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Compensating for Optical Beam Scattering and Wandering in FSO Communications

Mircea Hulea, Zabih Ghassemlooy, *Member, IEEE*, Sujan Rajbhandari, *Member, IEEE*, and Xuan Tang

***Abstract*— In this paper we introduce a simple and effective method for substantially reducing the spot wandering and scattering effects in the free space optical (FSO) communications using a spherical concave mirror (SCM). The advantages of using SCMs for focusing the light onto a small area photodetector (PD) are the high efficiency in collecting income scattered light beam in a turbulence channel and independency between the position of the SCM focal point and the fluctuations of the refractive index of the channel. The proposed method is experimentally evaluated in the controlled turbulence environment for a propagation distance up to 104 m. The results show that SCM can effectively compensate the optical spot scattering and wandering effect thus improving performance of the FSO system.**

***Index Terms*— FSO link, air turbulence, laser beams scattering and wandering, concave spherical mirrors**

I. INTRODUCTION

Compared to the radio frequency based technologies the emerging free space optical communications system offers numerous advantageous including license free operation, high data rates, high directionality (i.e. high security) and lower power consumption when using a highly directional laser beam for point-to-point links [1, 2]. However, the FSO link performance is highly susceptible to the weather condition [3]. Fog, aerosol, turbulence, and pointing error affect the link performance in a number of ways, with fog being the biggest problem mainly resulting in high optical attenuation. The atmospheric turbulences and building sway will affect the optical spot size at the receiver, thus making detection and tracking a challenging task.

The atmospheric turbulences cause intensity fluctuation and beam wandering due to variation of the refraction index between the different heated air masses [4-6]. The influence of the air turbulence on the laser beam diverging angle has been extensively studied by means of mathematical modelling [6-9]. In [10, 11] the relation between the link length and the spot aperture as well as the intensity fluctuation was experimentally investigated.

In order to improve the FSO link performance; a number of schemes have been proposed including (i) modulation schemes [5, 12, 13], (ii) channel coding [14]; (ii) automatic beam tracking for building swaying; and (iii) multiple transmitters and receivers for fading effects caused by the atmospheric turbulence [15, 16]. Alternatively, a fast steering mirror (FSM) can be used to dynamically direct the light towards the receiver [17]. FSM uses a flat mirror to correct the beam propagating path. This method, however, is unable to compensate for the laser beam scattering effects. FSM is also complex to implement because of the position-sensing detector and the associated control module. The simplest method to compensate for the scintillation effect is to use the aperture averaging technology in which a concentrating lens with a radius greater than the transverse coherence distance can effectively reduce the turbulence effect [2].

The main objective of this paper is to use a SCM at the receiver side of an FSO link to focus the incoming scattered laser beams onto a small area photodetector (PD) in order to mitigate the beam scattering and wandering effects. This method is simple and induces a minimum optical power loss. We have devised an experimental set up to demonstrate the potential ability of a SCM to compensate for turbulence effect. The maximum length of the optical link was 104 m and turbulence was generated using a number of heaters and fans positioned along the propagation path. The rest of this paper is organized as follows: the system analysis and experimental setup are introduced in Sections II and III, respectively. Results are presented in Section IV. Finally, the conclusions are given in Section V.

II. METHOD

The atmospheric turbulence affects the laser beam trajectory by refractions, as a result of light propagation through air masses with different temperatures (i.e. different refractive indices). The optical spot displacement from its normal position in the receiver plane is a function of the refraction indices of the propagation channel (i.e. air). The maximum amplitude of the spot wandering can be estimated using the resultant refraction index of the turbulence taking into account

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the temperature of the air as light propagates through it. The detailed evaluation of the laser beam trajectory which is determined by the distribution, size and temperatures of the air masses is not the goal of this paper.

A. Compensating the LASER beam trajectory perturbations

In FSO links, the scintillation and beam wandering result in a high outage probability. The scintillation induced can be reduced significantly using the aperture averaging technology where the receiver area is greater than the transverse coherence distance. For the aperture averaging, instead of using a large area PD, a large SCM together with a small area PD located close to the focal point can be used, as shown in Fig. 1.

The distance d_{SF} between the PD and the mirror focal point varies with the distance between the light source and the mirror. The expression of d_{SF} can be deduced using the drawing Fig. 2 where θ is the beam incidence angle, r is the mirror curvature radius and l represents the normal distance between the light source and the mirror.

For very long optical links comparing to the mirror diameter the beam incidence angle is $\theta \approx 0$ that implies $tg\theta \approx \theta$. Thus, starting from the expression $c_1 = r \cdot \frac{tg\theta}{tg2\theta} - x$ we obtain $c_1 \approx \frac{r}{2} - x$. From Fig. 2 we have $r^2 = a^2 + (r-x)^2$ that implies $a^2 - 2rx + x^2 = 0$. The positive solution of the second degree equation is $x = r \cdot \left(1 - \sqrt{1 - \frac{a^2}{r^2}}\right)$ which implies that:

$$c_1 \approx r \cdot \left(\sqrt{1 - \frac{a^2}{r^2}} - \frac{1}{2}\right) \tag{1}$$

The distance between the mirror focal point F and the maximum light intensity point S is defined as:

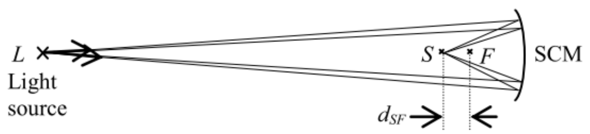

Fig. 1. Light reflection from a spherical concave mirror. The mirror focuses the incoming beams from light source L to the point S where the receiver photodiode is placed. Point S is at distance d_{SF} from the mirror focal point F.

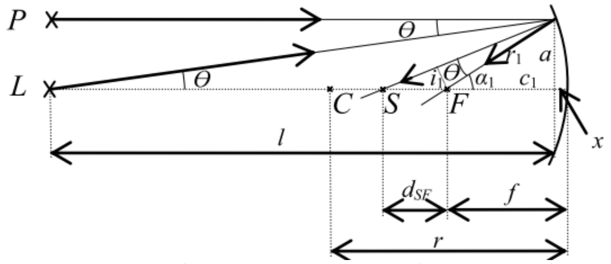

Fig. 2. The position of the point S related to the focal point F of a spherical concave mirror whose curvature centre is C. The trajectory of the incoming beam from point P which is parallel with the mirror normal axis is compared with the trajectory of the beam generated by point source L.

$$d_{SF} = \frac{r_1 \cdot \sin\theta}{\sin(\alpha_1 - \theta)} \tag{2}$$

Whereas the fraction denominator is defined as:

$$\begin{aligned}\sin(\alpha_1 - \theta) &= \sin\alpha_1 \cos\theta - \cos\alpha_1 \sin\theta \\ &= \frac{a}{r_1}\cos\theta - \frac{c_1}{r_1}\sin\theta\end{aligned} \quad . \tag{3}$$

Considering that $a = l \cdot tg\theta$, (2) can be written as:

$$d_{SF} = \frac{r_1^2 \cdot \sin\theta}{a\cos\theta - c_1\sin\theta} = \frac{a^2 + c_1^2}{\frac{a}{tg\theta} - c_1} = \frac{a^2 + c_1^2}{l - c_1} \tag{4}$$

Therefore, when the light is propagating from a light source towards a SCM, the maximum intensity of reflected beam is situated on the SCM normal axis at distance from the SCM focal point is defined by:

$$d_{SF} = \frac{a^2 + c_1^2}{l - c_1} \tag{5}$$

Assuming that all the light beams from the point source L pass through the point S, the PD can be located at this point where the spot area is at its minimum. However, for the outdoor FSO communications where the propagation distances are in the order of hundreds of meters to kilometres, light beams are almost parallel. Hence, $\theta \approx 0$ which implies that $d_{SF} \approx 0$. Thus, for longer propagation distances the PD can readily be positioned in the focal point of the SCM.

B. Minimum concave mirror radius

The atmospheric turbulence alters the laser beams trajectories by multiple refractions. The resultant refractions and the volume of the air mass which create the turbulence give the magnitude of light spot displacement from normal position in the receiver plane. In order to estimate the spot maximum displacement, we considered one of the less favourable cases where the beam trajectory is affected by the turbulence near the transmitter as shown in Fig. 3.

The light trajectory in the non-turbulent environment is perpendicular to the centre of the concave mirror. The distance l is measured on the normal axis of the SCM between T where the light escapes from turbulence and M. The amplitude of the spot wandering that increases with the distance l is denoted by d. We chose this setup for estimating the minimum radius of the SCM because under the same turbulence conditions the spot wandering amplitude varies around the maximum value. According to Fig. 3 and using the geometrical rules the following equations can be written:

$$h \cdot \frac{m_2}{m_1} = h \cdot \frac{r\sin\theta_2}{m_1} \tag{6}$$

Also, $m_2 = (h-d)\cos\theta_1$, $r_2 = d_2\sin\theta_1$, $m_2 = r\sin\theta_2$ and:

$$d_2^2(1 - \sin^2\theta_1) = r^2\sin^2\theta_2 . \tag{7}$$

Considering that $r^2 = d^2 + l^2$, $r^2 = r_1^2 + m_2^2$, $d_2^2 = (h-d)^2$, from (7) we have $(h-d)^2(1-\sin^2\theta_1) = (d^2 + l^2)\sin^2\theta_2$ that can be rewritten as:

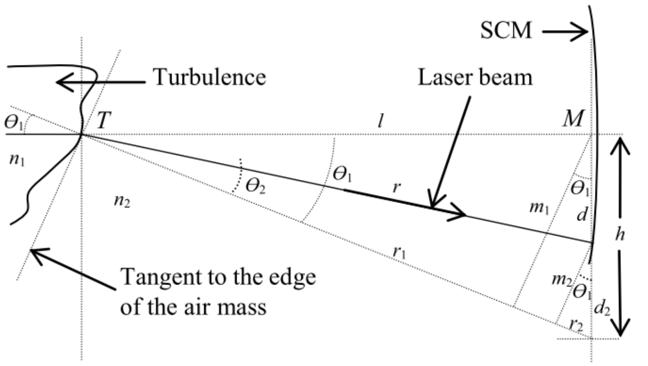

Fig. 3. Light resultant refraction at the edge of a turbulent environment which encloses the light transmitter; the minimum concave mirror radius r_c can be determined when the maximum ratio between refractive indexes $sin\theta_2/sin\theta_1$ is known.

$$\begin{aligned} & d^2\left(\cos^2\theta_1-\sin^2\theta_2\right)-d\cdot 2h\cos^2\theta_1 \\ & +\left(h^2\cos^2\theta_1-l^2\sin^2\theta_2\right)=0 \end{aligned} \tag{8}$$

The distance d is determined by solving (8), which is given by:

$$d=\frac{h\cdot(1-\frac{l}{h}\frac{\sin\theta_2}{\cos\theta_1}\sqrt{1+\frac{h^2}{l^2}-\frac{\sin^2\theta_2}{\cos^2\theta_1}}}{1-\frac{\sin^2\theta_2}{\cos^2\theta_1}} \tag{9}$$

Taking into account that $\frac{\sin\theta_2}{\sin\theta_1}=\frac{n_2}{n_1}$ and $\cos^2\theta_1=1-\sin^2\theta_1$ we obtain $\frac{\sin\theta_2}{\cos\theta_1}=\frac{n_2\sin\theta_1}{n_1\sqrt{1-\sin^2\theta_1}}$. Denoting the ratio of the refractive indexes of the turbulent and non-turbulent environments $k=\frac{\sin\theta_2}{\sin\theta_1}=\frac{n_2}{n_1}$ we have:

$$\frac{\sin\theta_2}{\cos\theta_1}=\frac{n_2}{n_1}tg\theta_1=k\cdot tg\theta_1\,. \tag{10}$$

From (9) and (10), we deduced the spot displacement from the centre on a plane surface due to difference in the refractive indices defined as:

$$d=l\cdot\frac{tg\theta_1}{1-k^2\cdot tg^2\theta_1}\cdot\left(1-k\cdot\sqrt{1+tg^2\theta_1\cdot(1-k^2)}\right). \tag{11}$$

Since (11) shows that the light refraction depends on k (i.e. the refractive indices of the two adjacent air masses) but not on the beam incidence angle, then we can consider $\theta_1=\frac{\pi}{4}$ and $tg(\theta_1)=1$. Thus (11) is simplified to:

$$d=l\cdot\frac{1}{1-k^2}(1-k\sqrt{2-k^2}) \tag{12}$$

The maximum ratio $k_{\max}$ between the refractive indices of two adjacent air volumes with different temperatures gives the maximum spot displacement denoted by $d_{\max}$.

In order to maintain the FSO link stability, all the beams refracted by the turbulent environment should propagate towards the mirror surface. For such beams the resultant ratio between refractive indices must satisfy the condition $k<k_{\max}$ for the constant value of *l*. This implies that the SCM radius r_c must be greater than $d_{\max}$. In order to determine the minimum radius of SCM we need to estimate the value of $k_{\max}$, which is the ratio of the refractive indices of the air mass that the laser beam is propagating through it.

III. EXPERIMENTAL SETUP

In order to demonstrate the potential of the SCM in compensating for the laser beam scattering and wandering, we have set up an indoor experimental test bed, which is described in this section.

A. Determination of the concave mirror radius

Using (12) and the results reported in [3] where the expression of the variation of spot wandering radius with the temperature difference ΔT is given, we can estimate the maximum amplitude of the spot wandering for our experiment. The results presented in [3] showed that the maximum spot wandering is ~139 image pixels (~0.486 mm) when the laser beam propagates a distance of 0.5 m under the strong turbulence condition. The maximum level of the turbulence was obtained when the temperature difference between the turbulent zone and the surrounding environment was 100 Kelvin [3]. We used these results to estimate the maximum resultant ratio $k_{\max}$ that gives the spot displacement $d_{\max}$ experimentally determined in [3]. For simplicity, the solution of (12) was estimated using MATLAB^{TM}. Thus, for $l=0.5$ m and $d_{\max}=0.486$mm (experimentally determined in [3] for $\Delta T=100$K), we obtained $k_{\max}=1.00094$. Because the maximum temperature difference was less than 100 K and we made the assumption that $k<k_{\max}$ for experimental purposes (12) is monotonic for $k>0$ and the spot wandering amplitude $d<d_{\max}$ for $k<k_{\max}$. This allows us to calculate the maximum amplitude of the spot wandering $d_{\max}=97.4$mm for $k_{\max}=1.00094$ and $l=104$m. We choose the SCM radius $r_c>d_{\max}=97.4$mm to ensure that beams refracted by the turbulent environment propagate towards SCM and are collected by SCM.

B. Optical arrangements

The experiment was performed in a controlled turbulent environment with a propagation channel length of 28 m. We used both visible and infrared light sources (Tx) and a single receiver (Rx). The Rx is placed on the focal point of SCM to ensure harvesting maximum optical power in the absence of turbulence. The propagation distances of 52 m and 104 m were achieved by means of single and three reflections of the laser beam within the channel, respectively, seen in Fig. 5.

Table I presents the critical parameters for the optical arrangement shown in Fig. 5 and for the configuration of the turbulence zones shown in Fig. 8. For an easy link alignment, visible wavelengths of 543 nm and 633 was used for the 104 m link set up and 633 nm and 830 nm wavelengths for the 52 m link. The visible light source (He-Ne gas laser) was modulated externally at 2 Kbit/s using an optical chopper. The 830 nm infrared laser source was intensity modulated using pseudorandom binary sequence (PRBS) with on-off keying at a data rate of 10 Mbit/s. Note that the turbulence effect does not depend on the data rate and hence less focus is been given on the data rate. For all wavelengths, the received digital data was recorded using a digital oscilloscope Tektronix TDS-2012.

Fig. 6 shows the beam spot size and shape in each point of reflection in the mirrors FM_1, FM_2 and SCM for the 543 nm. These spots are captured in a non-turbulent environment.The images (a) and (c) present the spot size before the first and the third reflections at FM_1, the image (b) represents the spot before the second reflection at FM_2 and the image (d) shows the spot size and shape at SCM. For being able to compare the spot sizes from different pictures, a black circle was drawn on the screen which allowed us to adjust the images zoom.

Fig. 7 shows the picture of the scattered laser spot (left-hand side) and focused laser spot taken in front of the receiver (right-hand side) that was taken by placing the screen in front of the concave mirror at 104 m from the light source. Note that both images have the same scale thus illustrating the focusing power of the SCM.

TABLE I
DISTANCES AND DIMENSIONS FOR THE OPTICAL ARRANGEMENT

Symbol	**Type**	**Value (m)**
l_1	transmitter – FM_1 distance	25±0.1
l_2	FM_1 – CM distance	26.5±0.1
l_3	FM_1 – FM_2 distance	25.5±0.1
c	Collimation arrangement length	0.6
d_1	Inter-reflection distance	0.18
d_2	Inter-reflection distance	0.18
d_3	Inter-reflection distance	0.3
f_c	Concave mirror focal distance	1.22
r_c	Concave mirror radius	0.165
x_0	Laser - turbulence zone Z_1 distance	2
x_1	Distance between turbulence zones Z_1 – Z_2	6
x_2	Distance between turbulence zones Z_2 – Z_3	12
x_3	Turbulence Z_3 – FM_1	6.5

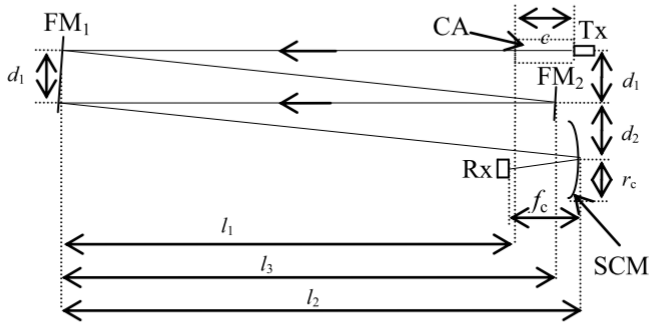

Fig. 5. Optical arrangement for evaluating the ability of the SCM to compensate the turbulence effect on laser beams propagation at 104 m. The laser beam that passes through the collimation arrangement (CA) is reflected twice in the flat mirror 1 (FM1) and one time in the flat mirror 2 (FM2). At the receiver side the spot is focused by the SCM to the receiver Rx.

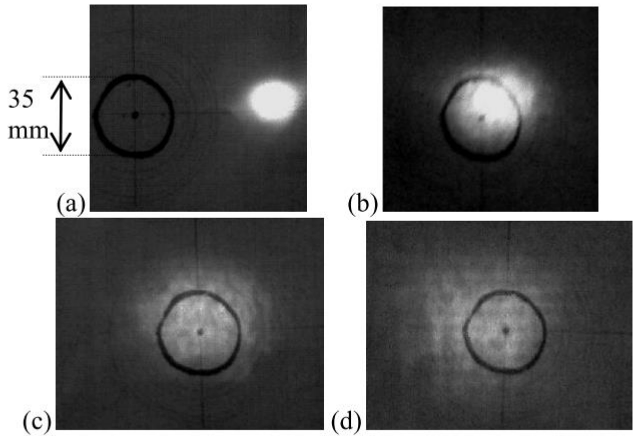

Fig. 6. Spot sizes and scattering at different points along the light propagation path for wavelength 543 nm (green) without turbulence; (a) and (c) 1^{st} and the 3^{rd} reflections at FM_1; (b) reflection from FM_2; and (d) reflection from SCM.

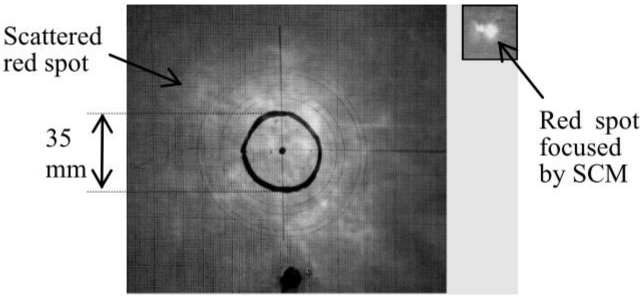

Fig. 7. Scattered spot at 104 m due to turbulence for 633 nm wavelength (left) and focused spot on the PD (top right); both images have the same scale which implies that they have similar number of pixels per mm^2.

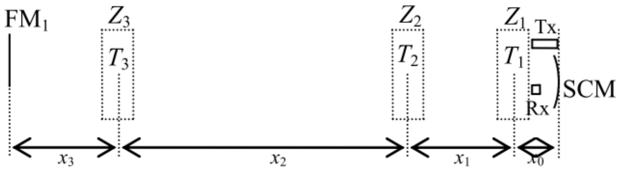

Fig 8. The link set up for assessing the FSO performance under the turbulence condition.

C. *Generation of artificial turbulence*

The turbulence is generated by using a number of heaters and fans positioned along the propagation path Z_1, Z_2, and Z_3 between the transmitter (Tx) and the receiver to ensure a temperature difference of ~9° C, see Fig. 8. We monitored the temperatures T_1, T_2 and T_3 at positions Z_1, Z_2 and FM_1, respectively.

D. *Characterization of channel performance*

At the receiver, the regenerated electrical signal is sampled and stored using a real-time digital oscilloscope for further analysis. The *Q*-factor and the scintillation index for the received signal are determined using:

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

$$\sigma_1 = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1, \qquad (13)$$

where v_H and v_L are the mean received voltages and σ_H and σ_L are the standard deviations for the 'high' and 'low' level signals, respectively, I is the irradiance of the optical wave in the presence of turbulence and $\langle\rangle$ denote an ensemble average. In a weak turbulence regime, the scintillation index is proportional to Rytov variance.

IV. RESULTS

The performance of the FSO link using a concave mirror at the receiver side was evaluated in the absence and presence of turbulence. In order to validate the effectiveness of the proposed scheme, we have measured Rytov variances and the Q-factors of the received signal with and without turbulence. The Q-factor is estimated using eye diagrams of the received 10 Mbps OOK-NRZ signal with and without turbulence and SCM, as shown in Fig. 9.

The eye-diagrams clearly illustrate the effectiveness of the SCM as shown in Fig. 9. The Rytov variance decreases from 0.2614 to a negligible value of 0.0006 for the system without and with the mirror, respectively. The Q-factor drops from a value of 12 to 10 in the absence and presence of turbulence, respectively. However, the Q-factor drops from ~ 11 in the absence of turbulence to < 2 in the presence of the turbulence without mirror. Negating the optical gain of mirror, the improvement is significant and the turbulence has very little effect on the received signal with mirror.

Similar experiment was repeated for two different laser sources at wavelengths of 543 nm and 633 nm with different propagation distances. Since these lasers were modulated using an external optical chopper, it is not possible to measure the bit error rate. Hence the performance is characterized using the Rytov variance calculated from the received optical signal. The measured Rytov variances for different cases are summarized in Table II. The Rytov variance with the mirror is insignificant compared to the variance for the link with no mirror.

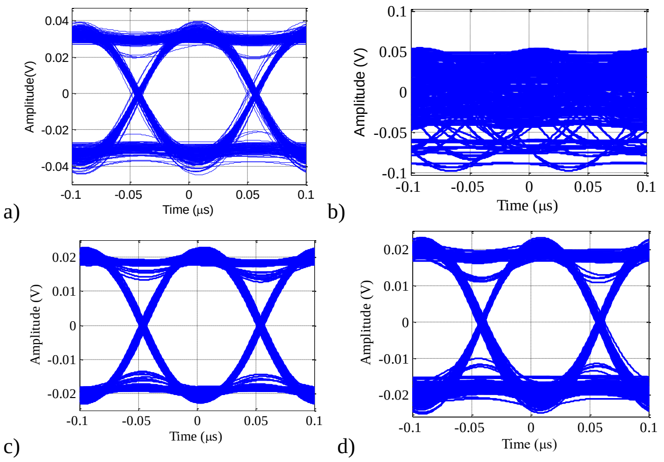

Fig 9. The eye-diagrams for OOK-NRZ received signal at 10 Mbps after propagation of 52 m : a) without turbulence and mirror; b) in turbulence environment without mirror; c) without turbulence and with mirror; d) with turbulence and with mirror.

Figure 10 shows the estimated Q-factors at different propagation lengths under different environments. The first two and the last two values of Q-factor in each plot were obtained with and without SCM and turbulence, respectively. Since the concave mirror offers a significant optical gain, there is a major difference in the Q-factor in the absence of the turbulence with and without mirror. This figure clearly demonstrates the effectiveness of the proposed scheme as there is very marginal changes in Q-factor in the presence and absence of the turbulence with SCM, though significant changes can be observed in the presence of the turbulence without mirror. For example in Fig. 10(b) the Q-factor is significantly increased the Q-factor when the light propagates in both turbulent and respectively non-turbulent environment.

The Q-factor values obtained demonstrate the efficiency of the SCM mitigating optical spot wandering and scattering at the receiver side on FSO link.

V. CONCLUSIONS

An indoor experimental test bed for assessing the FSO link performance using a SCM for compensating the laser beams scattering and wandering in a turbulence channel was introduced. The maximum link span of 104 m was obtained by means of multiple reflection of the laser beam using mirrors. SCM was used to harvest the scattered beam and focus it onto a small area PD positioned on the focal point of SCM. Results showed that with SCM the Q-factor is substantially improved. Even with no turbulence the received signal quality was improved when using the SCM. The method was tested for a range of light wavelengths (visible and infrared) showing the

TABLE II
SUMMARY OF RYTOV VARIANCE IN THE PRESENCE OF TURBULENCE WITH AND WITHOUT MIRROR

Wavelength (nm)	Link length (m)	Rytov variance	
		Without mirror	With mirror
543	52	0.0193	$2\cdot10^{-5}$
543	104	0.0906	10^{-4}
633	104	0.1029	10^{-5}
850	52	0.254	$6\cdot10^{-4}$

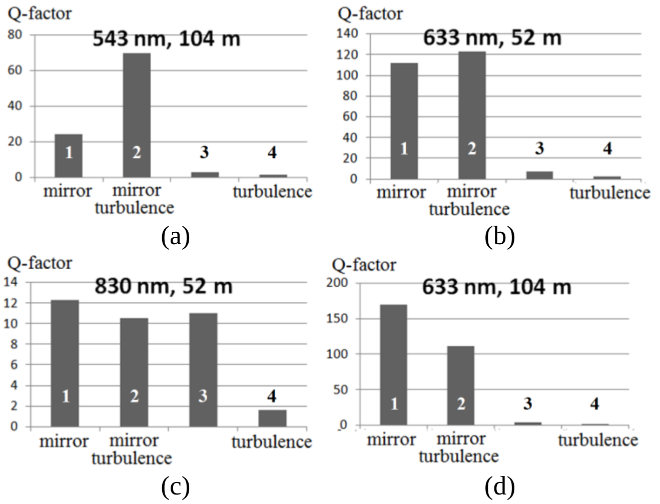

Fig. 10. The Q-factors for proposed link: (a) 543 nm, and 104 m, (b) 633 nm and 52 m, (c) 830 nm and 52 ms, and (d) 633 nm and 104 m. The bars numbers indicate: (1) – SCM with no turbulence; (2) with SCM and turbulence; (3) no SCM and turbulence; (4) no SCM and with turbulence.

highly improved performance. What need to be done next is to determine the minimum size of SCM, which is the subject of the next paper.

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