

Understanding the performance of free-space optics [Invited]

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Given the relative newness of free-space optics (FSO) technology in commercial applications, few standardized metrics exist for comparing the performance of different systems. Our goal here is to explain some of the design issues surrounding FSO systems and to provide sufficient information to allow potential users to evaluate the suitability of a specific FSO system for a particular application. In addition, we attempt to define the realistic performance limitations of FSO on the basis of existing technology and also to set reasonable expectations with regard to atmospheric conditions. © 2003 Optical Society of America

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1. How FSO Works

The concept of transmitting information through the air by means of a modulated light signal is quite old; and although significant advances have been made over the past 10 years, the concept remains relatively simple: a narrow beam of light is launched at a transmission station, transmitted through the atmosphere, and subsequently received at the receive station. The advances, which have led to what we now refer to as free-space optical communications, or FSO, have come about in response to a need for greater bandwidth and improved communications systems. Inasmuch as FSO and fiber-optic transmission systems use similar infrared (IR) wavelengths of light and have similar transmission bandwidth capabilities, FSO is often referred to as “fiberless optics” or “optical wireless” transmission. Furthermore, given the fact that the optical spectrum is unlicensed with frequencies of the order of hundreds of terahertz, most FSO systems use simple ON-OFF keying (OOK) as a modulation format, the same standard modulation technique that is used in digital fiber-optics systems, wherein data are typically transmitted in a digital format with light “ON” representing a “1” and light “OFF” representing a “0.” This simple modulation scheme allows FSO systems to be designed as bandwidth- and protocol-transparent physical layer connections.

In examining FSO performance, it is important to take several system parameters into consideration. In general, these parameters can be divided into two different categories: internal parameters and external parameters. Internal parameters are related to the design of a FSO system and include optical power, wavelength, transmission bandwidth, divergence angle, and optical loss on the transmit side and receiver sensitivity, bit-error rate

(BER), receive lens diameter, and receiver field of view (FOV) on the receive side. External parameters, or non-system-specific parameters, are related to the environment in which the system must operate and include visibility and atmospheric attenuation, scintillation, deployment distance, window loss, and pointing loss.

It is important to understand that many of these parameters are not independent but are linked together in specifying overall system performance. For example, system availability is a function of not only the deployment distance but also of local climate and transceiver design. In addition, a system optimized for long-range performance (>1 km) may not be optimally designed for high-availability (>99.9%) short-range performance. Overall, optimum FSO system design is highly dependent upon the intended application, required availability, and cost point.

2. Environmental Factors

The performance of a FSO link is primarily dependent upon the climatology and the physical characteristics of its installation location. In general, weather and installation characteristics that impair or reduce visibility also effect FSO link performance. A typical FSO system is capable of operating at a range of two to three times that of the naked eye in any particular environmental condition. The primary factors affecting performance include atmospheric attenuation, scintillation, window attenuation, alignment or building motion, solar interference, and line-of-sight obstructions.

3. Atmospheric Attenuation

Atmospheric attenuation of FSO systems is typically dominated by fog but can also be dependent upon low clouds, rain, snow, dust, and various combinations of each. The effects of fog on visibility and range can be seen in Fig. 1, which presents a series of photographs taken during a fog event in Denver, Colorado. The tall building in the foreground (on the right-hand side) is located approximately 300 m from the camera. The first panel shows clear atmospheric conditions with a visibility range of >2000 m as measured with a nephelometer mounted at the camera site. This corresponds to an attenuation of approximately 6.5 dB/km at near-IR wavelengths and according to the 5% contrast standard for visibility and as defined by the World Meteorological Organization (WMO). The distant mountain range is clearly visible, even though it is many kilometers away. The second panel depicts the onset of a fog event, at which time visibility is measured at approximately 113 m (115 dB/km). The near building is still visible at 300 m; all buildings and landmarks beyond this range are obscured. In the third panel, with a visibility range of approximately 75 m (173 dB/km), the building in the foreground is completely obscured.

4. Scintillation

Atmospheric scintillation can be defined as the changing of light intensities in time and space at the plane of a receiver that is detecting a signal from a transmitter located at a distance. The received signal at the detector fluctuates as a result of the thermally induced changes in the index of refraction of the air along the transmit path. These index changes cause the atmosphere to act like a series of small lenses that deflect portions of the light beam into and out of the transmit path. The time scale of these fluctuations is of the order of milliseconds, approximately equal to the time that it takes a volume of air the size of the beam to move across the path, and therefore is related to the wind speed.

Scintillation can change by more than an order of magnitude during the course of a day, being the worst, or most scintillated, during midday when the temperature is the highest. Some experiments have shown that, depending upon the atmospheric conditions along the

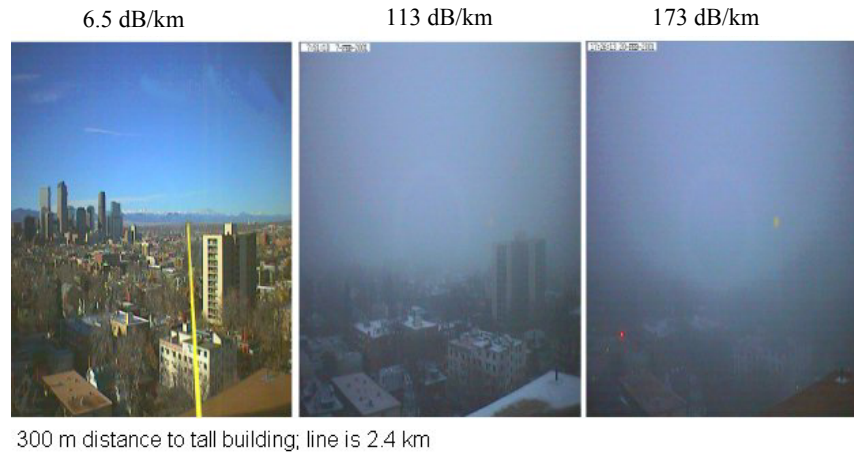


Fig. 1. Denver, Colorado, fog event.

beam path, the magnitude of scintillation-induced fades reaches a maximum that does not continue to increase with distance.

Overall, scintillation causes rapid fluctuations of received power and, in a worst case, results in high-error-rate FSO performance. However, at ranges less than 1 km, most FSO systems have enough dynamic range or margin to compensate for scintillation effects. In addition, FSO installations capable of 99.9% or better availability typically have enough margin to compensate for large amounts of atmospheric attenuation and thus have more than enough margin to compensate for scintillation. For longer, lower-availability links, transceiver design features such as the use of multiple laser transmitters can substantially reduce the effects of scintillation.

5. Window Attenuation

One of the advantages of FSO systems is that they allow communication through windows without the need for rooftop-mounted antennas. This is especially advantageous for connecting individual customers who may or may not have access to a building's roof and also may have to pay for access to the riser wiring of a building.

Even though windows allow optical signals to pass through them, they all add some amount of attenuation to the signal. Uncoated glass windows usually attenuate 4% per surface, because of reflection. This means that a perfectly clear double-pane window attenuates all optical signals at least 15% (four surfaces, each with 4% reflection). Windows that are tinted or coated can have much greater attenuation, and the actual magnitude is typically quite wavelength dependent.

For a high-availability FSO deployment behind windows, it is recommended that installers measure the actual attenuation of the window so that the expected link performance can be accurately calculated. In addition, when planning an installation on tall buildings, an installer may want to weigh the possibility of low clouds interrupting a rooftop-mounted system against the reduction in link performance that results from the lower-altitude window attenuation. In many cases, the window attenuation may have a lesser effect on overall link availability.

6. Alignment

One of the key challenges with FSO systems is maintaining transceiver alignment. FSO transceivers transmit highly directional and narrow beams of light that must impinge upon

the receive aperture of the transceiver at the opposite end of the link. A typical FSO transceiver transmits one or more beams of light, each of which is 5–8 cm in diameter at the transmitter and typically spreads to roughly 1–5 m in diameter at a range of 1 km. Adding to the challenge is the fact that FSO receivers have a limited FOV, which can be thought of as the receiver’s “cone of acceptance” and is similar to the cone of light projected by the transmitter. For a FSO link to function, it is very important that both the transmitted beam of light and the receive FOV cone encompass the transceiver at the opposite end of the link.

Despite our perceptions to the contrary, buildings are, in fact, constantly in motion. This movement is the result of a variety of factors, including thermal expansion, wind sway, and vibration. Because of the narrowness of the transmitted beam and the receiver’s FOV, building sway can affect a FSO transceiver’s alignment and interrupt communication. This building sway is generally referred to as “base motion.” In most circumstances, angular motion (azimuth and elevation), as opposed to linear motion, poses the greatest challenge for transceiver alignment. Base motion can usually be assigned to one of three classes: low, moderate, and high frequency. Low-frequency motion is defined as motion with periods from minutes to months and is dominated by diurnal and seasonal temperature variations. Moderate-frequency motion has periods of seconds and includes wind-induced building motion. High-frequency motion has periods of less than 1 s and is generally referred to as vibration, which includes motion induced by large machinery (e.g., large fans), as well as human activity (e.g., walking, shutting doors). Each class is discussed in more detail below.

7. Low-Frequency Base Motion

Thermal gradients induce bending and twisting in buildings, the magnitude of which varies greatly with the building size, shape, and structural type. Generally, this motion is so insignificant and slow that it goes unnoticed by building occupants. A correlation has been shown to exist between low-frequency base motion and daily temperature changes. As would be expected, the motion tends to increase with height in a building and can be significant for rooftop installations—even for installations on shorter buildings. Also, it is more pronounced in elevation angles than in azimuth angles.

8. Moderate-Frequency Base Motion

Moderate-frequency base motion is caused by wind and can be quite significant in tall buildings. Fortunately, minimizing building motion in strong winds is usually a key goal in the structural design of skyscrapers. Thus, only the most severe winds are likely to result in large building motions. FSO outages that result from building motion will be short in duration inasmuch as once the wind gust tapers off, the building will return to its original position and alignment. Wider-beam transceivers and transceivers with sufficiently capable automatic pointing and tracking systems will be able to “reject” even these rare large motions without outage.

9. High-Frequency Base Motion

High-frequency base motion is caused by vibration. Base motion faster than a few hertz is highly dependent on how and where a FSO terminal is mounted. Floor, wall, and rooftop (i.e., surface of roof or parapet wall) can all yield quite different levels of base motion. Figure 2 presents power spectral density plots of vibration for several buildings, including two rooftop mounts (surface of roof), two tall office buildings (floor mount), and a small wood-frame building (floor mount). The curves show the large variability in vibration from building to building. In addition, the magnitude of vibration due to occupant activity (e.g.,

walking, shutting doors) will vary greatly over time within the same building. It is interesting to note that almost all the integrated motion is due to frequency content below 10 Hz. Measurements show that peak angular base motion due to vibration above 1 Hz should rarely exceed 1 mrad and in many environments will rarely approach half this value. However, mounting hardware must be carefully designed (and installed) so that the mount does not amplify the base motion that the FSO terminal experiences.

10. Link Degradation from Base Motion

Base motion can cause link outages in two ways: excess geometric loss due to pointing errors and/or large detector coupling loss due to tracking errors. Geometric loss is the optical loss from the transmit terminal output aperture to the receive terminal input aperture. Errors in the pointing of the transmit laser beam toward the opposing terminal's receive aperture (angle in link space) will increase this geometric loss. Detector coupling loss is the ratio of the optical power in the receive focal plane to the power incident on the active area of the detector. As the receive spot moves away from the center of the detector, the detector coupling loss increases. The receive spot decenter can be expressed as a tracking error (angle in link space), and the increased loss resulting from this tracking error is referred to as a tracking loss. Given that the tracking error exceeds half the receive FOV, this tracking loss can increase quickly.

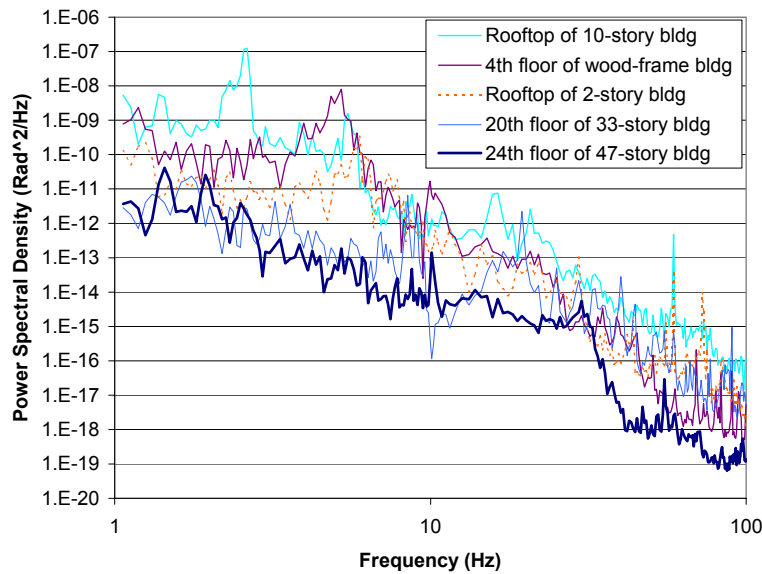


Fig. 2. Power spectral density of measured vibration.

There are two approaches to managing base motion: nontracking systems and systems with automatic pointing and tracking. Nontracking systems are designed to optimize transmit divergence in order to minimize geometric losses and attempt to match their receive FOV in order to handle base motion. Systems with automatic pointing and tracking can significantly compensate for the base motion before it can be translated into pointing and tracking errors. This enables a system with automatic pointing and tracking to have low geometric loss (with a small transmit divergence) and low tracking losses (even when used with a small receive FOV). The trade-off between nontracking and automatic pointing and tracking is performance versus cost, because tracking systems can add considerable cost

and complexity to a FSO system.

Total tracking and pointing errors must be determined by means of combining base motion (as described above) with other criteria, such as initial field alignment errors (for nontracking systems), coalignment errors, and terminal thermal drift. Table 1 presents examples of pointing and tracking error budgets for nontracking and automatic pointing and tracking FSO terminals. The tracking terminal uses residual base motion, which accounts for the expected compensation of the tracking system as a function of base motion frequency. The low-, moderate-, and high-frequency base motions are not independent. Therefore this budget, which directly adds the base motion components, has been tailored for conditions that emphasize low-frequency building motion with non-extreme moderate- and high-frequency motion.

Table 1. Sample Pointing and Tracking Error Budgets for FSO Terminals

Source	Pointing Errors (mrad)		Tracking Errors (mrad)	
	No Tracking	Tracking	No Tracking	Tracking
Initial alignment	0.2	N/A	0.2	N/A
TX/RX coalignment	0.2	0.05	N/A	N/A
Terminal thermal drift	0.1	0.02	0.1	0.02
Low-frequency motion	1.5	0.01	1.5	0.01
Moderate-frequency motion	0.5	0.02	0.5	0.02
High-frequency motion	0.5	0.05	0.5	0.05
Total	3.0	0.15	2.8	0.1

N/A, not applicable.

The above types of base motion can be summarized in a few rules of thumb for evaluating whether a particular FSO system will experience motion-induced outages.

- Short concrete structures (fewer than three stories) typically move less than taller buildings or wooden structures.
- Motion of the transceiver mount may dominate motion of the building.
- Less than 15% of buildings move more than 4-mrad full side to side over a 1-yr period.
- Less than 5% of buildings move more than 6-mrad full side to side over a 1-yr period.
- Less than 1% of buildings move more than 10-mrad full side to side over a 1-yr period.

11. Solar Interference

A FSO system uses a highly sensitive receiver in combination with a large-aperture lens, and, as a result, natural background light can potentially interfere with FSO signal reception. This is especially the case with the high levels of background radiation associated with intense sunlight. In some circumstances, direct sunlight may cause link outages for periods of several minutes when the Sun is within the receiver's FOV. However, the times when the receiver is most susceptible to the effects of direct solar illumination can be easily predicted. When direct exposure (i.e., pointing) of the equipment cannot be avoided, narrowing the receiver FOV and/or using a narrow-bandwidth light filter can improve system performance. It is important to remember that interference by sunlight reflected off a glass surface is possible as well.

12. Transceiver Design

The optimal design of a FSO system is highly dependent upon its desired price point as well as the required range, availability, and data rate for its intended application. Once the application-dependent design constraints have been established, several fundamental technical choices that will greatly influence the overall design of the FSO transceivers must be made by the design team. These fundamental design choices include transmission characteristics, nontracking versus automatic pointing and tracking, single transmitter/receiver versus multiple transmitter/receiver, and direct coupling versus fiber coupling.

13. Transmission Characteristics

Optical Wavelengths

Generally, all of today's commercially available FSO systems operate in the near-IR wavelength range between roughly 750 and 1600 nm, with one or two systems being developed to operate at the IR wavelength of 10,000 nm. The physics and transmission properties of optical energy as it travels through the atmosphere are similar throughout the visible and the near-IR wavelength range, but there are several factors that influence which wavelength is chosen by a given design team.

Atmospheric Transmission Windows

It is important to note that although the atmosphere is considered to be highly transparent in the visible and near-IR wavelengths, certain wavelengths (or wavelength bands) can experience severe absorption. In the near-IR wavelength, absorption occurs primarily in response to water particles (i.e., moisture), which are an inherent part of the atmosphere even under clear weather conditions. The contribution of gas absorption (e.g., CO_x or NO_x) to the overall absorption coefficient is not considered here because the gas-specific absorption coefficients are quite small when compared with water absorption. However, in the longer-IR wavelength range (>2000 nm), gas absorption can dominate the absorption properties of the atmosphere. Figure 3 shows the absorption of the atmosphere under clear weather conditions (visibility >10 miles) for various transmission wavelengths in the near-IR spectral range (between 0.7 and 1.6 μm) and was created with MODTRAN, a software program that was developed to facilitate the study of transmission properties of the atmosphere.

There are several transmission windows that are nearly transparent (i.e., have an attenuation of <0.2 dB/km) within the 700–10,000-nm wavelength range. These windows are located around specific center wavelengths, with the majority of FSO systems designed to operate in the windows of 780–850 nm and 1520–1600 nm.

780–850 nm. These wavelengths are suitable for FSO operation, and several vendors provide higher-power laser sources that operate in this region. At 780 nm, inexpensive CD lasers are available, but the average lifespan of these lasers can be an issue and must be addressed during system design (e.g., running the lasers at a fraction of their maximum rated output power, which will greatly increase their life). Around 850 nm, reliable, inexpensive, high-performance transmitter and detector components are readily available and commonly used in network and transmission equipment. Highly sensitive silicon (Si) avalanche photodiode (APD) detector technology and advanced vertical-cavity surface-emitting laser (VCSEL) technology can be used for operation in this wavelength. Possible disadvantages include beam detection through the use of a night-vision scope, although it is still not possible to demodulate the beam with this technique.

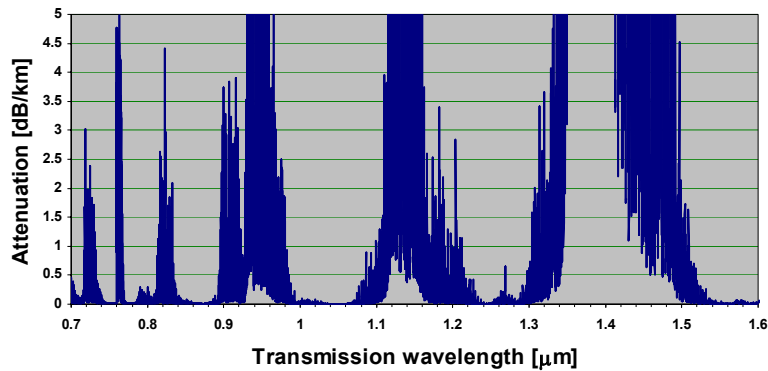


Fig. 3. MODTRAN transmission calculation under clear weather conditions.

1520–1600 nm. These wavelengths are well suited for free-space transmission, and high-quality transmitter and detector components are readily available. The combination of low attenuation and high component availability in this wavelength makes the development of wavelength-division multiplexing (WDM) FSO systems feasible. However, components are generally more expensive, and detectors are typically less sensitive and have a smaller receive surface area when compared with Si APD detectors that operate in the 850-nm wavelength. That being said, these wavelengths are also used in long-haul fiber systems, and many companies are working to reduce the cost and increase the performance of 1520–1600-nm components. In addition, these wavelengths are compatible with erbium-doped fiber amplifier (EDFA) technology, which is important for high-power (>500 mW) and high-data rate (>2.5 Gbit/s) systems. Finally, 50–65 times as much power can be transmitted at 1520–1600 nm than can be transmitted at 780–850 nm for the same eye safety classification, owing to the low transmission of the human eye at these wavelengths.

10,000 nm (10 μ m). This wavelength is relatively new to the commercial FSO arena and is being developed because of claims of better fog transmission characteristics. At this time, there is considerable debate regarding these characteristics because they are heavily dependent upon fog type and duration. In general, there are few components available at 10 μ m, inasmuch as it is not normally used in telecommunications equipment. In addition, 10-μ m energy does not penetrate glass, so it is ill-suited to behind-window deployments. However, the poor glass penetration means that it is highly unlikely to be concentrated by optical aids (binoculars), thus allowing for high-power operation in unrestricted environments.

Another topic concerning the performance of FSO systems is the issue of atmospheric propagation in heavy fog conditions for different wavelengths. Until recently, the generally held belief was that systems operating at longer wavelengths had better range performance than do those operating at shorter wavelengths. However, recent studies have shown that in heavy fog conditions, attenuation is almost constant with wavelength over the 780–1600-nm region and that, in fact, there are no benefits until one gets to millimeter-wave wavelengths. So far, the vast majority of research suggests that 10-μ m radiation propagates better under hazy and very moderate fog conditions. However, these conditions typically do not constitute a problem for well-designed shorter wavelength FSO transmission systems over transmission distances currently envisioned in commercial applications. Therefore, the actual magnitude of this improvement is likely to be highly dependent upon fog type and duration. Standard models of atmospheric scattering using either Mie theory or more integrated packages such as MODTRAN show no performance improvement at 10 μ m. Even

when the particle size distributions are centered on particles as small as 5 μm , the contribution from the upper end of the distribution (owing to the r^2 dependence of the scattering) negates any advantage for this wavelength.

14. Transmission

The modulated light source, which is typically a laser or light-emitting diode (LED), provides the transmitted optical signal and determines all the transmitter capabilities of the system. Only the detector sensitivity plays an equally important role in total system performance. For telecommunication purposes, only lasers that are capable of being modulated at 20 Mbit/s to 2.5 Gbit/s can meet current marketplace demands. In addition, how the device is modulated and how much modulated power is produced are both important to the selection of a device. Lasers in the 780–925-nm and 1525–1580-nm spectral bands meet frequency requirements and are available as off-the-shelf products. Although other operating wavelengths are used in commercial FSO systems, this discussion will focus on lasers that operate in the 850- and 1550-nm wavelength bands. Within these two wavelength windows, FSO systems should have the following characteristics:

- Ability to operate at higher power levels (important for longer-distance FSO systems).
- High-speed modulation (important for high-speed FSO systems).
- Small footprint and low power consumption (important for overall system design and maintenance).
- Ability to operate over a wide temperature range without major performance degradation (important for outdoor systems).
- Mean time between failure (MTBF) that exceeds 10 yr.

To meet the above requirements, FSO manufacturers generally use VCSELs for operation in the shorter-IR wavelength range and Fabry–Perot (FP) or distributed-feedback (DFB) lasers for operation in the longer-IR wavelength range. Several other laser types are not suitable for high-performance FSO systems.

15. VCSEL Lasers

The VCSEL (850-nm wavelength) is an outgrowth of fiber communications development and has many attractive features. VCSELs revolutionized the transmission component market because of their exceptional cost and performance advantages over previously available technology. Most notably, VCSELs have a reasonable, nominal average power level of several milliwatts of output at high-speed operation and high reliability numbers for MTBF. The average power, not the peak power, determines the link margin. Inasmuch as the 850-nm VCSEL is cheaper than many of its alternatives, the 850-nm products dominate the low-price FSO systems because operation speeds are generally below 1 Gbit/s for off-the-shelf systems. Because of their high efficiency, power dissipation is typically not an issue for VCSELs, and active cooling is not required. In addition, VCSELs emit light in the form of a circular beam instead of an elliptical beam. The round shape of the beam pattern perfectly matches the round core of an optical fiber, facilitating the coupling process and improving coupling efficiency. The success of VCSEL technology has been so tremendous that many VCSEL manufacturers can produce shorter-wavelength 850-nm laser structures with direct modulation speeds beyond 3 Gbit/s. The direct electrical modulation of VCSELs beyond 10 Gbit/s has been demonstrated and commercialized for OC-48 (STM-16) and 10-GigE operations.

16. Fabry–Perot and Distributed-Feedback Lasers

FP and DFB lasers based on InGaAs/InP semiconductor technology with operating wavelengths around 1550 nm were developed specifically for fiber-optic communications systems because of the low attenuation characteristics of optical fiber in this wavelength range. With the development of these lower-power laser sources came high modulation speed, wavelength stability, reliability, and long life spans. Today's lower-power 1550-nm DFB lasers have demonstrated excellent lifetime performance that satisfies the stringent requirements of the telecommunications industry. DFB lasers can drive fiber networks capable of 1–40 Gbit/s of modulation under highly controlled environmental conditions.

17. Amplification Sources

Amplification sources, such as EDFAs and semiconductor optical amplifiers (SOAs), are used to boost the power of lower-power laser sources. EDFA and SOA technologies also can amplify both single and multiple closely spaced wavelengths simultaneously, which is known as WDM. With high optical gains that exceed 30 dB, EDFAs can drive the 1550-nm optical output power of a FSO system up to between 1 and 2 W. At this time, EDFAs are quite expensive, and their use tends to be limited to very high-end performance systems that operate at or above 1 Gbit/s. As 1550-nm technology becomes more widely used in telecommunications, it is anticipated that the costs will come down.

18. Peak Output Power

The peak output power refers to the maximum allowable output power of a transmission source. The peak output power value is often important in pulsed laser operations, in which a high-power laser pulse is required for a short period of time. In general, the peak power and pulse repetition frequency are closely tied, and high peak power is usually coupled with a low pulse repetition frequency to prevent damage to the device. However, for most communication systems, the peak power capability of a laser source is irrelevant because most applications do not use high-power pulse/low duty cycle modulation schemes but instead typically rely on 50% duty cycle modulation schemes. For most FSO systems, the peak power rating would refer to the transmit power of a “1” and would be approximately twice the average output power of the signal.

19. Average Output Power

The average output power of a transmission system is a key factor in determining the system link margin because, as with the majority of digital fiber communication systems, most FSO systems are digital in terms of their transmission of bits across the link. These communication systems typically use a coding scheme (e.g., 8B/10B coding) to ensure that an approximately equal number of digital “1s” and “0s” are transmitted, thus maintaining a 50% duty cycle. In this case, where peak power is transmitted for a “1” and zero power is transmitted for a “0,” the average power is approximately half the peak power. This average power is what is used for eye-safety classification and is typically used to define the transmit power of a FSO transceiver.

20. Beam Divergence

One of the primary advantages of FSO transmission is the narrowness of the transmitted laser beam that can be achieved with well-designed optics. This narrow beam allows for secure and efficient transmission with a major fraction of the transmitted power being collected by the receiver. For our purposes here, we will restrict our discussion to circular

Gaussian or “top-hat” beam profiles. However, it is not necessary for the beam from a FSO system to have either of these characteristics.

Typically, the optical beam width from a FSO transceiver will be relatively wide (2–10-mrad divergence, which is equivalent to a beam spread of 2–10 m at 1 km), as is generally the case in nontracking applications. For such applications, the system must compensate for any platform motion by having a beam width and total FOV (TFOV) that is larger than either transceiver’s anticipated platform motion. If the system provides for automatic pointing and tracking, then the beam width can be narrowed significantly (typically, 0.05–1.0 mrad of divergence, which is equivalent to a beam spread of 5 cm to 1 m at 1 km), further improving link margin and providing the system with greater link margin to combat adverse weather conditions. However, the cost for the additional tracking feature can be significant.

21. Beam Propagation Models (Gaussian Beams, $1/e$, $1/e^2$, and FWHM)

The amount of beam divergence and the shape of the optical beam at the location of the receiving terminal are important criteria in the evaluation of system performance—especially in terms of the link margin.

Two types of beams are normally used in FSO: the Gaussian beam and the top-hat beam. The typical Gaussian beam is a natural byproduct of the laser resonant cavity. Most lasers produce Gaussian beams that have point-source spatial qualities. For instance, single-mode lasers produce the narrowest of Gaussian beams, and the output of the single-mode fiber coupled to such lasers also is Gaussian.

For a Gaussian beam, the intensity at a transverse or radial distance (ρ) from the center of the beam is given below for a beam width, β , at a wavelength, λ , and beam waist, ω_e :

$$\begin{aligned} J(\text{W/m}^2) &\simeq J_0/z^2 \exp[-2(\rho/\beta z)^2], \\ \beta &= (2/\pi)(\lambda/\omega_e). \end{aligned}$$

The power in the beam radius of ρ_0 is given by

$$P(W) = 1 - \exp[-2(\rho_0/\beta z)^2].$$

When the radial amplitude declines to 0.135 ($\sim 1/e^2$) of its peak intensity, 86% of the energy is encircled in this radius, thus defining the $1/e^2$ beam width, β . This is the fundamental parameter of a Gaussian beam profile. Alternatively, the beam can also be characterized to where its radial amplitude declines to 0.368 ($1/e$) of its peak intensity. A third alternative is to characterize the beam by the full-width at half-amplitude (FWHM), which for the Gaussian beam is $0.589 * \beta$. The gradual falloff of the Gaussian beam inherently results in weaker link performance at the edges of the beam for nontracking FSO systems.

Another shortcoming of the Gaussian beam profile is that its peak intensity limits the total power output when transmitter emissions must meet specific eye-safety classification levels (e.g., Class 1 or 1M). Depending upon the wavelength, the peak power must be maintained below a threshold value. However, this peak, or the on-axis intensity, then determines the total power and therefore the link margin of the Gaussian beam system. Thus the Gaussian beam characteristic limits the power capable of being projected onto the target.

An advantage of a Gaussian beam profile is that in a tracking FSO system, the beam can be dithered to provide tracking information via the communications detector, obviating the need for an additional tracking sensor and therefore additional cost. This functionality is also possible with a top-hat beam, discussed below, but with less sensitivity.

An alternative to a Gaussian beam profile is a top-hat beam, which has a virtually uniform power distribution over its entire wave front. The projection of such a beam typically requires a finite source size, which can be accomplished by use of a multimode optical fiber as a power transmit source. An in-focus transmitter, in which the exit aperture of the fiber is at the focus of the output lens, can produce a finite beam size that has a nearly flat intensity distribution across the majority of the beam. A beam of this profile is better characterized by its FWHA (as opposed to its $1/e$ or $1/e^2$ width) inasmuch as the intensity goes through a rapid transition at this diameter and maintains peak intensity over the widest possible angle or divergence. The resulting top-hat beam maximizes the total energy carried by the beam under eye-safe conditions. For most good top-hat designs, the FWHA is $\sim 0.9 * \beta$, which provides excellent area coverage for platform motion while maximizing the total beam power for the particular eye-safe threshold. The real challenge with the top-hat design is filling the modes of the fiber to produce a beam that is as wide as the fiber's physical core diameter.

It should be noted that at ranges in which the diameter of the transmitted beam has expanded to the point where the spot is several times larger than the receive aperture, there is little difference between the received beam profile of a Gaussian beam and of a top-hat beam.

In conclusion, it is important to understand the role of beam profile characteristics in comparing the performance of FSO systems. A Gaussian-like beam with a $1/e^2$ beam width is characterized by a relatively high on-axis power intensity that falls off sharply toward the edges of the beam. This can affect performance if the system does not incorporate tracking or is installed on a platform that experiences a considerable amount of sway. In contrast, a top-hat beam profile has lower on-axis beam intensity and, because of the relatively constant power distribution in a radial direction, is better suited to compensate for building sway. All the above beam profile characteristics also are valid for systems that use an active tracking mechanism.

22. Single- and Multiple-Aperture FSO System Designs

FSO systems require some type of optical system to receive and transmit the optical signals. Transceivers can use the same optical system for both transmit and receive (common aperture), but typically, separate optical systems are used for transmit and receive functionality. In either case, it is possible for the optical systems to incorporate more than one aperture for either or both transmit and receive functions.

There are several advantages to using a multiple-aperture design, including greater resistance to complete blockage, better scintillation compensation, and inherent redundancy. However, in comparing systems, it is important to take into account the optical system aperture size inasmuch as a single large aperture (for transmit and/or receive) may offer equal or better performance than several smaller apertures in the same "footprint."

An advantage of a multiple-aperture approach is that the potential for the temporary blockage of the beam by obstructions (e.g., birds) is significantly minimized because the likelihood that all beams would be blocked is drastically reduced. In addition, from an operational perspective, using multiple apertures with multiple lasers on the transmission side can provide redundancy of the transmission path in the event that a laser source should fail. Most important, from an atmospheric perspective, a multiple-aperture approach can be very beneficial in the reduction of scintillation (heat shimmer). Minimizing the effect of scintillation is especially important when FSO systems are installed over longer distances.

A disadvantage of a multiple-aperture approach is that it adds complexity because the light must be effectively coupled onto one or more receivers when multiple receive optics are used. In addition, it can be quite difficult to effectively coalign multiple transmit

and/or receive apertures and maintain that alignment over a wide temperature range. Furthermore, the addition of a tracking system can become more complicated when multiple apertures are used because it is unlikely that there will be a shared portion of the optical path where a single steering element will be able to steer all the transmit and receive beams simultaneously. This complexity can increase the overall system cost and, depending on the application, the advantage of using multiple apertures might not be justifiable.

23. Receivers and Material Systems

Compared with transmitters, receiver choices are much more limited. The two most common detector material systems used in the near-IR spectral range are based on Si or indium gallium arsenide (InGaAs) technology. Germanium is another material system that covers the operating wavelength range of commercially available FSO systems. However, germanium technology is not used very often because of the high dark current values of this material. All these materials have a rather broad spectral response in wavelength, and, unlike lasers, they are not tuned toward a specific wavelength. If there is a need to detect a specific wavelength, as, for example, in WDM systems, external wavelength filters must be incorporated into the design.

24. Short-Wavelength Detectors

Si is the most commonly used detector material in the visible and near-IR wavelength range. Si technology is quite mature, and Si receivers can detect extremely low levels of light. As with the majority of wideband detector material, Si has a wavelength-dependent spectral response, which must be matched to the operation wavelength of the transmitter. Detectors based on Si typically have a spectral response maximum sensitivity around 850 nm, making Si detectors ideal for use in conjunction with short-wavelength VCSELs operating at 850 nm. However, Si sensitivity drops off dramatically for wavelengths beyond 1 μm . As a result, 1100 nm marks the wavelength cutoff for the use of Si for light detection, and it cannot be used as a detector material beyond this wavelength range. Si detectors can operate at very high bandwidth; a recent application at 10 Gbit/s has been commercialized for use in short-wavelength 850-nm, 10-GigE systems.

Lower-bandwidth (1-Gbit/s) Si PIN (Si-PIN) and Si APD (Si-APD) detectors are widely available. Si-PIN detectors with integrated transimpedance amplifiers (TIAs) also are quite common. In these detectors, sensitivity is a function of signal modulation bandwidth, which decreases as the detection bandwidth increases. Typical sensitivity values for a Si-PIN diode are around -34 dBm at 155 Mbit/s. Si-APDs are far more sensitive, owing to an internal amplification (avalanche) process. Therefore, Si-APD detectors are highly useful for detection in FSO systems. Sensitivity values for higher-bandwidth applications can be as low as -55 dBm at speeds of several megabits/s, -52 dBm at 155 Mbit/s, or -46 dBm at 622 Mbit/s. Si detectors can be quite large in size (e.g., $0.2\text{ mm} \times 0.2\text{ mm}$) and still operate at higher bandwidths. This feature minimizes losses when light is focused on the detector and either a larger-diameter lens or a reflective parabolic mirror is used.

25. Long-Wavelength Detectors

InGaAs is the most commonly used detector material for the longer wavelength range. Similar to Si, InGaAs is a wideband detector material, and the spectral response or underlying quantum efficiency depends on the detection wavelength. Over the past decade, the performance of InGaAs detectors with regard to sensitivity, bandwidth capabilities, and the development of 1550-nm fiber optic-technology has been continually improving. Nearly 100% of all longer-wavelength fiber-optic systems use InGaAs as a detector material. Commercially, InGaAs detectors are optimized for operation at either 1310 or 1550 nm. Because of

the drastic decrease in sensitivity toward the shorter wavelength range, InGaAs detectors are typically not used in the 850-nm wavelength range.

The primary benefit of InGaAs detectors is their extremely high bandwidth capability combined with a high spectral response at 1550 nm. The majority of InGaAs receivers are based on PIN or APD technology. As with Si, InGaAs APDs are far more sensitive because of an internal amplification (avalanche) process. Sensitivity values for higher-bandwidth applications can be as low as -46 dBm at 155 Mbit/s, or -36 dBm at 1.25 Gbit/s; although, InGaAs detectors operating at higher speed are typically smaller in size than their Si counterparts. This makes the light coupling process more challenging.

Table 2 presents some of the more common detector materials used in FSO systems and their basic physical properties.

Table 2. Selected Detector Material System and Basic Physical Properties

Material/Structure	Wavelength (nm)	Responsivity (A/W)	Gain
Silicon PIN	300–1100	0.5	1
Germanium PIN	500–1800	0.7	1
InGaAs PIN	1000–1700	0.9	1
Silicon APD	400–1000	77	150
Germanium APD	800–1300	7	10
InGaAs APD	1000–1700	9	10

In summary, it is important to remember that detector performance plays a dominant role in the overall design of a FSO system. Selecting the appropriate transmitter–receiver combination can compensate for potential shortcomings, owing to the use of lower-power transmission sources.

26. Laser Safety

Laser safety is an important issue. The primary safety concern is the potential exposure of the eye or skin to the beam. High-power laser beams can cause injury to skin, but risks of injury to the eye are more significant because of the eye’s ability to focus light and thereby concentrate optical energy. In general, any laser that is considered to be “eye-safe” is also considered to be “skin-safe.” Like sunlight, laser light arrives in parallel rays, which, depending upon wavelength, the eye focuses to a point on the retina, the layer of cells that responds to light. Just as staring at the Sun can damage vision, exposure to a laser beam of sufficient power can cause eye injury.

The specific wavelength is important because only certain wavelengths— between approximately 0.4 and 1.4 μm —are focused by the eye onto the retina. Other wavelengths tend to be absorbed by the front part of the eye (the cornea) before the energy is focused and concentrated. The absorption of the eye varies with wavelength (see Fig. 4). With respect to IR radiation, the absorption coefficient of the cornea is much higher for longer wavelengths (>1.4 μm) than for shorter wavelengths. As such, damage from the UV and visible radiation of sunlight is more likely than from longer wavelengths located in the IR spectrum. Eye response also differs within the range that penetrates the eye (400–1400 nm) because the eye has a natural aversion response, which makes it turn away from a bright visible light. Wavelengths longer than 0.7 μm do not trigger an aversion response, because they are invisible. Although IR light can damage the surface of the eye, the damage threshold is higher than that for UV light.

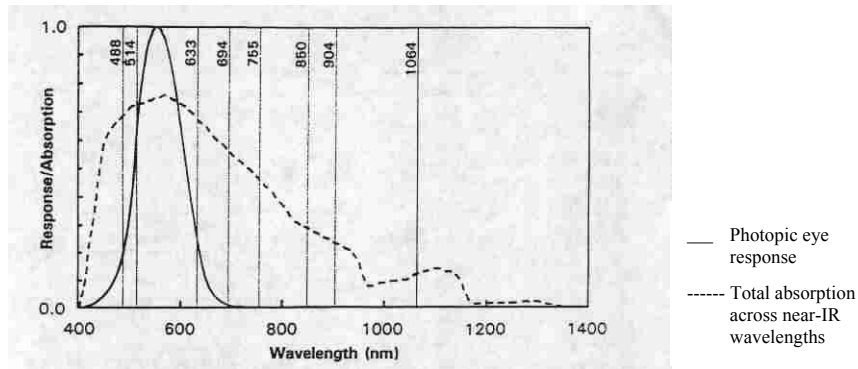


Fig. 4. Response/absorption of the human eye at various wavelengths.

27. Laser Safety Standards

Many countries have developed or adopted laser safety standards that apply to all laser products sold within their borders. These safety standards generally fall into two categories: those that address the safety of laser equipment and those that focus on the safe use of lasers. In addition, some entities have the authority to create legal standards, while others set laser safety standards and establish guidelines that are not enforceable by law. In general, laser safety standards include provisions for automatic or manual safety controls; warning labels and signs; training for operation, maintenance, and service; and use of protective equipment. A list of the principal laser safety standards organizations is presented below.

Center for Devices and Radiological Health (CDRH). CDRH is an agency within the United States (U.S.) Food and Drug Administration (FDA). It establishes regulatory standards for lasers and laser equipment that are enforceable by law (21 CFR 1040).

International Electrotechnical Commission (IEC). IEC publishes international standards related to all electrical equipment, including lasers and laser equipment (IEC60825-1). These standards are not automatically enforceable by law, and the decision to adopt and enforce IEC standards is at the discretion of individual countries.

American National Standards Institute (ANSI). ANSI is a U.S. organization that publishes standards for laser use (ANSI Z136.1). ANSI standards are not enforceable by law but do form the basis for the U.S. Occupational Safety and Health Administration (OSHA) legal standards, as well as comparable legal standards that have been adopted by various state regulatory agencies.

European Committee for Electrotechnical Standardization (CENELEC). CENELEC is an organization that establishes electrotechnical standards based on recommendations made by 19 European member nations. CENELEC standards are not directly enforceable by law but, as with IEC standards, are often integrated into the legal requirements developed by individual countries.

Laser Institute of America (LIA). LIA is an organization that promotes the safe use of lasers, provides laser safety information, and sponsors laser conferences, symposia, publications, and training courses.

Over the years, the above organizations have developed a mechanism for classifying lasers according to their type and power. Although the specific criteria vary slightly, these classifications have generally been divided into four groups, Class 1 through Class 4, with Class 1 being the least powerful and Class 4 being the most powerful. However, the fact that all of these organizations had adopted slightly different standards and classification schemes was somewhat overwhelming for companies wishing to do business in the global marketplace. To help remedy this situation, IEC, CDRH, and ANSI are in the process of harmonizing their classification methods and product requirements. On 27 May 2001, CDRH issued Laser Notice 50 that officially allows products that comply with IEC60825-1, Amendment 2, to be introduced into the United States. This notice is a first step in a process that is expected to result in the CDRH amending its own regulations to be consistent with the new IEC standards.

Under the new IEC standard, specific laser classes were identified, and each class assigned specific labeling and warning instructions. The document outlines installation compliance requirements based on the level of emitted power, defines specific hazardous zones in front of the transmit aperture that must be cleared for eye-safe viewing, and restricts the installation of certain high-power laser systems in areas that are easily accessible to the public. Within the new classification scheme, Class 1 and Class 1M systems are considered to be eye-safe for viewing at a close distance without (Class 1M) or even with (Class 1) an optical instrument such as binoculars.

IEC is in the process of writing a new standard, IEC60825-12 (in addition to the IEC60825-1, Amendment 2), which is intended specifically to cover FSO system classification and use. This new standard is currently in draft form and is expected to be officially released in 2003.

At this point, it is important to mention that the laser classification (e.g., Class 1, Class 1M, Class 3B) and not the transmission wavelength itself determines the laser classification standard. In other words, there is no wavelength that is either inherently eye-safe or inherently dangerous to the eye. It is fundamentally possible to design an eye-safe laser system that operates at any given wavelength; output power levels (and not the wavelength itself) determine the laser classification. It also is important to understand that the new regulation addresses the power density in front of the transmit aperture rather than the absolute power created by a laser diode inside the equipment. For example, the laser diode inside the FSO equipment can actually be Class 3B even though the system itself is considered to be a Class 1 or 1M laser product if the light is launched from a large-diameter lens that spreads out the radiation over a large area before it enters the space in front of the aperture. The new regulation also states that a Class 1M laser system operating at 1550 nm is allowed to transmit approximately 55 times more power than a system operating in the shorter IR wavelength range, such as 850 nm, when both have the same size aperture lens. Indeed, it is possible to increase the lens aperture size to allow higher laser power emission at a shorter wavelength. Another method of maintaining a Class 1 or 1M laser safety classification is to use multiple large transmission apertures.

The following discussion focuses on eye safety related to Class 1 and Class 1M laser systems inasmuch as they are the only ones that operate below the maximum permissible exposure (MPE) levels for naked-eye exposure and are thus suitable for wide-scale deployment. The specific features of each of these two classifications are summarized below.

Class 1. Class 1 lasers are safe under reasonably foreseeable operating conditions, including the use of optical instruments for intrabeam viewing. Class 1 systems can be installed in any location without restriction.

Class 1M. Class 1M laser systems operate in the wavelength range from 302.5 to 4000 nm, which is safe under reasonably foreseeable conditions but may be hazardous if the user employs optical instruments within some portion of the beam path. As a result, Class 1M systems should only be installed in locations where the unsafe use of optical aids can be prevented.

Table 3 presents permissible power levels according to the IEC standard (IEC60825-1, Amendment 2) for Class 1 and 1M laser systems for both the 850- and 1550-nm wavelengths.

Table 3. IEC 60825-1, Amendment 2 Laser Power Levels

Laser Classification	Power (mW)	Aperture Size (mm)	Distance (mm)	Power Density (mW/cm ²)
850-nm Wavelength ^a				
Class 1	0.78 ^b	7	14	2.03
		50	2000	0.04
Class 1M	0.78 ^c	7	100	2.03
1550-nm Wavelength				
Class 1	10	7	14	26.0
		25	2000	2.04
Class 1M	10	3.5	100	104

^a It is assumed here that the laser behaves as a point source. These power limits increase for extended sources that are focused to larger spots on the retina.

^b For sources with angular subtense < 0.21 mrad.

^c For sources with angular subtense < 1.5 mrad.

28. Atmospheric Effects and Availability

The link equation for a FSO system is actually quite simple at a high level (if we exclude optical efficiencies, detector noises, and so on). The equation is

$$P_{\text{received}} = P_{\text{transmitted}} * \frac{d_2^2}{[d_1 + (D * R)]^2} * 10^{(-a * R / 10)}, \quad (1)$$

where

P = power,

d_1 = transmit aperture diameter (m),

d_2 = receive aperture diameter (m),

D = beam divergence (mrad)($1/e$ for Gaussian beams; FWHM for flat top beams),

R = range (km),

a = atmospheric attenuation factor (dB/km).

In Eq. (1), the amount of received power is proportional to the amount of power transmitted and the area of the collection aperture but inversely proportional to the square of the beam divergence and the square of the link range. It is also inversely proportional to the exponential of the product of the atmospheric attenuation coefficient (in units of 1/distance) times the link range.

If we examine Eq. (1), the variables that can be controlled are the transmit power, the receive aperture size, the beam divergence, and the range of the link. The atmospheric attenuation coefficient is uncontrollable in an outdoor environment and is roughly independent of wavelength in heavy attenuation conditions. Unfortunately, the received power is exponentially dependent on the product of the atmospheric attenuation coefficient and the range; in real atmospheric situations, for applications with required availabilities of 99.9% or higher, this term overwhelms everything else in the equation.

A key issue in the deployment of FSO systems is availability, which is dependent on a variety of factors, including equipment reliability and network design (e.g., redundancy), but these are well known and fairly quantifiable. The biggest unknown is the effect of atmospheric attenuation. Although most major airports around the world collect and maintain visibility statistics (which can be converted to attenuation coefficients), the spatial scale of visibility measurements is rough (generally 100 m or so), and the temporal scale is infrequent (hourly in most cases). As a result, estimates of availability of 99.9% or better are difficult to obtain. Thus, airport databases are generally only marginally useful in accurately and reliably determining grades of service. As a result, FSO manufacturers have taken it upon themselves to gather more reliable atmospheric data by using sensitive instruments such as nephelometers, visibility meters, and path transmissometers.

29. Link Budgets

One of the key methods for determining how well a FSO link will perform is to calculate a link budget. At a minimum, a link budget is used to predict how much margin, or extra power, will be available in a link under any particular set of operating conditions. This margin can then be integrated with a model of atmospheric attenuation to calculate expected availability on the basis of losses from both scattering and scintillation. Typically, a FSO link budget includes inputs for transmit power, receive sensitivity, optical system losses, geometric losses, and mis-point or alignment loss.

Transmit power is the amount of optical energy transmitted by the FSO system; receive sensitivity is the minimum amount of optical energy that must be received by the FSO system for a specified error rate. Both of these are typically measured as either peak or average power. In addition, both can be measured either at the transmit or receive apertures or at the lasers or detectors. If the measurements are taken immediately in front of the detectors or lasers, it is necessary to factor in the additional optical system losses that will occur as the optical energy passes through the system. Optical system losses include scatter, surface reflections, absorption, and overfill losses.

Geometric losses are those losses that occur due to the spreading of the transmitted beam between the transmitter and the receiver. Typically, the beam spreads to a size larger than the receive aperture, and this “overfill” energy is lost. In general, larger receive apertures or smaller transmit divergences result in less geometric loss for a given range. For a uniform transmit power distribution with a nonobscured transmitter or receiver, geometric losses can be approximated with the following formula:

$$\text{Geometric loss (dB)} = 10 * \log \left\{ \frac{\text{Receive Aperture Diameter (m)}}{\text{TX Aperture (m)} + [\text{Range (km)} * \text{Divergence (mrad)}]} \right\}^2 \quad (2)$$

Equation (2) can also be used to approximate the geometric losses for a Gaussian power distribution by use of the $1/e$ divergence but with slightly less accuracy because it assumes a uniform power distribution. It should also be noted that Eq. (2) is appropriate for FSO systems only and is not typically used in microwave link budgets where geometric loss is based upon assumptions for transmit beam diffraction as limited by the antenna.

Mis-point loss represents the imperfect alignment of the transmitter and the receiver and results from the fact that most FSO systems transmit a beam with a Gaussian power distribution and that only a portion of the beam overlaps the receiver. In general, a system is perfectly aligned when the center of the Gaussian power distribution is at the center of the receiver. If this is not the case, then the receiver may only be collecting energy from the “edges” of the beam, where the energy intensity is lower. As discussed in Section 3, mis-point loss is primarily caused by base motion. FSO systems that incorporate automatic pointing and tracking inherently have less mis-point loss because they are constantly adjusting for optimal alignment but do experience some mis-point loss resulting from the limited ability of pointing and tracking systems to correct for all types of motion.

Tables 4 and 5 present simplified link budgets for nontracking and automatic tracking systems, respectively. It is interesting to note the improvement in link margin that can be obtained by use of an automatic tracking system. The tracking system reduces the residual pointing and tracking errors so that a smaller TX divergence can be used to substantially reduce the geometric link loss.

Table 4. Simplified Link Budgets for a Nontracking System

Parameter	Link Range		Comment
	300 m	2000 m	
Average laser power	10.0 dBm	10.0 dBm	
System loss	-6.0 dB	-6.0 dB	Combined TX/RX terminal losses
Geometric loss	-27.0 dB	-44.0 dB	8-mrad TX divergence; 3-mrad pointing error
Signal power on detector	-23.0 dBm	-40.0 dBm	In clear air, no window loss
Detector sensitivity	-46.0 dBm	-46.0 dBm	Wavelength and data-rate dependent
Clear air link margin	23.0 dB	6.0 dB	For atmospheric and window loss

Table 5. Simplified Link Budgets for an Automatic Tracking System

Parameter	Link Range		Comment
	300 m	2000 m	
Average laser power	10.0 dBm	10.0 dBm	
System loss	-8.0 dB	-8.0 dB	Combined TX/RX terminal losses
Geometric loss	-4.0 dB	-18.0 dB	0.5-mrad TX divergence; 0.15-mrad pointing error
Signal power on detector	-2.0 dBm	-16.0 dBm	In clear air, no window loss
Detector sensitivity	-46.0 dBm	-46.0 dBm	Wavelength and data rate dependent
Clear air link margin	44.0 dB	30.0 dB	For atmospheric and window loss

30. Metrics

One of the biggest challenges faced by potential users of FSO systems is accurately comparing the relative performance of products from different manufacturers. The reason for this is that each manufacturer tends to quote slightly different versions of similar performance specifications. For example, transmit power can be defined as either peak or average, and transmit divergence can be defined to either the $1/e$, $1/e^2$, or FWHM points.

As discussed in the abstract, one of our goals in this paper is to suggest a common set of metrics for FSO systems that will allow for the accurate comparison of performance. To that end, we would like to suggest that the following six metrics be used by manufacturers of FSO equipment when specifying performance.

- Transmit power
- Transmit beam divergence
- Receive sensitivity
- Receive field of view
- Pointing and tracking field of regard and closed-loop bandwidth
- Link margin and attenuation versus range curves

By using these six metrics, a potential end user should be able to fully evaluate the expected performance of a given FSO transceiver in a particular installation and be able to make a quantitative comparison of different systems.

Transmit Power

We would like to suggest that the industry adopt the standard metric “Total Maximum Average Power at the Output Aperture.” Using this guideline, each FSO transceiver specification sheet would list the integrated sum of the emitted power over the entire output aperture measured, with an averaging time of at least 25 times the operational bit period. Alternatively, a FSO manufacturer could list the “Maximum Average Output Power of the Transmit Laser” in conjunction with “Transmit System Optical Losses.”

Transmit Beam Divergence

We would like to suggest that the industry adopt the standard metric “Transmit Beam Divergence to the $1/e$, $1/e^2$, and FWHM points.” This combined information will allow a potential user to make an approximate determination of the transmit beam profile and be able to predict power distribution at various ranges.

Receive Sensitivity

We would like to suggest that the industry adopt the standard metric “Average Required Power at the Receive Aperture for a 10^{-9} Bit Error Rate.” Extrapolating to other error rates is pretty straightforward, with 10^{-12} approximately corresponding to 1 dB less sensitivity and 10^{-6} approximately corresponding to 1 dB more sensitivity. Alternatively, a FSO manufacturer could list the “Average Required Power at the Detector” in conjunction with “Receive System Optical Losses.”

Receive Field of View

We would like to suggest that the industry adopt the standard metric “Receive Field of View to the FWHM Points.”

Pointing and Tracking

For pointing and tracking systems, we would like to suggest that the industry adopt the standard metrics “Tracking System Field of Regard” and “Tracking System Closed-Loop Bandwidth.” We fully acknowledge that these two metrics would not provide sufficient information to fully quantify the capabilities of a pointing and tracking system, but they are typically fairly representative of overall performance and should allow for the accurate comparison of different transceivers.

31. Link Margin and Attenuation Versus Range

The final metrics that we would like to suggest are two curves showing link margin versus range and attenuation versus range as presented in Fig. 5. The first curve shows how much margin a given system has at a given range to compensate for both scattering and scintillation losses. The second curve is derived from the first and shows the maximum range in which a FSO system will operate for a given atmospheric attenuation. This second curve loses accuracy at low attenuation (<30 dB/km) because it does not take into account scintillation losses. These are by far the most important standard metrics inasmuch as curves of these types fully encompass almost all aspects of system performance. The exception to this is alignment sensitivity, which is addressed by several of the other recommended metrics. For a highly stable installation, the importance of the relative differences in the other metrics will be greatly diminished because the expected performance and availability can almost be entirely derived from these curves.

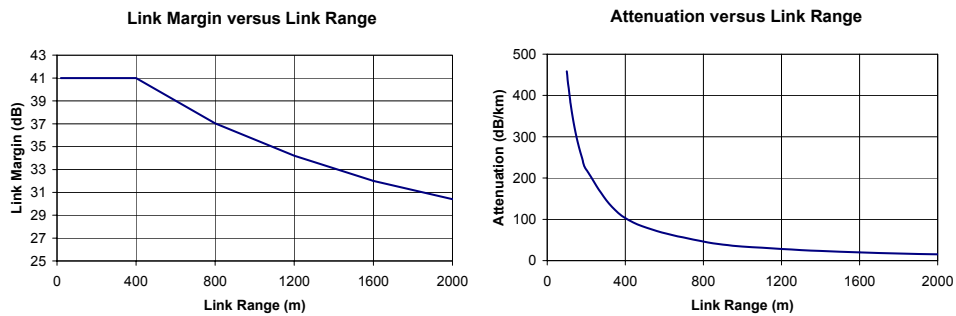


Fig. 5. Suggested standard metric: link margin versus link range and attenuation versus link range.

32. Practical Limits of FSO

One of the challenges currently faced by the FSO industry is inaccurate statements regarding the maximum performance of FSO links by members of the FSO community. In general, these statements are made in order to increase the likelihood of near-term sales but do long-term damage to the reputation of the industry, because links that do not live up to presales expectations leave the customer inclined to find fault with the technology rather than an overaggressive sales process.

Fundamentally, FSO is a 3(9s) technology and, for most parts of the world, is capable of only long-term 4(9s) or 5(9s) performance at short ranges. Table 6 summarizes the average yearly performance of a typical high-performance FSO system for various availabilities and in various climates.

As can be seen, FSO is quite capable of ranges around 1 km—even in poor-weather cities at 99.5% availability; but at higher availabilities, this maximum range is greatly reduced. At 99.99% or better availabilities, the maximum range is typically less than 300 m, except in the best climates.

To calculate the ranges in the above chart, historic visibility data for each potential location were gathered and analyzed. These data are available from a number of different sources, including the National Weather Service (NWS) branch of the U.S. National Oceanic and Atmospheric Administration (NOAA), the National Climatic Data Center (NCDC), and the U.S. military, and have been collected for cities around the world for a period of at least 16 yr. The data include both surface visibility and cloud statistics.

Table 6. Ranges for Various Annual Availabilities and Climates^a

Service Availability (%)	Cities	Range (m)
99.5	Phoenix – atmospherically excellent	10,000+
	Denver – atmospherically good	2400
	Seattle – atmospherically fair	1200
	London – atmospherically poor	630
99.9	Phoenix – atmospherically excellent	5200
	Denver – atmospherically good	850
	Seattle – atmospherically fair	420
	London – atmospherically poor	335
99.99	Phoenix – atmospherically excellent	460
	Denver – atmospherically good	290
	Seattle – atmospherically fair	255
	London – atmospherically poor	185

^aAvailability ranges are based upon two 125/155 Mbit/s FSO transceivers that are located outdoors and transmitting through clear air under normal operating conditions.

33. Conclusion

Well-designed FSO systems are capable of delivering 99.9% or better performance at 500–1000-m ranges for the vast majority of cities throughout the world. They are eye-safe and can be used to provision carrier-grade service as long as the appropriate processes have been used to calculate their expected performance.

The authors of this paper hope that the suggested metrics will be adopted by the FSO industry as a method for quantitatively defining system performance, because the long-term success and adoption of this very powerful technology depends upon consistent and accurate performance expectations.

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