

Suitability Analysis of Free Space Optical in Military Communication Technology

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Abstract

This paper reviews the FSOC technology and presents features based merits as well as unmatched advantages & associated major application in various fields collating them into a single reference point for future research. Efforts have also been invested to present a review of FSOC's limitations & innovative emerging mitigation techniques which can prove to be a one stop feeder & a launch pad for future research in FSOC domain. A literature survey has been undertaken of available FSOC related military application to review & gather relevant inputs to throw light on emerging trends in military applications including recent experiments & researched areas pertaining to lasers systems & weapons, Unmanned Aerial Vehicles (UAVs), under sea sages, terrestrial applications, aerial, naval ships/shore based applications & RF/hybrid systems. It has been endeavored to shed light on findings & developments in these classified military domain to generate inputs for future work in this domain. Finally, a future technical roadmap and way ahead & suggestions have been coined

Keywords: FSOC, Line of Sight, RF, UAVs, On-off Keying, Subcarrier Intensity Modulation,

Bandwidth

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1. Introduction

In FSOC, focused light is transmitted through free space medium for sending information for communications in a remote manner for space, terrestrial, aerial, marine, military & civil applications between various source points, receivers (Rx), transmitters (Tx), handsets, machine s, equipment including networks which are required to be in Line of Sight (LOS). It boasts of much lower costs & setup time, protection from Electromagnetic Interference/Electromagnetic Compatibility (EMI/EMC) issues & has much simpler equipment & infrastructure than Radio Frequency (RF) networks. There are numerous feature based merits of FSOC including higher Bandwidth (BW), better Bit Error Rates (BER) and data rates. Such advantages & features oriented merits have been studied & collated here point wise so as to make it a single point baseline for future surveys in FSOC domain. The FSOC transmissions degraded due to environmental factors & atmospheric turbulence (AT) like rain, mist, fog, heat, physical obstructions, scattering impediments & dispersing etc. However, numerous

mitigating techniques like coding, modulation, channel modeling, RF/Hybrid FSOC solutions are being researched & developed across the globe. A preview of these limitations & emerging mitigation techniques has been drawn out from various sources & prepared as a easy source point for researchers. Literature on FSOC Military applications, being customized, sensitive & classified in nature is not readily available. It has been endeavored to gather such information and provide a logical & practical futuristic way ahead. Collation of mitigation techniques along with details of emerging trends in military applications is not a common place and have rarely been surveyed & arranged together as a nodal reference which has been a motive in this paper.

Modulated & collimated light as infrared (IR) lasers, are utilized in FSOC to transmit data between Tx & Rx points. It brings in important useful features like enhanced security through much Lower Probability of Detection (LPD) & Probability of Intercept (LPI) without any interference & regulations unlike RF [1]. FSOC is fast shaping up as a technology option for mitigating bottlenecks of conn

activity in a supplementary role to existing RF links. Optical Wireless Communication (OWC) can ease out enormous data traffic from networks of microwave & RF. Therefore, combination of Radio over FSO (RoFSO) & FSO/RF systems can be a suitable solution to bear 5G & related technologies. In this context, paper [2] has presented several key technologies & applications of RoFSO underlining its superiority. FSO is being investigated extensively because it can improve the reach & last mile connectivity of OFC networks, has rapid-deployability & higher flexibility in operations related to disaster recovery & military projects. Presently, OWC has already been used to demonstrate 100 Gb/s data rate applications for both indoor & outdoor usage in varied ranges up to 10000 km. Technology overview of OWC including optical camera & visible light communication, FSOC, Lasers and light detection and ranging are being conducted by contemporary researchers worldwide [3]. Latest applications/trends of FSO include subcarrier multiplexing (SCM), OWC wavelength division multiplexing (WDM), visible light communications (VLC), worldwide interoperability for microwave access (WiMAX), vehicular visible light communications (V2VLC), next generation FSO wireless terrestrial/global network architecture & Deep space optical communications systems. Researchers are facing difficulties in evolving FSOC applications related to 5G, internet of everything/things (IoE/IoT), cell phone-network, underwater optical applications & quantum communication [4]. The journey of evolution of OWC technology spans right from ancient times to FSOC of today.

This review paper has been divided into various sections. Section 2 comprehensively elaborates different feature based merits & related major advantages. Section 3 enumerates major contemporary applications. Section 4 dwells upon limitations & few emerging mitigation techniques weaved in from various sources. Section 5 brings out emerging tactical military applications of FSOC which are specifically based on various types of Laser techniques including laser weapons & remote sensing systems. Section 6 lists out various evolving military applications & utilization in sea, air, ground and space/UA Vs. Section 7 spans across marine, underwater & RF/Hybrid systems based military applications and scenarios. Section 8 elaborates about future scope and way ahead for researchers. Section 9 has conclusion.

along with almost one-tenth of the RF antenna diameter with robust security [5]. Historically, research work on OWC can be traced to at least 50 years back related to space & defense projects, wherein, US military was sending telegraph signals between various points using sunlight energized equipment.

2.2. Advantages

FSO has garnered research interests owing to various inherent merits & numerous advantages. It can be deployed rapidly to obtain high-speed data connectivity in wireless applications at tough and remote geographical locations, hills & high altitudes. RF technology in these areas is an inaccessible and optical fibers laying is a daunting & expensive task. The usage of highly directional & focused laser beams results in lossless transmissions with a large chunk of optical power output gathered by Rx [6]. Due to these advantages, researchers across the globe are fielding FSOC systems for short distance high data rate wireless transmission & reception and they are being investigated for applications like last-mile connectivity, biomedical applications, multi-campus networks, military access, Metropolitan Area Network (MAN), backhaul of cellular communications, disaster management and recoveries. To sum up, the major advantages of FSOC systems are as listed [7]:-

- (a) Lasers used at Tx have narrow beam width giving high-grade security features unlike RF.
- (b) FSO offers 2000 THz Bandwidth (BW) leading to enhanced channel capacity.
- (c) It is installed with lower costs compared with the equivalent data rate RF systems.
- (d) In FSOC, ISM bands (Industrial, scientific & medical application bands) used are unlicensed. No spectrum regulations are applicable leading to much lower initial investments and operational/maintenance cost.
- (e) FSOC technology has low installation time frames, flexibility, rapid deployability in multiple architectures. It is an environmentally friendly and clean technology.
- (f) FSO is highly secure because optical interceptors that tap the transmitted beams are not there in intended narrow paths between transceiver pairs and no special security frameworks required view protected framework.
- (g) FSO uses lightweight & small equipment with no end-to-end cabling or intermediate transducers.
- (h) It has better transparency/interoperability & underlying transmission protocols are not altered.
- (i) Mean time between Failure (MTBF) is much better compared to RF systems.
- (j) Lower Power consumption with small beam divergence angle with better focus.
- (k) EMI/EMC resilience & electrical isolation due to the photonic nature of the signal.
- (l) Highly focused lasers provide least multipath propagation, fading & flexible topology.

3. Major Applications of FSOC

The fast deployability of the FSOC is poised to revolutionize the telecom & IT industry through migration from tower-based systems to more reliable unmanned and unsupervised communications systems that are more resilient & lower in cost. Humanitarian & homeland defense applications can be revived from damages using temporary FSO networks. Cinema, firefighting applications, medic

alfield,telecast,broadcast,securityapplications,equipmentforLawEnforcementAgencies(LEA),powermonitoringarefewcasesstudiedofcommercialFSOCprojects.Space,satellitecommunication,militaryapplications&terrestrialsystemsareseeingfastgrowthofrearchesonFSOCsystemsviewcompulsionsofbetterBERanddatarates.Byvirtueofutilizingtowersandbuildingsupport,laser-basedFSOCplatformscanbeinstalledrapidlyinminimumtimeframes,unlikeRF&satellitecommunicationequipment.MajorapplicationsofFSOCsystemsareencapsulatedbelow[8,9]:-

(a)StorageAreaNetwork(SAN).SANcanbeframedupthroughtheFSOCsystemfacilitatingintegratedandindividualdatapiecestocklevels.

(b)RemoteCommunication-

Outdoors.Idealforremotelyoperatingorganizationsforimplementingcommunicationinabsenceofflicenses/specialpermits.

(c)ReinforcementtoFiber.Itprovidesreinforcementsincaseoffailureoffiber-basedsystems.

(d)CellularSystemsApplications.Itprovidesfastdataratestocellularmobilenetworktraffic.

(e)MilitaryAccess.Itisasaft,undetected&imperceptibleframeworkconnectingzones;

SUITABILITY ANALYSIS OF FSO SYSTEMS IN THE MILITARY ENVIRONMENT

This chapter analyzes the suitability of FSO systems in the military environment. When discussing the military environment there are two factors that must be considered. First, there is the combat or tactical environment. Combat operations have unique communication requirements that are not necessarily directly translated from the civilian sector due to the need to operate in remote locations under very harsh conditions. Second, there is the administrative environment. The administrative environment would correlate to a major military installation that has access to a robust communication backbone like fiber optic cable. The military administrative environment's communication requirements, in many cases, translated directly from the civilian environment. The vast majority of the military operates in the administrative environment. Nevertheless, it can quickly change to the combat environment in the event of an attack. This chapter considers these requirements and weighs whether or not FSO is a viable option. This chapter analyzes each of the categories that were used to classify the dynamic FSO systems in the taxonomy presented in Chapter II.

A. GROUND-TO-GROUND

Ground-to-ground FSO links can be either bestatic, where both ends of the link are fixed, or dynamic where one or both links are capable of being operated while mobile. An example of a static ground-to-ground link in the military environment would be a link between a higher and lower headquarters COC. An example of a dynamic ground-to-ground link would be an operational link between two moving tactical vehicles such as A1A Abrams tanks.

1. Static

Static ground-to-ground FSO has been implemented with resounding success worldwide in the civilian sector and can be a very viable option for the

military. These systems are designed for establishing networks for enterprise and campus like environments. Military bases fit into this category. There is a significant demand for broadband network connectivity on and between military installations both domestically and abroad in both tactical and non-tactical environments. Of all the available FSO systems, static systems have been in production the longest and have proven performance records. These systems can be installed quickly and cheaply without expending the labor to lay cable or place personnel in harm's way. Furthermore, they are available as a commercial off the shelf (COTS) technology that can be acquired through the General Services Administration (GSA) for immediate deployment.

a. Intra-Base Networking

Intra-Base networking, or networking within the base, would be a direct translation of FSO technology from the civilian sector to the military for non-tactical applications. Most of the buildings on military installations are in fairly close proximity to another building, well within the range of capable FSO systems. Tactical applications, such as networking a remote Forward Operations Base (FOB) or Patrol Base (PB) may require more ruggedized equipment. However, this could be achieved through minor modifications to the COTS equipment. It should not be the intent to set up a network between all of the buildings on an installation, but to incorporate FSO in areas where there is a demand for fiber-like broadband connectivity and laying fiber optic cable is not viable due to operational constraints, cost, or safety to personnel.

I. Furthermore, an FSO-

RF hybrid solution with a sufficient tracking capability should be used to ensure maximum link performance and availability in all atmospheric conditions and periods of increased base motion caused by heavy vehicle and aircraft traffic as well as shock waves from exploding ordnance.

The high demand for broadband connectivity within COCs was discussed in Chapter I, and FSO would be able to meet that need. However, another area where there is an extremely high demand for broadband connectivity within

military installations is on the networks provided by Morale, Welfare, and Recreation (MWR). When deployed, military personnel rely very heavily on Internet connectivity for communication and entertainment purposes. As a

result it is not uncommon for Internet café's to be established by MWR

on

remote FOBs and for the larger bases to provide installation-wide Wi-

Fi access. These networks are stressed heavily by servicemembers conducting video and voice calls, downloading content, and streaming video. Low bandwidth makes call quality poor, and stresses the servicemember trying to communicate with friends and family. Incorporating FSO into these networks would improve their performance.

b. Inter-Base Networking

Inter-

Base networking, or networking between installations, presents a greater challenge due to the increased link distance requirements. In the case of non-

tactical military installations there is a high likelihood of access to the fiber infrastructure negating the need for FSO inter-

Base networking. However, tactical military installations are unlikely to have access to a secure wired infrastructure. Therefore, they must be connected by wireless means. Tactical military installations are usually placed within a proximity to other tactical military installations so that they can mutually support one another in the case of an overwhelming enemy attack. This usually translates to a few kilometers or even less in high threat environments. Again, this is well within the range of capable commercial FSO systems. For longer distance requirements, systems such as TALON, with a max range of 50 km [2], would prove effective. However, as distance increases obstacles may become an issue when trying to establish LOS between FSO units. Techniques such as elevating the unit and communication relay may be used to increase range and mitigate LOS issues as long as such techniques are tactically feasible.

c. Communication Relay Stations

FSO systems would also be a viable option for static ground-

based communication relay stations. However, considerations should be given to the relatively fragile nature of an FSO link due to poor atmospheric conditions and the LOS requirements. A hybrid solution, which incorporates FSO and RF communications, would probably be most viable in the case of communications relay. This would afford the station the bandwidth and security benefits of FSO communications in favorable conditions and the availability of RF communications otherwise.

d. Hastily Formed Networks

The ability to rapidly establish and reestablish communications is paramount in military operations. FSO and FSO-hybrid systems have the ability to set up high bandwidth links extremely quickly via the "flyaway" kits discussed in Chapter II. They are capable of doing so without interfering with RF communication through the use of IR energy and unlicensed radio frequencies. This is ideal for reestablishing communications in a disaster relief or post-attack situation where the communication architecture has been damaged or destroyed. This capability has already been proven in the civilian sector following the terrorist attacks on the World Trade Center in 2001 [13].

2. Dynamic

FSO would prove very beneficial in ship-to-ship and ship-to-

shore communications. This was demonstrated using the TALON system [2]. The likelihood that LOS between two ships on the open ocean, or the LOS between a ship at sea and a shore-

based communications station is blocked is minimal assuming proper maneuver coordination. Increasing the number of ships potentially would allow for a more robust network, again assuming proper coordination. Without proper coordination, the likelihood of link blockage grows as the number of ships in the area increases and as the communication station

ismovedfurtherinland.SomeofthechallengesencounteredinestablishingFSOlinksonsurfaceships canbefoundin[93].

For nearly every other tactical or administrative communications scenario a dynamic ground-to-ground FSO communication link is not suitable, except in applications that would require very short transmission ranges. This is simply due to the LOS requirement. Establishing and maintaining LOS over the ground dynamically would be difficult, if not impossible, especially in a tactical scenario where cover and concealment is required. Currently, most tactical ground communications are done over VHF frequencies vice UHF frequencies for this very reason. VHF frequencies are better able to mitigate obstacles between communication nodes. UHF is primarily used for air-to-ground and air-to-air communications due to its ability to transmit over longer distances with a better quality signal. However, UHF requires LOS. From personal experience, UHF frequencies have nowhere near the LOS requirements of FSO. With UHF, it is possible to establish a communication link from a covered position, such as under a tree or inside a building, to an aircraft. With FSO this would not be possible. Nevertheless, UHF is still considered unsuitable for ground-to-ground communications.

B. AIR-TO-GROUND

An air-to-ground FSO link is one established between an airborne platform and either a static or dynamic ground station. An example of an air-to-static ground link would be the FMV from a UAV transmitted back to a COC or to the UAV's static control center. An example of an air-to-dynamic ground FSO link would be a UAV transmitting its FMV feedback to a moving vehicle or foot mobile combat troop.

1. Dynamic Air to Static Ground

An FSO link from an airborne platform down to a static ground station may prove beneficial in both military and civilian communications. LOS is easily obtainable from an airborne platform as long as that platform has the ability to fly

at an altitude that can support an adequate look angle from the ground station to the airborne platform, and as long as the ground station transceiver is able to be exposed for signal transmission and reception. This is almost always achievable with high flying fixed-wing aircraft and high-altitude airships. However, lower flying rotary-winged aircraft and smaller UAVs may not be able to establish and maintain continuous LOS due to tactical necessity or aircraft limitations. This might be acceptable in certain communications scenarios as long as the link can be quickly reestablished. Vial Light successfully demonstrated this application of FSO with its MLT-20 system from a Tornado fighter jet [78]. John Hopkins University Applied Physics Lab and AOptix also demonstrated this capability by establishing an 80 Gbps link between a tethered aerostat and a ground terminal [80].

2. Dynamic Air to Dynamic Ground

The suitability of an FSO communications link from an airborne platform to a dynamic ground station is marginal. This is again due to the LOS requirement. Whether the ground station is vehicle-mounted or man-portable there is a very high likelihood that the movement of the ground station will inevitably find it in a position where an obstacle, man-made or natural, will interrupt the LOS between it and the airborne platform. A hybrid solution might work for this scenario, but size, weight, and power must be carefully considered especially for man-portable ground transceivers. For this reason, RF systems such as the Ghost Link are a more viable option for tactical scenarios.

The Ghost Link system, shown in Figure 53, is a high-bandwidth RF solution for air-to-dynamic-ground links currently being developed by General Atomics Aeronautical Systems Inc.

SUMMARY, CONCLUSION AND RECOMMENDATIONS

A. SUMMARY

This research surveyed the current state of FSO communications and then analyzed its suitability for application in the military operating environment. This was completed by first providing a thorough background of FSO to provide an understanding of their capabilities and limitations. Next, a systematic survey of current FSO systems relevant to military communications was

as completed. From this survey, a matrix of system capabilities and limitations was populated for ease of reference. Then the Analytical Hierarchy Process (AHP) was introduced, as a means of choosing an appropriate system, and an example was given of its application. Next, an experiment was conducted using two systems, establishing two separate links simultaneously to gain hands-on experience and an understanding of realistic performance expectations. Finally, a suitability analysis of FSO was completed for communications scenarios typical to the military operating environment.

The military has an ever-increasing demand for bandwidth in a very RF dense operating environment. The ability for FSO communication to securely transmit very large data rates impervious to RF energy makes it very appealing as a possible military communications solution.

B. CONCLUSION

FSO communication is a viable solution for certain military applications. There are undeniable performance advantages of FSO over RF communications for certain scenarios under certain conditions. The modulated light of FSO is capable of supporting much larger bandwidths than RF frequencies. The collimated laser energy of FSO provides LPI and LPD qualities making it very resistant to exploitation. FSO's immunity to RF interference makes the signal resilient to jamming and allows operation without frequency deconfliction. These benefits are significant for military communications where a great deal of money is spent on equipment and software and effort expended securing RF communications usually resulting in degraded link performance. However, there are also considerable limitations to FSO that prevent it from being a direct replacement for all RF communication links. These limitations are atmospheric interference, a strict LOS requirement and a limited ability to conduct areatransmissions.

The performance of an FSO link is directly correlated to the atmospheric conditions within which it is operating. Particulates in the air, turbulence and air density all impact FSO link performance. For this reason, it is difficult to accurately determine how FSO will perform in a given environment over time until it can actually be tested in that environment for an appropriate period of time. This is also true for RF communications, but the effect that atmosphere has on FSO is much greater than on RF. This is very concerning when considering FSO as a communications solution where high-availability in all weather conditions is a priority. Implementing a hybrid FSO-RF solution can mitigate link degradation in unfavorable atmospherics. However, in doing so the LPI/LPD and RF immunity of the link is compromised. Additionally, there are several possible applications of FSO where adverse atmospheric conditions will most likely not be encountered. These include space applications, high altitude air-to-air links and on UAVs that are only capable of operating in visual meteorological conditions (VMC) due to ISR sensor and/or aircraft limitations.

The requirement for LOS is the biggest limitation to FSO because it will simply not operate without it. Establishing LOS in tactical situations can be difficult and dangerous as it usually involves elevating and exposing the transceiver, the operator or both. Due to the LOS limitation, FSO systems are most suitable for static ground-to-ground, static ground-to-air, air-to-air and space applications. The LOS requirement makes FSO unsuitable for dynamic ground-to-ground and marginal for dynamic ground-to-air links, except in applications that only require very short transmission ranges. There are merely too many obstacles encountered between two moving ground stations and

between a moving ground station and an airborne platform. The exceptions to this are FSO links between surface ships, between a surface ship and an airborne platform and for ship-to-shore communications. The open sea provides a relatively obstacle-free environment across its surface. However, links over the ocean eventually fall victim to the LOS requirement due to the curvature of the Earth.

The collimated laser energy used in FSO communications aids in the security of the link through LPI and LPD, but is not effective in disseminating information to multiple receivers. The only way to transmit, from a single transmitter, over an area is by increasing beam divergence. As beam divergence increases, the range of the link decreases. Currently, FSO is not suitable for applications requiring the dissemination of information to multiple, geographically dispersed nodes from a single source.

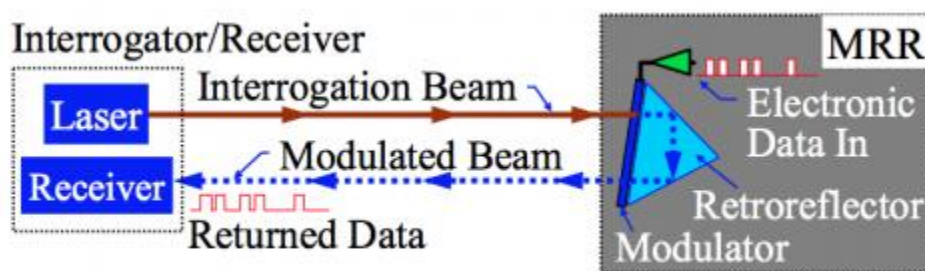
C. RECOMMENDATIONS Research in the area of FSO communications should continue to be aggressively pursued. The bandwidth, security, and RF immunity qualities of FSO communications present too many benefits to communications in the military environment to be ignored. This research should focus on better understanding the capabilities of current systems, improving the performance of

FSO in adverse atmospheric conditions, and exploring applications of FSO systems in the military communications construct.

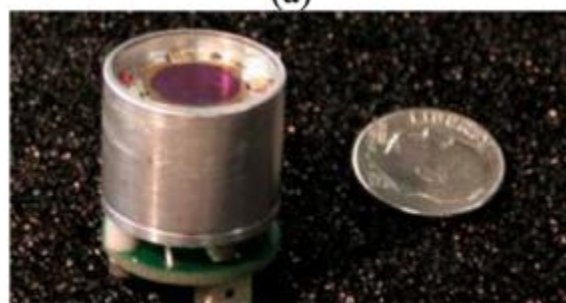
D. FUTURE WORK

1. Modulating Retro-reflectors (MRR)

The Naval Research Laboratory (NRL) has been conducting research on FSO since 1998. Some of their recent work has been in the area of modulating retro-reflectors (MRR). One of the current limitations to a standard dynamic FSO link is that a turret/gimbal is required at both ends of the link. This adds considerable complexity to the design and increases the cost, size, weight and power (CSWaP) requirements of the systems. An MRR, pictured in Figure 55, is very small and alleviates CSWaP requirements for one end of the FSO link [97].



(a)



(b)

Figure 55. A(a) MRR system diagram and (b) MRR transmitter, from [97].

This is potentially a very valuable application of FSO technology, especially in airborne applications where CSWA requirements tend to be more stringent. The NRL's work on MRRs has been published in [97]. The Command, Control, Communications, and Intelligence Division of the Australian Defence Science and Technology Organisation expanded on the work done by the NRL. That work can be found in [98]. Future work with MRRs should focus on the following areas:

- (1) Validate interrogation of an airborne MRR by a ground-based FSO system.
- (2) Validate the ability of an airborne MRR to simultaneously modulate two independent interrogations signals from two distant ground-based FSO systems.

B.5 CONCLUSION AND RECOMMENDATIONS

The Laser Fires system is not currently ready for deployment nor would it be a viable option for dynamic links in its current configuration. There are several issues that need to be addressed before the system could be used in an operational setting. First, the issue of overheating must be addressed. Second, link acquisition must be sped up. Third, the size of the system must be reduced. Finally, data rates should be made adjustable allowing for optimizing the transmission rate according to the link performance as measured by signal-to-noise ratio or packet loss.

The design of the Laser Fire V3 needs to be improved to allow for greater dissipation of heat from elements inside the modem and transmitter boxes. Currently, the boxes are completely sealed. Their aluminum construction provides some relief due to its relatively high conductivity, however this alone is nowhere near sufficient. On day four at the hills site, the transmitter and modem were placed in the shade and in well-ventilated positions. Both were cool to the touch on the outside of the box. However, the modem still shut down due to overheating. Upon inspection it was found that the network card inside the modem was the only element hot to the touch.

Initial link acquisition is a fairly time-consuming process. It requires the operator to manually align the two units and then initiate an automated search pattern. Once the pattern is initiated the amount of time to acquire varies depending on how well the units were realigned manually and the system's search configuration. There were several instances where the search pattern failed to identify the opposite end of the link and had to be restarted. Additionally, during testing there were several instances where the LOS of the link was interrupted either by someone walking through the beam's path or a car driving through it. In nearly every instance this caused the link to drop and sent the system into an automatic reacquisition search pattern. Incorporating the use of Global Positioning System (GPS) coordinates, increasing the search area through adjustable beam divergence, and by implementing an interrogation protocol that allows the system to identify the established link with the correct unit may help in speeding up the acquisition process. A dynamic application would not be possible without near instantaneous link reacquisition.

In order to increase link quality the users should have the ability to dial back the bandwidth. If a high rate of packet loss is experienced at 1 Gbps bandwidth, adjusting the bandwidth to 100 Mbps may improve link quality. A bandwidth of 100 Mbps is sufficient for nearly every application and greater than most RF options.

It is recommended to continue research and development efforts with Space Photonics Inc. as well as exploring other FSO systems.

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