Threading a Laser Through the Eye of a Needle: Multimode Fibre Coupling in Turbulence

Fortune Iga and Mitchell A. Cox

School of Electrical and Information Engineering, University of the Witwatersrand, Johannesburg, South Africa

E-mail: igakayala@gmail.com

Abstract. The unequal access to reliable internet connectivity between urban and peri-urban areas remains a concern in many developing countries, including South Africa. A major reason for this digital divide is the unequal distribution of fibre infrastructure, which is typically caused by economic or geographic factors. Free Space Optical (FSO) communication could be used to mitigate this disparity by extending the optical network without the need for additional fibre installation. This would provide users access to the larger unlicensed spectrum provided by optical networks. However, modern FSO systems remain expensive and inaccessible to low-income residents of peri-urban areas. The cost of such technology could be significantly improved by "hacking" off-the-shelf fibre hardware, such as small form-factor pluggable (SFP) transceiver modules. However, coupling light into fibre hardware is difficult due to the atmospheric factors which attenuate optical signals in free space. Most severe of these factors is atmospheric turbulence which causes beam wander and intensity fluctuations. This proceeding proposes research into the optimization of light coupling from free space into fibre hardware. This is done by investigating different coupling methods to determine the optimum method. In this proceeding, light is coupled into OM1, OM4 and OM5 multi-mode fibres cables. The received power and scintillation indices are compared. It was found that the OM4 fibre cable coupled the most optical power while the OM1 fibre cable had the least scintillation index.

1. Introduction

When compared to other African countries, South Africa has a high concentration of terrestrial fibre installations. This allows 67% of its population to live within 1 km of fibre infrastructure. However, the final connection which links the end-users to fibre infrastructure remains a challenge in many parts of the country. A reason for this is the high costs of drilling and trenching required for the extension of fibre networks. This leads to unequal fibre access between wealthy communities that can afford fibre cable installations and poorer communities whose residents have low disposable income [1]. A possible solution to the last mile fibre access challenge is free space optical (FSO) communication. Free space optical communication is the point to point transmission of information encoded on a laser beam which propagates through the atmosphere [2]. This concept could be used to bridge the gaps within the fibre optical network without the use of additional fibre cabling. Modern FSO systems are able to transmit large amounts of data at gigabit speeds across tens of kilometers [3]. However, such technology remains expensive and inaccessible to low income populations. This is due to the expensive high power lasers and custom electronics required to overcome the attenuating factors within the atmosphere.

Researchers have explored the use low-cost off-the-shelf fibre hardware, such as small form factor pluggable (SFP) transceiver modules, in FSO applications. This would significantly lower the cost of such technology and allow for easier deployment of FSO systems in different scenarios, including last mile connections. However, the challenge in doing this is coupling light from free space into fibre hardware. Different methods have been used to do this as seen in the following works. Ref. [4] demonstrates a cost-effective FSO system that uses a bidirectional SFP module to transmit data across 125 m. A short single mode fibre with an SC connector is used to guide the light into and out of a bidirectional SFP. In [5], a 1550 nm SFP transceiver module is used to develop a 500 m FSO system. A single mode fibre cable is used on the transmitting part of the SFP module, while a multimode fibre cable is used to receive the signal. A 1 Gbps FSO system is developed using a 1550 nm SFP module in [6]. The link is tested through a 7.2 m atmospheric chamber. The beam is coupled into the SFP using a multimode fibre with a core size of 1 mm for a large field of view. This work emphasized that the dominant power loss was a result of coupling light from free space into the fibre cable at the receiver side. A self-aligning FSO system is presented in [7]. Spatial division multiplexing was used by coupling light beams into eight multimode fibres cables of 50 μm cores which were connected to eight separate SFP transceivers. This link was tested across 210 m.

According to the literature reviewed above, fiber optical cables have been utilized to channel free-space light into fiber hardware. Literature has also shown that fiber coupling in such systems is the main source of power loss due to the inherent difficulty of fibre coupling [6]. There are different types of fibre cables available which have been designed and characterized for fibre network applications. However, little work has been done to characterize the light gathering capabilities of these fibre cables when used in free-space coupling. As such, the performance of fibre cables in free-space coupling remains largely unknown. Such information would be beneficial to designers as it would inform them of which fibre cable would lead to the lowest power loss.

For this reason, this proceeding aims to contribute to the optimized use of low-cost off-the-shelf fibre hardware in FSO systems, by comparing the coupling performance of different fibre cables in the presence of atmospheric turbulence. This is done to determine the optimal fibre cable to use for this application. Experimental testing will be done by coupling light that travels across a 140 m FSO link into various fiber cables and evaluating the results.

2. Background

2.1. Effects of Atmospheric Turbulence

One of the most detrimental factors that affect free space optical communication is atmospheric turbulence [8, 9]. Atmospheric turbulence is caused by random fluctuations in temperature and pressure which form regions of unstable air masses called turbulent eddies. These eddies have independent characteristics and vary in size and density. Turbulent eddies also vary in refractive indices. As such, when light propagates through them refraction takes place.[10]

The effect of turbulence on a propagating light beam is dependent on the size of the turbulent eddies encountered. If a turbulent eddy is larger than the beam diameter, the entire beam deflects. This is known as beam wander (or beam steering) which causes the light beam to have a ”cork screw” motion through the atmosphere. This results in lateral displacement and angular misalignment at the receiving aperture. If a small detector is used at the focal point, the misalignment caused by beam wander will attenuate the received power. This is known as signal fading and can lead to loss of information if the power is beneath the link margin. Deep fades refer to situations where the signal power or intensity is too low for reliable communication [11].

If a turbulent eddy is of a similar size to the beam diameter, it focuses or defocuses the light in a lens-like manner. This leads to fluctuations in the light intensity detected at the receiver plane. This is a phenomenon known as scintillation. Scintillation often leads to degradation of the signal-to-noise ratio and deep random signal fades. The amount of scintillation faced by an optical system is characterized using the normalized variance of intensity which is known as the scintillation index, σ_I^2. The scintillation index is calculated as follows:

$$\sigma_I^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2} = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1 \quad (1)$$

If the eddy is smaller than the diameter of the beam, a portion of the light is deflected away from the rest of the beam. This leads to loss in received power. This effect is minimized by ensuring that the beam diameter is smaller than the coherence length of the atmosphere which is known as the Fried parameter [10]. The coherence length is the radius in which turbulence is correlated. Outside this radius, turbulence is uncorrelated and independent [11].

2.2. Optical Fibre Cables

Optical fibers are cylindrical dielectric wave guides used to transport information in the form of optical energy. Optical fibres consist of three main concentric layers which are the core, cladding and coating. The core is the central region in which light is guided through. It is usually made up of low-loss silica glass and index modifying dopants. The core is embedded in the cladding which is made of a similar material, but with a slightly lower refractive index. Surrounding the cladding is a protective coating, which is the first non-optical layer. It is a cushioning polymer which protects the silica structure against physical and environmental damage. Extra protecting is often added by incorporating an outer coating reinforced with steel or kevlar material. Light in an optical cable travels through the fibre core, where it is confined by the principle of total internal reflection. For this to occur, light within the fibre core should strike cladding boundary at an incident angle which results in a refractive angle greater than 90°. This causes the light beam to reflect back into the core. The maximum angle of incident at the face of a fiber cable which results in total internal reflection is known as the acceptance angle. This angle is characterized by a dimensionless factor known as the numerical aperture (NA), which is a function of the acceptance angle θ_a, given by [12]

$$NA = sin(\theta_a). \quad (2)$$

There are two types of fibre cables which are single mode and multi-mode fibres. Single mode fibre cables can only transmit one ray (mode) of light and typically have very small core diameters of about 9 microns. This makes coupling into single mode fibre very challenging and impractical in long range FSO systems. Multi-mode fibre cables have much larger core sizes, with common core diameters being 50 and 62.5 microns. This allows easier coupling of light into a multi-mode fibre cables. For this reason, only multi-mode fibre cables are considered in this research. The effects of modal dispersion are assumed to be negligible in this work because only a short piece of multi-mode fibre is required to couple light into the fibre hardware.

There are five standard classes of multi-mode fibre cables, which are shown in Table 1. All fibre cables in these classes have graded index profiles. In a graded index profile, the refractive index of the fibre core gradually decreases in a concentric manner with the highest value being at the center. This causes the light rays to propagate through the fibre core in sinusoidal shapes, minimizing modal dispersion and allowing for high data rates across longer distances. The different multi-mode classes each have a unique graded-index profile. This is because manufacturers have attempted to improve performance by optimizing the refractive index profile. This has led to improved modal bandwidths in newer multi-mode classes as seen in Table 1. Despite the improved performances, the impact of the different graded-index profiles on free space coupling is unknown. However, through testing, it is possible to determine which fibre cable works best for this application.

OM1 and OM2 fibre cables have similar characteristics and can be used interchangeably in many applications. The same is true for OM3 and OM4 fibre cables. For this reason, only OM1, OM4 and OM5 multi-mode fibre cables were considered at this stage of the research.

Table 1: Characteristics of the 5 Multi-mode fibre cable Classes

Class	**Color Code**	**Core Diameter**	**NA**	**Modal Bandwidth**
OM1	Orange	62.5 μm	0.275	200 MHz*km
OM2	Orange	50 μm	0.2	500 MHz*km
OM3	Aqua	50 μm	0.2	2000 MHz*km
OM4	Aqua	50 μm	0.2	4700 MHz*km
OM5	Lime Green	50 μm	0.2	28000 MHz*km

3. Methodology and Data Collection

Atmospheric turbulence leads to power attenuation and scintillation. As such, the optimal fibre cable used for free space coupling should couple the highest amount of optical power and have the least scintillation index. To test this, a 140 m FSO link was established between two buildings at the University of the Witwatersrand. A custom designed optical cage system was used to focus light beams onto the fibre cable tips. A 75 mm plano-convex lens with a focal length of 250 mm is used in the cage system, resulting in an f-number of 3.33. At this f-number, the airy disk diameter focused on the fibre tips is 12.59 μm, as seen in Equation 3, and incoming half angle of 8.53°. This airy disk diameter and half angle are smaller than the fibre core diameters and within the numerical apertures of all three multi-mode fibre cables that will be tested, allowing for effective coupling.

$$\phi = 2.44\lambda F_{\#} \tag{3}$$

A 1510/1590 nm bidirectional small form factor pluggable transceiver module was used as the light source. After propagating through the link, the beam was coupled into a multi-mode fibre cable at the receiver and is measured and recorded using an optical power meter which operates at a sampling time of 90 ms. Power measurements taken for three minute intervals each, which leads to approximately 2000 samples for each measurement interval as in Figure 1. The fibre cables are tested sequentially and a total of eleven data sets were recorded for each cable at different times of the day.

4. Results and Discussion

The above mentioned experiment was carried out to determine which fibre cable couples the highest power and experiences the lowest scintillation. As expected, the received optical signal is turbulent and noisy due to the turbulent nature of the atmosphere. This is shown in Figure 1a, which is an example of the optical power coupled in an OM1 fibre cable. The scintillation index is calculated across 50 points using equation 1. The resulting scintillation index at different points is shown in Figure 1b. The average powers and scintillation indices of each data set are shown in Figures 1c and 1d. It is can be observed that data sets of high optical power had low the scintillation indices. Figure 1d shows that the highest scintillation index observed is 0.13, implying weak turbulence at this range.

The average of the power and scintillation index means was calculated and is shown in Figures 2a and 2b. These graphs show that on average the OM4 multi-mode fibre coupled the most optical power, while the OM1 fibre cable had the lowest scintillation index. However, the error bars of the two fibre cables overlap in each Figure, implying that they performed very similarly. Despite having the highest modal frequency as seen in Table 1, the OM5 cable performed the worst in the experiment. On average it coupled the lowest optical power and had the highest scintillation index. These results are further confirmed through the scatter plot of the average

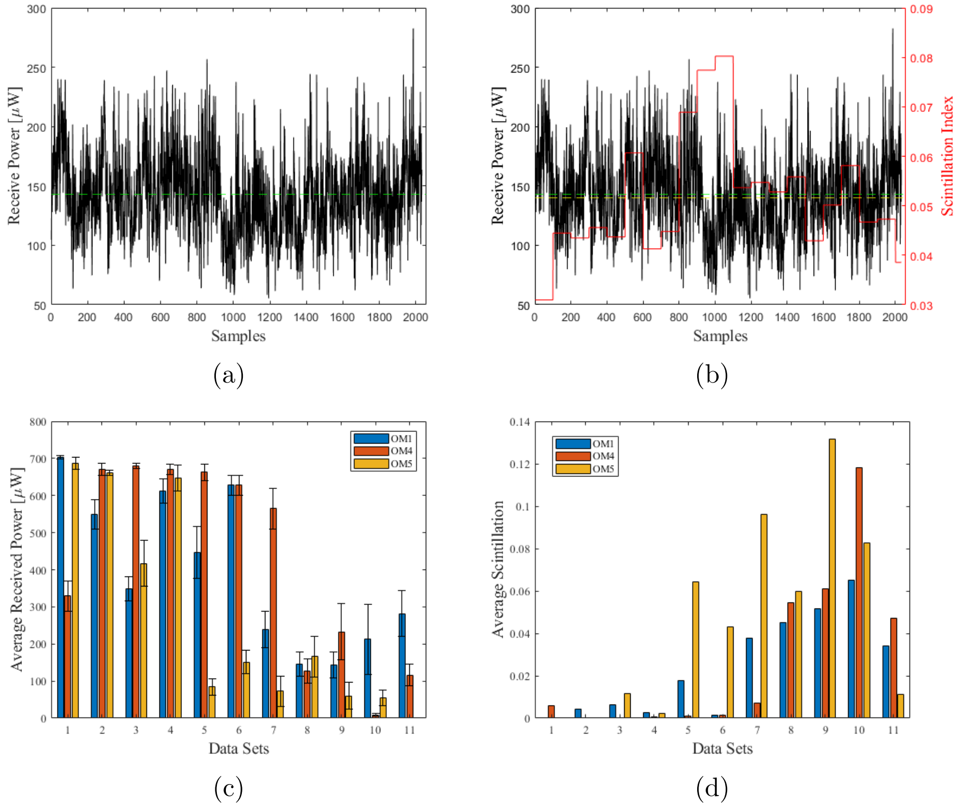

Figure 1: **Optical Power and Scintillation Index** (a) shows the optical power coupled into an OM1 multi-mode fibre cable with the average power represented by the green dashed line. (b) shows the scintillation index calculated across 50 power samples. The yellow dashed line represents the average scintillation index. (c) shows the average power coupled in each data set. OM1, OM4 and OM5 are represented by the blue, orange and yellow bars. (d) shows the average scintillation index experienced in each data set. Similarly, OM1, OM4 and OM5 are represented by the blue, orange and yellow bars

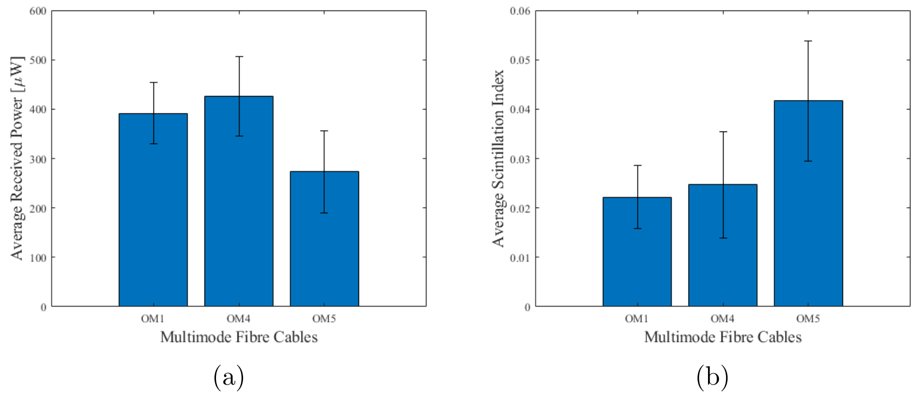

Figure 2: **Average of Power and Scintillation Index** (a) shows the average of the mean power values for each data set and the corresponding error bars. (b) shows the average of the mean scintillation index values of the each data set and the corresponding error bars.

received power and scintillation index is shown in figure 3. The average power and scintillation index values are calculated over 100 samples to generate the points in the scatter plot. The top left quadrant on the scatter plot represents a region of high received power and low scintillation index. The OM4 fibre cable resulted in the most points within this region.

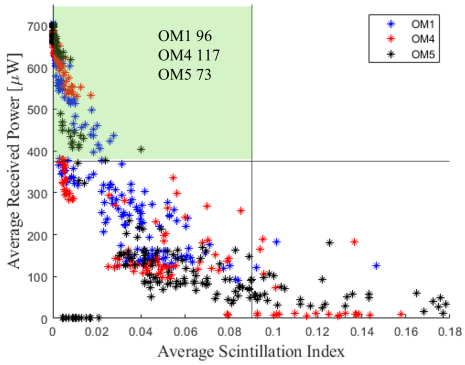

Figure 3: A scatter plot of the average powers and scintillation indices measured and calculated across 200 points. The top left quadrant represents high coupled power and low scintillation index. There are 96 OM1 points, 117 OM4 points and 73 OM5 points in this region.

5. Conclusion

This proceeding has presented an investigation carried out to determine the optimal fibre cable to use for free space light coupling in the presence of atmospheric turbulence. The results have shown that the OM1 and OM4 multi-mode fibre cables had a comparable performance with overlapping error bars. While the OM5 multi-mode fibre cable had the worst results, with the lowest power coupled and the highest scintillation index. This research will be extended upon by increasing the range in order to increase the atmospheric turbulence strength.

References

[1] Lavery M P, Abadi M M, Bauer R, Brambilla G, Cheng L, Cox M A, Dudley A, Ellis A D, Fontaine N K, Kelly A E, Marquardt C, Matlhane S, Ndagano B, Petruccione F, Slavík R, Romanato F, Rosales-Guzmán C, Roux F S, Roux K, Wang J and Forbes A 2018 *Nature Photonics* **12**(5) 249–252 ISSN 17494893

[2] Ghassemlooy Z and Popoola W O 2010 Terrestrial free-space optical communications URL `www.intechopen.com`

[3] Trichili A, Cox M, Ooi B and Alouini M S 2020 *Journal of the Optical Society of America B* **37**

[4] Mustafa L and Thomsen B 2013 Reintroducing free-space optical technology to community wireless networks *19th Americas Conference on Information Systems, AMCIS 2013, Chicago, Illinois, USA, August 15-17, 2013* (Association for Information Systems) URL `http://aisel.aisnet.org/amcis2013/ISUsage/RoundTablePresentations/3`

[5] Sekhar C, Agrawal J and Farook O 2005 Designing a free space optical/wireless link pp 10.416.1–10.416.13

[6] Abadi M M, Ghassemlooy Z, Mohan N, Zvanovec S, Bhatnagar M R and Hudson R 2019 Implementation and evaluation of a gigabit ethernet fso link for 'the last metre and last mile access network' (Institute of Electrical and Electronics Engineers) ISBN 9781728123738

[7] Abadi M M, Cox M A, Alsaigh R E, Viola S, Forbes A and Lavery M P 2019 *Scientific Reports* **9**(1) ISSN 20452322

[8] Hamza A, Deogun J and Alexander D 2018 *IEEE Communications Surveys Tutorials*

[9] Al-Gailani S, Mohd Salleh M F, Salem A, Shaddad R, Sheikh U, Algeelani N and Almohamad T 2020 *IEEE Access*

[10] Kaushal H, Jain V and Kar S 2017 *Optical Networks: Free Space Optical Communication* (Springer) ISBN 978-81-322-3689-4 URL `http://www.springer.com/series/6976`

[11] Cox M A, Gailele L, Cheng L and Forbes A 2019 URL `http://arxiv.org/abs/1907.10519`

[12] Saleh B E A and Teich M C 1991 Fiber optics