Experimental Analysis of the Impact of Indoor Turbulence on FSO for Intra-Datacenter Communications

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Abstract—With datacenters expanding their networks at a greater than ever rate, efficiently managing an extremely numerous a network of servers with high cabling complexity is a daunting task. This has motivated the rise of free-space optics (FSO) communication technologies, as a reliable new solution for high-capacity communication systems, which grants a possibility for the implementation of cable-free intra-datacenter communications as a way to reduce the level of network complexity. However, as the scientific community continuously explores FSO distinctive characteristics of unregulated large-bandwidth spectrum, to easily establish new communication links, atmospheric conditions threaten its commercial deployment. As such, the effects of atmospheric turbulence on FSO links have been under investigation by researchers from all over the world, leading to the proposal of several models in an attempt to predict and therefore mitigate the effects of adverse conditions. This study seeks to capture and analyze experimental data on the influence of turbulence on the received optical power of a FSO link in a controlled room, to simulate a datacenter environment, followed by the modeling of experimental data using the Log-Normal model. Using a small 2000 RPM Fan in three different positions we increased the atmospheric turbulence of the FSO channel and measured the differences in received optical power over the course of 1 hour per position. These measurements are then compared to a control obtained without externally induced turbulence. Using the obtained data, we demonstrate its Log-Normal fit, thus enabling to determine the Rytov variance for each scenario.

Index Terms—Free-Space Optics, Atmospheric Turbulence, Log-Normal mode, Intra-Datacenter Communications.

I. INTRODUCTION

The growing need for faster and more secure communication systems has led to the establishment of new use cases and features, initially defined for 5G, such as enhanced Mobile Broadband (eMBB) and ultra-reliable and low-latency communications (uRLLC) [1]. These new features imply a change of the typical Radio Frequency (RF) communications to the THz band to withstand future bandwidth demands [2]. With traditional Radio Architecture Networks (RANs) being forced to evolve, FSO communications rise as valid competitors to cope with the growing need for faster communication

technologies [3]. However, establishing a system in the THz-band requires Line-of-sight (LOS) communication [4], leading to a change in the status-quo of wireless signal propagation methods.

As FSO technologies manifest potential in providing ultra-high bandwidth connections in a license-free spectrum, the fact that they also possess ease of deployment, low maintenance costs and improved security as assets, further magnifies the case of such systems becoming a viable future option [5]. On this notion, these systems have been generating a growing interest in the scientific community for both experimental and commercial purposes [6]. However, as atmospheric conditions reveal themselves as the main hindrance to the stability of FSO links [7], the research community efforts have been focused in the mitigation of the effects of atmospheric events like wind [8], rain [9], fog [10], and hail. Moreover, atmospheric turbulence represents one of the main bottlenecks for the viable commercial deployment of FSO systems [11], as it leads to the scintillation effect inducing fast fluctuations of optical power on the receiver's end [12]. In order to study these impairments, several models have been appearing in the literature [13] [14].

With Warehouse scale data centers hosting thousands of servers, the underlying intra-datacenter network that connects and maintains all the racks of equipment suffers from poor scalability due to increased cabling complexity.

As FSO systems start to display the capability to support ultra-high bandwidth communications, they bring to light the possibility of reshaping traditional intra-network cabling architectures to new and simpler Free-space architectures [15] [16]. Yet the need for active cooling in datacenters forces the server rooms to depend on high air flow to avoid overheating, leading to a turbulent room that as previously mentioned is one of the main bottlenecks in the implementation of FSO links.

In this paper, we show the results of measuring the received optical power in a 1.15 m FSO link, using a Fan in different positions to emulate the effects of atmospheric turbulence on a controlled environment FSO link. With the data from the measurements, we contrast the turbulence affected measurements with the control to highlight the effects of induced atmospheric turbulence. We conclude the system's analysis, fitting the log-normal model to the Irradiance histogram, to extract the level

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of turbulence induced on the FSO link.

The work presented in this paper is organized as follows: in Section II, we introduce the concept of turbulent FSO channel modelling, exploring the log-normal model. Next, in Section III, we first pave the way for the optical power measurement by showing the experimental setup.

Then, we carry out the optical power measuring in an indoor FSO system making use of a fan as an atmospheric turbulence source and follow up by analyzing the power measurements utilizing power over time plots. Finally, we delve into a more statistical analysis of the measured data performing the fitting the Log-normal model into the normalized Irradiance histogram plot to determine the systems Rytov Variance asserting its turbulence regime.

Lastly, in Section IV we outline the paper's main conclusions.

II. TURBULENT FSO CHANNEL MODELLING

Atmospheric Turbulence is characterized by irregular air motions, in which warm surface air rises to higher altitudes as it gets less dense, leading to a turbulent mix of warm and cold air. This mixture leads to inhomogeneities in the air that change light beams wavefront, as these differences in the air (perceived as discrete-cells or eddies) embody refractive prisms with different indices of refraction and sizes.

With FSO systems working by emitting and receiving an information-bearing optical beam through open air, atmospheric turbulence can reduce the received optical power thus resulting in degradation of the FSO link performance. The level of atmospheric turbulence is commonly represented by the Rytov variance (σ_I^2) where:

- $\sigma_I^2 < 0.3$: represents weak-turbulence
- $0.3 \leq \sigma_I^2 < 5$: represents moderate-turbulence
- $5 \leq \sigma_I^2$: represents strong-turbulence

So far no general model for atmospheric turbulence has been settled, nonetheless, there are models that can accurately model turbulence depending on its Rytov variance, these being the log-normal ($\sigma_I^2 < 0.3$), Gamma-Gamma ($0.3 \leq \sigma_I^2 < 0.3$) and negative exponential models ($5 \leq \sigma_I^2$). Since we are working in a controlled environment and the only meaningful source of atmospheric turbulence is one Fan, we expect a very small Rytov variance, therefore we focused on exploring the Log-Normal model [14].

In order to obtain the Log-Normal model, we start by considering the turbulence-induce field amplitude fluctuation as:

$$\psi_1(r) = \ln \left[\frac{A(r)}{A_0(r)} \right] + i[\phi(r) - \phi_o(r)] = X + iS \quad (1)$$

where $A(r)$, $\phi(r)$, $A_0(r)$, and $\phi_o(r)$ represent the amplitude and phase of the electric field with and without atmospheric turbulence, respectively. Since $\psi_1(r)$ and S are Gaussian, then X is a Gaussian distributed log-amplitude fluctuation and S

Fig. 1. Log-normal probability density function of normalized Irradiance.

is a Gaussian distributed phase fluctuation of the field. By focusing only on the field amplitude, the PDF of X is

$$p(X) = \frac{1}{\sqrt{2\pi\sigma_x^2}} \exp \left\{ -\frac{(X - E[X])^2}{2\sigma_x^2} \right\} \quad (2)$$

With field Irradiance (intensity) in a turbulent medium being $I_t = |A(r)|^2$, and in free-space (no turbulence) being $I_0 = |A(r)_0|^2$, the intensity is thus then given by

$$l = \ln \left| \frac{A(r)}{A_0(r)} \right|^2 = 2X \quad (3)$$

Consequently

$$I_t = I_0 \exp(l) \quad (4)$$

Finally, to obtain the Irradiance PDF, we perform the variable transformation, $p(I) = p(X) \left| \frac{dX}{dI} \right|$, and thus arrive at the log-normal distribution function given by

$$p(I) = \frac{1}{\sqrt{2\pi\sigma_l^2}} \frac{1}{I} \exp \left\{ -\frac{\ln(I/I_0) - E[l]^2}{2\sigma_l^2} \right\} I \geq 0 \quad (5)$$

With the log-normal PDF, we can now model a FSO system's link turbulence using the common comparison factor σ_I^2 (Rytov Variance).

In Figure 1, we compare the log-normal PDF of different turbulence scenarios, ranging from weak turbulence ($\sigma_I^2 < 0.3$) to medium turbulence ($0.3 \leq \sigma_I^2 < 2$).

III. OPTICAL POWER MEASUREMENT OF TURBULENT FSO LINK

In this section, we aim at measuring the optical power received through a 1.15 m indoors FSO link, taking 1 hour long measurements in three different fan positions in order to compare to a control measurement taken without fan disturbance.

A. Experimental Setup

Figure 2 illustrates the experimental setup diagram used for measuring and inducing atmospheric turbulence in the FSO channel. The setup's optical power stems from a CWL (Continuous-Wave Laser) operating at 1550 nm with

Fig. 2. Experimental setup diagram of a fiber-FSO indoors link for optical power measurement. Color codes: Blue - Optical Components, Red - Weather turbulence simulation plane, Yellow - Measuring plane..

Fig. 3. Demonstration of the experimental setup used for optical power measurement of a fiber-FSO indoors link.

8.59 dBm output power. The fiber-FSO link is achieved by a pair of fiber collimators (Thorlabs F810APC-1550) with 24 mm of lens diameter, 0.24 numerical aperture and a divergence angle of 0.0017° . With a link length of 1.15 m, we chose three positions for the Fan, these being: i) at the transmitter, ii) in the middle of the link and iii) at the receiver, the fan is placed at 9 cm of the collimators beam when in the mentioned positions. The power received in Rx (receiver) collimator is fed to a power-meter (HP-8157A), with the measurement being read by a GPIB controller (Prologix GPIB-ETHERNET) who then sends it through an ethernet connection to a laptop running MATLAB. In Figure 3 we can see an actual photo of the experimental setup.

B. Power Measurement

As previously mentioned, we will analyze data captured over the course of 1 hour for each fan position plus 1 hour for a control measurement without fan interference. Using a MATLAB script to capture data from the Power-Meter at a Sampling Frequency of $\approx 0.95\text{Hz}$, we obtained an average of ≈ 3420 measurements for each scenario.

The instantaneous measured received optical power is depicted in Figure 4, distinctly showing that the FSO link becomes more unstable when exposed to atmospheric turbulence. If we compare the control measurement to the worst-case measured (Fan@Rx - Position 3), the range of registered received optical power goes from 0.0703 dB to 0.7894 dB a tenfold increase in the ratio between the maximum and minimum power.

Whilst the disparity in optical power produced by the introduction of turbulence in the system is clearly visible in Figure 4, It should be noted that in the worst case, we

Fig. 4. Power measurements of a Free-Space Optics link with different fan positions over the course of 1 hour.

are observing fluctuations in very small decimal places, thus even though the system's performance is affected, the level of turbulence experienced in this experiment is too small to affect a Free-Space Optics transmission.

However, we can only validate this claim, after performing the correct fitting of the model to the experimental data, obtaining the Rytov variance of our setup, in order to compare to the established standards. In the remainder of this paper, we will focus on modelling the channel's turbulence with the Log-normal model, in order to discover the link's turbulence regime.

C. Log-normal Model

With the previous section pointing towards a weak turbulence scenario, the log-normal model is the preferable FSO model to identify the turbulence regime of each case study. In order to apply (5), we first had to obtain the Irradiance (I) by

$$I = (\text{Power}/\text{Area}), \quad (6)$$

with Power being the received optical power in Watts and Area being the collimators output beam area. After obtaining the Irradiance, we normalize it by dividing it by its average. Figure 5 depicts the Normalized Irradiance over time for the FSO link. From the figure, it is clear that we are successfully introducing atmospheric turbulence with the Fan in the system.

After obtaining the Normalized Irradiance over time, we can directly fit the data distribution to the Log-Normal model. In Figure 6, we illustrate both the histogram of the measurements and the log-normal FSO model fitted curve, allowing the determination of the systems Rytov Variance (σ_I^2). With the control data showing the smallest Rytov Variance value at $\sigma_I^2 = 1.5385 \times 10^{-6}$, we can now quantify the impact of the fan on the system. All the three turbulence influenced systems share an increase in Rytov Variance with Position 3 showing more than a tenfold gain to $\sigma_I^2 = 1.8871 \times 10^{-5}$.

Table I demonstrates the accuracy of the log-normal fitting, exhibiting a good correlation between experimental data and the fitted curve, as verified by a minimum R^2 of 0.8678.

Fig. 5. Normalized Irradiance of a Free-Space Optics link fan positions over the course of 1 hour.

TABLE I
Rytov VARIANCE AND R-SQUARE FOR EACH FAN POSITION'S
LOG-NORMAL FITTING.

Position	σ_I^2	R^2
Control	1.5385×10^{-6}	0.8678
Fan @Tx	6.8153×10^{-6}	0.9729
Fan @Mid	9.3402×10^{-6}	0.9016
Fan @Rx	1.8871×10^{-5}	0.8887

IV. CONCLUSION

As FSO systems continuously demonstrate the ability to provide for unprecedented wireless communications, the ease of implementation and cut in costs in a data-center environment, bolstered by the re-usage of standard optical equipment together with optic fiber collimators, places FSO communications in a very bright spot for commercial deployment.

In this paper, we addressed the influence of atmospheric turbulence on an FSO link in a controlled environment similar to the one experienced in a datacenter's server room.

By analysing hour-long optical measurements in different fan positions, we surveyed the level of impact turbulence has on the link's received optical power. Through these measurements, we were able to confirm that turbulence did, in fact, induce instability in the link.

Using the log-normal model to assess the level of turbulence in the beam, we successfully determined position where the fan had a greater impact in the link's stability, with Position 3 (Fan @Rx) suffering the most from the fan induced turbulence. Thus, even though the results exhibit a clear influence from the fan's involvement in the system, we conclude that in a controlled environment the small 2000 RPM Fan is not enough to produce big enough turbulence levels to induce transmission instability in the FSO link, as even in the worst case the determined Rytov variance is still four orders of magnitude from a usual weak-turbulence system.

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Fig. 6. Histogram and Log-Normal Fitted Curves for all case studies.

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