Challenges Facing Mobile Free-Space Optical Communications

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ABSTRACT

Significant research efforts are underway to investigate the application of Free-Space Optics (FSO) for the provision of high-bandwidth communications links between mobile platforms. The use of FSO between mobile platforms introduces several interesting challenges in addition to those found in traditional fixed link FSO systems. In this paper, some of the major hurdles facing fixed FSO communications that carry over into links between mobile platforms are analyzed. These topics include: issues with alignment and tracking, an investigation into the weather and its effect on the link, and a study of the feasibility of having uninterrupted communications links. Other topics presented unique to mobile applications include: the security risks during link alignment, maintaining the link while tracking and optical power and beam divergence variations that are introduced into the system. In this paper the results from simulation work performed on some of these issues along with proposed solutions to the challenges are presented.

1 - INTRODUCTION

In today’s communications, many challenges arise in free space optical communications technology and limit its deployment in the communications field. Currently, static FSO links are more reliable than mobile FSO links since there are no continuous tracking and alignment requirements needed to maintain line of sight (LOS). In this paper, some of the major challenges that limit the productivity and use of mobile FSO nodes in today’s communications market are discussed.

Challenges facing FSO technology affects the communication links between the two transmitters and result in either disconnecting or attenuating the link, as shown in Figure 1. The first challenge addressed in this paper is the disruption of physical link and line of sight. In [1], Bilgi & Yuksel proposed forming spherical FSO structures on the nodes that will allow connectivity between mobile nodes. The spherical FSO node is built of hexagonal shapes and put together in a soccer ball arrangement. A VCSEL laser and photo-detector, in addition to their associated circuitry, are found in each hexagonal shape. This setup allows for continuous LOS and limits the disruption of the physical link.

Optical signal propagation in different atmospheric conditions is another challenge for mobile FSO. The atmospheric turbulence produces gaps of air with different indices of refraction. Thus, intensity fluctuation results due to the laser beam phase-front random variation [3].

Low power and light weight are essential qualities that appear in the design of mobile FSO nodes [4]. In a research supported by the Office of Naval Research, a demonstration of a 10MHz mobile FSO communication with low power consumption, light weight and low cost was shown. Batteries power the FSO system which is mounted on a
mobile platform. The source used for this system is an LD which consumes 600mW of total power, and outputs 15mW of optical power.

![Figure 1 – FSO Challenges and their effect](image)

Two other challenges that face mobile FSO links are the variation in receiver beam profile of the FSO link and the variation in received optical power due to the constantly changing transmitter-receiver separation distance. Harris & Giuma [5] simulated a mobile FSO scenario taking into consideration the optical beam divergence and power variations present in the communications link.

High data rates is the most attractive feature in FSO communications and draws researchers attention on having the capability to send intense loads of information through its secure communication links. To date, many experiments have been conducted to test the highest rates FSO links can reach. One of these experiments was performed by scientists from Discovery Semiconductors, Science Applications International, the Air Force Research Laboratory, and Schafer [2]. They have demonstrated a satellite free-space optical communications system that maintains a 10.7 Gbps data rate using a laser of 1.55 µm wavelength. The demonstration of the earth to satellite link was simulated in a “turbulence box”. The system is also supported by a commercial +37 dBm optical-booster amplifier that provides transmission over a distance of several tens of thousands of kilometers. A return-to-zero differential phase-shift keying is used for transmission. The receiver’s sensitivity is of 27 photons per bit at 10.7 GHz having a bit-error rate of $10^{-9}$.

### 2 – CHALLENGES FACING STATIC FSO LINKS

FSO systems commonly use infrared light source to transmit data over the communications link. Heavy fog is a major weather constraint that almost completely blocks sources of infrared light. Thus, it threatens FSO links by attenuating the light signal and almost breaking it. This constraint is similar to the RF signals case with rainfall.

#### 2.1 Absorption

Light can be absorbed into the atmosphere. The phenomenon of absorption is caused mainly by the presence of water vapor and carbon dioxide in the air. These gases in addition to other types create what is called transmission windows that limit the passage of some light frequencies. The frequencies of infrared sources are not in the range of absorption by these transmission windows, resulting in no effect on the communications link. FSO infrared sources are not affected by the atmospheric absorption of light during the transmission and receiving process.

#### 2.2 Scattering

Scattering is more of a concern to FSO links than absorption. This is true because scattering is a function of the light wavelength and the quantity and size of scattering elements in the atmosphere. Even though rain and snow do
scatter FSO light sources but the effect is considered negligible. The main weather contributor to signal attenuation is fog. Fog occurs when humidity of the air reaches a certain saturation level which condensates vapor to water droplets of microns of radius. These droplets are the major cause of scattering for infrared light. Even though fog droplets are smaller on average than cloud droplets but are huge when compared to the wavelength of the light.

A simple example of scattering due to fog is when drivers use their yellow low beam in case of a decrease in road vision because of fog. If the driver shifts to high beam headlights, the white light will be scattered and would not help the driver have a better vision of the road. Figure 2, shows a simple diagram of light particles traveling from a light source through the fog and to a light receiver. The particles will collide with the water droplets and scatter away resulting in much less light particles passing to be detected by the receiver. This will certainly increase the error rate and decrease the power of light traveling through the atmosphere.

![Figure 2 – Scattered light due to fog](image)

2.3 Alignment and Tracking

In [6], a study about tracking and alignment has been performed. Consider two mobile objects connected by an FSO communications link. Mechanical gimbals are used on each mobile platform in order to implement alignment and tracking algorithms to ensure continuous connectivity. These gimbals are steered using certain applications that input parameters of: speed, heading, altitude, longitude, latitude, pitch, roll and yaw of the two vehicles. Figure 3, shows the movement of the two vehicles and the communications link at time $t_0$, $t_1$, and $t_2$.

![Figure 3 – Alignment and tracking of two moving vehicles [6]](image)
2.4 Uninterrupted Communications Links

A laser beam is considerably narrow when it travels for short distances. The link will be more secure, since taping the free light can be easily detected due to the close proximity required in order to gain access to the laser beam. On the other hand, this narrow beam can be interrupted by several natural obstructions. In [7], a study of the feasibility of having an uninterrupted FSO communications link is demonstrated. An outdoor experiment is conducted showing the placement of two FSO nodes on two campuses at Ankara University. The nodes are supported by a redundant Radio Frequency (RF) link to overcome different weather conditions.

3 – CHALLENGES FACING MOBILE FSO LINKS

3.1 Security Risks

During data transmission, mobile FSO links might be subject to security breaches. This occurs especially when light is used in long distance communications. Let us assume the scenario mentioned in [6], where a UAV has an FSO link established with a battle tank as shown in Figure 4.

As light travels through the atmosphere the narrow laser beam diverges and expands to reach a divergent beam of diameter 13.5 m when the transmission distance between the two vehicles is 13,716 m. The receiver occupies part of the diverged light but not all, thus resulting in some margin of light that can be detected by intruders or other parties.

![Figure 4 – Showing the effect of divergence of the FSO laser beam [6]](http://proceedings.spiedigitallibrary.org/)

The FSO communications link is particularly susceptible to interference and eavesdropping during the period in which the initial link alignment algorithm is implemented. In order to successfully establish an FSO link between two mobile platforms, a search algorithm needs to be implemented in order to perform the initial course alignment between the transmitter and receiver. During this search algorithm, the link could become susceptible to eavesdropping if the eavesdropper were able to provide incorrect coordinates for the initial search, resulting in an alignment with their eavesdropping equipment.

4 – ATMOSPHERIC EFFECTS

While issues previously discussed, such as tracking and alignment provide significant challenges in establishing and maintaining mobile FSO communications links, atmospheric effects, particularly those of weather phenomena still remain the largest hurdle to overcome. Based on this, several simulations were implemented in order to demonstrate
the severe effect weather has on mobile FSO links. Figure 5 shows the implemented configuration, which consisted of establishing an FSO link between a fixed ground station and an unmanned aerial vehicle flying in a fixed circular path at an altitude of 4-km above the ground station. A wavelength diversified FSO link consisting of three wavelengths (0.85µm, 1.55 µm, and 10 µm) is then simulated between the UAV and ground station for several different configurations.

In order to establish a baseline configuration for comparative purposes, an initial simulation was implemented under clear atmospheric conditions using the 1976 Standard U.S. Atmospheric model. Figure 6 shows a plot of transmittance versus UAV altitude for the uplink configuration. These results verify that for each of the three wavelengths, transmittance levels above 78% were able to be maintained.

Figure 7 shows the corresponding data for the downlink simulation. This data is presented as a plot of transmittance versus altitude above the ground station. Again for this data, the transmittance level is maintained above 78% for each of the three wavelengths in the wavelength diversity scheme.

After verifying that the baseline simulation configurations resulted in an operable FSO link between a fixed ground station and a mobile UAV, different weather phenomena are simulated in order to show how changing weather can greatly impact a mobile FSO link.
Figure 6 – Uplink transmittance data for clear weather conditions

Figure 7 – Downlink transmittance data for clear weather conditions
Figure 8 shows the uplink transmittance for the same configuration, but in the presence of radiation fog. Fog is one of the largest atmospheric impediments to FSO transmission due to Mie scattering present in the link. Figure 9 shows the corresponding data for the downlink in the presence of fog. Immediately it becomes apparent that both the 0.85 μm and 1.55 μm wavelengths are unsuitable for use in the presence of fog, even on a slanted uplink path which results in transmission above the fog layer. The 10 μm wavelength does result in limited transmittance, but at the expense of increased cost and design complexity due to, for example, the requirement for active laser cooling to operate at this wavelength.

![Figure 8 – Uplink Transmittance vs. Altitude](image1)

![Figure 9 – Downlink Transmittance vs. Altitude in the presence of fog](image2)
In order to discover if the transmittance data presented would result in an operable FSO link, the data was converted into received power plots. In order to accomplish this, several other losses needed to be accounted for in the FSO link. The link was configured to have a transmission power of 20mW. The receiver was configured with a -43dBm sensitivity. Pointing losses were set to -10 dB, geometric losses to -18.7 dB (based on expected beam sizes at the receiver) and optical losses were set at -3 dB. This resulted in a maximum loss of -11.3 dB for pure atmospheric losses.

Figure 10 shows a plot of received power versus UAV altitude for the uplink data transmission. It is evident that for both the 0.85 μm and 1.55 μm wavelengths, transmission becomes impossible at a UAV altitude of between 500m and 750m above the ground. Transmission at the 10 μm wavelength remains possible to the maximum simulated altitude of 4000m.

![Figure 10 – Received power vs. Altitude (uplink)](image)

Figure 11 shows the corresponding data for the downlink. The data shows that for the 0.85 μm and 1.55 μm links, once the laser light enters the layer of fog surrounding the area, transmission becomes impossible. The 10 μm wavelength does result in an FSO link that is usable, but is subject to the increased complexity already discussed.

While fog is extremely detrimental to FSO transmission, it is a far less common atmospheric phenomena that that of clouds. Ground-to-ground implementation of FSO links are not subject to the interference of clouds, but a link between a ground station and a UAV would introduce the possibility of having to transmit data through layers of different cloud formations. It was decided to compare the effects of two different cloud formations on FSO transmission, altostratus and cumulus. Altostratus clouds are a kind of cloud formation that carry ice crystals and have a considerable affect on FSO links going in altitudes ranging between 2000 and 6000 m. Figure 12 shows this effect on the received power at the UAV.
Figure 11 – Received power vs. Altitude (downlink)

Figure 12 – Received power vs. Altitude (Altostratus clouds)
The next configuration simulated was that involving cumulus clouds. Cumulus clouds develop at far lower atmospheric levels than altostratus clouds and can extend for many kilometers into the atmosphere. Figure 13 shows the received power plot for an FSO link versus the altitude of the UAV in presence of cumulus clouds.

![Received power as a function of UAV altitude in the presence of cumulus clouds](image)

Figure 13 – Received power vs. Altitude (Cumulus clouds)

As can be seen from the simulations involving the presence of clouds between the FSO transmitter and receiver, clouds introduce an impediment to the system that eliminates the transmission of data between mobile platforms where one of the platforms is aerially based. This greatly affects the possibility of using FSO transmission between mobile platforms, since the presence of cloud formations is one that is often expected.

5 – CONCLUSION

In this paper, several of the major hurdles facing FSO communications have been highlighted. Issues with alignment and tracking, an investigation into the weather and its affect on the link, and a study of the feasibility of having uninterrupted communications links were shown. Security risks during link alignment, maintaining the link while tracking and optical power and beam divergence variations that are introduced into the system were also discussed. Simulation results were shown and analyzed to contribute in a clearer view of the different weather conditions that affect mobile FSO communications links. While FSO is definitely an attractive option for the provision of high bandwidth data links between mobile platforms, particularly in military applications, significant research is required in order to overcome several major impediments to implementation of the technology.

REFERENCES


