A Practical Approach to Improve Optical Channel Utilization Period for Hybrid FSO/RF Systems

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Abstract. *In hybrid FSO/RF systems, mostly a hard switching mechanism is preferred in case of the FSO signal level falls below to the predefined threshold. In this work, a computationally simple approach is proposed to increase the utilization of the FSO channel's bandwidth advantage. For the channel, clear air conditions have been supposed with the atmospheric turbulence. In this approach, FSO bit rate is adaptively changed to achieve desired BER performance. An IM/DD modulation, OOK (NRZ format) has been used to show the benefit of the proposed method. Furthermore, to be more realistic with respect to the atmospheric turbulence variations within a day, some experimental observations have been followed up.*

Keywords

Atmospheric turbulence, bit rate adjustment, hybrid FSO/RF, log-normal distribution, OOK modulation.

1. Introduction

Due to the high date rate capability of optical transmitters and the advances in laser and optical components technology, free-space optical (FSO) systems for wireless communication channels have attracted considerable attention recently for many different applications, such as ground-ground, ground-to-satellite and inter-satellite links. The advantages of an optical communication system compared with an RF counterpart are (a) greater bandwidth, (b) smaller size and weight, (c) less power consumption [1], [2].

Despite the advantages that an FSO system holds over RF links, the signal intensity fluctuations caused by atmospheric turbulence can seriously degrade the system performance. Turbulence is a phenomenon which arises from the changes of the index of refraction along the laser path and exhibits its effects as beam wander, phase variations in the beam front, beam spread wider than caused by diffraction. The result being the fluctuations in the received laser signal intensity called scintillation. The effect of all these factors appears as an atmospheric attenuation that produces the level of received power at the receiver and is uncontrollable in an outdoor environment [3], [4], [5]. Thus, in heavy attenuation conditions the operation of an FSO link cannot be always maintained, which reduces the availability. This problem must be addressed properly in order to achieve a high available link. A practical solution to this problem is to back up the FSO link with a lower data rate RF link. The existing work related to high data rate applications has focused on hybrid FSO/RF and FSO communication systems using OOK modulation [6], [7], [8]. However, atmospheric turbulence remains as a significant problem for OOK systems [9], [10], [11], [12]. In this paper, a low-complexity transmission scheme for hybrid FSO/RF transmission is proposed. The FSO link will be used so long as optical channel quality is above a certain threshold. In current hybrid systems, when the FSO link becomes unavailable, the system will switch to the RF link to maintain the communication. On the other hand, this approach does not provide maximum utilization of the available bandwidth. This paper investigates the possible use of varying bit rate control to reduce the turbulence effect on laser performance, for different scintillation levels. To accomplish this, a practical look-up table based bit rate tune-up scheme is proposed to maintain FSO link. In this way, the FSO link can be used as long as its bit rate is acceptable to channel; thus it demands no switching to the RF link. The system switches to the RF link if the atmospheric turbulence level in clear air conditions prevents from maintaining the FSO link's BER performance. Furthermore, atmospheric turbulence variation pattern within a day, which acquired by an experiment, is used in simulations.

The rest of this paper is organized as follows. In Section 2, the system and channel model is introduced. The performance of the hybrid FSO/RF system with the proposed method is analyzed in Section 3. The paper is finally concluded in Section 4.

2. The System and Channel Model

For a transmission path without turbulence, the laser power reaching the receiver detector, P_r, is given by:

$$P_r = P_t \cdot \eta_t \cdot \eta_r \cdot G_t \cdot G_r \cdot T_A \cdot L_{FS}, \tag{1}$$

where P_t is transmitter laser power, η_t and η_r are transmitter and receiver optical efficiency, respectively, T_A is atmospheric transmission coefficient. Transmitter and receiver telescope gains G_t, G_r, T_A and the free space loss L_{FS} are expressed by:

$$G_t \approx \left(\frac{\pi D_t}{\lambda}\right), \tag{2}$$

$$G_r \approx \left(\frac{\pi D_r}{\lambda}\right), \tag{3}$$

$$T_A = e^{-\alpha L}, \tag{4}$$

$$L_{FS} = \left(\frac{\lambda}{4\pi L}\right), \tag{5}$$

where λ is a laser wavelength, D_t and D_r are transmitter and receiver aperture diameter, L is link distance, and atmospheric attenuation factor, α (dB·km^{-1}) at a wavelength λ.

Atmospheric turbulence has been studied extensively, and various models proposed to qualify turbulence-induced signal fading. Clear air turbulence affect the propagation of the laser beam by both spatial and temporal random fluctuations of refractive index due to temperature, pressure, and wind variations along the optical propagation path. The laser beam scintillations caused by atmospheric turbulence are a prominent concern for high data-rates and long-distance optical communications. These scintillations are characterized by the scintillation index (SI):

$$\sigma_1^2 = \frac{\langle I^2\rangle - \langle I\rangle^2}{\langle I\rangle^2} = \frac{\langle I^2\rangle}{\langle I\rangle^2} - 1, \tag{6}$$

where I is the irradiance of the optical wave and denotes the ensemble average which is also equal to long-time average. In weak fluctuation theory, the scintillation index is proportional to the Rytov variance given by:

$$\sigma_1^2 = 1.23 C_n^2 k^{7/6} L^{11/6}, \tag{7}$$

where C_n^2 is the refractive index structure parameter, $k = 2\pi/\lambda$, is the optical wavenumber, and L is the path length between the communication transmitter and the receiver.

Among the models which describe the optical wireless channel statistical characteristics, the log-normal distribution has been found to be the most suitable for the weak-to-moderate turbulence channels. In this work, the log-normal fading model for turbulence-induced fading is adopted while assuming that there are no pointing errors associated with the laser beam. In a turbulence channel, received optical signal intensity is given by:

$$I = I_0 \exp(2X), \tag{8}$$

where I_0 is an optical signal intensity without turbulence and X is identically distributed normal random variables with mean μ_x and variance σ_x^2.

Thereby, I follows a log-normal distribution:

$$p(I) = \frac{1}{2\sqrt{2\pi} I \sigma_x} \exp\left[-\frac{(\ln\frac{I}{I_0} - 2\mu_x)^2}{8\sigma_x^2}\right], I > 0. \tag{9}$$

Between the geographical locations 39°56’18.6"N 32°49’33.3"E and 39°55’54.3"N 32°51’31.3"E, along the distance about to 2900 m, an experiment have been conducted. In clear days, variance of the power fluctuation variance, σ_p^2 values, nearly exhibit the same diurnal cycle on all those days. In Fig. 1 and Fig. 2 it can be seen these fluctuations. Around noon, maximum σ_p^2 values have been observed, when the air temperature is close to ground temperature, on the other hand at sunrise and during the night, σ_p^2 values were lower. The σ_p^2 values were generally higher in summer than those in winter.

3. Numerical Results

In this section, numerical results for the BER performance of FSO links for various numbers of σ_I^2 values have been presented. FSO system which has been considered in this work, is the same as used in the experiments except that the system was taking advantage of site diversity by using 4 transmitters. FSO system has a transmitter and a receiver aperture of size 5 cm and 20 cm, respectively with the wavelength of $\lambda = 1.55$ µm. The link distance is assumed to be

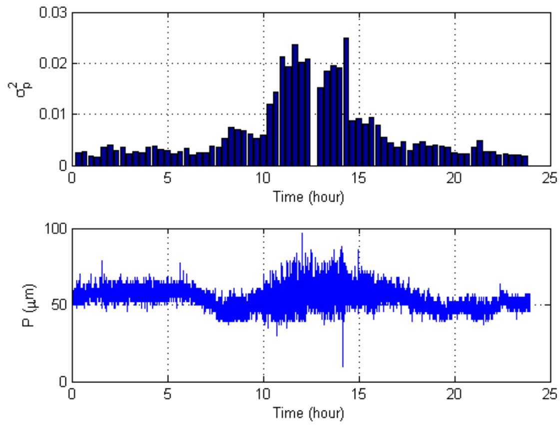

Fig. 1: In March 5, power variances and received power fluctuating.

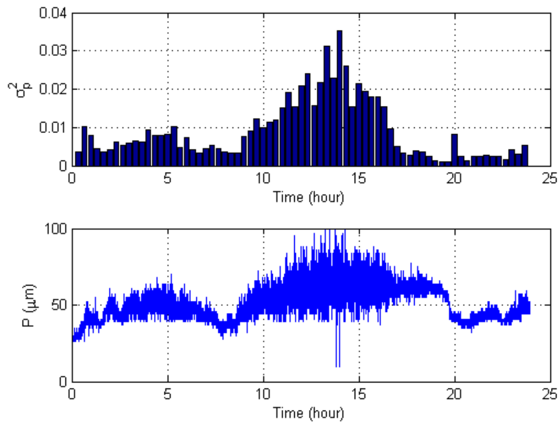

Fig. 2: In April 12, power variances and received power fluctuating.

L = 3 km. In a binary OOK system, the transmitter sends a laser pulse into the channel to represent a "1" and does not send any laser light for a "0". When signal plus noise is appeared at the receiver input, there are two ways in which errors can occur. The receiver decides a "0" has been sent when actually a "1" has been transmitted and vise versa. The probability of error or the bit-error rate (BER) can be expressed as:

$$P_e = P(1|0)P(0) + P(0|1)P(1), \tag{10}$$

where $P(0)$ and $P(l)$ are the probability of a binary "0" and "1" respectively, and $P(1|0)$ and $P(0|1)$ are the conditional probabilities. Assuming the transmitter is sending "1"s and "0"s with equal probability, each has a probability equaled to 0.5, and the probability of bit error is given by:

$$P_e = \frac{1}{2}\left[P(1|0) + P(0|1)\right]. \tag{11}$$

Averaging over the I, it is then obtained:

$$P(1|0) = P(0|1) = \int_0^\infty f_I Q\left(\frac{\eta I}{\sqrt{2N_0}}\right) dI, \tag{12}$$

where Q is the Gaussian-Q function. It is assumed the availability of perfect channel state information (log-normal variance values). The integration in Eq. (12) can be approximately computed by Gauss-Hermite quadrature formula [13], [14].

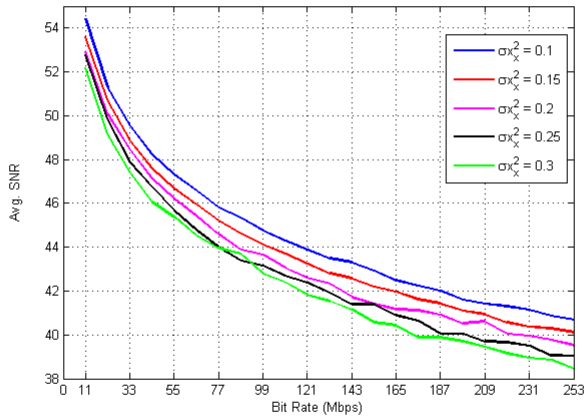

Fig. 3: Average SNR vs. bit rate ($P_t = 120$ mW).

Figure 3 illustrates the bit rate performance of a FSO link with respect to SNR levels over a turbulence channel with variance of $\sigma_x^2 = 0.1$, $\sigma_x^2 = 0.15$, $\sigma_x^2 = 0.2$, $\sigma_x^2 = 0.25$, and $\sigma_x^2 = 0.3$. For fixed transmitter power, as the figure illustrates, with the increasing the FSO system's bit rate, reduces the SNR values.

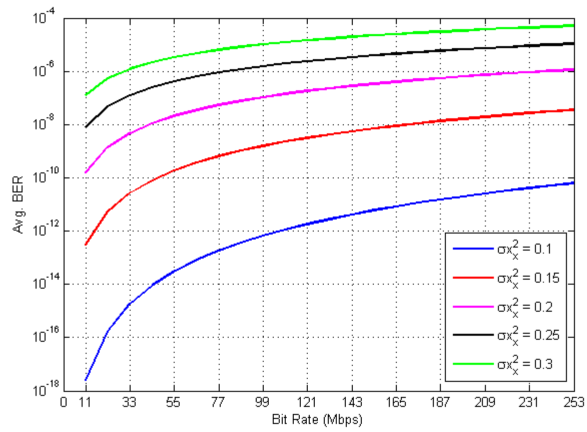

Fig. 4: Average BER vs. bit rate ($P_t = 120$ mW).

Figure 4 illustrates the BER performance of the FSO link over a turbulence channel with the same variance values as in the Fig. 3. With the increasing FSO system's bit rate the BER values increases. A look-up table of calculated data is needed to acquire a determination of the bit rate in accordance to σ_x^2 values to maintain the FSO link without switching to the RF link (Tab. 1).

Tab. 1: Look-up table for σ_x^2 vs. bit rates to retain the FSO link.

σ_x^2	Bit rate [Mb·s^{-1}]	BER	SNR [dB]
0.25 - 0.01	11	$8.0081 \cdot 10^{-9}$	52.7801
0.22 - 0.01	22	$6.8161 \cdot 10^{-9}$	49.9021
0.20 – 0.01	33	$4.7935 \cdot 10^{-9}$	48.4297
0.19 – 0.01	44	$5.0176 \cdot 10^{-9}$	47.0550
0.19 – 0.01	55	$9.8011 \cdot 10^{-9}$	46.2111
0.18 – 0.01	66	$7.4414 \cdot 10^{-9}$	45.3948
0.17 – 0.01	77	$4.9844 \cdot 10^{-9}$	44.9816
0.17 – 0.01	88	$7.6088 \cdot 10^{-9}$	44.2716
0.16 – 0.01	99	$4.3840 \cdot 10^{-9}$	43.9373
0.16 – 0.01	110	$6.1887 \cdot 10^{-9}$	43.6016
0.16 – 0.01	121	$8.4262 \cdot 10^{-9}$	43.1260
0.15 – 0.01	132	$4.2249 \cdot 10^{-9}$	42.8127
0.15 – 0.01	143	$5.5356 \cdot 10^{-9}$	42.5777
0.15 – 0.01	154	$7.0944 \cdot 10^{-9}$	42.1917
0.15 – 0.01	165	$8.9218 \cdot 10^{-9}$	41.9575
0.14 – 0.01	176	$3.9529 \cdot 10^{-9}$	41.7957
0.14 – 0.01	187	$4.8848 \cdot 10^{-9}$	41.4801
0.14 – 0.01	198	$5.9559 \cdot 10^{-9}$	41.3437
0.14 – 0.01	209	$7.1762 \cdot 10^{-9}$	41.0524
0.14 – 0.01	220	$8.5554 \cdot 10^{-9}$	40.8143
0.13 – 0.01	231	$3.3703 \cdot 10^{-9}$	40.7328
0.13 – 0.01	242	$3.9900 \cdot 10^{-9}$	40.5779
0.13 – 0.01	253	$4.6845 \cdot 10^{-9}$	40.2881

To construct the table, σ_x^2 values from 0.01 to 0.3 (in total 46 equally spaced values) and bit rates from 11 Mb·s^{-1} to 253 Mb·s^{-1} (23 equally spaced values) have been considered. Using the Tab. 1, transmitter and receiver can decide on bit rate with respect to the observed log-normal intensity variation.

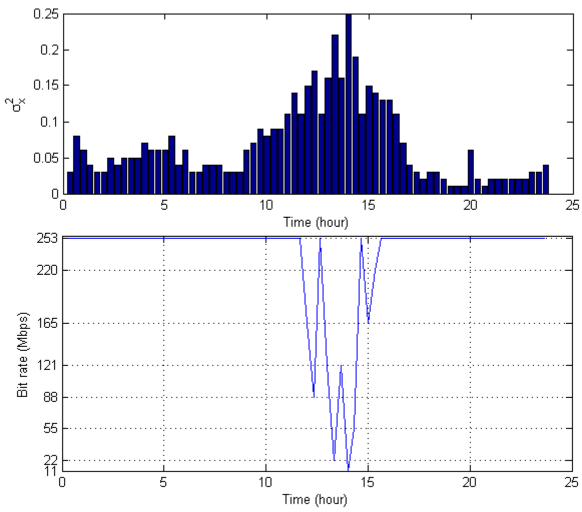

Fig. 5: Simulated bit rate performance for the FSO link in a typical clear air conditions during the day.

Finally, in Fig. 5, one of the simulation results shows the bit rates achieved by the FSO link without switching to the RF link. Log-normal variations have been chosen to be compatible with the experimental observations.

4. Conclusion

The effect of the bit rate for the transmitted signal on the BER performance of an OOK FSO link was investigated. For hybrid FSO/RF systems a practical look-up table based variable bit rate scheme is proposed to increase the FSO link's utilization period. In this way, the FSO link can be used most of the time in clear air weak turbulence conditions, especially in the spring and winter seasons. Simulations have been done for different log-normal variance levels. Therefore, a time-variant log-normal fading channel considered which would be suitable for the daily variance fluctuations. This approach could decrease the switching frequency to the RF link through the adjustment of the bit rate. Moreover, it requires relatively low computational complexity through a look-up table.

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