Ad Hoc FSO Communication

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***Abstract*—This paper presents a new framework for long range Free Space Optical communication (FSO). Motivated by the ever-growing demand for communication in 5G networks, the suggested framework tackles the natural FSO link drawbacks, commonly: complicated installation, limited range, size and pricing. The new FSO concept assumes a "best effort" model. It uses a new control and aiming mechanism for the Tx laser beam based on COTS components. This methodology is mostly suitable for urban FSO links but might also be applicable for both short range (IoT) and long range (satellite) communication. Based on simulations and preliminary field results we expect that such FSO links will be widely used in "best-effort" 5G applications allowing an affordable alternative to fiber optics and standard FSO systems.**

***Index Terms*—5G Backbone, Best-effort communication model, Free Space Optics (FSO), Laser LED long range communication, LiFi**

I. INTRODUCTION

Free Space optical (FSO) Communication is an optical communication technology that uses light propagating in free space to transmit data wirelessly for telecommunications or computer networking. In this context, "Free space" means air, outer space or vacuum. This contrasts with using solids such as optical fiber cables or an optical transmission line. The technology is useful where physical connections are impractical due to high costs or other considerations [1] [2] [3] . The basic concept of FSO half-duplex link is shown in Fig. 1

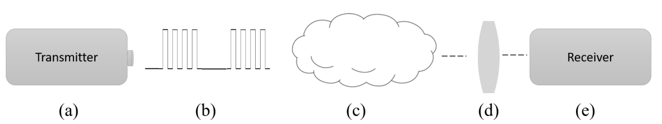


Figure 1: A simple half-duplex FSO Communication model: (a) is the optical transmitter (LED or Laser Diode). (b) is the transmitter signal. (c) is the atmosphere medium. (d) is the optical lens. (e) is the optical detector that convert the optical signal into a bit-stream.

FSO communication systems are an alternative solution to optical fibered communication systems as they are easier to install (and uninstall), cheaper, secure, and need no frequency regulation. However, they have two substantial challenges [4]:

1) *Atmospheric properties*. As opposed to Fiber Communication, where the medium known and the attenuation can be calculated, FSO Communication face an unknown medium. For example, atmospheric disruptions like fog, rain or snow, can cause to a signal attenuation. In addition, beam divergence loss, ambient light and atmospheric turbulence can also damage the signal and its stability.

2) *Line of Sight (LOS)* communication, means that the transmitter and the receiver must be perfectly aligned to each other. Working with Laser source as a transmitter makes this demand very hard to achieve due to the laser's inherent narrow beam.

A. Motivation

As the internet's consumption continues to grow, the need of wider bandwidth becomes more and more urgent. The next generation of the mobile communication, .i.e. 5G, will need to provide a higher capacity than current 4G, allowing a higher density of mobile broadband users, and supporting device-to-device, ultra reliable, and massive machine communications. In order to increase the backhaul capacitance, FSO Systems can be utilized to replace the need of placing fibers underground and can be a foundation to the 5G generation. FSO systems are easy to install and they are regulation free, they can be placed quickly and connect isolated areas like distant villages or disaster areas to interment services. In addition, FSO systems are important due to the development of the Light Fidelity (Li-Fi) [5]. In this work, we address the FSO challenges from a different aspect than the prevailing approach. Instead of guarantee communication reliability of 99.X% (X being close to 1), we suggest working at a "best effort" communication model (such as WiFi offloading, of LiFi). Before we discuss our ad hoc FSO framework, it is necessary to understand the operation principle of the existing systems.

B. Related Works

There are FSO communication researches due to its importance to the next generation communication. We begin by resenting two key examples, each has its own weaknesses and strengths. The first example is the Lightpointe System. Lightpointe Communication LTD specializes at communication solutions. It manufactures point-to-point Gigabit Ethernet FSO systems and Hybrid Optical-Radio Bridges. Lightpointe has two main products. FLIGHTLITE 100 & 100E, with Bit Rate of 10 Mbps to 100 Mbps and Operational Ranges of 1.6-2.9 Km. The second product is FLIGHTLITE G , with Bit Rate of 1.25 Gbps and Operational Ranges of 500 meters. Each transceiver weights 4.5Kg [6]. While that system work fine, there are other approaches as well as the next example demonstrates. Koruza system- Koruza has developed as an open source project in cooperation with IRNAS Institute for Development of Advanced Applied Systems and company

Fabrikor. The main goal was to make an FSO technology affordable and accessible to everyone. The Koruza system is about the size of a security camera and include two sub-systems: tuning sub-system and the communication sub-system [7]. The tuning sub-system consist three motors and a RaspberryPi board that controls all motors. Two motors for the x-y movement and a third motor to adjust the lens' focus. The communication sub-system consists of a media converter, a Small Form-factor Pluggable (SFP) electro-optical transceiver and a lens. The signal is transferred from a LAN port into the media converter that converts with the SFP the electrical signal into an optical signal and sends it through the lens to the open space. On the receiver side, the light is focusing through the lens and enters the SFP receiver, into the media converter that converts the detected light into an electrical signal. Those systems were designated for a specific usage. They are complex to install, hard to maintain and must be perfectly mounted to the surface.

C. *Our Contribution*

We present a new concept of FSO system. Without the accuracy and the bit rates obligations, a "best effort" network model can achieve a much larger operation range. Moreover, this model can be implemented in multiple scenarios that will be detailed later in this paper. In addition, our model describes an FSO system that is both adjustable and affordable; it is cost effective and easy to install and uninstall.

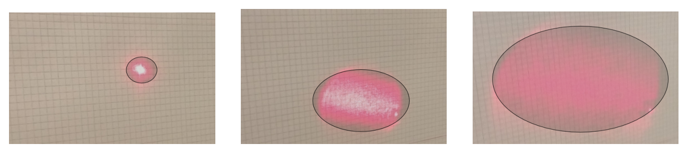
II. Ad Hoc FSO Framework

Most of the FSO systems were designed according to specific paradigms. In this section, we will analyze those paradigms that led to the existing FSO systems and the disadvantages of these paradigms. Afterwards, we will describe the ad hoc framework of our FSO system. We will demonstrate the theoretical background that supports the framework feasibility.

A. *FSO Paradigms*

Network's Service Level Agreements (SLA). The network's SLA determines that a communication link must be available 99.99% of the time. Unlike working with fibers or radio frequency (RF) communication, FSO systems face with unknown attenuation in the medium that can be close to zero and up to several hundred decibels per kilometer [dB/Km]. Compliance with the network's SLA force the system to consider the worst-case weather that possible. The attenuation at this case is about 400dB/Km while at the rest of the time the attenuation can be a few fractions of dB/Km. Obeying the SLA regulation results in a significant reduction at the operation range. The Ad Hoc FSO communication method does not apply the network's SLA. It is based on a "best effort" method that considers only the best weather scenario on a clear day when the atmospheric attenuation is 0.2dB/Km. Atmosphere turbulence can be neglected since the system is placed on high buildings or at open space when the turbulences are not significant. Nonetheless, if turbulence do occur, the 'best effort' model will patiently wait. The same principle applicable for ambient light disturbance; One can work only in dark places or at lower rates. The overall scheme of the FSO system is based on mesh logic; there are a lot of FSO systems at multiple places and the control system choses continuously the optimal available link. A poor weather at point A will steer the system to point B that has a good weather and the signal will be transferred through that point.

Combined/ One Part Transmitter and Receiver.. Most of the existing FSO systems combine the transmitter and the receiver physically into one part. The receiver sub-system is relatively large because the need of lenses focusing system and signal amplification, while the transmitter sub-system can consists of only a lightweight laser diode. Gluing those two systems together is difficult, cumbersome and unstable. In addition, examination Koruza system discovers that its focus lens damages the communications ability and significantly decreases the operation range. The lens is placed in front of the receiver in order to collect and focus the detected signal into the receiver and increase the system efficiency. Due to the structure of the SFP that consist both transmitter and receiver, the focusing lens also doing the opposite target; the transmitted signal that comes from the SFP also passes through the lens and becomes scattered as it can be shown from experiment results in Fig. 2.



(a) laser spot at 3 meter without lens (b) laser spot at 3 meter after the lens (c) laser spot at 6 meter after the lens

Figure 2: Comparison between laser spot without Koruza's lens and after the lens at deifferent ranges. Figure shows that laser spot at 3 meter after the lens is one order of magnitude bigger than laser spot without the lens and the laser spot at 6 meters is bigger of two order of magnitude than the original laser spot size

Physically separating the receiver from the transmitter has fundamental advantages. Tuning mission becomes easier and the operation range of a system like Koruza increases significantly since the lens is no longer in front of the transmitter.

Our system implements this idea and separates these two components. The receiver system is fixed to a stable surface and includes a detector, a lens and a small light source like LED or laser that transmits a beacon. The transmitter system consists of a small and lightweight laser calibrated to a small camera or simple CCD that connect to a Gimbal. The camera detects the beacon and by using a navigation algorithm the Gimbal points direct to the detector in a closed control loop.

B. *FSO Scenarios*

In accordance with the classic FSO assumptions, FSO systems are commonly operate in the middle range area. Our FSO framework can also provide a solution for wide range operation abilities that can be categorized into four scenarios with different goals and working methods.

1) Short Range FSO $\leq$ 1Km. The increased development in the Internet Of Things (IOT) technology demands multiple SIMs for each user. This new reality overloads the network. FSO Communication can overcome this problem. By using a Light Emitting Diode (LED) as a transmitter and a simple PIN or APD detector as the receiver, one can get a simple FSO system that transmits information from one machine to another without using a SIM card and without loading the network. The system can operate at low speed and perhaps only in dark conditions. Nevertheless, it is adequate for IOT cases. This method can be implemented also on aircrafts such as planes and drones.

2) Middle Range FSO $\sim$ 0.1-1Km. This scenario is relevant for 5G communication in metro areas. FSO systems are utilizing a Laser Diode as the transmitter, a simple lens and a detector and can work at high speed, around 10 Giga Bps, for middle range operation. These systems have the ability of increasing the internet capacitance by adding more lines into a building without the need of underground digging and fibers placing. In addition, these systems can also expand the back-haul to the city by gaining wider bandwidth communication.

3) Long Range FSO $\sim$ 10Km. FSO systems builds of Laser Transmitter and a telescope with a detector can provide communication around 1 Giga Bps between isolated rural villages or aircrafts like planes and drones.

4) Extreme Long Range FSO $\geq$ 500Km. communication between spaceships.

C. Theoretical Background

Atmospheric attenuation. Among the rest of the challenges, FSO systems are hard to implement due to the unknown behavior of the medium. On the other hand, some atmosphere models can assist at this task [8].

Table I: Typical optical attenuation (e.g 1550nm)

Atmospheric Condition	Attenuation
Clear weather	0.2 dB/Km
Urban (because of dust)	10 dB/Km
Rain	2-35 dB/Km
Snow	10-100 dB/Km
Light fog	120 dB/Km
Dense fog	300 dB/Km
Maritime fog	480 dB/Km

Since the new paradigm is the "best effort" model, one can only relates to clear weather when atmospheric attenuation is 0.2dB/Km.

Geometric Attenuation. Unlike Fiber communication, at free space the signal is expended sideways in the space and not only in the detector's direction. This causes the detector to lose a lot of the signal energy and it limits the operation range.

$$D_s = 2d \tan\left(\frac{\theta}{2}\right) \tag{1}$$

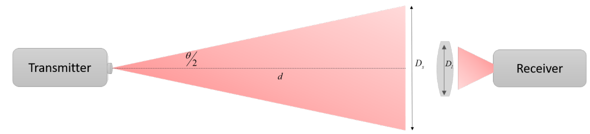


Figure 3: Geometric attenuation diagram.

$$P_r = \left(\frac{D_l}{D_s}\right)^2 P_t \tag{2}$$

There is an inherent tradeoff between the operation range and the operation speed of the system since the sensitivity of the detector dependent on the detector Noise Equivalent Power (NEP) that in root of inverse ratio of the frequency. Fig. 4 demonstrates this tradeoff at the mentioned scenarios.

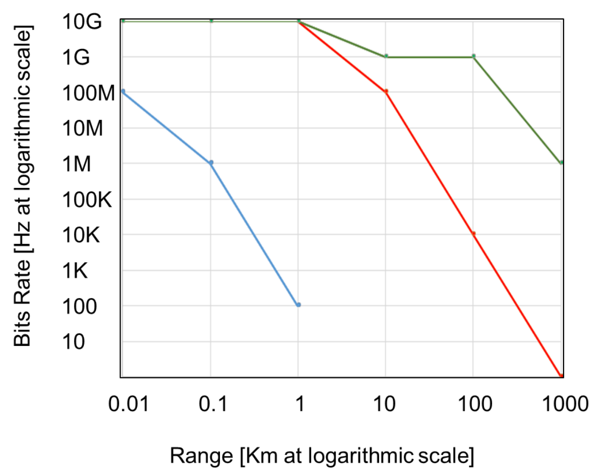


Figure 4: Range Vs. Speed at three main FSO scenarios. Blue line describes IOT scenario with LED Transmitter, red line describes 5G scenario with laser transmitter and a small lens and green line describes a long rang FSO scenario with laser transmitter and a telescope.

D. System Design

The building blocks of our system are shown at Fig 5. Every system consists of two half-duplex systems that create a full duplex communication. On the detector, there is an IR beacon and a small camera that connected to the Gimbal and recognizes the beacon. Once the beacon is detected, the gimbal turns to the detector using a microprocessor monitoring that makes a gimbal lock algorithm, which keeps the gimbal tuned to the detector. The laser source is connected and calibrated to the gimbal in a manner that when the gimbal is tuned, the laser source is facing direct to the lenses system of the receiver, which focuses the signal to the detector.

In addition, the IR beacon has two additional utilities.
1) When knowing the fixed distnce between the receiver and the transmitter and knowing the optical IR power, the camera can provide information about the atmospheric conditions from the SNR calculation.

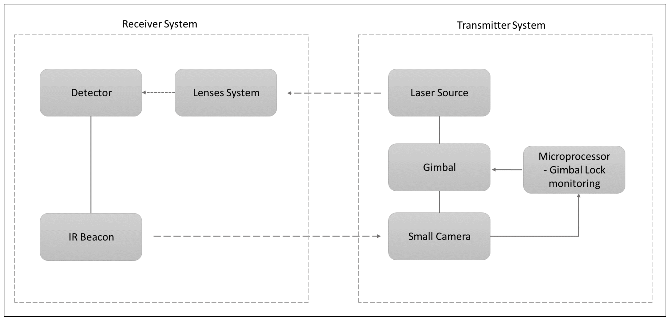


Figure 5: Building Blocks of our half duplex FSO System.

2) The IR beacon can also function as a very low rate communication line. For example, if there a problem in the detector, the IR beacon can use to inform the transmitter to stop the transmission.

Transmitter wavelength. An important parameter that needs to chosen carefully is the wavelength of the transmitted signal. Fig. 6 demonstrates that at 1550nm there is a great atmospheric window [9]. In addition, we will want to work at that wavelength due to his safety level and because it has many Commercial off-the-shelf (COTS) that make the optical components cheaper.

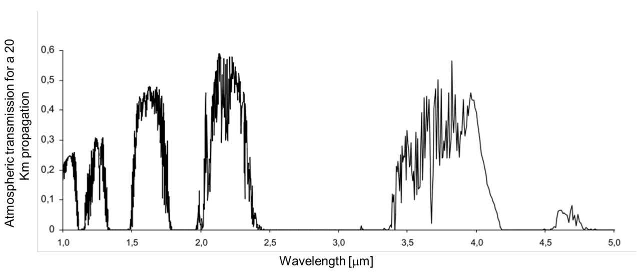


Figure 6: Example of atmospheric transmission versus wavelength in clear weather.

Lens. The lens diameter has an important influence of the system performances and operation range. A larger lens will collect more optical power to the detector and decrease the geometric attenuation. It is important to select the suitable lens according to usages and budget.

Laser source parameters. When selecting the laser source it is important to check his beam divergence. It should be as small as possible so that the optical loss from the geometric attenuation will be minimize. In addition, a large optical power will achieve larger operation range.

Detector parameters. The detector should be in his high sensitivity peak at the transmitter wavelength in order to achieve best results. In addition, the rise time of the detector is the limiter of the higher frequency that it can detect and the detector sensitivity is depends on the signal frequency.

III. Results

In order to prove the theoretical concepts described so far, some relevant experiments were conducted.

IOT- LED Transmitter. In this experiment, we have tested the system abilities of transfer optical data from tens of meters using a simple LED as a transmitter and a 45mm lens with an APD detector as the receiver as shown in Fig. 7

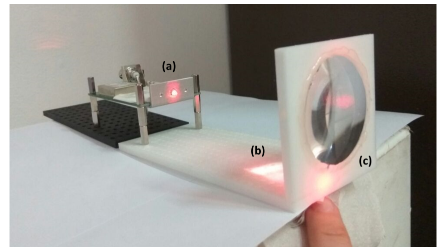
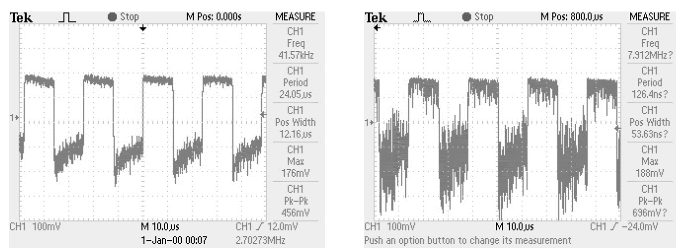


Figure 7: IOT FSO system's receiver when (a) is an APD detector, (b) is energy waste and (c) is the optical lens.

In order to confirm that the receiver successes detecting the signal we send a square waveform as the signal and displayed the receiver output on the scope. The experiment done at night due to the dark condition we wanted to have. The LED we used was at 870nm wavelength with forward optical power of 8.2mW and a beam divergence of 20 degrees. We got clear results at 12.2 meters, and at 15 meters the results started to be unstable due to a street light we got underneath, but a simple averaging or error correction algorithm can get the information easily.



(a) 12.2 meters range

(b) 15 meters range

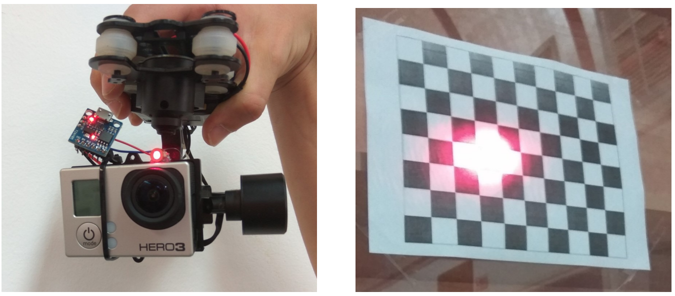
Figure 8: Scope screen at different ranges.

Laser Tuning on Gimbal. In this experiment, we have tested the concept of accurate tuning a small laser transmitter on a Gimbal. The point was accurate for a distance of 20 meters. The Gimbal system can make a closed loop monitoring and save the tuning position

SFP Experiment. From the results in the experiment that displayed in Fig. 2, one can notice the lens problem. Even though the Koruza's transmitter has a laser source, due to the scattered lens that after the transmitter it acts like a LED. From (3) we can calculate the equal beam divergence of the laser with the lens and see that the result is beam divergence of 246.2 milliradian, means 14 degrees. That value is equal to a typical LED beam divergence.

$$\theta = 2\arctan\left(\frac{(D_{scattered} - D_{laser})0.5}{d}\right) \tag{3}$$

In order to overcome this problem, we suggested to separate the transmitter from the SFP and connecting it back with



(a) the gimbal (b) the laser spot

Figure 9: Laser tuning on specific square at range of 20 meters using the Gimbal (a), at that range every square is equal to one mili radian of the laser beam divergence. Gimbal system with the Laser source, Tiny Teensy microprocessor and a camera (b).

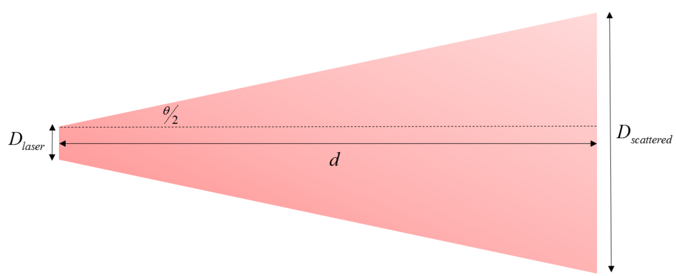
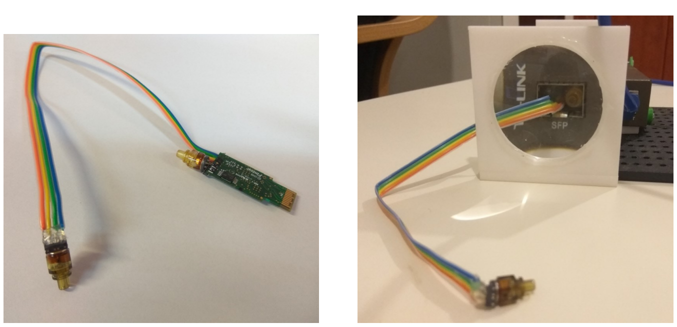


Figure 10: Parameter diagram of calculates teta of the scattered laser.

wires that will enable the transmitter to be beside the lens instead of in front of it (as shown in Fig. 11). Using the Tx and Rx separation the lens will focus the optical signal to the detector and the laser will work independently. If the Koruza-like systems can achieve an operation range of about 100 meters when the lens is damaging the transmitter, with the suggested solution one can achieve a significantly larger operation range.



(a) separating SFP (b) the separating system

Figure 11: The separated SFP, where the transmitter's weight is 0.8 gram (a) and where the detector behind the focusing lens and the transmitter is not (b).

IV. Discussion And Future Work

Fifth generation mobile networks, (i.e. 5G), require more bandwidth to support the ever growing network capacity. In this work, we have presented a "best effort" communication model that can provide some of the network transmission under fundamental change of the working assumptions of FSO links. The suggested solution is applicable for a wide range of networks and scenarios including: 5G backhauling in urban region, IoT, Isolated and satellites communication.

Acknowledgment

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