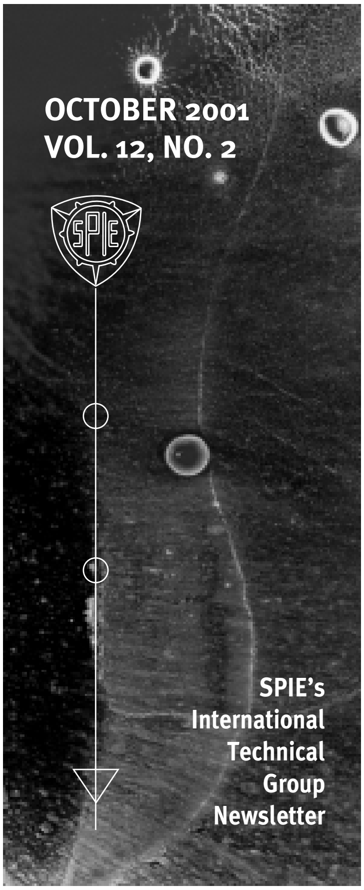

Optics in Information Systems

(Formerly Optical Processing and Computing)

Special Issue:

Optical Wireless Communications

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Wireless optical networking

Several key factors are bringing wireless optical networking (WON) technology into the carrier space as a means for broadband access. The first is a growing and seemingly insatiable demand for bandwidth in the marketplace. WON technology provides fiber-like speeds without significant initial capital expenditures for scarce resources such as spectrum. Deregulation of the telecommunications industry in the US and abroad has brought about a new class of carriers that are providing broadband services and require a scalable and affordable infrastructure to bring those services to their customers. While fiber rings are becoming ubiquitous, getting the bandwidth from the rings to customers remains challenging.

While WON infrastructure sounds inviting, there are many near-term hurdles for products. The primary customer concern is availability: this needs to be statistically demonstrated with real WON systems in the field

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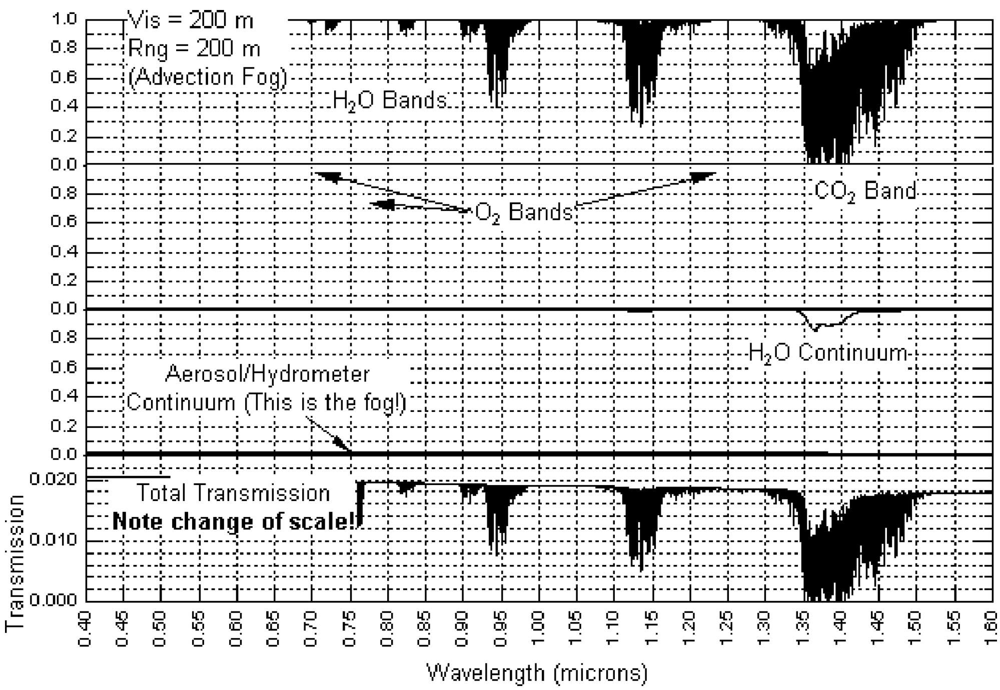

Figure 1. MODTRAN calculation of atmospheric transmission along a 200m path: the visibility due to advection fog is about 200m. The top panel shows the strong H_2O absorption bands. The second panel shows minor components, CO_2 and O_2, while the third panel shows the continuum absorptions of H_2O and attenuation caused by aerosol and hydrometer scattering. The bottom panel is a sum of all three: note that the transmission at 785nm is actually better than transmission at 1550nm.

Editorial

Today, the field of optical wireless communications, also known as free-space laser communications, is undergoing a resurgence. In the last couple of years, several commercial companies have been launched to deliver "last mile" optical access for high bandwidth services. Many of these companies are in field trials with carriers, and some are already providing data communications services in the Manhattan business district.

Free-space laser communications or lasercom can trace its roots to the early period after the first successful commercial demonstration of the laser. The military has always been interested in using lasercom to form highly-secure, low-probability-of-intercept (LPI), communication links. So far, most terrestrial military applications of these links have been limited by hostile battlefield and weather conditions, which restricted their use to short (< 1 km) distances. In space, however, lasercom is an ideal candidate for high data-rate communications. Here, the challenge is not fog and dust, but the accurate pointing of laser beams.

It has been reported that a large fraction of business buildings are only about a mile away from a from a fiber that carries optical signals. This has produced business opportunites for commercial lasercom systems providers, who are rapidly installing high-bandwidth connectivity without the exorbitant fiber-cable digging and deployment costs. Typically, these systems are positioned at building windows and rooftops. Each includes a transmitter and a receiver, with common operating wavelengths at 850nm and 1550nm. With tremendous recent hardware developments in the fiber-optics telecommunications sector, eye-safe 1550nm has become a viable choice for lasercom, particularly as high power is now available at this wavelength.

Today, most commercial lasercom systems are point-to-point fixed channels. As networks evolve and grow, there will be a need to form rapidly agile and reconfigurable optical wireless links. This is also true for military environments, where on-the-move secure communications is required. One approach to reaching this goal is via the development of fast, programmable, optical-beam-steering technology, such as is under development through the DARPA/MTO STAB program. Given the ever-present weather concern with lasercom, the hybrid approach—using a radio frequency (RF) backup link—seems a logical choice.

Considering the fresh outlook of the optical wireless community and the economic impetus for the new technology, we are sure to reap the data-flow benefits of this truly elegant means of communication.

As chair of the recent special panel on "Optical Technologies for Wireless Communications," held through the SPIE Optics in Information Systems Technical Group at the SPIE Annual Meeting in San Diego this year, I would like to thank the distinguished panelists for their valuable contributions. Panel members included S. Fainman (UC-San Diego), P. MacManamon (Wright Labs-USAF), S. Mecherle (fSona), E. Korevaar (Optical Access), and H. Willebrand (LightPointe).

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The past, present, and future of free-space optics

Free-space optics (FSO) products have been commercially available since the 1970s. Until recently, the technology was more commonly referred to as "laser communications" or "lasercom." One reason for the name change was to market the technology as "safe." Even though most commercial FSO systems operate at output powers that are safe for both skin and eyes, the word "laser" still has some negative connotations.

In the past, FSO has struggled to gain acceptance as a viable commercial technology. Currently it is gaining market share as a functional, wireless, high-bandwidth connectivity tool. This observation is based on a history of interactions with potential customers at trade shows. When we presented our first FSO system at the 1996 Networld-Interop event, the majority of people who visited our booth were amazed that a technology existed which could send 155Mbps through the air. We demonstrated this by transmitting live, uncompressed, digital video between two transceivers. Although there was great interest in the technology, initial product sales were slow.

At that time, several barriers to FSO sales existed: FSO was a new and unproven wireless technology for most, and customers would prefer to use more familiar but lower data rate microwave (RF) technology; we were a new, small company without a proven track record or a very comprehensive reference customer base; the demand for wireless 155Mbps bandwidth was not high; the cost of our first FSO link was $75,000, too expensive for most to spend on an unproven technology; and early FSO companies sold some systems based on immature technology. Reports of early failures left customers, and potential customers, with negative impressions of FSO.

To improve the FSO technology, we incorporated technological innovations from our government satellite-to-ground lasercom program.[1-4] The satellite program required pointing a rapidly-moving low-earth-orbit satellite to a stationary ground terminal while using laser communication to transmit full-duplex data at 1Gbps. Both the satellite and ground terminal had to continually point and track to each others' lasers with the extremely tight tolerances of +/- 200μradians.

Technologies developed during the satellite program made the pointing and aligning of our commercial systems more precise. Our CCD-based lookback video-alignment system not only simplified alignment initially, but also guaranteed centering on the detector. This exact alignment maximizes our system's ability to tolerate building sway. The technique also provides a very useful diagnostic tool to remotely monitor and maintain the alignment of the system. Multiple transmit aperture technology was also incorporated into our commercial FSO systems from the satellite work. Multiple apertures reduced the effects of atmospheric scintillation, thus producing a more robust transmitted laser signal, especially at longer link ranges.[5,6]

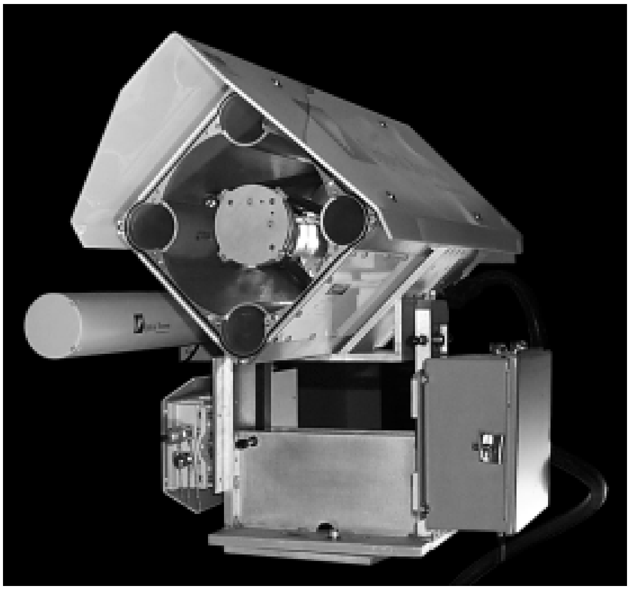

Figure 1. Free-space optics terminal with microwave back-up. The multiple transmit and large receive aperture are features that reduce atmospheric scintillation. The radio backup can increase the availability of the tandem wireless system to 99.999%.

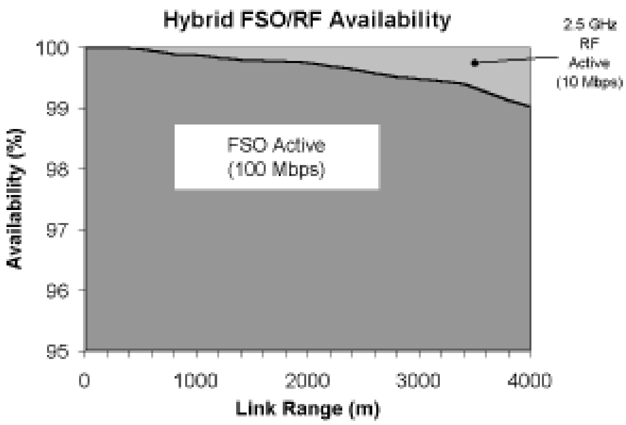

Figure 2. Availability as a function of link range for a hybrid FSO/RF system. The dark area below the curve represents the percentage of time the high-bandwidth FSO system will be active. The lighter area above the curve represents the percentage of time the lower bandwidth RF system will be active. Adding the RF back-up boosts the total availability of the complete system. However, the longer the link range, the greater the percentage of time the RF system will be functioning.

Incorporating these innovations, and placing much more of an emphasis on a good site survey and solid installation, resulted in the increased reliability of the FSO links. After re-engineering the FSO units to a cost of $35,000 each, we began to see an increase in sales. Further redesign resulted in a per-unit-price of $15,000 to $20,000, which increased sales further, and significantly. This was a price that network engineers could justify to their managers.

During this time, Fast Ethernet NIC cards for PCs and simple Layer 2 switches became inexpensive, resulting in many companies running Fast Ethernet networks. This jump in bandwidth from 10 to 100Mbps was inexpensive to upgrade within a building, but difficult and expensive to bridge between buildings, since most only had access to low-bandwidth copper-based xDSL or T1 lines. It was here that FSO found a niche in Fast Ethernet connectivity between buildings for the enterprise market.

A more scientific and quantitative approach to explaining the effects of weather on FSO links also provided customers with a higher level of knowledge and awareness of the capabilities of FSO systems.[7] All of these factors resulted in more sales of commercial FSO products and a growing base of satisfied FSO users. The barriers to sales were slowly coming down.

Another major step in the acceptance of FSO technology was the involvement of the larger, well-known telecom companies. To this point, most FSO companies were small startups. As their sales increased, they were able to slowly add to their marketing budgets and achieve recognition for their company and the technology. Then, companies like Lucent and Nortel became involved with FSO. This further legitimized the FSO technology to a much broader base of customers. More publicity was also provided by using FSO at high profile events such as the Super Bowl and the Olympics *(See page 12)*.[8] All of this marketed FSO as a technology that would contribute significantly to solving high-bandwidth access problems.

As for the future, today's FSO is much better positioned than RF to provide gigabit and 10Gbit

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Free space optics: what lays ahead?

The intriguing option of using free-space optics (FSO) to fill communication holes in metropolitan area networks has been discussed recently, and quite extensively, in the media and technical community. One of the main drivers behind this discussion is the fact that fiber deployments are far behind the optimistic projections that were anticipated in the early 1990s. Since then, various types of fiber deployment scenario have been suggested, yet well-researched figures indicate that only 3% percent to 5% of the commercial buildings in U.S. metropolitan areas are connected to a fiber network. These figures are far lower for the multi-tenant housing market or the residential market.

Various commercial vendors today offer FSO equipment that targets metropolitan areas, and these companies, as well as research groups from the academic world, are developing techniques to further increase and enhance the performance of FSO systems. Many domestic and international service providers are currently testing FSO equipment, and performing trials to study the feasibility of using this technology in networks.

FSO systems have many characteristics in common with fiber optics. It uses the same optical transmission wavelengths, namely 850nm and 1550nm, the same components: such a lasers, receivers, amplifiers, etc. (Some systems, such as the LightPointe product line, already include fiber connections inside the transmission link heads to separate electronics and optics.) Similar to fiber optics, FSO systems also target the high-bandwidth market. However, while fiber optics can be used over longer distances, FSO targets shorter distances, such as applications in metropolitan area networks. Finally FSO systems can, like their fiber-optic counterparts, be designed to provide simple, one-layer, physical connectivity.

One common feature of all FSO equipment commercially available today is related to the fact that all of these systems use quite a few O-E-O (optical to electronic to optical) conversion steps during the process of communicating information through the air and connecting back to the attached networking gear. Although this feature does not automatically constitute a performance limitation, O-E-O conversion can impact the ability to scale an FSO system easily to higher bandwidth operation. Early on, the fiber optic communications industry realized the importance of a more all-optical system approach, as higher backbone capacity—in conjunction with wavelength division multiplexing technology—became a customer requirement in long and medium haul communication networks. An important breakthrough towards this goal was reached in fiber systems when erbium-doped fiber amplifiers (EDFA) became commercially available. At that point in time, the idea of carrying multiple wavelengths over a single piece of optical fiber achieved its commercial breakthrough. The invention of EDFA amplifier technology allowed for information to be sent at multiple wavelengths over longer distances: this without performing expensive O-E-O conversion and separate electrical amplification of each specific wavelength at every repeater station. Advances in high-speed electronics—in combination with wavelength-division-multiplexing (WDM) technology finally enabled the bandwidth revolution in high capacity fiber systems.

We are foreseeing a development in FSO systems that will follow the recent historical development in fiber optics. Already, now, vendors such as LightPointe are starting to use EDFA technology in next-generation high capacity OC-48/STM16 products. These incorporate DFB lasers operating at any specific ITU wavelengths in the EDFA amplification band. Therefore, such a system will also be able to handle WDM traffic. The capability of FSO systems (or, better, the transparency of the atmosphere) to be able handle WDM operation is another important similarity to optical fiber. In laboratory experiments, 40-wavelength operation at 2.5 Gbps/wavelength has already been demonstrated successfully by a research team from Lucent Technologies, in Murray Hill, New Jersey.

Next-generation FSO system development can take advantage of the similarity between FSO and optical fiber transport. One aspect to consider: this certainly relates to the O-E-O conversion process that was already partially eliminated in fiber optic communication when WDM operation was enabled through EDFA technology. In an all-optical FSO system, multiple wavelengths from a single fiber can be amplified by an EDFA and transmitted through free space and to the opposite link head. At the receive side, a lens or a mirror system can be used to receive the light and send it back into a fiber without performing any O-E-O conversion. A system like this will be extremely beneficial because, similar to fiber optic systems, it will eliminate the expensive O-E-O conversion process. Figure 1 illustrates a part of the all-optical FSO system.

In addition, this approach will be extremely scalable: adding another wavelength will not require changing the link heads. This transport can be constructed as a completely protocol-transparent platform. Therefore these hybrid fiber laser—or HFL™ systems—could provide the ultimate optical transport platform in environments where fiber deployment is limited, too expensive, or even not feasible. There is the strong tendency in the fiber-optics industry to drive the O-E-O elimination process even further towards the networking edge by incorporating all-optical switches based on micro-mirror technology. An all-optical transparent FSO system will also be able to follow this migration path. The outcome of this approach could be an optical transport system where light itself, and the confining media (fiber), would represent the physical layer.

These kinds of hybrid fiber laser systems are certainly a little bit out in time and, in the meantime, O-E-O will certainly dominate the FSO system market. However, the potential benefit of all-optical HFL systems is too appealing. LightPointe is current working towards its implementation.

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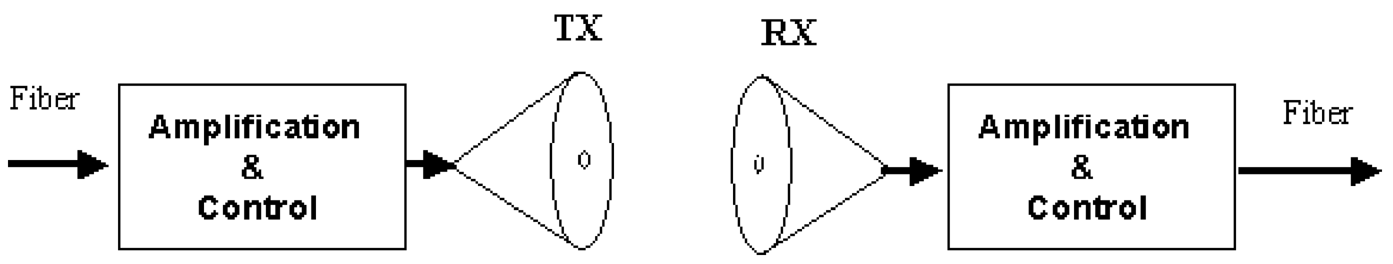

Figure1. Illustration of an all-optical hybrid fiber laser (HFL™) transport system.

Reliability and availability in free-space optical systems

People sometimes confuse *reliability* with *availability*. 'Reliability' generally refers to the hardware and the expected failure rate of the equipment, whereas 'availability' refers to the amount of time a link is operational.

Reliability in free-space optical (FSO) systems can be accomplished by selecting high-reliability, long-life components, and assuring, through system design, that the selected components operate at the lowest stress levels possible. Low-stress engineering for high reliability also includes active laser cooling to ensure the laser operates at a low temperature in hot weather; adaptive laser power to greatly reduce that expended in clear weather and thus enhance the laser lifetime; and redundancy for the lasers, laser drivers, coolers and cooler controllers. These design features and redundancy are crucial to realize a high-reliability (high-rel) system that must operate continuously for a decade or more. In addition, such a system requires an environmentally sealed housing and interior heating to prevent optics fogging or snow accumulation.

Weather availability refers to the fraction of time the link is available (usable). Link availability due to weather is typically quoted in 9s. For example, 0.9995 availability means, on average, the link is expected to go down due to harsh weather only 0.05% of the time due to fog, severe snowstorms, etc. A weather availability of 4-9s is exceptional, meaning an expectation of only 4 minutes per month of down time. Practically speaking, 4-9s is nearly perfect, and well on the way to the holy grail of 5-9s availability: only 26 seconds of downtime per month.

Table 1. Link margins for various weather conditions.

Worst-case weather condition	Link margin required, d/B/km for 1550 nm
Urban haze	0.5 dB/km
Typical rainfall	3 dB/km
Very heavy rainfall	6 dB/km
Tropical downpour; typical snow; light fog	10 dB/km
White-out snowfall; moderate fog	20 dB/km
Heavy fog	30 dB/km
Very heavy fog	60 dB/km

Link range and link availability

FSO link availability due to adverse weather conditions depends on your microclimate, and will differ for the Pacific Northwest, Mexico City, Kuwait, or London. Furthermore, it should be noted that link availability during adverse weather is often dependent on the local seasons. For example, a measured annual link availability of 0.9995 could be the result of measuring 100% availability for 6 months of the year, but 99.9% for the other 6 months. Also, note that extreme events of long duration can severely impact the annual availability number. For example, a link that had 0.9998 availability for 11 months, but dropped to 0.99 in one month with an abnormally high occurrence of heavy fog, results in an annual availability of only 0.999. For such reasons, availability is often of interest on a monthly basis.

The link range or distance between terminals is the other variable that must be considered when assessing link availability due to weather. It is probably intuitive that an optical link is capable of operating over a longer range in clear weather than in a whiteout blizzard. Long distance transmission means less power at the other end of the link, which means less link margin is available to maintain the link through foul weather. A longer-range deployment means lower link availability due to weather: i.e., the link is more susceptible to foul weather than it would be if it were deployed at closer range. Penetrating severe weather requires shorter link ranges.

Visibility with the naked eye is a qualitative indicator of laser transmission impairment in foul weather. (A FSO system can actually penetrate farther than the eye can see, but the visual range can be used as a guide.) Raindrops are large (a few millimeters) compared to the laser wavelength (1.5 microns) and thus cause minimal scattering of the laser energy. And since water has minimal absorption at a 1550 nm laser wavelength, it is not so surprising to learn that optical transmission is not heavily impacted by rain. (Using the visual analogy, one can see quite a distance even in a rainstorm.) Similarly, it is not surprising to find that optical transmission is impacted by heavy fog, in the same way that visibility can be seriously impaired under foggy conditions. This is because fog aerosols are comparable in size to the laser wavelength, causing a great deal of scattered laser energy as the fog gets thicker.

Link margin vs. weather

When deploying optical links in different climates, the maximum permissible link range is a function of the local weather conditions and the user's link availability requirements. To overcome adverse weather conditions, one must engineer the system to provide excess power in clear conditions (see Table 1). For example, to provide a 2km link that can penetrate very heavy rain requires a 20 dB link margin (10 dB/km).

This excess link margin is necessary to ensure the link will still perform well during poor weather. Users with a requirement for the link to operate through extreme events such as a blizzard or heavy fog, even if such an event rarely occurs, should install their links at a range which provides a minimum link margin of 60 dB/km if there is no backup alternative.

Engineering for availability

In general, systems with higher laser transmitter power will achieve higher availabilities in adverse weather conditions. Large receiver apertures will also achieve better results due to their larger collecting areas.

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Predicting the availability of free-space optical communication links

Terabeam provides free-space optical (FSO) connections at high bit rates (up to 1.25Gb/s) from the nationwide backbone wide-area network to local customers. The operation of these links at high availability (>99.9%) despite adverse weather conditions is naturally of prime importance. Predicting the availability for an FSO link requires knowledge of the average expected visibility at that location and the link's range. Fortunately, visibility and several other atmospheric parameters have been systematically recorded for decades at numerous sites, mainly airports. Although not perfect (FSO links are seldom deployed at airports) this data provides vital information for predicting performance.

FSO works well when two ends of a link are "visible" to each other, with the poorest visibility conditions a result of fog or low clouds. As visibility *V* drops, the attenuation G necessarily increases. It can be shown that in the visible and near infrared the optical attenuation due to fog, rain and snow is related to the visibility by:

$$\Gamma = \frac{\kappa}{V} \qquad (1)$$

where *k* is an empirical parameter typically having a value of 8-17dB. (Optical attenuation for fog, rain and snow is very nearly independent of wavelength in the visible and near-IR.) Given visibility data, one can estimate typical optical losses due to fog.

Thirty years of visibility data from La Guardia airport is shown in Figure 1 as an example. The term *P(V)* is defined as the probability that the visibility will be greater than *V*. For 30 years, visibility dropped, on average, below 1000m at this airport for about 1% of all hourly observations. (It should be noted that data gathered over the past ten years has been typically measured using electronic visibility monitors rather than human observers in towers, thus creating some inconsistencies in the data. Such monitors, although less susceptible to some human errors, do not provide the same type of visibility data; they interpolate *V* at single locations based upon light scattering rather than across long distances. Since fog can be inhomogeneous, a local visibility monitor will necessarily produce systematic errors.)

Given such visibility observations, one may interpolate to find the visibility corresponding to a required availability, for example 99.9%. The value for V_{999} can be used to calculate the distance for the link (that should operate 364.6 days per year.) If the allowed loss for fog is *g*, then the maximum link distance for three nine availability is:

$$d_{999} = \frac{\gamma}{\kappa} V_{999} \qquad (2)$$

Unfortunately, it is rarely that simple. Links are not typically erected at airports, rather, they are often miles away. Airport visibility observations are usually at runway level, while FSO links can be many stories above ground. In our experience, there is a distinct degradation in visibility with increasing elevation, since fog may lift to become low clouds that do not impact surface visibility but do significantly increase attenuation at altitudes where FSO links are frequently installed. Such variability strongly depends on the geographical location, and accurately predicting link availability must include correlating ceiling data with visibility data.

Another complication is that, since visibility is a measure of the contrast of an image, visibility may drop while the attenuation stays the same. This happens because the contrast can vary due to background light. Contrast can be defined in terms of the brightness of "bright" and "dark" parts of an image, as indicated in Figure 2. A contrast function, defined as:

$$C(z) = \frac{I_1(z) - I_2(z)}{I_1(z) + I_2(z)} \qquad (3)$$

provides a measure of the ability to discern a target at a distance *z*. (This is the basis of observer-based visibility measurements, which account for over 66% of all data taken at airports over the past 30 years.) By definition, *z* = *V* when the contrast *C(z)* drops to 2% of *C(0)*. This is one of several steps in the derivation of Equation 1. But this formula does not account for background light.

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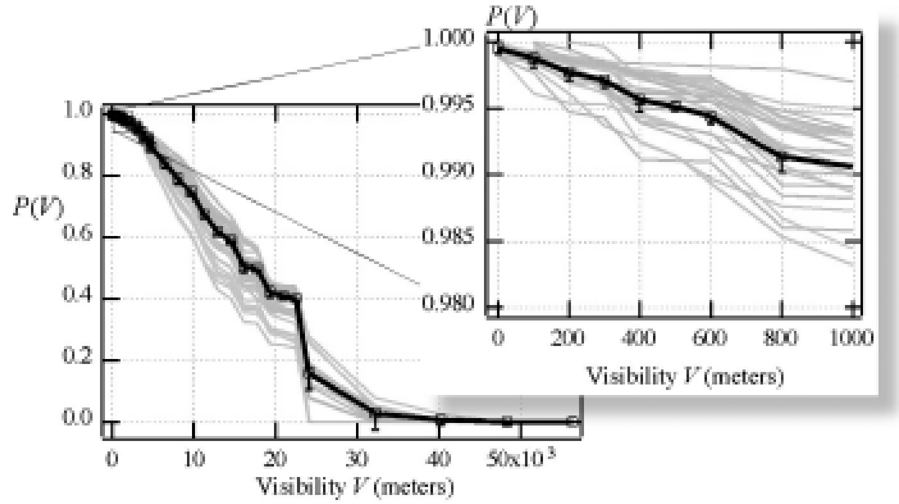

Figure 1. Each of the yearly availabilities for La Guardia airport (1961-1990). P(V) is the probability that the visibility will be greater than V. The heavy central line is the average value of P over 30 years. The other lines are for each of the 30 years.

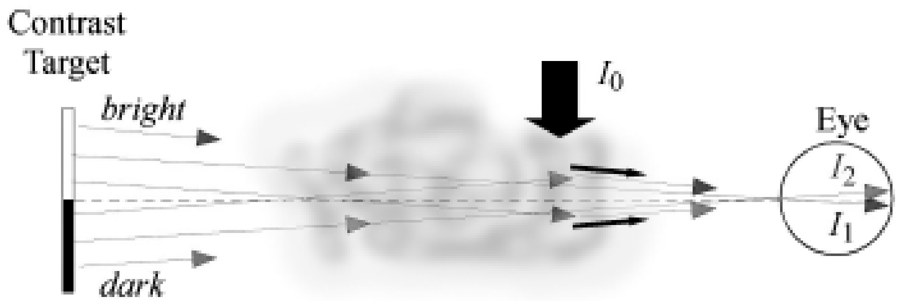

Figure 2. A representation of how the light from two separate angles mixes due to scattering from the original light sources and from an external source. The intensities that reaches the retina (I_1 from the bright object and I_2 from the darker object) become mixed due to this forward scattering. Background light I_0 causes additional scattered light that can reduce visibility.

The past, present, and future of free-space optics

continued from p.3

Ethernet wireless links. Companies are already offering gigabit FSO links. Early fiber-coupled FSO experiments, performed by Lucent and AstroTerra/Optical Access, resulted in the first 2.5Gbps FSO link.[9] Also, 10 and 40Gbps FSO links have been demonstrated in further experiments by incorporating WDM with this fiber-coupled equipment.[10,11]

To tackle the service provider market demands for 99.999% availability, some form of a hybrid FSO/RF system, such as the TereScope Fusion system shown in Figure 1, will most likely have to be used. These systems provide higher availability across longer ranges and in all weather conditions. However, it is important to realize that, as the link range increases, so does the percentage of time that the lower bandwidth RF system will be used (see Figure 2).[12]

The three main elements driving the evolution of FSO technology can be summarized as: changing market demand, consumer resistance, and technological maturity. As the requirements for bandwidth continue to increase, and the FSO technology continues to mature, we will see the decline and virtual elimination of customer resistance.

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Predicting the availability of free-space optical communication links

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Contrast can easily be reduced by bright sunlight, for example. Since fog often occurs early in the morning, with the sun in the field of view, observer-based visibilities are reduced while scattering based transmissometer visibilities are not. In other words, it is likely that the historical visibility data overestimates the attenuation, when attenuation is calculated from Equation 1. That's the good news.

The bad news is that, although the attenuation is not as bad as the visibility data argues, the same background light can add noise to FSO receivers. The magnitude of this effect depends on other parameters of the FSO system, including receiver aperture size, field of view, and wavelength (e.g. there is less background light at 1550nm than at 800nm).

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Eight-channel broadcast video feed service at Sydney 2000 Olympic Games

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ditions during the games ranged from moderate to heavy winds, with occasional periods of light rain.

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Wireless optical networking

continued from cover

before there is widespread customer acceptance of the technology. Other concerns are compatibility with existing local exchange carrier (LEC) and premise networks, cost, carrier-class hardware, ease of installation, and network management.

Design challenges for WON systems

Current long-haul DWDM optical fiber systems routinely transmit data and voice at rates exceeding 10Gb/sec over distances of 100km. This technology would seem to hold promise for WON technology as well. Unfortunately such systems take advantage of the very controlled stable channel provided by the optical fiber. As I'll show, taking a fiber technology and converting it into a WON technology is not straightforward: nor, necessarily, cost effective. The primary reasons are the extreme losses caused by the atmosphere on a WON system. In some situations, atmospheric loss can be as high 350dB/km during heavy fog. There is no laser technology that can overcome this loss with sheer power. The only way to overcome this magnitude of attenuation is to shorten the distance between links and use a redundant (mesh) architecture.

- **Laser sources**

  The CD-ROM industry and the long-haul telecommunications DWDM industry have both developed semiconductor lasers with broad bandwidths, high powers, and high reliability. There is, however, a significant difference between these two types of lasers: the CD-ROM laser costs about two orders of magnitude less than the long-haul DWDM laser. Unless there is a compelling reason—such as eye-safety—to use DWDM technology, it does not make for a very cost effective solution given that the links must be short for carrier-class services.

- **Eye safety**

  WON systems, like radio frequencies, can be hazardous to the public if they are designed or operated incorrectly. There are laser safety standards in both the US and abroad that recommend the power levels should be viewed by both the aided (using binoculars, for example) and unaided eye. At AirFiber we have been able to engineer our product to meet the Class 1 IEC 60825 eye safety standard (as tested and certified by TÜV Product Service). This essentially means we have no restrictions on where our product can be located: it is eyesafe to view in any situation.

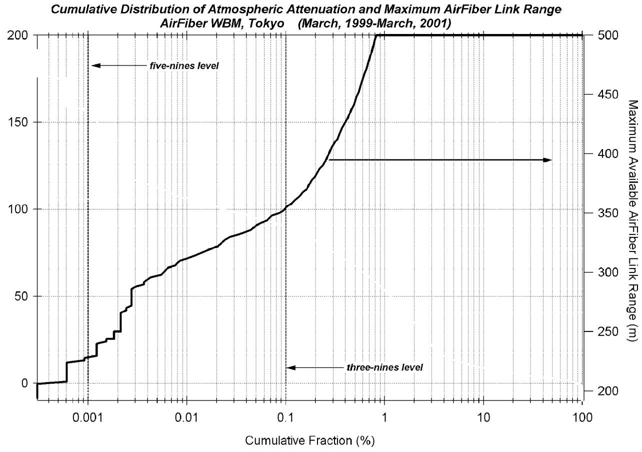

Figure 2. Cumulative Distribution Function of the atmospheric attenuation (in dB/km) and the corresponding AirFiber maximum link ranges.[3] This link range is determined with zero margin and a BER = 10^{-12}.

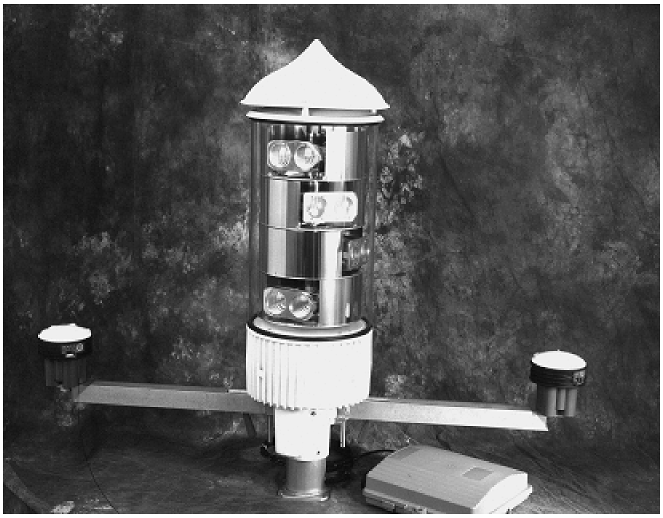

Figure 3. The photograph shows an AirFiber WON product with a DCGPS system attached for positioning. The GPS system gives xyz and bearing. A biaxial tiltmeter measures pitch and roll. These six pieces of data are enough to compute the WOL azimuth and elevation angles for autonomous acquisitions.

WOL and the atmosphere

The subject of link availability and link range is a very complex and far ranging one: we can only touch, at a high level, the effects the atmosphere has on a WON product. The main atmospheric effects on a wireless optical link (WOL) are geometric losses, absorption, scattering, and scintillation.

- **Geometrical loss**

  This is the fraction of laser power that actually reaches the receiver in the absence of atmospheric losses. The divergence of the transmitter beam essentially sets this fraction assuming the receive aperture is smaller than the spot size at the receiving end (a non-focusing system).

- **Visibility**

  WOL performance is associated with visibility because the infra-red laser sources used in WON systems propagate through the atmosphere in the same way as visible light does. It turns out that a good rule of thumb for determining link range is, roughly, that if you can see it you can communicate with it (there are many subtleties not taken into account in this statement, but for short-range links it is a good approximation).

  This rule of thumb also gives potential users an intuitive feel for the relative importance of fog, snow, and rain, in preventing WOL operation. Fog can be extremely thick, with attenuation values of 350dB/km or more. Rain hardly ever comes down hard enough to prevent seeing the building across the street, and snow lies somewhere in between the two.

- **Absorption**

  There are many species of gas in the atmosphere that can cause absorption, the dominant one being water vapor in the wavelength region of interest for a WON system. By staying out of the "water" windows and keeping the path lengths short, such absorption can largely be ignored.

- **Scattering**

  There are two types of scattering mechanism: Rayleigh and Mie scattering. Rayleigh scattering is really only significant for very long paths, but scattering by particles (Mie scattering) is a different story. This is especially true as the size of the particles approaches the wavelength of the transmitted light. The amount of scattering depends on the particle-size distribution and the density of the particles. Wavelengths near the particle size are scattered very effectively (so thick fogs or clouds look white). This is illustrated in Figure 1, which plots the transmission along a 200m path, obscured by an advection fog that reduces visibility to 200m.

- **Scintillation**

  Scintillation is caused by small-scale fluctuations in the index of refraction of the atmosphere on small spatial scales.[1] Its major effect is signal fading due to phase changes in the wavefront arriving at the receiver, causing both null and high signal receive levels. Unless the receiver has a very high dynamic range or the aperture is large enough to average out the scintillation spots, this can have an extremely detrimental effect on the signal.[2] Fortunately, for short-range systems, these effects are relatively small: on the order of several dB for a typical link range of 100-200m.

Link availability and other issues

Generation of link availability versus link range requires several pieces of data to be analyzed. Data from weather service archives, commercial met instruments, and WOL statistics, combined with the system link margin or "allowable attenuation" curve, can be used to generate plots like the one shown in Figure 2. This describes the frequency with which attenuation events greater than or equal to the value shown were measured.

- **Receiver design**

  Generally there are two types of detectors used in WON products: PIN photodiodes or avalanche photodiodes (APDs). In almost all situations where a WON system would like to operate, the system becomes detector-noise limited. Therefore, APD detectors—which have internal gain that greatly increases their sensitivity—are generally used on the most sensitive systems.

- **Background light**

  The sun contains significant energy in its spectrum at all wavelengths of WON interest. Most WON products use a combination of spatial and spectral (bandpass) filtering to reject this energy and help increase the SNR of a WOL. Typical values are rejection of 25dB or so compared with a non-filtered system.

- **Acquisition and tracking**

  A key benefit of an optical communications system is that the beam divergence is very small, which means most of the transmitted power is received at the target system. This comes at a price, as optical systems can be very difficult to align initially (acquisition) and keep aligned throughout their useful life (tracking). Engineers at AirFiber have developed a GPS based system (Figure 3) that permits installation of new equipment into the network with an installer present only at the new site.

  Once WOLs have been acquired they must accurately maintain alignment over their lifetime. Unequal heating and cooling of building interiors and exteriors causes movement that, in some cases, significantly degrades link margin unless corrective action is taken. At AirFiber we have developed a very simple and inexpensive system that requires no additional optics or detectors, yet maintains the initial beam alignment to a fraction of the beam-width.

Conclusion

WON systems can be engineered to deliver fiber-like bandwidth and carrier-grade reliability at a fraction of the cost and time of laying fiber. The mesh-network architecture provides high penetration potential to carriers that deploy the technology. Its economics, when properly engineered, permits carriers to offer highly reliable, scalable, fiber-like services.

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Eight-channel broadcast video feed service at Sydney 2000 Olympic Games

High-power optical amplifiers are an enabling technology for terrestrial free-space transmission as well as fiber optic systems. Repeater distances have been extended in terrestrial and submarine fiber systems and DWDM transmission architectures have been introduced. With the advent of high-power optical amplifiers, similar advances—as seen in fiber-optic transmission—have been applied to optical wireless or free-space laser communications systems. Such systems, where light propagates through the random medium of the atmosphere, are not as well-modelled as fiber-based systems. Atmospheric conditions degrade transmission in two ways that do not occur in fiber optic systems. First, the atmosphere acts as a variable attenuator between the transmitting and receiving telescope terminals. There is low atmospheric attenuation during clear days and high atmospheric attenuation during foggy, snowy and rainy days. The second impairment that a free-space laser link is subjected to is scintillation: intensity fluctuation in the received optical signal. Scintillation-induced error bursts usually occur during periods of atmospheric turbulence, typically caused by temperature gradients near the ground.

Sydney, Australia field demonstration

A free-space optical transmission system was designed and installed within the Olympic Park complex, located in Homebush Bay, Australia. The purpose of this installation was to provide a return video service from the International Broadcasting Center (IBC) to the International Aquatic Center for the duration of the Sydney XXVII Olympic Games. The 0.89km optical data link went from the IBC facility, over access roads and venue areas within Olympic Park. The signal was transmitted from a location approximately 10m above ground level from the IBC facility (Figure 1 illustrates transmit site elevation details). The link went east from the IBC facility, crossing approximately 300m of parking and access areas, a pedestrian walkway, and an athletics practice field. The beam then travelled over the parking lot of the Aquatic Center, finally reaching the receive location on the building's rooftop.

The project called for the service to operate continuously twenty-four hours per day from 14 September-1 October 2000, and to allow the transportation of up to eight broadcast-quality PAL-video and ancillary audio feeds, error-free, over the 0.89km link. At the Aquatic Center, the signals could then be distributed to various rights holders of the games who were within the Aquatic Center complex. The returned video and audio channels contained post-production editing features and provided the directors within the Aquatic Center with the complex, real-time status of the world-wide transmission. Figure 3 describes the interior segment of the Technical Operation Center (TOC) located at the Aquatic Center complex.

Figure 1. IBC transmit location (exit window above B).

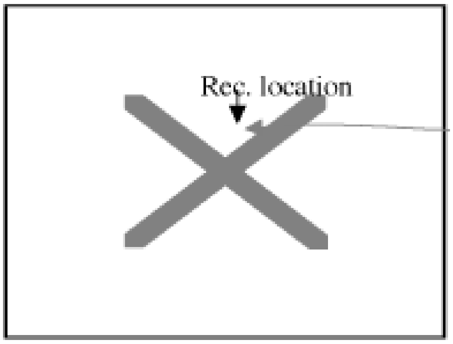

Figure 2. Path of transmit beam to Aquatic Center receive location.

Figure 3. Control room at the Aquatic Technical Operation Center.

A video encoder was used to multiplex up to eight analog video channels along with associated audio content. Up to eight analog PAL video signals could be Time-Division-Multiplexed (TDM) and transmitted onto a single-mode optical fiber at 1.485Gb/s. The encoder contained a 1.5µm DFB laser module and provided a transport system for multi-channel non-compressed digital and signal video over a single-mode optical fiber medium. The analog video inputs were multiplexed into a 1.485Gb/s digital data stream that, in turn, modulated a 1550nm DFB laser transmitter. The optical output from the encoder was connected to a high-power optical amplifier for link transmission.

Received video transmission and beacon monitoring

A second telescope, mounted approximately 30 meters above the ground, was installed at the receive location to collect the transmitted video data stream and focus it into a 62.5µm core, multimode optical fiber. The coupled signal was routed down from the roof to the TOC, approximately 200m away, using a multi-mode optical cable, and was then interfaced to a video decoder. The backplane of the decoder provided access to the eight demultiplexed video and audio components. Analog outputs were then passed along through available routers within the control room.

The free-space laser video system operated error-free over the 0.89km link duration the entire period of the Olympic Games. Weather con-

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