Model of FSO Path for Network Simulation

Zdenek Kolka, Viera Biolkova, and Dalibor Biolek

***Abstract*—**The paper deals with a parameterized model for simulation of packet transmission on atmospheric Free-Space Optical (FSO) links. Due to the effect of atmospheric turbulence the channel is characterized by signal fluctuations in the order of tens of milliseconds. For moderate transmission rates the FSO channel can be simply modeled as a channel with slowly varying random attenuation, which is generated by the proposed model by means of low-pass filtering a random number sequence. The probability of occurrence of errors in each packet can be computed using analytical formulae based on the generated signal level and noise performance of the receiver. The model shows a good agreement with measured data. It has been implemented into the OMNeT++ simulator.

***Keywords*—**Atmospheric turbulence, data transmission, free-space optical links, Monte-Carlo simulation, network simulation.

I. Introduction

THE technology of point-to-point Free-Space Optical (FSO) links consists in transmitting information by means of narrow light beams in space or in the atmosphere. At present, terrestrial systems of up to gigabit capacity with a range of up to several kilometers are commercially available. The majority of the links are designed as simple protocol-independent repeaters with ON-OFF keying (OOK). Other types (ground-space, mobile, aerial, e.g.) are still in experimental stage [1]. The development of terrestrial FSO systems towards higher data rates, better reliability and network performance requires abandoning the simple repeater design. A number of nontrivial communication techniques based on detailed analyses of the atmospheric channel have been proposed (see [2] for a comprehensive review).

The atmosphere causes long outages due to the occurrence of fog, heavy rain and snow, and relatively short outages on the millisecond scale due to atmospheric turbulence. The long outages determine the link availability which also depends on the value of the fade margin [3], [4].

Long-range terrestrial links with a tight power budget are, in addition, influenced by atmospheric turbulence. Inhomogeneity in the atmosphere causes power fluctuations at the receiver on the millisecond time scale for static terminals. These short outages interfere with communication protocols.

A general theory of turbulence can be found in the classical book [5]. A number of studies have shown suboptimal performance of the TCP, the most popular transport-layer protocol, over the turbulent channel. The TCP congestion-avoidance mechanism misinterprets the short fades, which results in decreased data rates (see e.g. [6]). Therefore a number of FEC coding schemes, diversity techniques, or link-layer protocols have been proposed to mitigate the fades [2], [8].

The analysis of the performance of communication protocols is usually based on statistical models, which are powerful tools when it is possible to describe the protocol analytically or in the form of Markov process. Paper [7] analyzes the performance of TCP over the turbulent atmospheric optical channel using a two-state continuous-time Markov process, where the durations of “good” and “outage” states were modeled by exponential distribution. In [6] a 3D Markov model is used to analyze various flavors of TCP, including the exponential back-off.

On the other hand, in cases when a simple solvable model cannot be formulated, the time-domain (Monte-Carlo) simulation can be used for protocols of any complexity at the expense of computational cost. Multivalued Markov models [7], [10] provide discrete power levels, which may not be suitable for short-term BER calculation. Moreover, there is no clear link to the FSO design parameters. Paper [9] proposes a channel model in terms of a pair of stochastic differential equations which can be numerically evolved in time to produce continuous-value time records of faded optical intensities. However, the parameters of the model can only be identified from measured time series. A feasible method for generating scintillations was proposed in [12]. A Gaussian random number generator with a suitable low-pass filter simulates the fluctuating received optical power.

This paper presents a fully parameterized model simulating packet transmission in IM/DD FSO systems over a turbulent channel by means of generating random power levels of received signal. It is based on the assumption that the packet duration is shorter by orders of magnitude than the channel correlation time. Then it is possible to calculate directly the short-time BER and the probability of successful packet transmission. The model has been experimentally implemented in the OMNeT++ network simulator.

Section 2 explains the model and Section 3 presents a comparison between measured and simulated data.

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II. SIMULATION MODEL

A. Received Power

Let us consider the point-to-point FSO terrestrial link in Fig. 1.

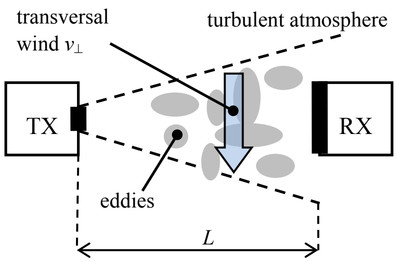

Fig. 1 Point-to-point FSO link configuration

With respect to the supposed channel linearity the mean received optical power $p_{m,RX}$ can be expressed as

$$p_{m,RX} = p_{m,TX}\, a_{FSL}\, a_{ATM}\, a_T \,. \tag{1}$$

To avoid unnecessary complexity of the model, both the transmitted $p_{m,TX}$ and the received $p_{m,RX}$ mean optical powers are related to the transmitting and receiving apertures, respectively.

Let us assume the diameter of the optical beam at the receiver is large enough for the whole receiving aperture to be uniformly irradiated. Then the free space propagation coefficient a_{FSL} at the beam center can be simply expressed as

$$a_{FSL} = \left(\frac{D_{RX}}{\theta_{TXe}\, L} \right)^2 , \tag{2}$$

where L is the path length, D_{RX} is the receiver aperture diameter, and θ_{TXe} is the divergence full angle of the equivalent beam with uniform distribution of irradiance. For an ideal top-hat beam, θ_{TXe} represents its divergence full angle. For the Gaussian beam $\theta_{TXe} = \theta_{Gauss} / \sqrt{2}$.

Transmission coefficient a_{ATM} represents the atmospheric attenuation caused by absorption and scattering, which increases significantly during fog, rain, and snowfall, and may cause a long outage. It is a very slow process, which determines the overall link availability [3], [4]. For the purpose of network simulation the coefficient can be regarded as a constant.

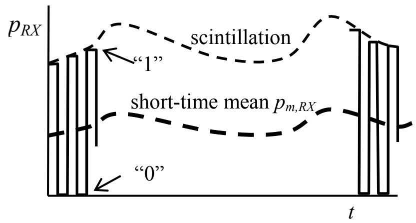

Fig. 2 Short-time mean optical power for ON-OFF keying

The term a_T represents the effect of atmospheric turbulence, which just redistributes energy in the beam with no loss. Because the receiving aperture is smaller than the beam cross-section, the received power fluctuates.

Considering the ON-OFF keying with transmission rates of 100Mb/s and above the duration of one bit is several orders of magnitude shorter than the turbulence "period", i.e. the channel coherence time. The mean powers in (1) are computed over a sufficient number of bit periods, which is still shorter that the channel coherence time. Therefore $p_{m,TX}$ and $p_{m,RX}$ represent short-time mean powers which fluctuate randomly due to atmospheric turbulence, see Fig. 2.

B. Short-time bit error probability

With the above assumption on data rate, the optical atmospheric channel can be modeled by a slowly varying "short-time" bit error rate, which can be considered constant during a packet transmission [14].

For ON-OFF keying with equal probability of symbols "0" and "1" the short-time BER is

$$P_b = Q(p_{m,RX} / P_N) , \tag{3}$$

where P_N characterizes the equivalent optical noise properties of the whole receiver and Q is the standard Gaussian tail integral. The simplified formula was derived for AC-coupled photodiode and ignores the signal-induced shot noise.

In many cases a threshold optical power level p_{m0} for a given P_{b0} is specified (e.g. for $P_{b0} = 10^{-9}$ or $P_{b0} = 10^{-12}$). Considering (3) the noise floor P_N is

$$P_N = \frac{p_{m0}}{-F^{-1}(P_{b0})} , \tag{4}$$

where F^{-1} is the normal inverse cumulative distribution function.

Alternatively to (1) the received power can be expressed as

$$p_{m,RX} = M\, a_T\, p_{m0} , \tag{5}$$

where M is the link fade margin characterizing the allowable fade depth. Combining (3) - (5) the short-time BER is then

$$P_b = Q\big(-M\, a_T\, F^{-1}(P_{b0}) \big) \,. \tag{6}$$

In the case of a simple frame-level FEC coding the transmitted frame of n bits will be lost (or "erased") with the probability

$$P_F = 1 - \sum_{i=0}^{N_{FEC}} \binom{n}{i} P_b^i (1 - P_b)^{n-i} \tag{7}$$

given by the binomial distribution as the bit errors are independent. N_{FEC} is the acceptable number of errors in the frame. For links without FEC, $N_{FEC} = 0$.

C. Atmospheric turbulence

Atmospheric turbulence is represented by randomly varying coefficient a_T in (1) with unity mean and variance σ_T^2 , which characterizes the depth of scintillations and is called the *Power Scintillation Index* (PSI). Weak turbulence is characterized by

$\sigma_T^2 < 1$, while $\sigma_T^2 > 1$ for strong turbulence.

For realistic aperture size the received power statistics can be approximated by lognormal distribution [15] due to the effect of averaging. Therefore a_T will be characterized by the lognormal PDF

$$f_{a_T}(a) = \frac{1}{a\sigma_L\sqrt{2\pi}} \exp\left(-\frac{\left[\ln a + \sigma_L^2/2\right]^2}{2\sigma_L^2}\right), \tag{8}$$

where σ_L is the log variance related to PSI as

$$\sigma_L^2 = \ln(\sigma_T^2 + 1). \tag{9}$$

The log amplitude of scintillation ($\ln a_T$) can be represented by a random process with autocorrelation function

$$R_{\ln a_T}(\tau) = \exp\left(-a\left|\tau/\tau_0\right|^b\right), \tag{10}$$

with $a = 1/2$, $b = 1$ for Gauss-Markov process [11] or with $a = 1$, $b = 2$ [12]. The channel correlation time τ_0 is inversely proportional to the transversal wind speed [5], see Fig. 1.

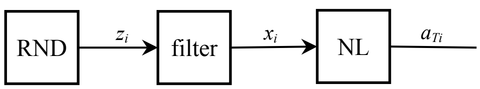

Fig. 3 Generation of samples of random coefficient a_T

Random process with prescribed autocorrelation function (or PSD) can be generated by linear filtering a spectrally white zero-mean Gaussian distributed random sequence z_i. The colored signal x_i is then subject to a zero memory, nonlinear transformation

$$a_{Ti} = \exp\left(x_i - \sigma_L^2/2\right) \tag{11}$$

in order to produce samples a_{Ti} with exponential PDF (8), [13], see Fig. 3.

The linear filter in Fig. 3 can be advantageously realized as a FIR filter with causal impulse response

$$h_k = R_{\ln a_T}\left[t_s(k-N)\right] \text{ for } k = 0, ..., 2N, \tag{12}$$

where t_s is the sampling period and $(2N + 1)$ represents the number of samples to characterize the autocorrelation function (10). A possible choice of sampling period is $t_s = \tau_0/5$ [12]. The number of samples is chosen $R_{\ln a_T}(N t_s) << 1$ so that the truncation error is negligible.

Let us suppose the filter is supplied by uncorrelated random numbers z_i with variance σ_G^2 from the RND block. After an initial transient of $2N + 1$ samples, each x_i is given as a sum of $2N + 1$ normal random numbers weighted by h_k. Therefore the log variance (of x_i) will be

$$\sigma_L^2 = \sigma_G^2 \sum_{k=0}^{N-1} h_k^2 . \tag{13}$$

D. Event-driven simulation

The simulation in OMNeT++ (or other network simulators) is event-driven, i.e. the model procedure is “woken up” at the time of packet transmission while the generating process in Fig. 3 works with equidistant sampling.

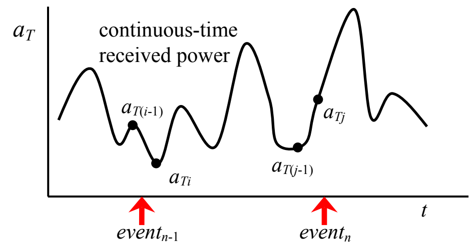

Fig. 4 Generating a_{Ti} in event-driven environment

The $2N + 1$ random numbers z_i, which are used to compute the response of FIR filter, are held in a circular buffer. To compute a new value of z_i, one random number is written to the head of the buffer and the indices are updated.

When an event occurs, say the (n-1)th in Fig. 4, the instant attenuation a_T is linearly interpolated from two adjacent samples of a_{Ti}. At the occurrence of the next event, the generating process from Fig. 3 has to advance from time t_{n-1} to t_n. If

$$t_n - t_{n-1} < (2N+1)t_s , \tag{14}$$

an appropriate number of z_i is updated in the circular buffer to calculate $a_{T(j-1)}$ and a_{Tj}. For a longer interval than $(2M + 1)\ t_s$ the buffer is simply reinitialized as $a_T(t_{n-1})$, and $a_T(t_n)$ are treated as uncorrelated due to the finite representation of (10).

III. Real and Simulated Data

Data for the model evaluation at the weak turbulence scenario was obtained from an experimental link with the following parameters: $\lambda = 1550$nm, $L = 500$m, $D = 25$mm, $R = 125$Mbs [16]. The sampling frequency was 10 kHz with a 2 kHz anti-aliasing filter. The calculated power scintillation index was $\sigma_T^2 = 0.12$, which corresponds to weak turbulence.

Fig. 5 shows the normalized autocorrelation function of measured and generated signals a_T. The best fit was obtained for $\tau_0 = 2.5$ ms, a = 0.5, b = 1.4 in (10). The figure shows that the autocorrelation function of generated signal decays quickly in comparison with real data. The good agreement is confirmed by comparing PSD of both signals in Fig. 6.

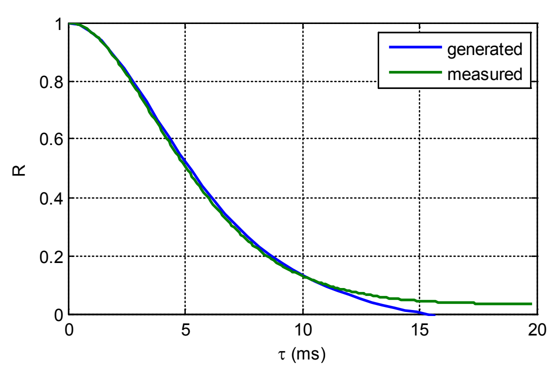

Fig. 5 Normalized autocorrelation function of a_T

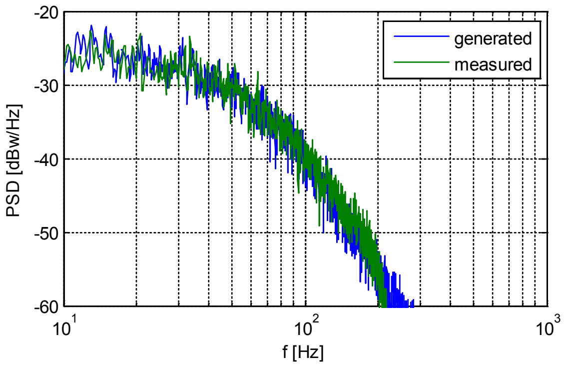

Fig. 6 Power spectral density of a_T

The FIR filter was designed using $N = 32$ and $t_s = \tau_0/5$ in (12). The procedure used assures the same PSI of the generated a_T. The time domain properties, which are relevant to communication protocol modeling, are demonstrated in Fig. 7. The channel-bad-time represents a continuous interval where $a_T < a_{thr}$.

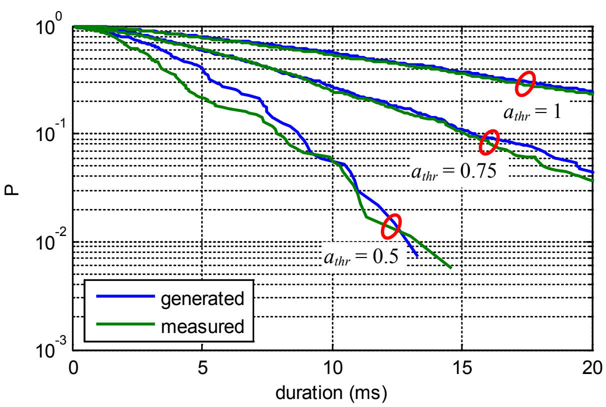

Fig. 7 Complementary cumulative distribution function of channel-bad-times

Fig. 8 shows a simulation of average packet error rate on a 20s interval for measured and generated received signals. The simulation was performed for a 1Gbs Ethernet link ($N_{\mathrm{FEC}} = 0$) transmitting maximum-length packets. The threshold bit-error rate used in (6) was $P_{b0} = 10^{-12}$ for p_{m0} = -30dBm (SFP module with all-optical frontend). The link margin M represents the average received power above p_{m0} in turbulence-free environment.

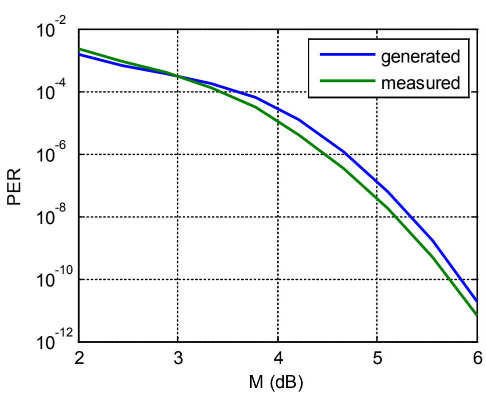

Fig. 8 Packet error rate as function of link margin M

IV. Conclusion

The paper presents a fully parameterized simple model for simulating packet transmission on FSO channels by generating random levels of received power. Both statistics and autocorrelation properties of the generated signal agree with data measured on the test link. The generation of a new sample of received power requires calculation of the FIR filter output sample, which typically represents a 65-point convolution.

The depth of received power scintillations can be set by specifying PSI and the "frequency" of fades can be specified by channel correlation time τ_0.

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