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Analysis of Free Space Optics as a Transmission Technology

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Abstract

Free space optics (FSO) is an emerging technology that has found application in several areas of the short- and long-haul communications space. From inter-satellite links to inter-building links, it has been tried and tested. As with any technology, FSO has worked much better in some applications than in others. In this white paper we analyze FSO from several angles, all from the perspective of finding where it can fit into the terrestrial data link picture.

The analysis we conducted of the technology has shown that FSO technology's inherent strengths are its lack of use of in-ground cable (which makes it much quicker and often cheaper to install), the fact that it operates in an unlicensed spectrum (making it easier from a political/ bureaucratic perspective to install), the fact that it can be removed and installed elsewhere (allowing recycling of equipment), and its relatively high bandwidth (up to 1 Gigabit per second (Gb/s) and beyond).

Despite these strengths, however, our analysis also revealed significant weaknesses. Specifically, we found that because FSO uses air as its transmission medium, its performance and reliability are severely limited, both potentially and actually. Atmospheric factors such as fog, dust, sand, and heat can easily cause significant degradation or even disruption of FSO links. Maximum range for FSO links may be stated in kilometers (km), but practical application has found that, in most cases, 200 to 500 meters provide telco grades of performance.

Our analysis showed that the application that FSO technology seems most suited to is clear weather, short distance link establishment, such as last-mile connections to broadband network backbones and backbone links between buildings in a metropolitan area network (MAN) or campus area network (CAN) environment. There is also significant potential for use of this technology in temporary networks, where the advantages of being able to establish a CAN quickly or being able to relocate the network in a relatively short time frame outweigh the network unreliability issues. It should be noted that tactical implementations of this technology, or any highly-mobile implementation, are possible, but in its current state FSO has challenges providing adequate enough reliability to be considered a solution for the mobile Warfighter without resorting to a hybrid solution of FSO paired with another transmission technology (typically Millimeter Wave). Finally, past and current implementations and tests indicate that any future implementations of FSO technology should be carefully evaluated to ensure that no potential link interruptions are a factor before making the decision to actually implement an FSO link.

INTRODUCTION.

A fiber optic communication link uses light sources and detectors to send and receive information through a fiber optic cable. Similarly, FSO uses light sources and detectors to send and receive information, but through the atmosphere instead of a cable (1). The motivation for FSO is to eliminate the cost, time, and effort of installing fiber optic cable, yet retain the benefit of high data rates (up to 1 Gb/s and beyond) for transmission of voice, data, images, and video. However, swapping light propagation through a precisely manufactured dielectric waveguide for propagation through the atmosphere imposes significant penalties on performance. Specifically, the effective distance of FSO links is limited; depending on atmospheric conditions the maximum range is 2-3 km, but 200-500 meters is typical to meet telco grades of availability. Thus, at present, FSO systems are used primarily in *last mile* applications to connect end users to a broadband network backbone as shown in Figure 1. Although FSO equipment is undergoing continuous development, the emphasis is on improving its application to local area networks (LAN) and, in some cases, MANs (e.g., to close a short gap in a ring network), but not to long-haul relay systems. The design goal of a long-haul transmission system is to maximize the separation of relays in spanning distances between cities and countries. For that purpose, FSO is uneconomical compared to fiber optic or microwave radio systems (2).

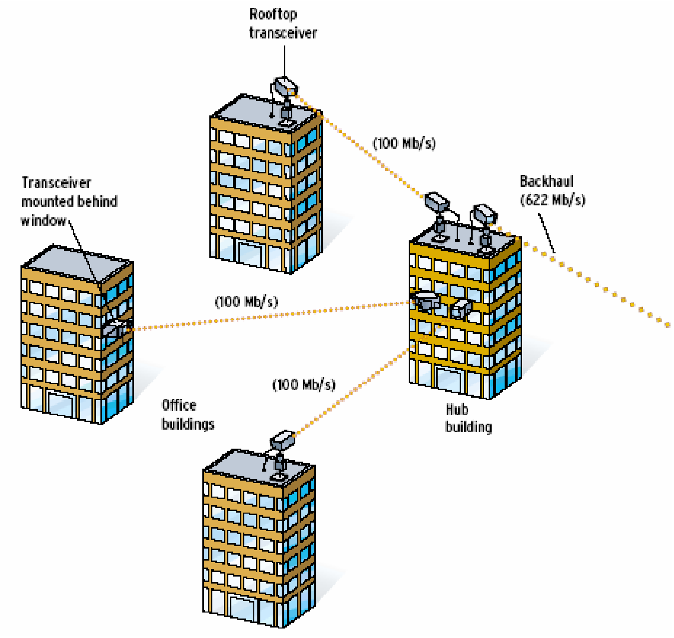

Figure 1. Example of End-user Access to Backbone Network using FSO. (Reproduced with permission from Institute of Electrical and Electronics Engineers (IEEE), © 2001, Willebrand, H.A. et al., "Fiber Optics without Fiber," IEEE Spectrum, Aug. 2001, Fig. 3.)

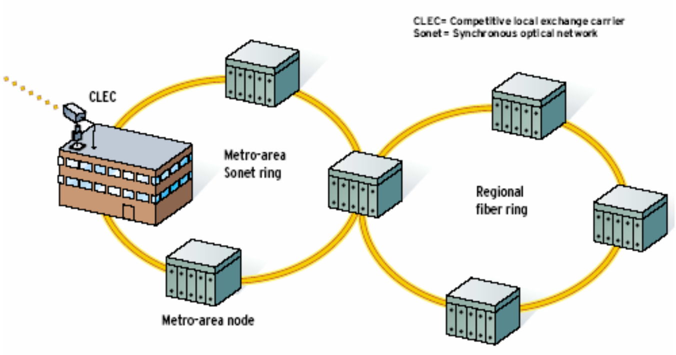

Figure 1 (continued).

In the following sections, FSO technology is described by comparing it to fiber optic communications for a single-link communication system. This provides a basis for understanding the direction FSO is heading relative to developments in fiber optics. Benefits of FSO are then considered, particularly those of military interest, such as portability and quick deployment. Drawbacks of FSO are discussed as well as some current research to overcome them. Finally, network considerations as well as current products and potential applications are discussed.

TECHNOLOGY DESCRIPTION.

General Framework.

Communication system design is concerned with tradeoffs between channel length, bit rate, and error performance. The generalized schema of a single-link communication system in Figure 2 provides the necessary framework to compare fiber optic and FSO technologies [ref 1]. Under each block are characteristics that transform its signal input to the different physical form of the signal output. The superscript N for each block transform represents noise contributed to the signal. For example, the "channel" block degrades the transmitter output signal due to processes listed under the block for fiber optic cable or FSO.

Although both are optical communication systems, the fundamental difference between fiber optic and FSO systems is their propagation channels: dielectric waveguide versus the atmosphere. As a consequence, signal propagation, equipment design, and system planning are different for each type of system. The main thesis of the following discussion is that, because of their different propagation channels, the performance of FSO cannot be expected to match that of advanced fiber optic systems; therefore FSO applications will be more limited.

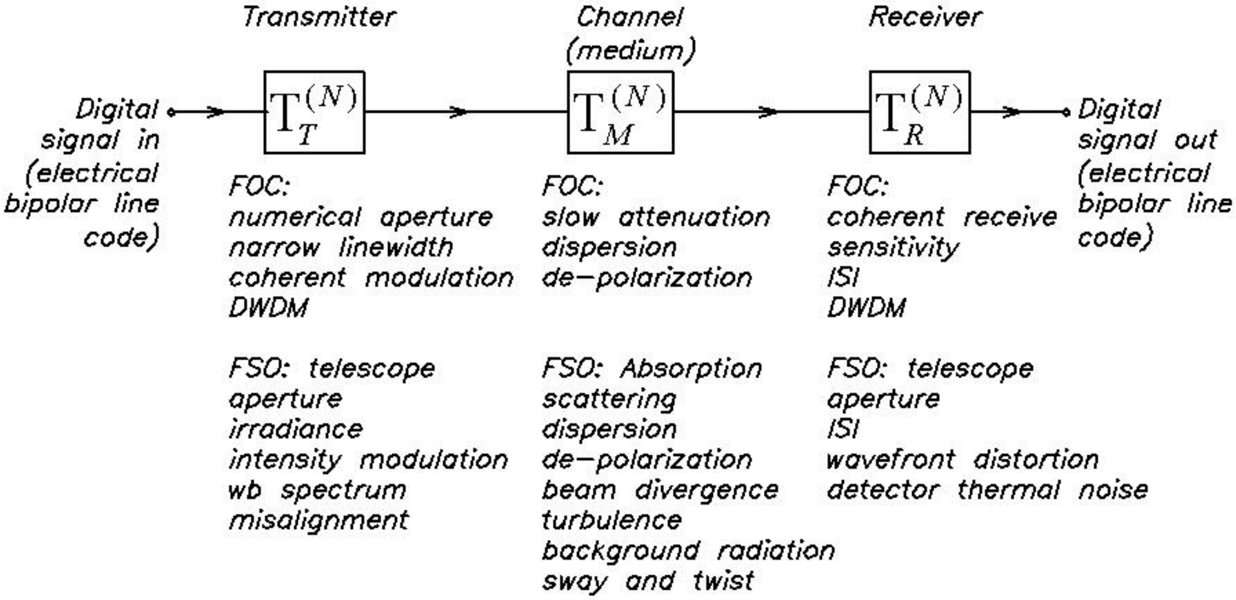

Figure 2. Single-link Communication System

Optical Fiber Evolution.

The evolution of fiber optics has been to increase the distance of unrepeatered communication links at higher and higher bit rates while maintaining a specified level of error performance (e.g., 10^{-9}). In the way of historical summary [ref 2, 3], the first generation of fiber optics employed 0.8 µm multimode fiber for a maximum bit rate of 1 or 2 Megabits per second (Mb/s) over repeater spacings of about 10 km. The second generation shifted the wavelength to 1.3 µm over multimode fiber for a small increase in bit rate, but a significant increase in distance (~50 km). The third generation changed to single mode fiber optimized for 1.3 µm and introduced multifrequency laser light sources. This breakthrough generation attained data rates up to 1 Gb/s over roughly 100 km spacing. The fourth generation changed to single mode fiber optimized for 1.5 µm wavelength and introduced single-frequency laser sources for yet more capacity and distance. The present fifth generation introduced the coherent optical communication system in which the detector uses a local oscillator for greater receiver sensitivity. This has enabled *dense wave-division multiplexing* (DWDM) in which a single fiber can transmit multiple channel wavelengths, analogous to the *frequency division multiplexing* (FDM) of analog carrier cable and microwave systems.

In the laboratory, to quote Davis et al [ref 4], "at least 10 Terabits per second (Tb/s) of capacity on a single fiber had been demonstrated as of early 2002." Today the highest capacity commercial fiber optic system operating in the world is the i2iCN submarine cable linking Singapore and Madras, India. This is an end-to-end optical channel comprised of eight fiber pairs, each using DWDM to carry 100 channels of 10 Gb/s for a total design capacity of 8.4 Tb/s with 10^{-13} bit error rate (BER). Next generation commercial systems are projected to go beyond 10 Tb/s [ref 5].

An important thread from generation to generation is the continuous advancement in fiber technology in terms of materials, design, and manufacturing. Of course, advances in other fiber optic components (light sources, detectors, modulators, etc.) are interlocked with the progress of fiber, but the key point is that improvements in fiber optics depend significantly on technical advances in properties and characteristics of the fiber *channel*. It is on this point that a major difference between fiber optics and FSO becomes apparent, because in the latter case one has no control over the atmosphere, except to limit its unpredictability by keeping links short. Thus, improvements in FSO technology cannot be expected to depend on its channel: the atmosphere. Instead, the future development of FSO will amount to adding features to optical transmitters and receivers to overcome inherent disturbances in the atmosphere, which as a channel cannot itself be improved beyond a judicious choice of path.

Optical Fiber Characteristics.

The basic characteristics of an optical fiber are *attenuation, numerical aperture, dispersion,* and *polarization loss*. *Attenuation* is defined as the diminishing intensity of a propagating beam caused by physical processes, and the increasing distance from the source. The general form of attenuation is expressed mathematically as an exponential decay over distance,

$$I(x) = I_0 e^{-\alpha x} \quad (1)$$

where I_0 is the optical intensity (watts) at the source, $I(x)$ is the beam's intensity at a distance of x meters, and α is a positive real-value empirical attenuation coefficient of the atmosphere (meters^{-1}). All the empirical physical processes that cause the exponential weakening of an optical beam over distance are subsumed in I_0 and α [ref 6].

Signal attenuation in optical fibers, due to molecular absorption and Rayleigh scattering, continues to be reduced. It is also important to note the dependence of attenuation on the wavelength of light. Considering both the material medium of a fiber and light source, compared to window glass, which has an attenuation of 50,000 decibels (dB)/km, crystalline KCl has an attenuation of 0.0001 dB/km at 6 µm wavelength. Analogous advances for light propagation through the atmosphere are not possible since it is an uncontrolled medium.

Numerical aperture is the allowable angle within which light enters a fiber. Within this light acceptance cone, nearly perfect internal reflection occurs along the entire length of the fiber. Thus the light signal in a fiber is not attenuated due to beam divergence as would be the light spreading from a source through free space.

Chromatic dispersion is the characteristic of a channel that causes signal pulses to broaden as they propagate along the line. If the broadening is sufficient so that pulses begin to overlap, then *intersymbol interference* (ISI) results, which makes detection of individual pulses more difficult, and BER increases. During the manufacture of single-mode fiber, *material* and *waveguide* dispersion are processed so as to shift total dispersion to the minimum dispersion wavelength of 1.55 µm. In FSO operation, dispersion shifting techniques cannot be applied to the atmosphere (3).

Finally, single-mode fiber is susceptible to *polarization (modal birefringence) loss* for coherent fiber optic systems. Polarization controller devices and polarization maintaining fiber exist to remedy this problem. Narrow linewidth laser sources and coherent optical detection are the basis for the greater transmission capacity of DWDM and the greater transmission distance on a single fiber [ref 7]. To date, commercial FSO systems do not use coherent optical techniques, and it is not clear whether such techniques are feasible over an FSO link. However without them, the transmission capacity and distance of FSO appear to be limited to what can be accomplished using intensity modulation (i.e., on-off keying (OOK).

FSO Characteristics.

A generalized FSO system is shown in Figure 3, and the optical transmitter and receiver are shown in greater detail in Figure 4. The baseband transmission bit stream is an input to the modulator, turning the direct current bias current on and off to modulate the laser diode (LD) or light emitting diode (LED) light source. The modulated beam then passes through a collimating lens that forms the beam into a parallel ray propagating through the atmosphere. A fundamental physical constraint, the *diffraction limit*, comes into play at this point. It says that the beam of an intensity modulated (non-coherent) light source cannot be focused to an area smaller than that at its source [ref 6]. Apart from the effects of atmospheric processes, even in vacuum, a light beam propagating through free space undergoes divergence or spreading.

Recalling the single-link communication system in Figure 2, the transmitted FSO beam is transformed by several physical processes inherent to the atmosphere: frequency-selective (line) absorption, scattering, turbulence, and sporadic misalignment of transmitter and receiver due to displacement (twist and sway) of buildings or structures upon which the FSO equipment is mounted. These processes are *non-*

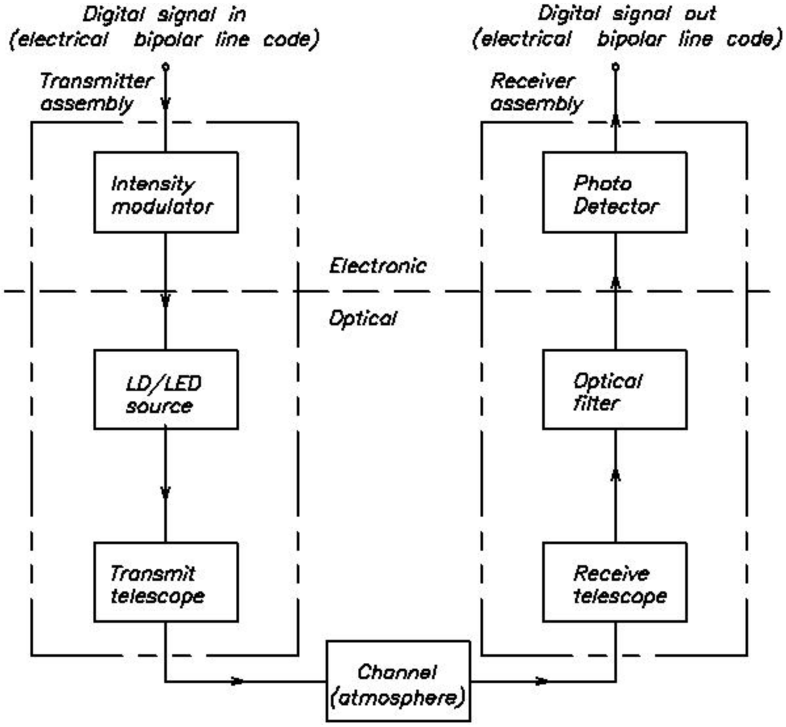

Figure 3. Block Diagram, FSO Communication System

stationary, which means that their influence on a link changes unpredictably with time and position. At the distant end, a telescope collects and focuses a fraction of the light beam onto a photo-detector that converts the optical signal to an electrical signal. The detected signal is then amplified and passes to processing, switching, and distribution stages. The basic signal processing functions of the transmitter and receiver are shown schematically in Figure 4. Figure 5 is an illustration of a simplified single-beam FSO transceiver that shows how the major functional blocks of the equipment are arranged and integrated.

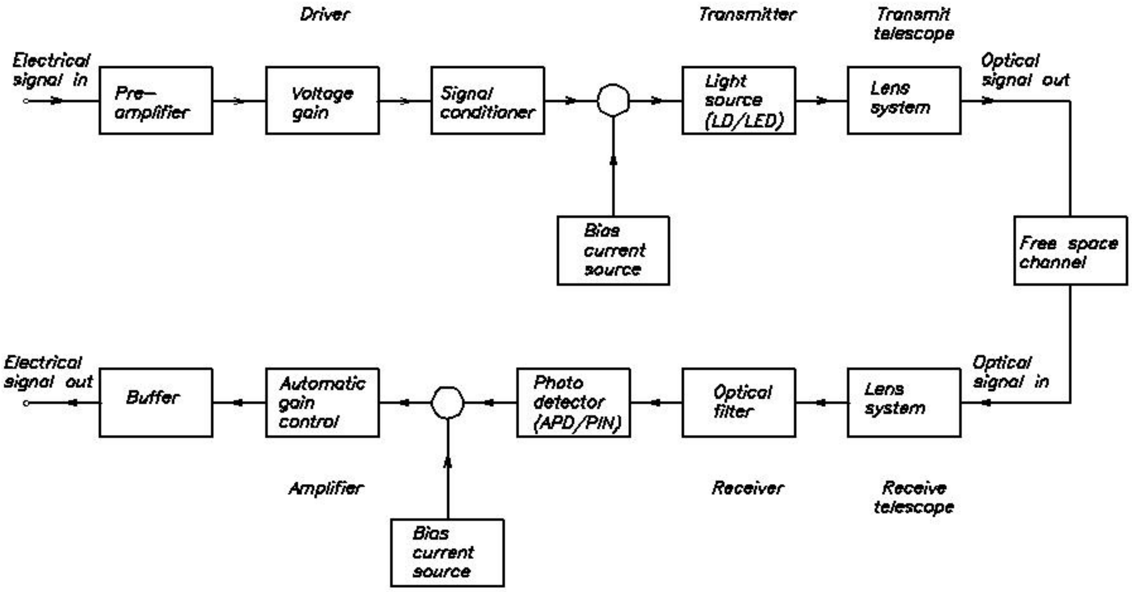

Figure 4. Block Diagram of Fiber Optic Transmitter and Receiver Assemblies (based on MIL-HDBK-415) [ref 12]

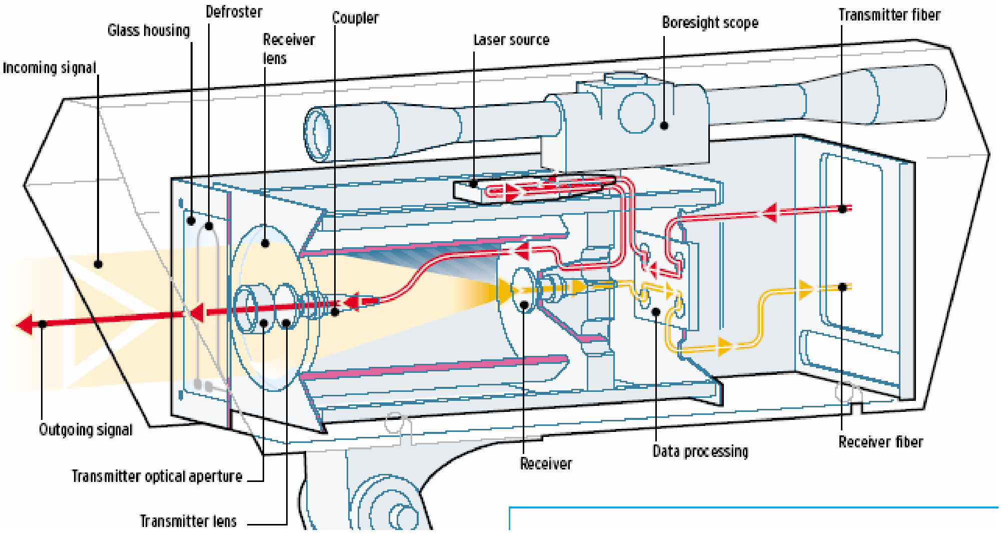

Figure 5. Single-beam FSO Transceiver. (Reproduced with permission from IEEE, © 2001, Willebrand, H.A. et al., "Fiber Optics without Fiber," IEEE Spectrum, Aug. 2001.) [ref 8]

The non-stationary atmospheric processes, *divergence* (or *beam spreading*), *absorption*, *scattering*, *refractive turbulence*, and *displacement*, are the factors that most limit the performance of FSO systems. A brief description of each is given in the following paragraphs.

Divergence. Divergence determines how much useful signal energy will be collected at the receive end of a communication link. It also determines how sensitive a link will be to displacement disturbances (see below). Of the processes that cause attenuation, divergence is the only one that is independent of the transmission medium; it will occur *in vacuo* just as much as in a stratified atmosphere. Laser light can be characterized as partially coherent, quasi-monochromatic electromagnetic waves passing a point in a wave field [ref 15]. At the transmitter, beam divergence is caused by diffraction around the circular aperture at the end of the telescope. The half-angle β of the beam spread is

$$\sin\beta = \frac{1.22\lambda}{D} M^2 \quad (2)$$

where λ is the laser wavelength, D is aperture diameter, and M is the dimensionless laser mode structure parameter value. In practice, an FSO transmit beam is defocused from the diffraction limit enough to be larger than the diameter of the telescope at the receive end, and thus maintain alignment with the receiver in the face of random displacement disturbances.

Absorption. Molecules of some gases in the atmosphere absorb laser light energy; primarily water vapor, Carbon Dioxide (CO_2), and Methane, Natural Gas (CH_4). The transmission spectra in Figure 6 show wavelength dependent absorption lines caused, in part, by light energy exciting resonant vibrational and rotational modes in gas molecules. The presence of these gases along a path changes unpredictably with the weather over time. Thus their effect on the availability of the link is also unpredictable. Another way of stating this is that different spectrum windows of transmission open up at different times, but to take advantage of these, the transmitter would have to be able to switch (or retune) to different wavelengths in a sort of wavelength diversity technique.

Scattering. Another cause of light wave attenuation in the atmosphere is scattering from aerosols and particles. The actual mechanism is known as *Mie scatter* in which aerosols and particles comprising fog, clouds, and dust, roughly the same size as the light's wavelength, deflect the light from its original direction. Some scattered wavelets travel a longer path to the receiver, arriving out of phase with the direct (unscattered) ray. Thus destructive interference may occur which causes attenuation. Note how attenuation is much more pronounced for the spectrum in 6(b) for transmission through fog.

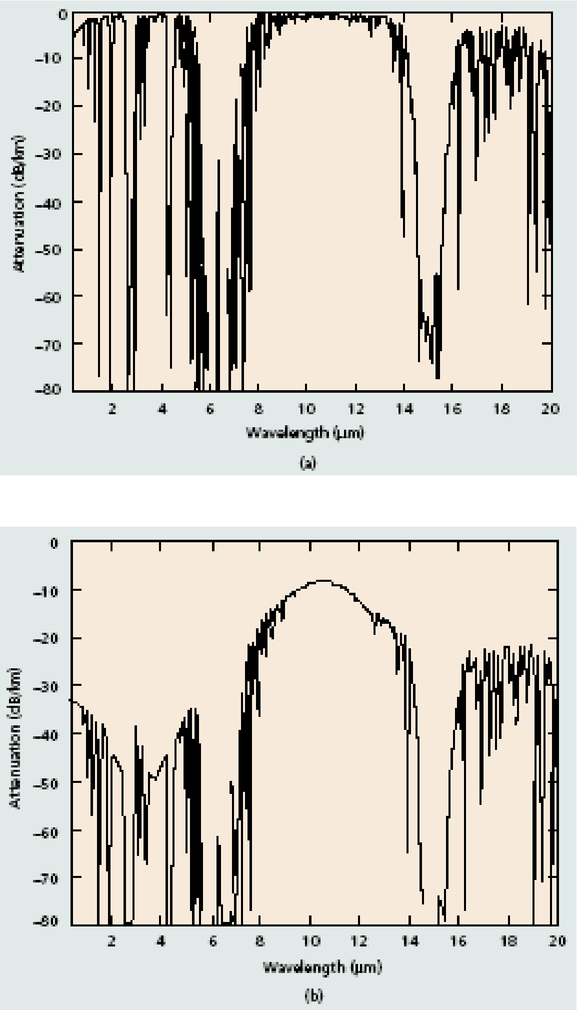

Figure 6. Transmission Spectra for Light Traveling through (a) Clear Air, and (b) Moderate Fog. (Reproduced with permission from IEEE, © 2003, Kedar, D. and Arnon, S., "Urban Optical Wireless Communication Networks: the Main Challenges and Possible Solutions," IEEE Comms. Mag., Feb. 2003, Fig. 3.)

Refractive turbulence. The photograph in Figure 7 shows the change from a smooth laminar structure of the atmosphere to turbulence. In the laminar region light refraction is predictable and constant, whereas in the turbulent region it changes from point to point, and from instant to instant. Small temperature fluctuations in regions of turbulence along a path cause changes in the index of refraction. One effect of the varying refraction is *scintillation*, the twinkling or shimmer of objects on a horizon, which is caused by random fluctuations in the amplitude of the light. Another effect is random fluctuations in the phases of the light's constituent wavelengths, which reduces the resolution of an image.

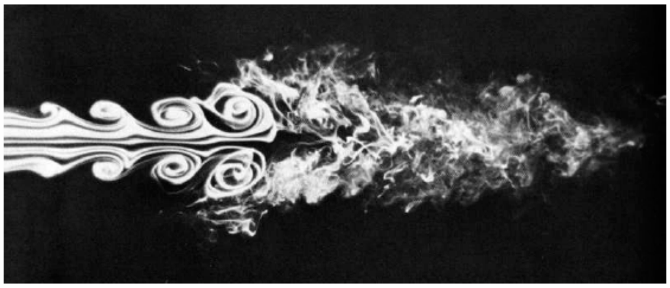

Figure 7. Transition from Laminar to Turbulent Flow in the Atmosphere

Refractive turbulence is common on rooftops where heating of the surface during daylight hours leads to heat radiation throughout the day. Also, rooftop air conditioning units are a source of refractive turbulence. These items must be considered when installing FSO transceivers to minimize signal fluctuations and beam shifts over time.

Displacement. For an FSO link, alignment is necessary to ensure that the transmit beam divergence angle matches up with the field of view of the receive telescope. However, since FSO beams are quite narrow, misalignment due to building twist and sway as well as refractive turbulence can interrupt the communication link. One method of combating displacement is to defocus the beam so that a certain amount of displacement is possible without breaking the link. Another method is to design the FSO head with a spatial array of multiple beams so that at least one is received when the others are displaced. The latter technique circumvents the problem of displacement without sacrificing the intensity of the beam.

FSO Transmission Formula. A transmission formula allows one to calculate the useful signal power transferred from a transmitter to a distant receiver over a desired link. The FSO transmission formula in Killinger [ref 6] elaborates on the law of exponential decay of Eq. 1 above:

$$P_R = P_T \cdot \left(\frac{A_r}{A_t} \right) \cdot T \cdot K \cdot e^{-\alpha R} \quad (3)$$

where P_R is the received optical signal power, P_T is the transmitted optical power of the laser or LED, A_r is the area of the receive telescope lens, A_t is the transmitted beam's cross sectional area at the receive telescope lens, T is a combined transmitter-receiver optical efficiency, K takes the value 1 for a laser and a fractional value for an LED, R is the link distance, and α is the empirical attenuation coefficient from Eq. 1.

The transmission formula guides system design. The choice of transmitter power considers trade-offs between types of sources (LD or LED), their costs, wavelength, and permissible power levels for eye safety. The ratio of areas accounts for the trade-off between beam divergence and displacement. Greater divergence means less power density, i.e., a weaker signal at the receiver, but allows for a looser tolerance in alignment. Although displacement as a stochastic process is accounted for in the attenuation coefficient, it is compensated for in the ratio of areas factor by adjusting A_t to control the divergence. Likewise the link distance R in the exponent is a design requirement, and its impact on divergence is implicit in A_r through Eq. 2. The factors T and K are strictly equipment parameters. All four factors taken together correspond to the intensity I_0 at the source in Eq. 1. Finally the attenuation coefficient lumps together the effects of the atmospheric attenuation processes described in preceding paragraphs. For practical purposes α is obtained from graphs for different atmospheric conditions (clouds, fog, haze, Mie scattering, etc.) plotted against wavelength.

In addition to a calculated value of received signal power P_R, an estimate is required of the noise present during the signal detection process. It can be shown that an FSO system's *digital signal-to-noise ratio* (DSNR) is proportional to P_R over the sum of Gaussian variables for detector internal thermal noise and external background radiation noise [ref 16, 19]. DSNR and BER are the criteria for evaluating a link's performance.

Simulation studies of FSO system performance have been done [ref 16] using the *Moderate-Transmission (MODTRAN) Resolution* atmospheric model, developed by the U.S. Air Force's Phillips Laboratory, incorporated into the Matrix Laboratory (MATLAB) Program. The simulation outputs are transmission spectra of attenuation versus wavelength (refer to Figure 6), and plots of received background radiation power versus wavelength. These are combined to obtain plots of DSNR versus wavelength for background noise limited-, thermal noise limited-, or total noise-systems.

Maturity of the Technology.

As noted earlier, the free space propagation channel is essentially uncontrollable, so that FSO is more akin to microwave radio than to fiber optics. The opportunities for advancing the FSO art fall into two areas: equipment enhancements at the physical layer and system enhancements at the network layer. The physical layer enhancements would mitigate atmospheric and displacement disturbances, whereas the network layer would implement decision logic to buffer, retransmit, or reroute traffic in the event of an impassable link.

Equipment. Changeable atmospheric conditions along a path favor different wavelengths at different times; no single wavelength is optimal under all conditions. This raises the question whether FSO link performance can be improved by adaptively changing the source wavelength to match the conditions. Quantum cascade lasers (QCL), for example, can be tuned over a wide range of long-infrared (IR) wavelengths (4-20 µm) that includes the known atmospheric low absorption windows. Adaptive retuning to an optimal transmission wavelength, in response to dynamic conditions, might be done using either a single laser or an array of fixed wavelength lasers. In any case, one study indicates that adaptive retuning may result in only marginal improvements to link performance [ref 16]. At the receive end of a link, it turns out that the thermal noise from an array of small photo detectors is less than the noise from a single large detector with an equivalent field of view. Thus a significant improvement in the noise performance of FSO receivers is possible using the photo detector array.

Scattering through fog and dust causes pulse spreading that leads to inter-symbol interference. A decision feedback adaptive equalizer has been proposed [ref 17] to combat this effect, but the authors caution that it would be effective only for relatively low data rates. Furthermore, adaptive optics could use wavefront sensors, and deformable mirrors and lenses to reduce FSO wavefront distortion from refractive turbulence. One author claims that, under certain circumstances, adaptive optics could provide several orders of magnitude improvement in BER against scintillation caused by turbulence [ref 18].

Several commercial FSO products use pointing and tracking control systems to compensate for displacement induced alignment errors. Existing systems employ electromechanical two-axis gimbal designs, therefore they are relatively expensive to adjust and maintain. As a non-mechanical alternative, *optical phased arrays* (OPA) [ref 9] are under development in which the phase difference of an array of lasers is controlled to form a desired beamwidth and orientation. Such arrays would be part of both the transmitter and receiver assemblies so as to achieve the maximum alignment over a path. The algorithms for such control systems are also an active research area in which the goal is replace simple *proportional-integral-derivative* (PID) loops with *adaptive neural-network-based* algorithms that enable more accurate estimates of the stochastic processes of particular FSO links.

Network. At the network level buffering and retransmitting data are conventional communication protocol strategies, but they are less than optimal for networks bearing real-time services such as voice and video in addition to computer data. The concept of *topology control* has been proposed [ref 4, 9] as a method of dealing with link degradation or outages without interrupting services. The idea is to establish a mesh of stations over a desired coverage area that would adaptively reroute traffic in response to link interruptions. This scheme requires either a proliferation of point-to-point transceivers for the network or an advanced pointing and tracking control system to accomplish the rerouting. Sophisticated software would also be required to monitor and control the route switching.

Benefits of the Technology.

The attraction of FSO is its high data transmission rate and its exemption from spectrum regulation. The latter is especially significant for military ground forces setting up camps and forward operating bases overseas. Whereas application for frequency assignments in the United States is a ponderous process, in a foreign country it is all the more so, and fraught with some uncertainty; the request may be denied, or services may be impaired by interferers due to poor frequency planning or intentional jamming. At the very least it is time consuming. To be able to circumvent the spectrum management bureaucracy is a huge advantage given urgent communication requirements. Since light beams do not interfere with each other as long as they are not coaxial, commanders need not be concerned with electromagnetic compatibility problems. FSO is as ready a resource as a light bulb in a socket, and installation of FSO equipment is quick and inexpensive.

FSO's drawbacks in the commercial world are perhaps not as serious in the military context. Using short FSO repeater spacings for camp communications may still be more economical than installing fiber optic cable, and it allows more flexibility for re-routing lines of communication as the camp grows. In the Southwest Asia Theater for example, FSO could free up tactical equipment that has been used as a stop-gap for camp communications, and eliminate runs of loose field wire. FSO would carry all communication services, not just voice or data separately.

In the future the layout of new camps should perhaps plan for lanes for the paths of an FSO network. The transceivers should be placed low to the ground to employ short rigid mounts, but not so low as to be adversely affected by the bottom atmospheric layer disturbed by radiative heat energy from the ground surface.

Drawbacks or Challenges of the Technology.

Laser eye safety. It is important to keep in mind, especially if FSO is to gain widespread use for camp communications, that lasers must be operated within certain levels of irradiance [w/m^2] for eye safety. The harmful level of exposure is a function of wavelength and is tabulated in American National Standards Institute (ANSI) Standard Z136.1 [ref 20].

Disruption by weather. Although FSO may at times be capable of greater range, its greater susceptibility to degradation from incidents of heavy fog or dust will drive down its attainable availability figures. This will depend on which region of the world FSO is planned for. For example, frequent dust storms of such severity as to result in black out conditions often occur in tactical desert conditions. Furthermore, the summer heat in the desert and along coastlines induces extreme refractive turbulence that would cause optical defocusing and beam wander.

NETWORK CONSIDERATIONS.

Serial Networking Considerations.

Technical control facilities (TCF) are currently based on multiplexing data serially. The majority of the information processed through a TCF is serial data and voice. The usual multiplexing technique is Time Division Multiplexing (TDM) where each user is assigned to one (or more) ports of a multiplexer. All of the ports are then aggregated into one data stream. The current infrastructure allows transmission from point to point by many different means including radio transmission, wire, and fiber. FSO is able to transmit and receive this data seamlessly. User networks and the networks in the TCFs have started migrating to Internet Protocol (IP) based systems and will continue to do so. FSO is able to handle the transmission requirements for this migration.

Advantages

The transmission medium selection is based on many differing engineering requirements with cost and schedule being major considerations. FSO in serial transmission may be advantageous when requirements call for short transmission paths requiring quick installations. FSO devices have advantages to radio and fiber based systems if speed of installation is the dominating concern when providing the last mile connectivity. The setup of these systems is quick and as long as the distance requirements are within their scope of operation these devices may be considered as a viable option.

Disadvantages

As the serial data nature of TCFs change into IP based infrastructures point-to-point applications will decrease in favor of network centric infrastructures. This will reduce point-to-point applications in general. The limited link distance provided by FSO equipment limits the consideration of transmission applications to last mile applications. Path selection must be engineered to ensure that there are no obstacles that would impair signal quality.

IP Networking Considerations.

Characteristics of Transmission Control Protocol (TCP).

Because TCP does not differentiate between packet loss due to link errors and packet delay due to network congestion, FSO networking can be seriously crippled by packet loss due to signal attenuation (such as that caused by heat, fog, sand, or dirt). The effect of attenuation-induced packet loss is to invoke TCP's congestion control algorithms, seriously reducing throughput on any particular link.

Routing Protocol Issues.

To maintain link and path availability, multiple routes from each node must be maintained due to the easily disrupted nature of FSO networking.

Because FSO links are easily disrupted due to occlusion and other factors both on a very short time scale (millisecond to minute) as well as on a longer scale (minutes or more), normal routing protocols are not adequate. Normal routing protocols do not deal well with the very short time scale disruptions and, by design, are intended to deal with longer disruptions only (minutes or more). Three normal routing protocols, Routing Information Protocol (RIP), Open Shortest Path First (OSPF), and Enhanced Interior Gateway Routing Protocol (EIGRP), can take 10 to 90 seconds to discover a wireless link failure and re-route the traffic accordingly; during which time, data will be lost as the network will continue to attempt to use the failed link. To reacquire or reestablish a link that went down for perhaps a second or less at an inopportune time in the route status discovery cycle could take just as long.

Mobile Ad Hoc Network (MANET) Protocols are being developed to be more responsive to topology dynamics, but are better suited to bandwidth constrained links as they trade routing performance for a reduction in network overhead.

The best option that we have seen to date to overcome the routing problem is to exploit the ability of OSPF and EIGRP to respond to a loss of carrier at the physical interface. One study has shown that, after linking this to the existing re-route triggering mechanism in EIGRP, that re-routing can occur after 10 milliseconds as opposed to an average of 12 seconds.

(Pam Clark and Arjan Sengers, "Wireless Optical Networking Challenges and Solutions," MILCOM 2004, www.milcom.org/2004)

PRODUCTS AND POTENTIAL APPLICATIONS.

Current Products.

Current FSO technology is still developing. The number of manufacturers and types of systems are growing. In traditional FSO technology a single light source transmits to a single receiver. These systems typically have a throughput of 1 Gb/s. The distance transmitted is very limited from 200 to 1000 meters (typical systems operate up to 500 meters). Reliability of these devices is typically 99.9 percent in clear conditions, varying greatly depending on distance and weather conditions. The current cost of these systems is from $2500 - $3000 per unit (twice that per link).

These traditional types of FSO products were evaluated by USAISEC's engineering and evaluation facility, the Technology Integration Center (TIC) at Fort Huachuca, Arizona. The evaluations were to determine if an FSO solution could provide extensions to, a back up for, or an alternative to wired link technology in support of the Installation Information Infrastructure Modernization Program (I3MP). Recommendations for use were made for LightPointe Flight Spectrum 1.25G (TR. No. AMSEL-IE-TI-03067, July 2003), MRV TS3000G (TR. No. AMSEL-IE-TI-03070, July 2003), and Alcatel SONAbeam (TR. No. AMSEL-IE-TI-03081, September 2003). The Terabeam Elliptica (TR. No. AMSEL-IE-TI-03068, July 2003)) was recommended as a backup link only due to bandwidth limitations (TR No. AMSEL-IE-04009, November 2003). Another product, AirFiber 5800 (TR No. AMSEL-IE-TI-03059, July 2003) was not recommended, because the manufacturer is no longer in business.

Field testing was scheduled (TR No. AMSEL-IE-TI-05003) in Germany to test FSO technology over time and varying weather conditions. The preliminary field tests indicated that weather was a significant factor in link performance. In another military field application at the Pentagon, the SONAbeam S-Series FSO configuration performed with no link outages except when the line of sight path was blocked by helicopter air traffic. This was a point-to-point link and the loss of line of site path caused link outages. The link between the Pentagon and the Navy Annex covered approximately 500 meters. This loss of line-of-sight issue was significant at the Pentagon due to repeated path blockage by the air traffic eventually leading to the link being discontinued after 1 year of service.

Industry has recognized the weather anomaly as a significant issue. SonaBeam and WaveBridge systems have four redundant lasers transmitting to a receiver. This provides physical diversity, increases link performance, and allows for a limited extended range increase over single source FSO products. The range increase provides an additional 1000 meters extending the total link distance to 2000 plus meters. Several manufacturers such as Pulse's Omni-Node use active pointing and tracking control systems. FSO Mesh Network systems have also been developed. Omni-Node by Pulse provides three transceivers per device with an active tracking system. Also included in this product offering is redundant link fail-over.

Hybrid systems using FSO and millimeter microwave technology are also available. Such systems are available from AirFiber and LightPointe. Hybrid systems approach carrier class reliability of 99.999 percent over 1 km at 1.25 GBs. These systems reduce the vulnerability of FSO during heavy fog conditions by using the millimeter microwave path and conversely reduce the vulnerability of millimeter microwave during heavy rain by using the FSO system. The two weather conditions rarely are simultaneous. Distance limitations are still less than 2 kms.

Near Future Products.

Crinis Networks has introduced an FSO product that competes with Ethernet and Fast Ethernet LAN connectivity for indoor applications. Crinis uses the terminology "indoor Free Space Optics (iFSO)" to describe this application.

The Federal Communications Commission (FCC) issued license guidance for "E-Band" in October 2003. E-Band is an upper-millimeter wave band that operates over 71-76 Gigahertz (GHz), 81-86 GHz, and 92-95 GHz bands. It is licensed by the link, which can be done on line in a matter of days. It is meant to allow industry to use as a last mile solution for broadband applications. This technology should be a competitor with FSO and/or as part of the Hybrid system. Bandwidth of these devices is 1.25 Gb/s. Range is up to 2 kms. Manufacturers include Loea and ElvaLink. Costs are approximately $20K per link.

Potential Applications.

The current reliability of FSO systems with varying weather conditions severely limit the wide spread military application of these devices. Under conditions of rapid deployment requiring interconnected network nodes, these products provide a good temporary solution. This is especially true in urban areas. Due to the possibility of link interference due to obstruction and weather instability, the systems should be replaced with a cable infrastructure when possible. Mesh systems and multiple transmitter systems are an upgrade to the original FSO concept but have similar issues of reliability. Hybrid systems offer higher reliability and performance approaching carrier class reliability. Hybrid systems offer the most likely solution for military systems, but need further testing in varying conditions to confirm reliability in the deployed environment.

CONCLUSIONS.

This white paper presents analysis of several aspects of FSO. While it is obviously an up and coming technology, it could also easily be described as only mature enough in its current state to use in limited applications. The applications that FSO technology seems most suited to are clear weather, short distance link establishment, such as last-mile connections to broadband network backbones, and backbone links between buildings in a MAN or CAN environment.

There is also significant potential for use of this technology in temporary networks, where the advantages of being able to establish a CAN quickly or be able to relocate the network in the relatively short time frame outweigh the network unreliability issues. It should be noted that tactical implementations of this technology, or any highly-mobile implementation, are possible, but in its current state FSO has challenges providing adequate enough reliability to be considered a solution for the mobile Warfighter without resorting to a hybrid solution of FSO paired with another transmission technology (typically Millimeter Wave). Finally, past and current implementations and tests indicate that any future implementations of FSO technology should be carefully evaluated to ensure that no potential link interruptions are a factor before making the decision to actually implement an FSO link.

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ENDNOTES

(1) FSO communication links exist between satellites, where the propagation is through vacuum; thus the technical problems reduce basically to beam tracking and pointing over a long path. The other major applications of FSO are optical spatial switching between backplanes in interconnect and

computing devices and quasi-optical antenna feed systems in the millimeter- and sub-millimeter-wave regions of the spectrum [13]; however, the discussion in this paper is limited to terrestrial telecommunications.

(2) FSO in a repeater configuration might be appropriate at a forward operating base (FOB) where a network of FSO transceivers, including repeaters, is employed for converged (all services) base communications. This is discussed in greater detail in Section 3, Network Considerations.

(3) Adaptive equalization techniques could compensate for atmospheric dispersion. See discussion in Section 4, Products and Potential Applications.

BIOGRAPHICAL SKETCHES.

Mr. Tom Garlington is a subject matter expert for USAISEC. He has a Bachelor of Science in Mechanical Engineering Degree from the University of Washington, is a registered professional electrical engineer in the State of Arizona, and has 27 years of experience in the radio frequency and microwave industries. Mr. Garlington authored the technology description section and parts of the products and potential applications section for this paper.

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GLOSSARY. ACRONYMS AND ABBREVIATIONS

ANSI American National Standards Institute, 9
BER Bit error rate, 3
CAN Campus area network, 2
CH4 Methane, Natural Gas, 6
CO2 Carbon Dioxide, 6
db decibels, 4
DSNR digital signal-to-noise ratio, 8
DWDM dense wave-division multiplexing, 3
EIGRP Enhanced Interior Gateway Routing Protocol, 9
FCC Federal Communications Commission, 10
FDM frequency division multiplexing, 3
FSO Free space optics, 2
Gb/s Gigabit per second, 2
GHz Gigahertz, 10
I3MP Installation Information Infrastructure Modernization Program, 10
IEEE Institute of Electrical and Electronics Engineers, 2
iFSO Indoor Free Space Optics, 10
IP Internet Protocol, 9
IR infrared, 8
ISI intersymbol interference, 4
km kilometer, 2
LAN Local area network, 2
LD laser diode, 4
LED light emitting diode, 4
MAN Metropolitan area network, 2
MANET Mobile Ad Hoc Network, 9
MATRIX Matrix Laboratory, 8
Mb/s Megabits per second, 3
MODTRAN Moderate-Transmission, 8
MSE Mobile Subscriber Equipment, 9
OOK on-off keying, 4
OPA optical phased array, 8
OSPF Open Shortest Path First, 9
PID proportional-integral-derivative, 8
QCL Quantum cascade lasers, 8
RIP Routing Information Protocol, 9
Tb/s Terabits per second, 3
TCF Technical control facility, 9
TCP Transmission Control Protocol, 9
TDM Time Division Multiplexing, 9
TIC Technology Integration Center, 10
USAISEC U.S. Army Information Systems Engineering Command, 2