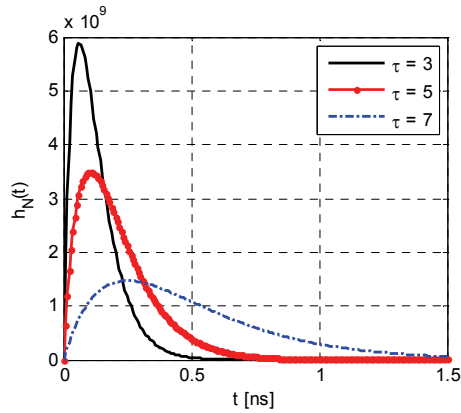


Fig. 3 Impulse response for a 1km link [8].

Fig. 3 shows results for a 1km link. If the pulse width corresponds to the transmitted symbol interval the intersymbol interference becomes significant. The “bandwidth” of fog channel depends, above all, on the optical thickness τ , i.e. on the scattering attenuation α_{sc} , Fig. 4. For a fixed link the channel parameters can be estimated from the measurements of the mean received power (RSS signal from the receiver frontend).

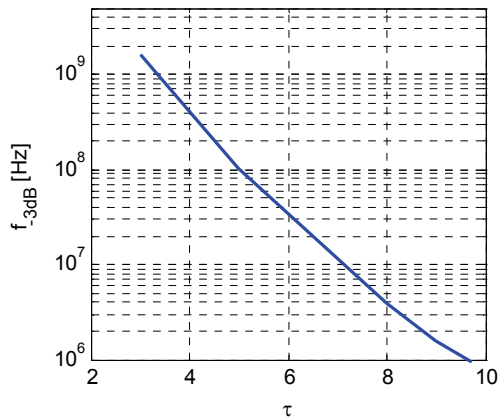


Fig. 4 Bandwidth as function of optical thickness for a 1km link.

3 Receiver model

Fig. 5 shows the receiver configuration. After being amplified in the transimpedance amplifier (TIA), the signal is filtered and sampled by a hard decision circuit (sampler).

The impulse response of the whole chain can be expressed in the normalized form as

$$g(t) = p_N(t) \otimes h_N(t) \otimes r_N(t) \quad (11)$$

where p_N , h_N , and r_N are normalized responses of the transmitter, the channel, and the receiver, respectively.

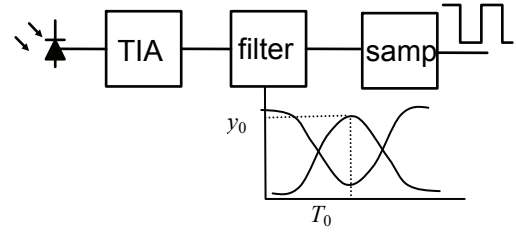


Fig. 5 Receiver configuration.

Let us assume, for simplicity, the transmitted pulse is rectangular, i.e. the input signal is $x = 1$ for $0 \leq t \leq T$, where T is the symbol period. The output pulse at the decision circuit is then

$$y(t) = x(t) \otimes g(t). \quad (12)$$

The ideal sampling point T_0 maximizes the sample value y_0 , Fig. 5. If $y_0 < 1$ due to the bandwidth limitation the eye “closes” and for $y_0 < 0.5$ no detection is possible. On the assumption of low BER, the power penalty can be estimated as [6]

$$\alpha_{ISI} \approx 10 \log \left[\frac{Q^{-1}(2^N P_{b0})}{(2y_0 - 1) Q^{-1}(P_{b0})} \right] = -10 \log(2y_0 - 1) + C \quad (13)$$

where Q is the Gaussian tail integral, P_{b0} is the error rate of the ideal system, and N is the length of channel memory in the number of symbol intervals.

Fig. 6 shows a simple suboptimal zero-forcing (analog) equalizer, which can be easily implemented.

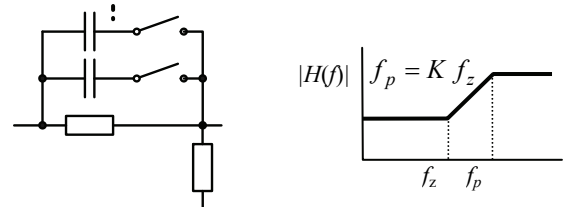


Fig. 6 Simple analog equalizer.

The frequency response can be controlled in discrete steps by switching the capacitors.

$$H_{ekv}(\omega) = \frac{1 + j\omega/\omega_z}{1 + j\omega/(K\omega_z)} \quad (14)$$

The parameter K controls the ratio between zero and pole frequencies.

For fixed K the equalizer is controlled by only one parameter (switches). The equalizer can be simply included in (11) by modifying the receiver pulse response to

$$\tilde{r}_N(t) = r_N(t) \otimes e_N(t) \quad (15)$$

where e_N is the normalized pulse response of the equalizer.

4 Performance evaluation

The performance of the system depends on the normalized impulse response parameter, see (8)

$$k_{2N} = k_2 / T \quad (16)$$

where T is the symbol period. The equalizer zero-frequency was fixed to the (normalized) 3dB bandwidth of the channel, i.e. $f_z = f_{3dB}$. The receiver included a 4th-order Bessel filter whose 3dB frequency was set to $0.6/T$, i.e. to 0.6 [6].

Fig. 7 shows the eye closing penalty – the first term of (13) as a function of normalized channel bandwidth.

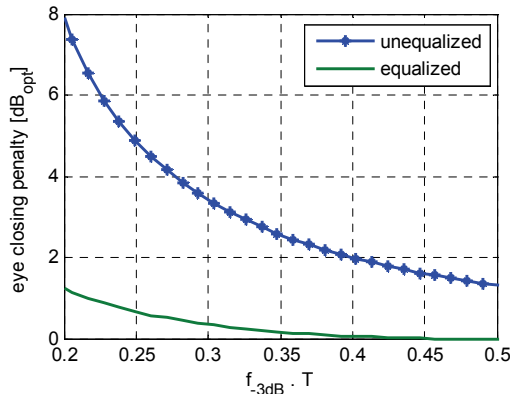


Fig. 7 Eye closing penalty (in optical dB).

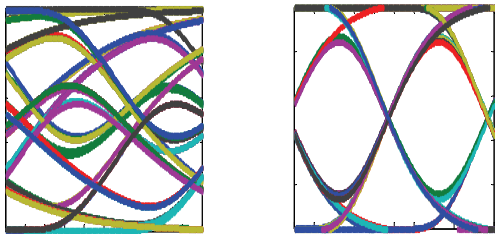


Fig. 8 Comparison of eye diagrams ($K = 5$, $f_{3dB}T = 0.2$).

5 Conclusions

The paper presented a simple methodology for

simulation of atmospheric optical channel with ISI. A simple analog equalizer for application in FSO receivers was evaluated.

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