Published version available at https://doi.org/10.1109/LCOMM.2012.012412.112072

Ethernet FSO Communications Link Performance Study Under a Controlled Fog Environment

J. Perez, *Member, IEEE,* Z. Ghassemlooy, *Senior Member, IEEE,* S. Rajbhandari, *Member, IEEE,* M. Ijaz, and H. Le Minh, *Member, IEEE*

***Abstract*—In this letter the performance of a free space optical (FSO) communication link in the presence of fog is experimentally investigated in an indoor environment. A dedicated indoor atmospheric chamber, replicating the outdoor environment, is being used to evaluate the FSO link performance under the fog condition. Theoretical analysis supported by the experimental evaluation has been carried out for the intensity modulation/direct detection on-off keying non-return-to-zero (OOK-NRZ), OOK return-to-zero (OOK-RZ) and four pulse position modulation (4-PPM) modulation formats at the Ethernet baseline data-rate. The results shown indicate that the 4-PPM signalling scheme is the most robust to the fog attenuation due to its high peak-to-average power ratio. Moreover, results also show the potential of the indoor atmospheric chamber to replicate outdoor atmospheric effects (such as fog) and be able to quickly characterise and assess the FSO system under a controlled environment.**

***Index Terms*—Free space optics, atmospheric propagation, weather impairments, optical link.**

I. Introduction

In recent years, the demand for deployment of the FSO technology for a number of outdoor applications has increased considerably due to its free (unlicensed) and enormous bandwidth, lower power consumption and relatively low deployment costs compared to the radio frequency technology [1]. However, the outdoor FSO link performance and the link availability as well as the link range are highly dependent on the weather and atmospheric conditions [2]. Fog is one of the major impairment factors contributing to the optical power attenuation, which limits the FSO link range from a few kilometres to a few meters and can induce a high outage probability. Under fog conditions optical signal is scattered in random directions thus resulting in signal attenuation (up to 130 dB/km and 480 dB/km for the moderate continental fog and the dense maritime fog, respectively) [3]. A number of research works investigating the effect of fog on FSO systems have been reported [4]. These are mostly theoretical focusing mainly on channel modelling. Practical FSO link characterization and assessment have also been reported, which are based on long term observation of the link. Therefore, the measurements taken are highly dependent on the location, time of the year, and long waiting time to observe and experience reoccurrence of atmospheric conditions. To be able to carry out a complete system measurement under all weather conditions, we have developed a dedicated indoor laboratory atmospheric chamber to investigate the effects of fog, smoke, temperature induced turbulence and wind on the FSO link performance. The chamber enables us to carry out full characterization and performance measurements of the outdoor FSO system under a controlled environment without the need for longer waiting times as would be in the case of outdoor FSO links. In [5] such an indoor system replicating the outdoor conditions has been successfully reported with interesting results on scintillation and turbulence effects. This paper takes the idea further by investigating fog impairments over the FSO link under a controlled indoor environment.

Manuscript received by October 4, 2011.
This work was supported by COST Action IC0802.
The authors are with the Optical Communications Research Group, Northumbria Communications Research Laboratory, School of Computing, Engineering and Information Sciences, Northumbria University, Newcastle-upon-Tyne, NE1 8ST, UK (e-mail: joaquin.perez@northumbria.ac.uk).

Digital Object Identifier 10.1109/LCOMM.xxxxxxx

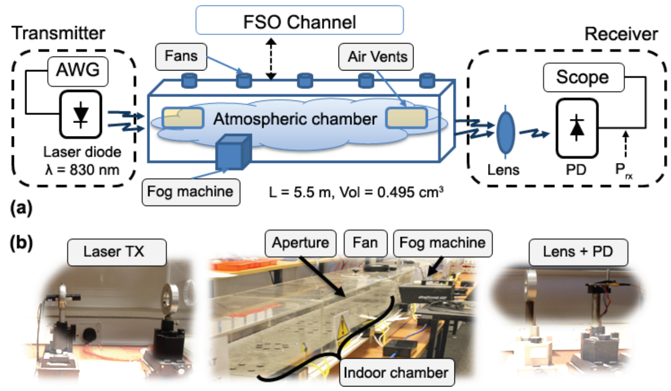

Fig. 1. (a) Block diagram and (b) snapshot of the experimental FSO link with a controlled dedicated atmospheric chamber under study.

In Section II the indoor FSO chamber design and measurement procedures are discussed. The results for an Ethernet (10BASE-T) link under the fog condition for different modulation formats are reported and analysed in the followed section. Finally, the main conclusions are summarized.

II. Experimental Indoor FSO Link Set-up

A dedicated indoor atmospheric chamber adopted for this work is shown in Fig. 1. The chamber has a dimension of $550 \times 30 \times 30$ cm^3, with seven compartments each having an air vent to allow air circulation in and out of the chamber. In each compartment a temperature controlled hotplate and fans are included to simulate the effect of turbulence, wind speed and slow or fast fog. A fog generating machine is used to pump in fog, at a rate of 0.94 m^3/s, to the chamber. The fog density in the chamber is controlled by a combination of the amount of fog pumped in and the ventilation system.

TABLE I
SET-UP PARAMETERS FOR THE FSO LINK UNDER STUDY

TRANSMITTER (LASER + AWG)	
Operating wavelength	830 nm
Average optical output power	10 mW
Laser modulation depth, m	20 %
Laser 3-dB bandwidth	50 MHz
PRBS length	$2^{13}-1$ bits
Baseline data-rate (R)	10 Mbit/s and 10BASE-T
Modulations formats	OOK-NRZ, OOK-RZ, 4-PPM
OOK-NRZ amplitude	250 mV$_{p-p}$
Optical transmitted power, P_{tx}	-1.32 dBm
RECEIVER SIDE (PHOTODIODE + LENS)	
Lens focal length	20 cm
Lens diameter	30 mm
Photodetector responsivity	0.59 A/W @ 850 nm
Photodetector active area	1 mm^2
Photodetector half angle view	$\pm 75\,^\circ$
Electrical filter at receiver	$0.75 * \|R\|$ Hz

An arbitrary waveform generator (AWG) is used to generate a stream of $2^{13}-1$ pseudo random bit sequence (PRBS) in OOK-NRZ, OOK-RZ and 4-PPM formats prior to the direct intensity modulation of the laser diode. The baseline data-rate for OOK-RZ and 4-PPM is 10 Mbit/s and for OOK-NRZ is 12.5 Mbit/s, which corresponds to the Ethernet 10BASE-T LAN data-link with a 4B5B coding format. The PRBS length of $2^{13}-1$ bits used is based on the IEEE 802.3 Ethernet data standard with an average frame length of around 600 bytes. At the receiver side, a photodiode followed by a wide-bandwidth transimpedance amplifier are employed to recover the electrical signal. A digital storage oscilloscope is used to capture the signal for post processing using the Matlab software. A 1^{st} order low pass filter with a cut-off frequency of $0.75 * |R|$ Hz is used to reduce noise, where $R = 1/T$ and T is the minimum pulse duration.The main system parameters are summarized in Table I.

In order to evaluate the performance of the FSO link, the *Q-factor* of the received signal is analysed at a transmittances T of $\{0-1\}$. T is calculated by comparing the average received optical intensity in the presence and absence of fog, derived from the Beer-Lambert law [6]:

$$T = I(f)/I(0) = \exp\left(-\beta_\lambda z\right), \tag{1}$$

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 the average received optical intensities in the presence and absence of fog, respectively. In (1) β_λ corresponds to the measured T at a wavelength (λ) of 830 nm. Here the link visibility V is derived from the fog attenuation using the Kim's model [7] for the transmission range shorter than 500 m. Therefore, β_λ is defined as:

$$\beta_\lambda = 3.912/V(\lambda_{nm}/550)^{-q}, \tag{2}$$

where V (km) presents meteorological visibility and the coefficient q is related to the particles size distribution in the atmosphere. The particle size distribution is expressed by Kim

TABLE II
FSO LINK CHARACTERISTIC VALUES FOR $\lambda = 830\,nm$ AND $P_{tx} = -1.32\,dBm$

Fog	Dense	Thick	Moderate	Light	Clear
$V(m)$	$25-70$	$70-250$	$250-500$	$500-1000$	>1000
T	<0.36	$0.36-0.67$	$0.67-0.85$	$0.85-0.92$	>0.92
$M(dB)$	<2.6	$2.6-5.3$	$5.3-6.4$	$6.4-6.8$	>6.8

[7] based on Kruse [8] mathematical model, as follows:

$$q = \begin{cases} 1.6 & V(km) > 50, \\ 1.3 & 6 < V < 50, \\ 0.16V + 0.34 & 1 < V < 6, \\ V - 0.5 & 0.5 < V < 1, \\ 0 & V < 0.5\ . \end{cases} \tag{3}$$

According to eqs. (2) and (3), this model relates V and T, thus enabling us to experimentally analyze the performance of the FSO link, *Q-factor*, in the presence of fog. The link margin defines the availability of the outdoor FSO link according to the different sources of attenuation, noise and other link impairments. These values are usually expressed in power level diagrams over a typical link distance of 1 km [9]. The link margin M (in dB) is defined as:

$$M = P_{tx} + S_{pd} - L_{fog} - L_{geo} - L_{dev}, \tag{4}$$

where in our case S_{pd} is the photodetector sensitivity at a desired bit-error rate (BER) ($S_{pd} = -36$ dBm @ 12.5 Mbit/s, BER$< 10^{-6}$) [10], L_{geo} represents losses related to the geometry of the propagating beam ($L_{geo} = -22.51$ dBm), L_{fog} is the loss due to the fog according to received T ($L_{fog} = 10\log(T)$), L_{dev} is the transceiver losses ($L_{dev} = 2$ dB), and the total transmit optical power $P_{tx} = -1.32$ dBm.

Table II shows the main values that define the connection between M, V and T for the proposed FSO link for different fog conditions, according to eqs. (1), (2) and (4). The visibility zones or fog conditions are calculated according to the Kim's model. For a clear FSO link, $M > 6$ dB which is similar to the link budget calculated for commercial non-tracking outdoor FSO systems over a distance of 2 km, as reported in [11].

III. FSO LINK PERFORMANCE UNDER FOG CONDITIONS

In Fig. 2 the measured and predicted *Q-factor* against the transmittance and the BER performance against the received optical power for OOK-NRZ, OOK-RZ and 4-PPM formats are illustrated. The results show that the experimental data (dots) follow closely the theoretical prediction for all modulation formats [4], [7]. The experimental *Q-factor* for different transmittance values has been calculated from the raw data using post processing methods to calculate the variance of the received signal, the decision threshold and the eye-opening received signal, which depends on the signalling format. The BER is calculated from the *Q-factor* for all three modulation formats. In Fig. 2, it is indicated that 4-PPM followed by the OOK-RZ signalling format offers the best *Q-factor* and BER performance compared to the OOK-NRZ for all values of T. This is due to the high peak-to-average power ratio of 4-PPM and OOK-RZ signalling format (with 4-PPM being the best). Moreover, for Ethernet data rate, the FSO link employing all modulation formats can operate at the required link availability

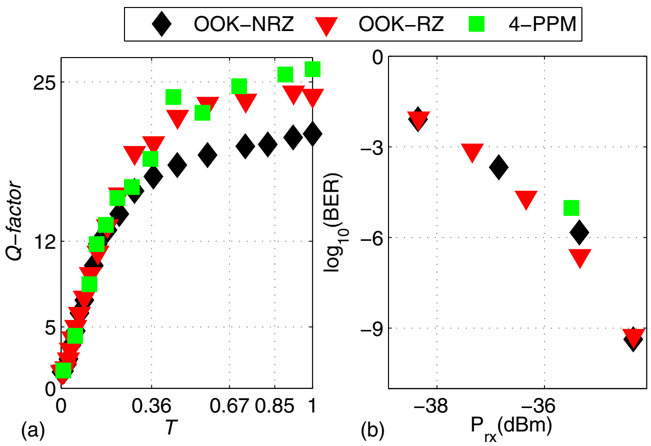

Fig. 2. Experimental results for (a) *Q-factor*, and (b) BER for OOK-NRZ, OOK-RZ and 4-PPM signals.

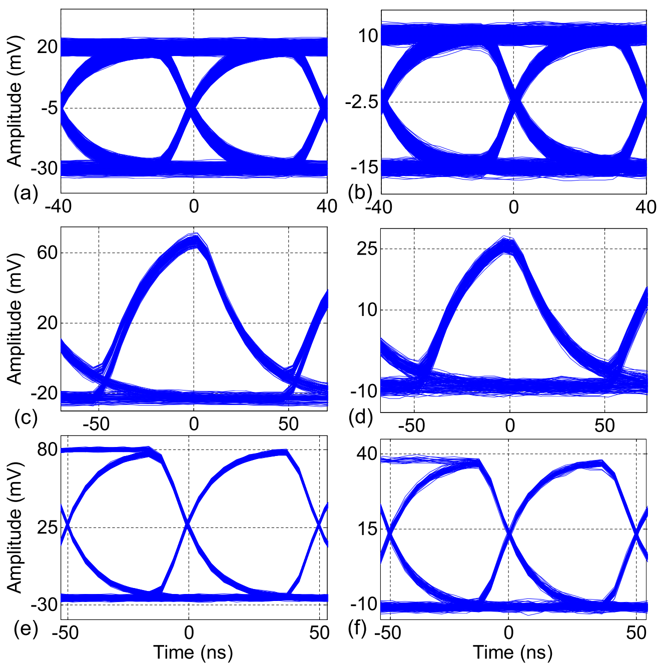

Fig. 3. Measured eye-diagrams post-processed for (a-b) OOK-NRZ, (c-d) OOK-RZ and (e-f) 4-PPM received signals for $T = 0.37$ and $T = 0.70$, for dense and light fog conditions, respectively. Obtained after filtering the capture signal with a $0.75 * |R|$ Hz low pass filter.

of 99.9999% at a BER of less than 10^{-6} defined by the photoreceiver for $T > 0.36$ and for the thick fog condition, see Fig. 2(a). Note that the BER of 10^{-6} corresponds to the *Q-factor* greater than 4.7.

The obtained *Q-factor* remains almost linearly constant for the dense fog condition (i.e. $T < 0.36$) for all modulation formats. This is mainly due to the background ambient light being the dominant noise source in real practical systems. Indeed, the higher order PPM format would offer further improvement in the link performance albeit at the cost of increased bandwidth requirement and system complexity. The received signal eye diagrams for OOK-NRZ, OOK-RZ and 4-PPM formats are displayed in Fig. 3 for the dense fog ($T = 0.37$) and moderate fog ($T = 0.70$) conditions and for the transmitted optical power level of -1.32 dBm. They were obtained after $0.75 * |R|$ Hz low pass filtering. Notice the wide eye-opening at $T = 0.70$ compared to $T = 0.37$, while both have almost identical noise variance, e.g. Fig. 3 (c-d). The eye-opening indicates the quality of the Ethernet FSO link for different signalling format, for example OOK-NRZ and 4-PPM in Fig. 3 (b) and (d), as illustrated by the previous *Q-factor* results.

IV. Conclusions

A dedicated indoor atmospheric chamber, replicating the outdoor environment, has been used to evaluate the FSO link performance under the fog condition. We have shown theoretical as well as experimental data for the *Q-factor* and the BER for OOK-NRZ, OOK-RZ and 4-PPM modulation formats at the Ethernet line data-rate. The results have outlined that the 4-PPM signalling scheme is the most robust to the fog attenuation due to its high peak-to-average power ratio. Since the effect of fog is similar at different data rates, the results could be used to evaluate higher data rate links. Moreover, results have shown the enormous potential of the indoor atmospheric chamber to replicate outdoor atmospheric effects for full characterization and assessment of an FSO link.

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