Simulation of FSO Transmission Channel

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Abstract: The paper deals with the modeling and simulation of atmospheric Free-Space Optical (FSO) links. Due to the effect of atmospheric turbulence the links are characterized by outages in the order of tens of milliseconds, which are several orders of magnitude longer than the duration of frames (packets) being transmitted. For high transmission rates the optical channel can be simply modeled as a slowly varying AWGN channel. It allows computing the probability of the occurrence of errors in each packet by means of analytical formulae. The method is demonstrated on the simulation of channel coding for mitigating short fades for unidirectional link using the OOK modulation.

Key-Words: Free-space optics, simulation, channel coding

1 Introduction

The technology of Free-Space Optical (FSO) links consists in transmitting information by means of light beams in space or in the atmosphere. At present, terrestrial systems up to 1.25 Gb/s with a range of up to 2 km are commercially available. The majority of the links are designed as simple protocol-independent repeaters on the physical layer, using on-off keying (OOK) of laser diode or LED in the transmitter. Other types (ground-air, ground-space, and space-space) are still in experimental stage [1].

Atmospheric links are influenced by atmospheric attenuation and turbulence. Attenuation caused by scattering on particles increases significantly during fog, rain, and snowfall and may cause a long outage. It is a very slow process, which determines the overall availability of link [2], [3].

Long-range links with a tight power budget are, in addition, influenced by atmospheric turbulence. Inhomogeneities in the atmosphere cause power fluctuations at the receiver in the millisecond time scale for static terminals. These short outages increase the bit-error rate and interfere with communication protocols. General theory of turbulence can be found in the classical book [4]. Theoretical information capacity of the channel for different scintillation models was analyzed, for example, in [5]. Many practical experiments for terrestrial and ground-space links have been conducted at DLR [1], [8]. Spatial diversity has been studied with the aim of mitigating scintillation effects [6].

A millisecond outage results in the loss of hundreds or thousands of packets for high-speed networks. The significant difference between the packet duration and the “period” of atmospheric turbulence allows using analytic formulae for the calculation of packet error probability. The simulation event rate is derived from the packet rate rather than from the bit rate.

Sections 2 and 3 of the paper provide a simple framework for FSO channel modeling, using samples of power received from a real link or from a model. Section 4 deals with an example simulation of a coding scheme for mitigating short-time fades based on a combination of bit-level and packet-level coding.

2 Model of Atmospheric Channel

Let us consider the OOK FSO atmospheric link influenced by atmospheric turbulence, Fig. 1.

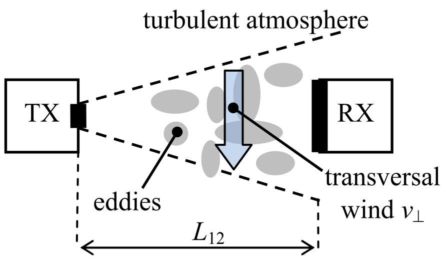

Fig. 1 FSO link.

A atmospheric turbulence just redistributes energy in the beam without loss. Usually the receiving aperture is smaller than the beam cross-section, which causes fluctuation in the received power, Fig. 2.

The time scales of transmitted data and power fluctuations can be described by the relation

$$\tau_{DATA} << \tau_{TURB} \tag{1}$$

with typical values $\tau_{DATA} < 100\text{ns}$, $\tau_{TURB} \approx 10\text{ms}$.

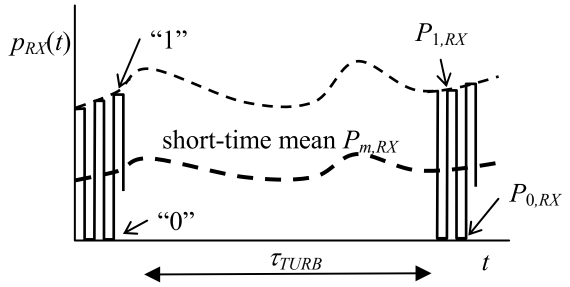

Fig. 2 Received optical power of atmospheric FSO with ON-OFF keying.

Neglecting $P_{0,\text{RX}}$ and considering the equal probability of the symbols "0" and "1" and with respect to (1) we can define the short-time mean power at the receiver

$$P_{m,RX} = 0.5\,P_{1,RX} \ , \tag{2}$$

which fluctuates randomly due to atmospheric turbulence. $P_{m,RX}$ can be easily monitored and recorded at the receiver. The normalized received power is

$$P_N = \frac{P_{m,RX}}{\left\langle P_{m,RX} \right\rangle} \ , \tag{3}$$

where the mean value $\left\langle P_{m,RX} \right\rangle$ is computed for a sufficiently long interval. The normalized variance, called *power scintillation index* (PSI)

$$\sigma_p^2 = \left\langle P_N^2 \right\rangle - 1 \tag{4}$$

provides a measure of the scintillation strength.

The scintillation index is inversely proportional to the diameter D of receiving aperture due to the effect of averaging. Atmospheric turbulence reduces the beam spatial coherence. The larger the receiver aperture the more uncorrelated contributions are summed at the photodetector. The effect can be expressed as [4].

$$\frac{\sigma_p^2(D_1)}{\sigma_p^2(D_2)} \approx \frac{A(D_1)}{A(D_2)} \ , \tag{5}$$

where D_1 and D_2 are two diameters of the receiving aperture and $A(D)$ is the aperture-averaging factor

$$A(D) = \left[1 + 0.333\left(\frac{\pi D^2}{2L_{12}\lambda}\right)^{5/6}\right]^{-7/5} \ , \tag{6}$$

where λ is the wavelength, and L_{12} is the distance.

On the assumption of weak fluctuations and a small receiving aperture, P_N is theoretically log-normally distributed with the probability density function [4]

$$f_{P_N,w}(p) = \frac{1}{p\sigma_p\sqrt{2\pi}} \exp\left(-\frac{\left[\ln p + 0.5\sigma_P^2\right]^2}{2\sigma_P^2}\right). \tag{7}$$

Analysis of experimental data showed that the lognormal distribution can be used with a sufficient accuracy even in the case of strong turbulence [12].

The PDF of received power does not describe the temporal behavior of the channel, which is crucial for simulation. Using the Taylor principle of *frozen turbulence*, the "frequency" of scintillations is proportional to the transversal wind speed. The *eddies* in Fig. 1 can be thought of as wafted by the transversal component $v_\perp$ of wind (or by relative speed of mobile terminal) [4]. The average fade duration is then inversely proportional to $v_\perp$

$$\tau \approx \frac{1}{v_\perp} \ . \tag{8}$$

Changing the time scale simply models different wind conditions.

3 Model of Receiver

Considering transmission rates of 100Mb/s and above, an interval of 100μs, during which the received power is practically constant, corresponds to a block of more than 10^4 bits. Bit error probability during the interval depends on constant signal-to-noise ratio in the receiver. The optical atmospheric channel can be modeled by a slowly varying probability of independent single-bit error that is called "short-time" bit error rate [9].

For On-Off Keying a realistic formula for short-time BER in AWGN channel was proposed in [9]

$$p_b = Q\left[\frac{P_{m,RX}/P_0}{1 + \sqrt{1 + \xi_0 P_{m,RX}/P_0}}\right] \ , \tag{9}$$

where the empirically determined parameters P_0 and ξ_0 characterize the noise properties of the whole receiver, and Q is the standard Gaussian tail integral. The formula was derived for the adaptive hard-decision threshold in the receiver and for the infinite extinction ratio of the transmitter.

For a channel with independent bit errors, the probability of k errors occurring in a block of n bits is given by the Binomial distribution

$$P_n(k) = \binom{n}{k} p_b^k (1 - p_b)^{n-k} \ . \tag{10}$$

Fig. 3 shows the number of errors in a block of 12500 bits as a function of received power obtained experimentally from an FSO link ($\lambda = 1550$nm, $L_{12} = 500$m, receiving aperture $D = 25$mm, $R = 125$Mb/s) [10]. The dashed curves represent the mean and 1- and 99- percentiles calculated using (9) and (10).

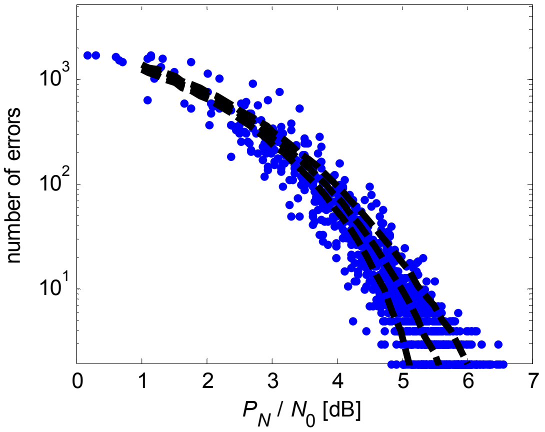

Fig. 3 Number of errors in block of 12500 bits.

Clock recovery circuitry of the receiver should be capable of operating under frequent channel outages, i.e. symbol and frame synchronization time should be considerably shorter than periods of good channel state. Fig. 4 shows the statistics of good channel time when p_b is lower than a chosen value.

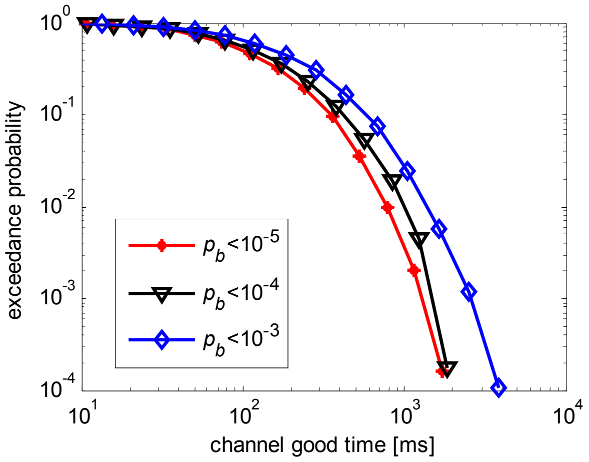

Fig. 4 Statistics of good channel time (for the link from Section 4).

Ethernet is one of the technologies suitable for application in FSO links. There are readily available chipsets as well as modules for implementation in FPGA. Since the introduction of Fast Ethernet (100Mb/s) the frame preamble has no longer been used for clock synchronization. The clock recovery acquisition time is longer (e.g. 250 µs@100Mb/s for DP83840A from National Semiconductor). Fig. 5 shows a general model of receiver synchronization used for simulations. Its parameters (P_{up}, P_{down}, t_{lock}) depend on receiver used.

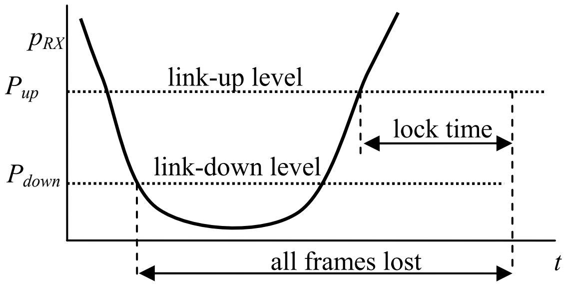

Fig. 5 Model of receiver synchronization.

Let us consider the application of a correcting code at the receiver. Frames of length n containing at most t bit errors are acceptable. Frames containing more errors are discarded. For the classic Ethernet $t = 0$. With regard to (10) the probability of packet erasure is

$$P_{erasure} = 1 - \sum_{i=0}^{t} \binom{n}{i} p_b^i (1 - p_b)^{n-i} \ . \tag{11}$$

During simulation, for a transmitted packet the instantaneous short-time BER is determined using (9) and the packet erasure probability is determined from (11). The packet is discarded if

$$P_{erasure} > \xi \ , \tag{12}$$

where ξ is the generated random number with uniform distribution on the interval (0, 1). Samples of received power for (9) can be obtained either from a model or from an actual link.

4 Simulation of Channel Coding

The effect of atmospheric turbulence presents almost no problem for very short terrestrial links. Their link margin, designed for high availability, absorbs the power fluctuations. For longer links with a tight power budget, atmospheric turbulence causes short outages [6]. In this case the utilization of channel coding is advantageous.

The channel model has been tested for the simulation of FEC data protection suitable for long unidirectional links with no back channel for potential ARQ procedures, Fig. 6. It is based on a combination of the correcting code on bit level with the correcting code on packet level.

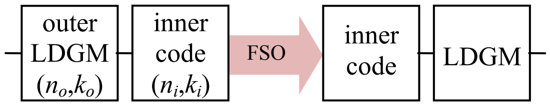

Fig. 6. Tested coding scheme for long-range link.

Each frame (packet) is protected by an error-correcting inner block code (n_i,k_i,t_i), which is capable of correcting $t_i \le (n_i\text{-}k_i)/2$ errors. As shown in section 3, the input power is almost constant during packet reception, i.e. the channel is similar to the AWGN channel with a flow of independent errors. Frames are either corrected and passed to the outer-code module or discarded.

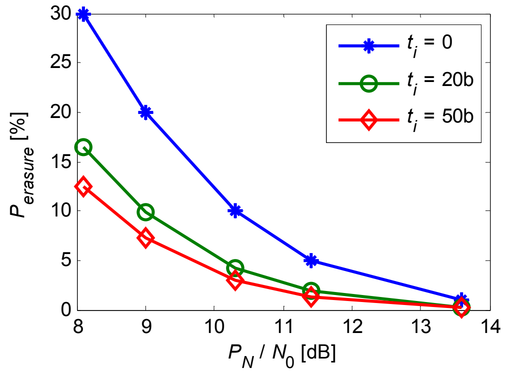

Fig. 7. Effect of inner coding for different numbers of correctable bits (n_i = 1024B).

Fig. 7 shows the effect of inner coding on the probability of packet erasure. The statistics are the result of channel simulation (see section 3) using samples of received power from a 7km static test link (λ = 850nm, D = 200mm, sunny day 23°C, wind up to 20km/h, $\sigma_p^2 \approx 0.5$, rate 100Mb/s, 17.2 million packets simulated). It can be seen that correcting relatively small number of bits brings the gain of about 2dB.

The outer code should be capable of covering ten-millisecond outages, i.e. the erasure of hundreds or thousands of packets. Fig. 8 shows the exceedance probability of packet erasure in a block of size n_o (up to 30 thousands packets) for P_N/N_0 = 8.1dB, where 30% of packets in average were erased for uncoded transmission. The ratio of erased packets in a block of n_o packets approaches asymptotically the average value of 30% for large n_o.

A suitable outer code is the LDGM code (Low Density Generator Matrix – *Triangle* or *Staircase*), which is capable of operating on source blocks that are composed of several tens of thousands of packets [7], [8]. Packets that are transmitted between LDGM codecs should be either error-free or discarded by the lower layer [7]. A software implementation of LDGM attains a speed of 2.2Gb/s for encoding and 816Mb/s for decoding on a Pentium IV/3.06GHz/Linux (k = 20,000, n = 30,000, packet size 1kB) [11]. Higher speeds can be achieved using hardware acceleration.

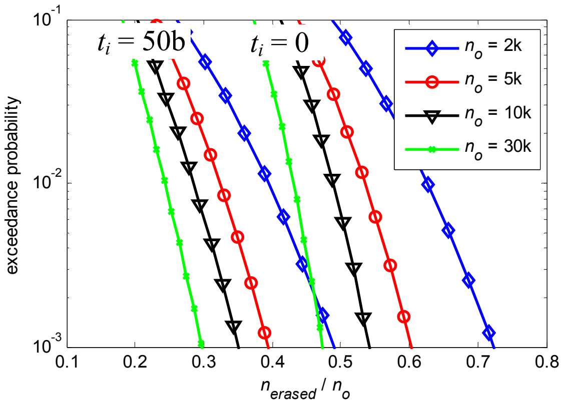

Fig. 8. Effect of block size of outer code (P_N/N_0 = 8.1dB).

LDGM is a block code generating for k_o information packets (n_o-k_o) parity packets. It does not belong to the class of MDS codes. To reconstruct k_o information packets it is necessary to successfully transmit slightly more than k_o packets. The upper limit for the decoding delay is given as the time needed to transmit the whole block of n_o packets (10,000 packets correspond to an interval of 0.8s at 100Mb/s).

The block size n_o and the k_o/n_o ratio is a subject of tradeoff between packet loss and latency. For block size of 10,000 packets and for t_i = 50 bits the coded packet erasure probability will be decreased from uncoded 30% down to 0.1% for k_o/n_o = 0.65.

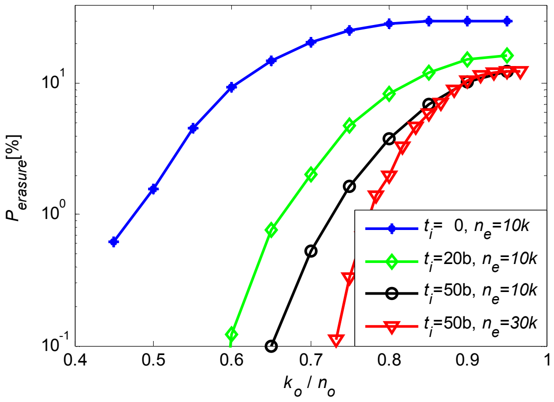

Fig. 9. Probability of packet erasure as function of outer code rate (P_N/N_0 = 8.1dB, LDGM Triangle, degree 3).

4 Conclusions

The paper presents a simple model for simulating the FSO channel, using samples of optical power received from a real link or generated by a turbulence model. The model was used to simulate the coding scheme for different conditions.

Outages caused by turbulent atmosphere require the use of large-block codes in combination with error correction codes on the packet level. The paper shows that adding an error correction capability to the MAC layer can significantly improve the properties of FSO channel in the case of a tight power budget.

5 Acknowledgements

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