Mitigation of Atmospheric Turbulence on Terrestrial FSO Paths using Buffering

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Abstract. The paper deals with a study of buffering techniques for terrestrial Free-Space Optical links to mitigate short-time fades caused by the atmospheric turbulence. Under certain conditions the optical propagation through atmospheric turbulence is reciprocal, i.e. the transmitter has knowledge of the channel state based on the local RSSI and can block transmission during fades and store the incoming data in a FIFO buffer. The study is based on the Monte-Carlo method using the generation of correlated and colored lognormal time series of the received optical power. The link with buffering is simulated for typical application scenarios.

Keywords: Free-space optical links, atmospheric turbulence, reciprocity.

1 Introduction

Terrestrial point-to-point Free-Space Optical (FSO) systems are subject to the influence of near-ground atmosphere [1]. Precipitation (fog, rain, snow) causes slowly-changing attenuation in the transmission channel. In addition, the atmospheric turbulence induced by pressure and temperature inhomogeneity causes power fluctuations at the receiver on the millisecond time scale [2]. These short outages interfere with communication protocols. Therefore a number of FEC coding schemes, diversity techniques, or link-layer protocols have been proposed to mitigate the fades [3].

A millisecond outage results in the loss of hundreds or thousands of packets for high-speed networks. The drawback of FEC-based techniques, in particular interleaving, is increased latency. In addition, a considerable processing power in transmitter and receiver is required to encode and decode large blocks.

The hardware and software requirements of fade mitigation can be alleviated significantly in case of channel state knowledge at the transmitter. The transmitter may simply stop transmitting during the fade. Theoretically, the information can be obtained from the far end of a full-duplex link via the backward data stream. However, this scheme may fail under high BER condition or complete outage.

A more promising solution can be based on the principle of reciprocity. The optical propagation through atmospheric turbulence is point reciprocal [4], [5], i.e. the power fluctuation in forward and backward channels is the same for sufficiently small FSO terminals. It was confirmed by practical measurements and simulations that the correlation coefficient between both channels can reach values ρ ∈ [0.95; 0.99] even for separated transmitting and receiving lenses with different diameters [6].

This paper studies the feasibility of designing a link adaptation unit for FSO, which implements the transmitter blocking. The study is based on the Monte-Carlo simulation with a newly developed time-domain model for generating correlated and colored lognormal time series [7]. Section 2 introduces the model briefly, while Section 3 presents the simulation study.

2 Model of Duplex Turbulent Channel

Let us consider the link in Fig. 1 (a) under steady atmospheric condition. Considering transmission rates of 1 Gb/s and above, the duration of one symbol is several orders of magnitude shorter than the turbulence "period", i.e. the channel coherence time. Thus the received signal can be characterized by "short-time" mean power $p_{m,RX}$ computed over a sufficient number of symbols, which slowly fluctuates around the long time mean $\langle p_{m,RX} \rangle$.

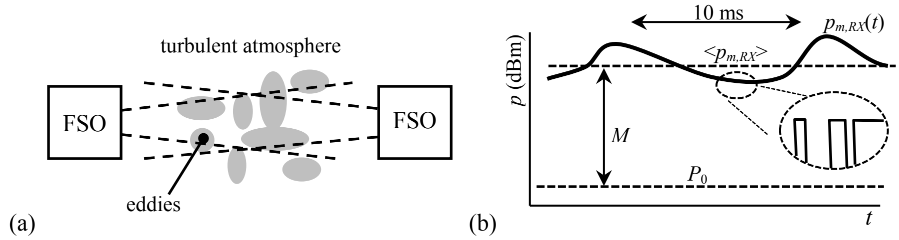

Fig. 1. (a) FSO link configuration; (b) Received power budget model.

The time varying received power can be represented by its normalized value

$$a_T = p_{m,RX} / \langle p_{m,RX} \rangle \tag{1}$$

and the strength of atmospheric turbulence is assessed by the variance σ_T^2 of a_T, which is called the *Power Scintillation Index* (PSI). Weak turbulence is characterized by $\sigma_T^2 \approx 0.1$, while $\sigma_T^2 \approx 1$ holds for strong turbulence.

The noise properties of receiver are expressed by optical power level P_0 for a given bit error rate P_{BE0} (e.g. P_0 = -36 dBm @ $P_{BE0} = 10^{-12}$ for APD receivers).

The power budget of FSO is represented by the link fade margin M defined as

$$M = \langle p_{m,RX} \rangle / P_0 , \tag{2}$$

which is, in fact, the maximum allowable attenuation in the channel for maintaining BER below the threshold P_{BE0}.

Considering an ideal AWGN channel and ON/OFF keying scheme the short-time BER is then

$$P_{BE} = Q\left(-M\, a_T\, F^{-1}(P_{BE0})\right), \tag{3}$$

where Q is the standard Gaussian tail integral and F^{-1} is the normal inverse cumulative distribution function.

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

$$P_{FE} = 1 - \sum_{i=0}^{N_{FEC}} \binom{n}{i} P_{BE}^{i} (1 - P_{BE})^{n-i} \tag{4}$$

given by the binomial distribution as the bit errors are considered independent. N_{FEC} is the acceptable number of errors in the frame.

The statistical properties of the normalized received power a_T are characterized by the log-normal distribution function [8] with an autocorrelation function of $\ln(a_T)$ [9]

$$R_{\ln a_T}(\tau) = \exp\left(-\frac{1}{2}\left|\tau/\tau_0\right|\right), \tag{5}$$

where the channel correlation time is τ_0. In the case of a duplex link, both channels are linearly correlated with the coefficient ρ. Study [6] shows the possibility of obtaining the correlation coefficient $\rho \in [0.95; 0.99]$.

Our paper [7] presents a time-domain generator of correlated and colored lognormal random time series of a_T for the Monte-Carlo simulation of packet transmission over an FSO path.

3 Link Adaptation Unit for FSO

When the propagation delay is negligible in comparison with the channel correlation time, i.e. for kilometer paths, it is possible to implement a simple link adaptation unit, which performs transmission blocking when the received power (RSSI signal) drops below a chosen threshold. During the blocking the incoming data is stored in a FIFO buffer. This simple mechanism does not require any buffer in receiver, see Fig. 2.

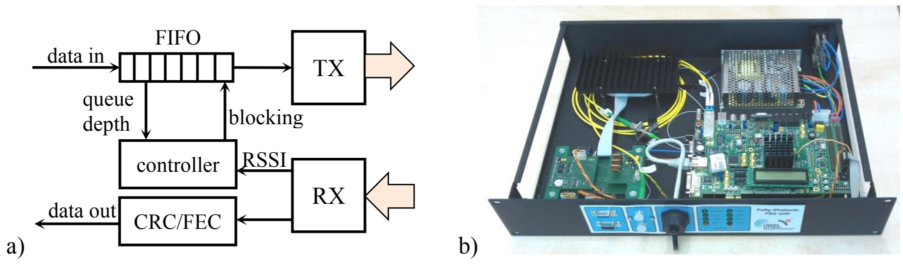

Fig. 2. (a) Structure of link adaptation unit; b) Actual implementation based on Virtex-5 FPGA.

The controller monitors the RSSI signal and blocks the queue head to stop transmitting during fade events. The unit in Fig. 2 is based on the Gigabit Ethernet (GbE) technology. The integrity of each received frame is checked by CRC32. Bad frames are dropped, i.e. $N_{FEC} = 0$ in (4) for calculating the frame-error rate. However, a more elaborate scheme can be used. The transmitted Ethernet frames can be embedded into transport frames with Forward Error Correction (FEC). The processing power of modern FPGAs is sufficient for a coding gain of about 6dB for gigabit streams.

The queue depth depends on the blocking threshold and incoming traffic. With low traffic, the threshold can be increased, i.e. there will be more frames in the queue, in order to decrease the packet erasure ratio. The algorithm is designed so that the controller keeps the maximum queue depth at a given fraction of the full FIFO capacity.

The simulation of various scenarios using the model from Section 2 is inevitable since real experiments with the same conditions are hard to perform due to the unsteady nature of the near-ground atmosphere.

The duplex FSO link will be characterized by the following parameters: M – link margin, PSI – power scintillation index (0.1 – calm weather, 1 – sunny day), τ_0 – channel correlation time (typically 5 ms), ρ – correlation coefficient between received powers at both ends (from 0.95 to 0.99), threshold BER of receiver ($P_{BE0} = 10^{-12}$). For simplicity, let the clock synchronization time be negligible in comparison with channel-good periods.

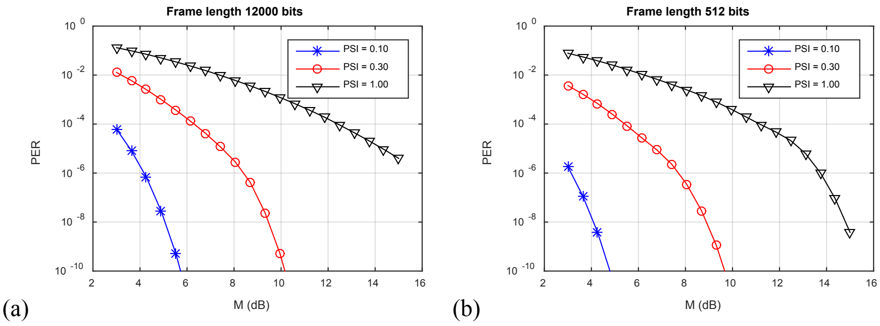

Fig. 3. Frame error ratio without blocking for (a) 1500 byte frames; (b) 64 byte frames.

Fig. 3 shows the long-term frame error ratio without transmitter blocking. The result for strong turbulence regime (PSI = 1) shows a significant degradation of data transmission even for $M > 10$ dB, for both long and short frames.

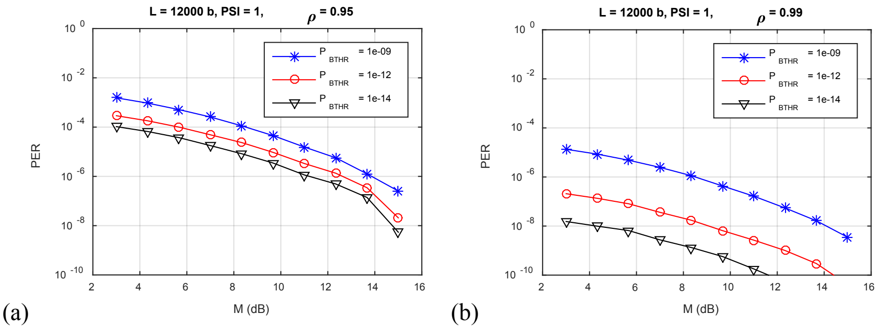

Fig. 4. Adaptation unit performance as a function of threshold for (a) ρ = 0.95; (b) ρ = 0.99.

Fig. 4 shows the results for the worst-case situation, i.e. for 1500 B frames and strong turbulence with blocking enabled. The blocking threshold is expressed indirectly by the equivalent bit-error ratio. From (2) and (3) we have the actual power threshold

$$p_{m,THR} = P_0\, F^{-1}(P_{BTHR}) / F^{-1}(P_{BE0})\,. \qquad (6)$$

The results clearly show that setting the threshold near the receiver sensitivity can improve the error ratio by two orders of magnitude even for ρ = 0.95. For FSO with an optical telescope shared by RX and TX the correlation may reach ρ = 0.99 and the improvement will be even more significant.

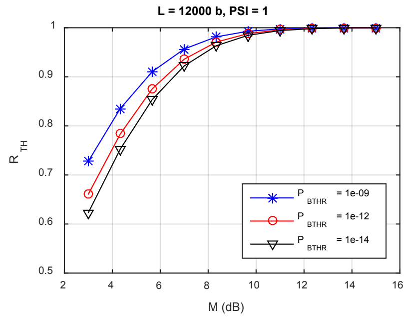

Fig. 5. Relative throughput as a function of link margin

The relative throughput of the FSO link with the adaptation module is shown in Fig. 5. For M below 10 dB, the total blocking period becomes more significant and the incoming traffic should be limited accordingly, otherwise the FIFO will overflow. For $M > 10$dB the degradation is negligible.

(a)

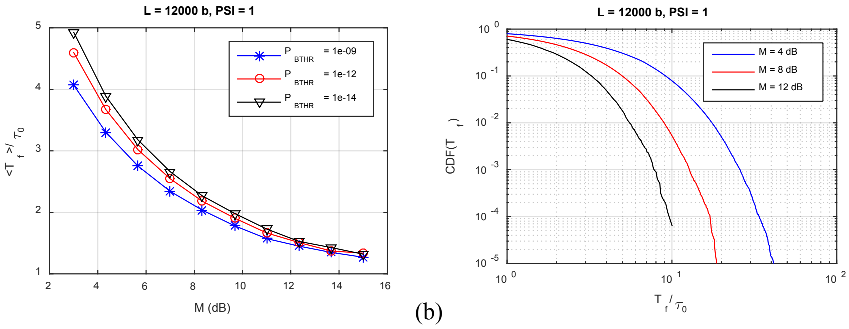

Fig. 6. (a) Average blocking time; (b) CDF of blocking times.

The average blocking time $\langle T_f \rangle$ reaches multiples of τ_0 for low link margins M, see Fig. 6 (a). However, the FIFO size should be chosen such that it accommodates extreme fades. Fig. 6 (b) shows the cumulative exceedance function of the blocking intervals. For example, for $M = 8$ dB the fade will be longer than 20 τ_0 with a probability of less than 10^{-5}. For a gigabit link it gives a 100 Mb memory, which is easily feasible.

4 Conclusions

By means of simulation the paper studies the feasibility of the link adaptation module for FSO, which blocks data transmission during fades. The improvement of frame error rate would be more than two orders of magnitude even with an off-the-shelf FPGA board with moderate memory requirements.

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References

[1] F. Nadeem, V. Kvicera, M. S. Awan, E. Leitgeb, S. S. Muhammad, G. Kandus, Weather Effects on Hybrid FSO/RF Communication Link. *IEEE J. Sel. Areas in Comm.*, vol.27, no.9, Dec. 2009, pp. 1687-1697.

[2] L. C. Andrews, C. Y. Phillips, J. Hopen, *Laser Beam Scintillation with Applications*. SPIE Press, Bellingham (WA), USA, 2001.

[3] D. K. Borah, A. C. Boucouvalas, C. C. Davis, S. Hranilovic, K. Yiannopoulos, A review of communication-oriented optical wireless systems. *EURASIP Journal on Wireless Communications and Networking*, 2012:91, doi:10.1186/1687-1499-2012-91.

[4] J. H. Shapiro, Reciprocity of the turbulent atmosphere. *J. Opt. Soc. Am.*, Apr. 1971, vol. 61, no. 4, pp. 492-495.

[5] J. H. Shapiro, A. L. Puryear, Reciprocity-enhanced optical communication through atmospheric turbulence - part I: reciprocity proofs and far-field power transfer optimization. *J. Opt. Commun. Netw.*, vol. 4, no. 12, Dec. 2012, pp. 947-954.

[6] J. Minet, M. A. Vorontsov, E. Polnau, D. Dolfi, Enhanced correlation of received power-signal fluctuations in bidirectional optical links. *Journal of Optics*, vol. 15, no. 2, pp. 022401.

[7] Z. Kolka, V. Biolkova, D. Biolek, Simulation model of correlated FSO channels. In *Proc. of Conference on Microwave Techniques (COMITE 2015)*, 2015, pp. 1-4.

[8] F. S. Vetelino, C. Young, L. Andrews, J. Recolons, Aperture averaging effects on the probability density of irradiance fluctuations in moderate-to-strong turbulence. *Applied Optics*, April 2007, vol. 46, no. 11, pp. 2099-2108.

[9] A. Puryear, R. Jin, E. Lee, V. W. S. Chan, Experimental analysis of the time dynamics of coherent communication through turbulence: Markovianity and channel prediction. In proc. of *International Conference on Space Optical Systems and Applications (ICSOS)*, 2011, pp.28-37.