On The Study of the FSO Link Performance under Controlled Turbulence and Fog Atmospheric Conditions

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***Abstract*— In this paper, the effect of turbulence and fog on the free space optical (FSO) communication systems for on-off-keying (OOK), pulse amplitude modulation (PAM) and subcarrier intensity modulation (SIM) based on binary phase shift keying (BPSK) is experimentally investigated. The experiment is carried out in a controlled laboratory environment where turbulence and fog could be generated in a dedicated FSO chamber. In comparison to 4-PAM signal, the BPSK and OOK-NRZ modulation signalling format are more robust against the fog and turbulence effects. In addition BPSK system is much less susceptible to the signal amplitude fluctuation due to turbulence compared to the other two modulation formats.**

I. Introduction

Free space optical communication is a broadband access technology that offers very high data rate point-to-point links. FSO becomes appealing to research community due to its huge bandwidth, low bit error rate, licence free operation and it easy deployment. These features of FSO communications are very attractive for applications in free web browsing, electronic commerce, data library access, enterprise networking, work-sharing capabilities, real time medical imaging transfer and high speed interplanetary links [1-3]. However, the FSO link performance highly depends on the atmospheric conditions to achieve total availability due to impairments associated with atmospheric and weather effects. As a result the need for research on predictable models of optical attenuation and impairments due to the fog, rain, temperature, wind, clouds, and snowfall is steadily increasing [4, 5]. Recent studies concluded that optical power losses for the dense maritime fog and for the moderate continental fog conditions are up to 480 dB/km and 130 dB/km, respectively [6]. Regarding the weather effects, theoretical models has been validated against the real atmospheric conditions thorough different studies. However, it is very difficult to practically measure and verify the atmospheric turbulence and fog effects under diverse conditions as reoccurrence of the same atmospheric events is unpredictable. Therefore, here at Northumbria Optical Communications Research Group it has been developed a dedicated laboratory test-bed to simulate and demonstrate the atmospheric effects on the FSO signal in a control environment. The test-bed comprises a laboratory FSO chamber that enables us to study the effects of atmospheric impairments, e.g. turbulence, wind, smoke or fog, on the optical beam propagating through the FSO channel for a range of wavelengths and modulation schemes. In this paper we focus our study on the fog and turbulence atmospheric impairments in the FSO channel.

This paper reports the study of the performance of received signal for OOK non-return-to zero (OOK-NRZ), PAM and SIM based on a BPSK schemes under the influence of fog and turbulence for the FSO link. Since information is carried in phase of the carrier, the BPSK should in principle offer improved performance in the presence of the turbulence induced random amplitude fluctuation [7]. On the other hand, due to shorter Euclidian distance in the signal constellation, the 4-PAM should be more vulnerable to turbulence compared to the OOK. This study provides the validation of previous developed theoretical model and demonstrates the availability of weather condition replication on this dedicated FSO chamber. This comparison confirms the replication of previous theoretical studies on SIM-BPSK and 4-PAM schemes on FSO systems [7]. The paper is organized as follows: the first section is the experimental set-up description, followed by the experimental results on fog and turbulence, while final section comprises main discussion analysis, conclusion and future works.

II. Experimental Set-Up

The FSO link set up under study is shown in Fig. 1. In this set up, the transmit signal could be generated by an arbitrary waveform generator (AWG) with different modulation formats and levels. The signal is used to directly modulate a laser diode which has a wavelength λ of 830 nm and the maximum optical peak transmitted power P_{tx} achieved is 10 mW. The transmitter has a 3-dB modulation bandwidth of 50 MHz and a modulation depth m is set at 20%.

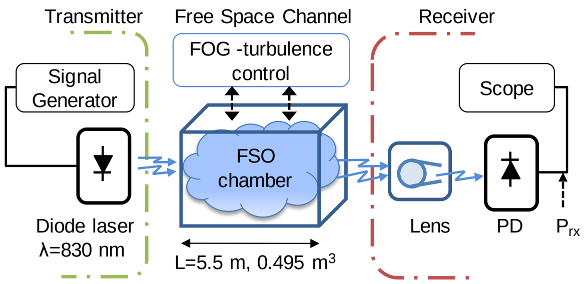

Figure 1. Experimental set-up block diagram

The FSO channel is deployed on a closed glass chamber with dimension of 550×30×30 cm^3 (0.49 m^3). In our experiment OOK-RZ, 4-PAM and SIM-BPSK signals are generated with a pseudorandom binary sequence (PRBS) of length 2^{10}-1 bits using an AWG. The average optical transmitted power P_{tx} is maintained to ensure fair comparison between modulation schemes.

In the chamber, the signal of FSO link experiences different atmospheric effects including attenuation, absorption and scattering before it is being collected at the receiver. The generation of fog and turbulence within the chamber is controlled externally. To generate controlled level of turbulence inside the chamber, independent fans that blow either hot air or cold air in the direction perpendicular to signal propagation is utilized. Using a series of air vents, the temperature control is achieved thus ensuring a constant temperature gradient between the source and the detector. Moreover, in order to control the fog conditions, we used different apertures and fans along the chamber. Using a fog machine with the output rate of 0.94 m^3/s during less than two seconds in combination with fans provides fog control.

The receiver front end consists of an optical telescope (or concentration lens) and PIN photodetector followed by a transimpedance amplifier. The receiver lens has 20 mm diameter and a focal length of 10 cm where the receiver is located. The PIN photodetector has a spectral sensitivity of 0.59 A/W at the peak wavelength (λ = 700-1000 nm) with an active collection area of 1 mm^2. The electrical signal at the output of the photodetector is amplified using a trans-impedance amplifier.

The setup depicted in Fig. 1 allows capturing and analyzing the raw data to quantify the effect of atmosphere impairments, in this case fog and turbulence, on the performance of the FSO system using the laboratory chamber. Therefore, in the set up, the received data are recorded and analyzed using a specialized digital scope and is further post-processed using numerical processing software. In order to demodulate SIM-BPSK scheme correctly, transmitted BPSK signal is also recorded at same time with the received signal.

The implementation of 4-PAM, OOK-NRZ and BPSK signalling schemes has taken account the equivalence on the bit-rate, the signal amplitude and the bandwidth to ensure that fair system performance comparison is achieved. The modulating signal amplitude has been fixed to 100 mV peak-to-peak (corresponding to an average optical power of -1.32 dBm), for all the modulation schemes for fair comparison. The baseline data rate of the all modulation schemes is kept fixed. Therefore, in this paper a comparison between 5 Mbit/s OOK and BPSK, 5 Mbaud/s 4-PAM signals are considered. Though 4-PAM transmits 2-bits per symbol, giving overall data rate of 10 Mbps, in this study the Q-factors are normalized for the comparative study. In addition, 10 Mbit/s OOK have also been tested.

III. FSO LINK PERFORMANCE WITH FOG

The *Q*-factor at transmittance *T* for {0-1} is estimated from the received signal for OOK- NRZ, 4-PAM and BPSK under different P_{tx}. *T* is calculated by comparing the average received optical power in the presence and absence of fog, derived from the Beer-Lambert law [8],

$$T = I(f)/I(0) = \exp(-\beta_\lambda z) \quad (1)$$

where β_λ is the attenuation or the scattering coefficient due to fog, in units of km^{-1}, z is the propagation length and $I(f)$ and $I(0)$ are average received optical intensities in the presence and absence of fog, respectively. Hence, we can evaluate the scattering co-efficient β_λ using (1), corresponding to the measured *T* at a wavelength of 830 nm. Therefore, the link visibility is derived from the fog attenuation using the Kim's model [9].

In order to characterize the FSO link under fog conditions the *Q-factor* of the received signals is calculated for different fog conditions related to the measured transmittance *T* values. Fig. 2 shows experimental *Q-factor* results for the OOK-NRZ, 4-PAM and BPSK modulation schemes. The *Q-factor* for the 4-PAM and BPSK is normalized so that the *Q-factors* at *T* = 1 are equal to OOK-NRZ.

The *Q-factor* results depicted in Fig. 2 shows that BPSK and OOK-NRZ modulation signalling format are more robust to fog impairments on the FSO link than 4-PAM. The behaviour of the three modulations schemes under fog conditions are similar, however in absolute terms at *T*=1 the *Q-factor* is 30 for BPSK and 9 for OOK-NRZ and 4.5 for 4-PAM. In dense fog conditions 4-PAM scheme does not achieve BER values lower than 10^{-6}, on the other hand OOK-NRZ and BPSK schemes overcome that values for $T > 0.2$.

Fig. 2 illustrates the predominant gain of OOK-NRZ format over the rest of modulation schemes, although in absolute terms for this experimental setup BPSK obtain better BER results. Thus indicates that BPSK has an optimum behaviour under fog conditions, with a higher receiver complexity, despite OOK-NRZ is the most deployed signalling format for commercial FSO links. Further the experimental results evidence the feasibility of replicate outdoor FSO link fog conditions in the laboratory FSO chamber prototype.

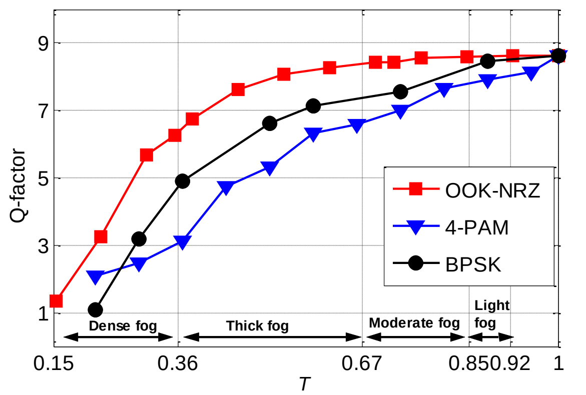

Figure 2. Measured *Q-factor* values for OOK-NRZ, 4-PAM and BPSK received signals at same P_{tx} and 5 Mbit/s data rate for different *T* link values and fog conditions.

IV. FSO Link Performance With Turbulence

In order to analyse the effect of turbulence in the FSO channel, received signals in the presence of turbulence are compared with that of ideal channel (without turbulence), and estimated the scintillation index. The scintillation index (Rytov variance,) is calculated using:

(2)

where *I* denotes received optical irradiance and denote an ensemble average.

The *Q-factor* against the Rytov variance of {0-0.2} for the OOK-NRZ, 4-PAM and BPSK at the same transmitted power level of -1.32 dBm is shown in Fig. 3(a). It can be observed that the *Q-factor* decreases with the increase in turbulence level for both OOK-NRZ and 4-PAM modulation due to random fluctuation of received signal. Notice that the *Q-factor* linearly decreases with the logarithmic scale of the Rytov variance. However, *Q-factor* for BPSK decrease less sharply and offer much improved performance compared to OOK and PAM.

For the comparative studies, the performance of the modulation schemes at different data rates and under different turbulence levels are carried out. The average *Q-factor* is normalized using the average *Q-factor* of the OOK-NRZ at given Rytov variance value and the normalized *Q-factor* against the scintillation index is illustrated in Fig. 3(b). The ratio of *Q-factor* for the OOK and PAM does not vary significantly for the range of Rytov variance but already small. However, the *Q-factor* of the BPSK diverges from the *Q-factor* of OOK as the level of turbulence increases and the BPSK offer ~ 6.5 times higher *Q-factor* than that of OOK and ~ 16 times higher than that of 4-PAM. Unlike OOK and PAM, the information is hidden in the phase of the carrier in BPSK and since the turbulence does not affect the phase of carrier significantly, BPSK is less sensitive to the scintillation. The performance difference between OOK and PAM can be explained using the histogram of the received signal, as shown in Fig. 4. The expected received signal level for '1' and '0' for OOK are well separated. As a result, there is less signal overlapping even in the presence of weak turbulence. However, in the case of 4-PAM, the Euclidean distance is reduced by 67% and hence the small turbulence variance can cause signal overlapping (Fig. 4(d)). Note that the information is hidden in phase in BPSK and hence the histogram of received signal will not carry much insight information.

V. Conclusions

In this paper, the experimental evaluation of the performance of different modulation schemes under the effect of atmospheric turbulence and fog for FSO communication links in a controlled laboratory test-bed was carried out. The results indicate that BPSK and OOK-NRZ modulation signalling format are more robust to fog and turbulence impairments on the FSO link, in comparison with 4-PAM. The use of BPSK signalling increase the efficiency of the FSO link under fog conditions nevertheless implies a higher receiver complexity and lower normalized gain compared with OOK-NRZ. The effect of turbulence at FSO link communications is more severe and the Q-factor falls very sharply with the Rytov variance for OOK and PAM. On the other hand, the BPSK show significantly higher resilience to turbulence and offers up to 16 times higher Q-factor than PAM. The results show that there would be a trade-off necessary to select different modulation techniques to adapt with the changes of weather effect on the FSO link (i.e. fog or turbulence).

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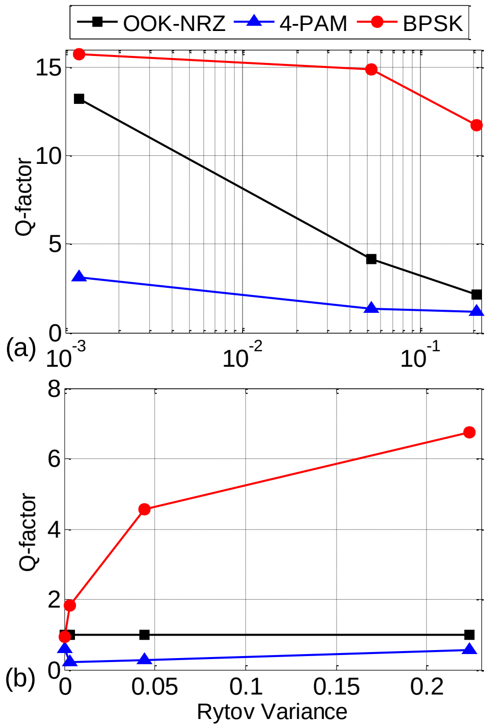

Figure 3. Measured *Q-factor* values against a range of Rytov variance for OOK, 4-PAM and BPSK signalling (a) the absolute scale at 5 Mbit/s, and (b) normalized to the *Q-factor* of OOK-NRZ.

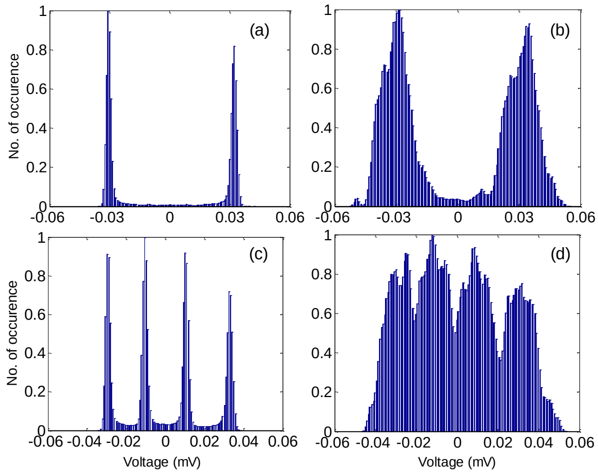

Figure 4. Histograms for the OOK (a) without turbulence and (b) Rytov variance of 0.005; and 4-PAM, (c) without turbulence and (d) Rytov variance of 0.005 received signals at 20 Mbit/s

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