Northumbria Research Link

Citation: Hulea, Mircea, Ghassemlooy, Zabih, Abadi, Mojtaba, Rajbhandari, Sujan and Tang, Xuan (2019) Fog Mitigation Using SCM and Lens in FSO Communications. In: The 2nd West Asian Colloquium on Optical Wireless Communications (WACOWC2019): 27-28 April, Shahid Beheshti University, Tehran, Iran. IEEE, Piscataway, NJ, pp. 46-50. ISBN 9781728137681, 9781728137674

Published by: IEEE

URL: https://doi.org/10.1109/wacowc.2019.8770201 <https://doi.org/10.1109/wacowc.2019.8770201>

This version was downloaded from Northumbria Research Link: https://nrl.northumbria.ac.uk/id/eprint/40189/

Northumbria University has developed Northumbria Research Link (NRL) to enable users to access the University's research output. Copyright © and moral rights for items on NRL are retained by the individual author(s) and/or other copyright owners. Single copies of full items can be reproduced, displayed or performed, and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided the authors, title and full bibliographic details are given, as well as a hyperlink and/or URL to the original metadata page. The content must not be changed in any way. Full items must not be sold commercially in any format or medium without formal permission of the copyright holder. The full policy is available online: http://nrl.northumbria.ac.uk/policies.html

This document may differ from the final, published version of the research and has been made available online in accordance with publisher policies. To read and/or cite from the published version of the research, please visit the publisher's website (a subscription may be required.)

Northumbria University NEWCASTLE

UniversityLibrary

Fog Mitigation using SCM and Lens in FSO Communications

Mircea Hulea[1], Zabih Ghassemlooy[2], Mojtaba Mansour Abadi[2], Sujan Rajbhandari[3], Xuan Tang[4]

[1] School of Automatic Control and Computer Engineering, 'Gheorghe Asachi' Technical University of Iasi, Romania, mhulea@tuiasi.ro

[2] Optical Communications Research Group, Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne, UK

[3] Institute for Future Transport and Cities, School of Computing, Electronics and Mathematics, Coventry University, UK

[4] Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences, Fujian, China

Abstract **– A free space optical (FSO) communications link performance is highly affected by the atmospheric conditions. This paper compares the effectiveness of employing a spherical concave mirror (SCM) and a convex lens at the receiver to compensate for the effect of fog in FSO communication links. The results show that, for the fog induced signal attenuation lower than 9.17dB there is a marginal improvement in the FSO link performance in terms of the *Q*-factor by a maximum of 8% when using an SCM at the receiver compared with a regular lens.**

Keywords **– FSO link, spherical concave mirror, convex lens, SCM-lens comparison, fog.**

I. Introduction

In recent years, we have seen a growing interest in the use of free space optical (FSO) communications, which is a promising alternative and complementary technology to the radio frequency (RF) wireless systems, in a number of applications including the last meter and the last mile access networks. FSO systems use the unlicensed optical spectrum to offer a massive bandwidth (orders of magnitude high the RF) particularly to overcome the last mile bandwidth bottleneck problem experienced in RF based wireless technologies in the urban areas [1, 2]. In addition, FSO systems offer a number of key features including inherent security at the physical layer, free from RF induced electromagnetic interference and introducing no interference to other wireless technologies, lower energy consumption (i.e., a green communications technology), and easy to deploy in areas where laying optical fibres and/or copper cables is not practical and very costly. The FSO link ranges from a few meters for indoor applications as part of radio over fibre/FSO and femtocells (mostly in indoor environment) to a few kilometres in outdoor environments, for example, in multi-campus university networks, airports, hospitals and as a backup and disaster recovery link [3], [4].

However, the FSO link performance is severely affected by the atmospheric phenomena such as fog, smoke, dust, aerosols, air pollution and turbulence, thus imposing several challenges for the link reliability and availability [2], [3]. Among these, fog is one of the biggest problem in outdoor FSO systems, where the link availability can be reduced from a few kilometres to a few meters in highly dense fog conditions. Based on the measurements at several locations, fog droplets, which are the major contributor to Mie scattering with size varying between 0.5 μm to 2 μm, results in severe attenuations of > 300 dB/km and 130 dB/km in dense maritime and moderate continental fog conditions, respectively [5], [6]. To address this problem and to ensure that the FSO link is fully adopted as a preferred communication technology in certain applications, a number of mitigation techniques have been proposed over the last few decades in order to ensure FSO link availability (i.e., 99.999%) at all times [6 – 9].

The mitigation techniques include increasing the transmit optical power, spatial diversity [10, 11], hybrid FSO/RF system [7, 12], imaging receiver [13], and others. Increasing the transmit optical power is costly and is limited by the eye safety regulations. Adopting the spatial diversity schemes leads to increased cost and complexity of the system. The hybrid FSO/RF technique reduces the link throughput when the transmission mode is switched from FSO to the RF (i.e., RF operating a lower data rates). The imaging receiver-based FSO links employs a lens, a telescope or similar optical systems to focus the received optical signal onto an image sensor. In such systems, the electrical signal-to-noise ratio (SNR) at the receiver is reduced because of the spreading of received signal power over a larger number of pixels, each with its own noise contributions [14]. Since in most FSO links, the optical beam spot size at the receiver is larger than receiver aperture area due to the beam divergence, a relatively large aperture will also be required to capture most of the incoming optical beam. Beam focusing represents a simple method to combat the small-scale fading channel (mostly due to the atmospheric turbulence) by increasing the receiver aperture diameter compared to the coherent length of the atmosphere turbulence.

This paper studies an alternative simple method to compensate for the fog-induced losses in a FSO link by adopting both a spherical concave mirror (SCM) and a lens at the receiver. The focal length of a lens can vary with the operating optical wavelength due to the chromatic aberration, while mirrors are truly wideband in applications. SCM has several advantages compared to the lens including low cost, low loss, no useless reflections from the glass surface and a focal distance that does not depend on the environment's refractive index. The variation of the channel refractive index, caused by changes in the temperature and humidity affects the focal distance of a lens. This aspect can change the size of the focused optical beam spot on the photodetector (PD), thus leading to a reduced received signal amplitude. This is more problematic in high-speed FSO links where PDs needs to be small in order to ensure high-bandwidth due to low capacitance. We show that, there is a marginal improvement in the FSO link performance in terms of the Q-factor by about

8% when using the SCM as a focusing device at the receiver compared to the lens.

The rest of the paper is organized as follows: Sections II describes the experimental set-up of the FSO system using SCM and lens, while Section III presents the results and discussions. The conclusion is finally given in Section IV.

II. EXPERIMENTAL SET-UP

Figure 1 shows a schematic block diagram of the experimental set-up for the FSO link showing the arrangement of both the SCM and lens.

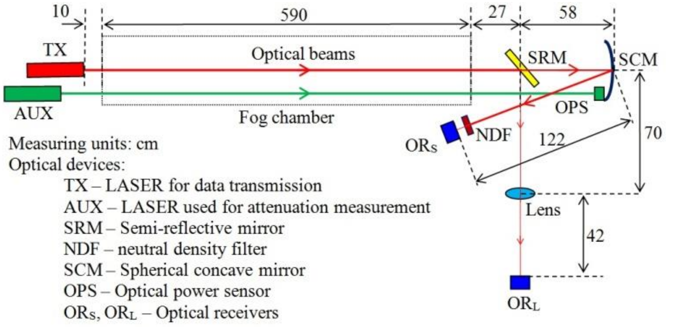

Fig. 1. The experimental setup for assessing comparatively the FSO link performance with the spherical concave mirror (SCM) and lens under the fog condition. The red beam transmitted by TX carries the data and the green beam was used to measure the attenuation induced by the fog.

We have used the widely adopted on and off keying (OOK) modulation format, which is generated using an arbitrary waveform generator at a data rate of 10 Mbps, for intensity modulate (IM) of the laser source (i.e., LASER type Beta) at a wavelength of 670 nm with a beam divergence < 5 mrad and a bore sighting of < 10 mrad. The intensity modulated laser beam is launched into a dedicated atmospheric chamber of 5.9 m long. At the receiver side, the optical beam is split into two using a semi-reflective mirror (SRM) with 33% and 67% of reflectivity and transmission, respectively. We used a SCM with an aperture diameter d_{SCM} of 33 cm and a focal length f_{SCM} of 1.22 m, as well as a lens with an aperture diameter d_{Lens} of 4.7 cm and a focal length f_{Lens} of 42 cm, see Fig. 1.

As shown in Fig. 2, under a clear channel condition the beam spot diameter d_S, which was measured on a paper screen placed in front of the SCM at 6.85 m from the TX, was about 3.7 cm.

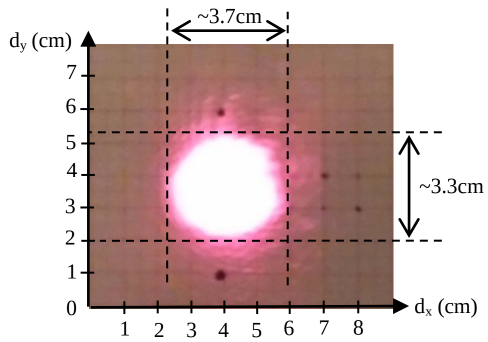

Fig. 2. The laser beam spot at 6.85m from the TX on a paper screen placed in front of the SCM when the light propagates in clear environment.

The optical beam spot diameter d_S is smaller than the diameters of both SCM and lens, implying that with no fog both the SCM and lens will capture the entire received optical beam and focus it onto the PDs.

At the receiver side, we have used two identical optical receivers (OR) (type THORLABS PDA10A-EC), where the laser beams were focused onto the PDs with a surface area of 1.5 mm^2 via the SCM and lens. The regenerated electrical signals at the output of ORs were captured using a digital storage oscilloscope for post signal processing in the MATLAB domain.

Considering that, the SRM ratio between the transmitted and received optical powers is 2:1 we placed a neutral density filter (NDF) with a transmittance of 50% in front of the ORs for reducing the signal level of the beam, which is focussed by the SCM.

The total noise variance in terms of the shot noise σ_{shot}^2, thermal noise σ_{th}^2 and ambient noise σ_{am}^2 is given as [2]:

$$\sigma_T^2 = \sigma_{shot}^2 + \sigma_{th}^2 + \sigma_{am}^2. \quad (1)$$

Note that, $\sigma_{am}^2 = 2qRP_{am}B_{pamp}$, where q is the elementary charge, R is the PD's responsivity (A/W) and B_{pamp} is the equivalent noise bandwidth of the preamplifier. $P_{am} \propto B_{sky}AB_{rx}$, which is the incident ambient light power B_{sky} is the spectral radiance of the skylight (W/m^2·sr·nm), A is the PD's surface area and B_{rx} is the receiver bandwidth.

The field of view (FOV) of the receiver defined in terms of the PD width w_{PD} and the focal point of a lens f is given as:

$$FOV = 2\tan^{-1}\left(\frac{0.5w_{PD}}{f}\right). \quad (2)$$

A. Fog generation

The fog was pumped into the fog chamber using a fog generator. The optical attenuation due to fog along the 5.9 m chamber was measured using a second green laser at a wavelength of 543 nm (see Fig. 1). A photo of the optical setup showing the optical arrangement section at the receiver side including the SCM and the lens, as well as the semi-reflective mirror is illustrated in Fig. 3.

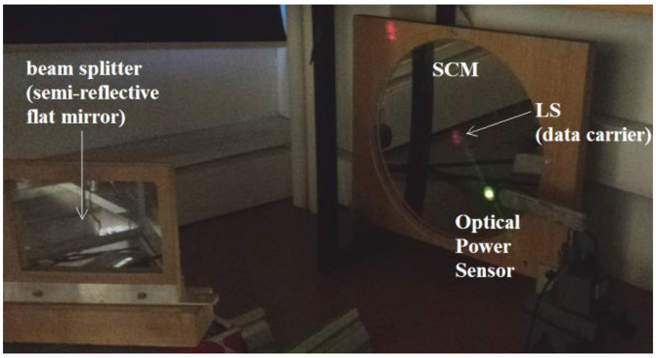

Fig. 3. Picture of a part of the optical setup including the semi-reflective mirror for beam splitting, the SCM and the sensor of the optical power meter. On the SCM centre is the main laser spot (LS) that carries the data.

The optical power sensor was located in front of the SCM at least 7 cm from its centre to ensure that there is no blocking of the red optical beam carrying the data. Note that, the green laser beam did not pass through the semi-reflective mirror.

For this experiment, we assumed that the fog is homogeneous considering the deviation in optical power measurement was around the target value of ±1 dBm. For a qualitative estimation of the fog homogeneity. Fig. 4 presents a picture showing the two laser beams propagating along the atmospheric chamber.

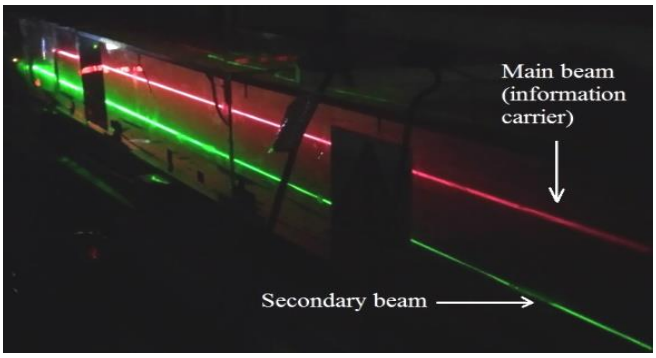

Fig. 4. The main beam (red) that carries the data and the secondary beam (green) that is used for fog attenuation measurement.

Taking into account that the optical beam was split into two following transmission through the fog chamber and that the goal of this experiment was to compare the FSO link performance using SCM and lens, therefore knowing the exact value of the fog attenuation on the data carrying red laser was not that critical.

B. Fog channel characterization

The attenuation in terms of the total received optical powers with fog P_{fog} and without fog (i.e., clear air) P_{air} is defined as:

$$\alpha_{\text{fog}} = 10\log_{10}\left(P_{\text{fog}}/P_{\text{air}}\right). \tag{3}$$

The fog induced attenuation of the optical signal can be predicted using simple empirical fog models, which uses the measured visibility V data in order to characterize the fog. Note that, by definition the fog is present in the real outdoor atmosphere environment when V < 1 km. Therefore, the link visibility is used to measure the attenuation due to the fog. Visibility can be used to determine how dense and thick the fog is. For instance the criteria of $V > 0.5$ km and $V < 0.5$ km can be used to distinguish light and dense fog, respectively. At a wavelength of 543 nm the relation between V and the optical beam attenuation coefficient β_λ (dB/km) is given by [8]:

$$V = 16.9897/\beta_\lambda. \tag{4}$$

In practice, a green laser with a wavelength of 543 nm is used to measure the attenuation of the fog channel relative to the clear channel. β_λ is mathematically defined by Beer-Lambert law [2], which is given as:

$$\beta_\lambda = \alpha_{\text{fog}}/(4.343 \cdot L) \tag{5}$$

where L (km) denotes the FSO linkspan. Using the measured attenuation β_λ is obtained using (5) and V is also determined from (4). The Q-factor parameter is simply defined as [15]:

$$Q = \frac{v_H - v_L}{\sigma_H + \sigma_L}, \tag{6}$$

where v_H and v_L denote the average of received high and low signal levels, respectively. The parameters σ_H and σ_L refer to the noise standard deviations for high and low levels, respectively.

III. Results

The performances of the FSO link using two aperture averaging schemes based on SCM and lens is assessed in terms of the Q-factor and the bit error rate (BER). Note that, the Q-factor and the BER are related as given by [17]:

$$BER = Er(Q) \tag{7}$$

where $Er(x) = \left(1/\sqrt{2\pi}\right)\int_x^\infty \exp(-t^2/2)dt$.

The signal quality was evaluated for the case without and with fog. The measured received optical power for the green laser was -5.83 dB for the case of a clear chamber reducing to the interval [-13 -15] dB in the presence of fog. Thus, the total attenuation due to the fog varied within the range of 7.17 to 9.17 dB corresponds to the visibility ranges of 48 m and 62 m, respectively.

We observed that, the optical beam size, although scattered, under the fog condition was considerably smaller than the surface areas of both SCM and the lens, thus all scattered light rays were collimated onto the PD.

For qualitative evaluation of the results, we present the eye diagrams in Fig. 5 for the FSO link with a lens and a SCM for visibilities of 0.062 km and 0.080 km.

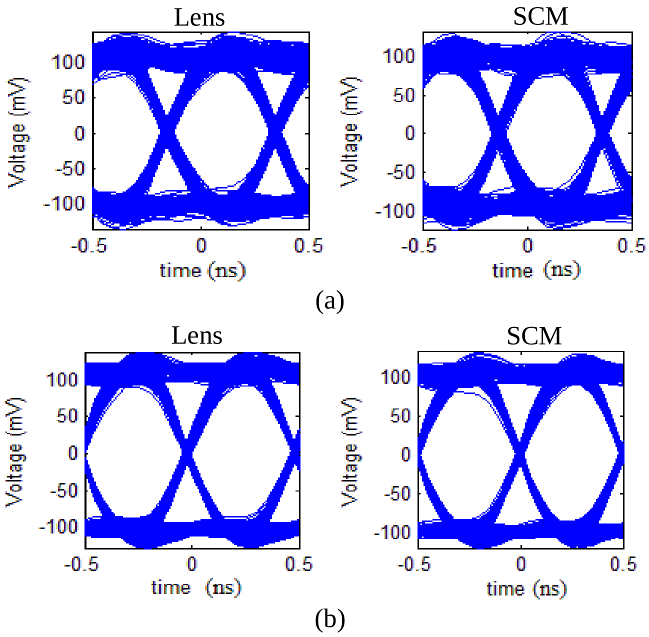

Fig. 5 The eye diagrams of the received signals obtained when Lens or SCM was used at the visibilities of: (a) 0.062 km, and (b) 0.080 km.

Note that, for both visibilities the difference between the eye diagrams for SCM and Lens is insignificant showing that, the two focusing methods have similar performance in compensation of the fog effect on the propagating laser beam. Table I shows the calculated Q-factor and BER for the link with and without fog for the SCM and the lens, as well as the visibility for the fog condition together with the ratio Q_S/Q_L between the Q-factors for SCM and lens, respectively.

TABLE I
SIGNAL PARAMETERS FOR LENS AND SCM

Parameter	Lens	SCM	Q_S/Q_L	Condition	*V*(km)
Q-Factor	16.9	17.2	1.018	No fog	-
BER	$< 10^{-6}$	$< 10^{-6}$	-		
Q-Factor	14.4	15.0	1.041	Fog	0.080
BER	$< 10^{-6}$	$< 10^{-6}$	-		
Q-Factor	11.2	12.1	1.08	Fog	0.062
BER	$< 10^{-6}$	$< 10^{-6}$	-		

The obtained measured results for the FSO link with the SCM and the lens show that, the Q-Factor for the SCM is improved by about 2% for the clear channel condition and up to 8% for the case of fog. These *Q*-factor values show a marginal improvement for the FSO link with SCM while with both SCM and lens the link BER is lower than 10^{-6}, i.e., well below the standard forward error correction BER limit of 3.8 $\times 10^{-3}$.

IV. DISCUSSIONS AND CONCLUSIONS

The purpose of this preliminary study was to check if SCM represent are more efficient then lenses in compensating the effects of fog on signal quality in FSO systems. In order to achieve this goal, we compared the FSO link employing the two focusing schemes of SCM and lens in the presence of fog. The results presented showed that the Q-factor for the link with SCM offered marginal improvement of 1.8% and 8% without and with fog, respectively. This marginal improvement in the FSO link performance with SCM may be due to the fact that SCM purely reflects the entire incoming beam with no losses compared to the link with a lens. Another observed aspect was the higher ratio between the Q-Factors for SCM and lens when the signal was attenuated by the fog. Considering that besides attenuation the fog determines the light beam scattering [6], [16], the signal quality improvement with SCM may be due to the fact that the SCM captures more scattered light than the lens.

For the future research works, we intend to compare the performance of the SCM and the lens over longer FSO links and assess the link performance for a range of SCM and lens sizes with different focal distances. We, also, intend to determine the variation of the signal quality in terms of the SNR and BERS with the SCM diameter and to test the efficiency of the SCM for longer transmission distances when the optical spot size is considered to be bigger than the SCM diameter.

ACKNOWLEDGEMENT

This work was supported by a National Research Grant of the TUIASI, project code GNaC2018_66/01.03.2019.

The experiments were performed at the Faculty of Engineering and Environment from Northumbria University, Newcastle upon Tyne, United Kingdom.

REFERENCES

[1]. V. W. S. Chan, "Free-space optical communications," *Lightwave Technology, Journal of,* vol. 24, pp. 4750-4762, Dec. 2006.

[2]. Z. Ghassemlooy, W. O. Popoola, and S. Rajbhandari, *Optical Wireless Communications – System and Channel Modelling with Matlab*, 1st ed.: CRC Press, 2012.

[3]. M. Uysal, C. Capsoni, Z. Ghassemlooy, A. C. Boucouvalas, and Udvary E. G., *Optical Wireless Communications – An Emerging Technology*, Springer, 2016.

[4]. L. Han, H. Jiang, Y. You and Z. Ghassemlooy, “On the performance of a mixed RF/MIMO FSO variable gain dual-hop transmission system,” *Optics Communications*, vol. 420, pp. 59-64, 2018.

[5]. M. S. Awan, L. C. Horwath, S. S. Muhammad, E. Leitgeb, F. Nadeem, and M. S. Khan, “Characterization of Fog and Snow Attenuations for Free-Space Optical Propagation” *Communications, Journal of*, vol. 4, no. 8, pp. 533–545, 2009.

[6]. M. Ijaz, Z. Ghassemlooy, J. Pesek, O. Fiser, H. Le Minh, and E. Bentley, "Modeling of fog and smoke attenuation in free space optical communications link under controlled laboratory conditions," *Lightwave Technology, Journal of,* vol. 31, pp. 1720-1726, 2013.

[7]. F. Nadeem, V. Kvicera, M. S. Awan, E. Leitgeb, S. Muhammad, and G. Kandus, "Weather effects on hybrid FSO/RF communication link," *Selected Areas in Communications, IEEE Journal on,* vol. 27, pp. 1687-1697, 2009.

[8]. M. Ijaz, Z. Ghassemlooy, J. Perez, V. Brazda, and O. Fiser, "Enhancing the atmospheric visibility and fog attenuation using a controlled FSO channel," *Photonics Technology Letters, IEEE,* vol. 25, pp. 1262-1265, 2013.

[9]. F. Nadeem, B. Geiger, E. Leitgeb, S. S. Muhammad, M. Loeschnig, and G. Kandus, "Comparison of link selection algorithms for free space optics/radio frequency hybrid network," *Communications, IET,* vol. 5, pp. 2751-2759, 2011.

[10]. S. M. Navidpour, M. Uysal, and M. Kavehrad, "BER performance of free-space optical transmission with spatial diversity," *Wireless Communications, IEEE Transactions on,* vol. 6, pp. 2813-2819, 2007.

[11]. W. Zixiong, Z. Wen-De, F. Songnian, and L. Chinlon, "Performance comparison of different modulation formats over free-space optical (FSO) turbulence links with space diversity reception technique," *Photonics Journal, IEEE,* vol. 1, pp. 277-285, 2009.

[12]. Z. Wenzhe, S. Hranilovic, and S. Ce, "Soft-switching hybrid FSO/RF links using short-length raptor codes: design and implementation," *Selected Areas in Communications, IEEE Journal on,* vol. 27, pp. 1698-1708, 2009.

[13]. R. N Mahalati, J. M. Khan, “Effect of fog on free-space optical links employing imaging receivers,” *Optics Express*, vol. 20, no. 2, pp. 1650-61, Jan. 2012.

[14]. P. Djahani, and J. M. Kahn, “Analysis of infrared wireless links employing multi-beam transmitters and imaging diversity receivers,” *Communications, IEEE Transactions on* 48, 2077-2088, 2000.

[15]. International Telecommunications Union, “Test methods applicable to optical fibre submarine cable systems”, recommendation G.976, June 2004

[16]. K. S. Shaik, “Atmospheric Propagation Effects Relevant to Optical Communications” TDA-Progress Report 42-94, pp. 180-200, 1988.

[17]. Maxim Integrated, “Optical Signal-to-Noise Ratio and the Q-Factor in Fiber-Optic Communication Systems”, Application Note: HFAN-9.0.2 Rev.1; 2008.