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How to Design a Reliable FSO System

INTRODUCTION

Free space optics (FSO) has been used for more than a decade as a short/medium distance point-to-point (building-to-building) connectivity solution in campus enterprise LAN markets. The license free nature of this technology combined with its high-speed bandwidth capabilities, comparable to optical fiber, allow network administrators to interconnect LAN segments at real networking speeds (e.g. 100 Mbps or 1000 Mbps) without the hastle of digging to install optical fiber. Since digging to install fiber is typically a very expensive and time-consuming process, the value proposition of using FSO can be very appealing. Only recently has the carrier market started to look into FSO technology as an alternative network connectivity solution. However, when considering the carrier market, the requirements in terms of component reliability and overall weather related system availability are much more stringent than system requirements in the enterprise market. This paper addresses some of the issues that are most important in the design of an overall carrier system architecture. Briefly described are the basic physics of transmission at various short and long infrared wavelengths and their overall impact on the system design. This is followed by an overview of basic transmitter and detector technologies. When selecting suitable components, reliability and commercial availability of those components should play an important factor. Eye safety is another factor that has to be taken into consideration in a carrier class system design. Finally, the link budget will determine the overall system availability under various weather conditions. This aspect is discussed near the close of this document.

BASIC OPERATION AND ATMOSPHERIC TRANSMISSION WINDOWS

FSO systems are based on the transmission of infrared radiation through the atmosphere. The basic concept is very simple: An infrared light source (typically a laser or an LED) sends a light beam through "free space" and a detector at the target location receives the beam. Data transmission is made possible by a modulation of the light beam, most commonly accomplished by switching the beam on and off (a process known as "on-off keying"). A simple analogy to this process could be switching a flashlight on and off and detecting the modulated light stream with the human eye. While the human eye is well capable of detecting light in the visible spectrum between 400 nanometers (nm), blue, and 700 nm, red, the range of infrared spectral wavelength is located just outside the visible spectrum and is, consequently, not visible to the human eye.

Generally, all commercially available FSO systems operate in the near infrared wavelength range between roughly 750 – 1600 nm. However, the physics and transmission properties of radiation as it pentetrates the atmosphere are very similar in both visible and near infrared wavelength ranges. The capability of the human eye to see light or objects from a distance is limited by atmospheric conditions. Visibility is also an important and somewhat limiting factor for the operating ranges of FSO systems. Later, the relationship between visibility and overall system availability is discussed.

At this point it is certainly important to note that, although the atmosphere is considered to be highly transparent in the visible and near infrared wavelength range, certain wavelengths (or wavelength bands) can suffer from severe atmospheric absorption. In the near infrared wavelength range, absorption occurs primarily due to water particles (moisture) that 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 can be neglected because the gas specific absorption coefficients are very small when compared to water absorption. However, in the longer infrared wavelength range (> 2000 nm), gaseous absorption can dominate the absorption properties of the atmosphere.

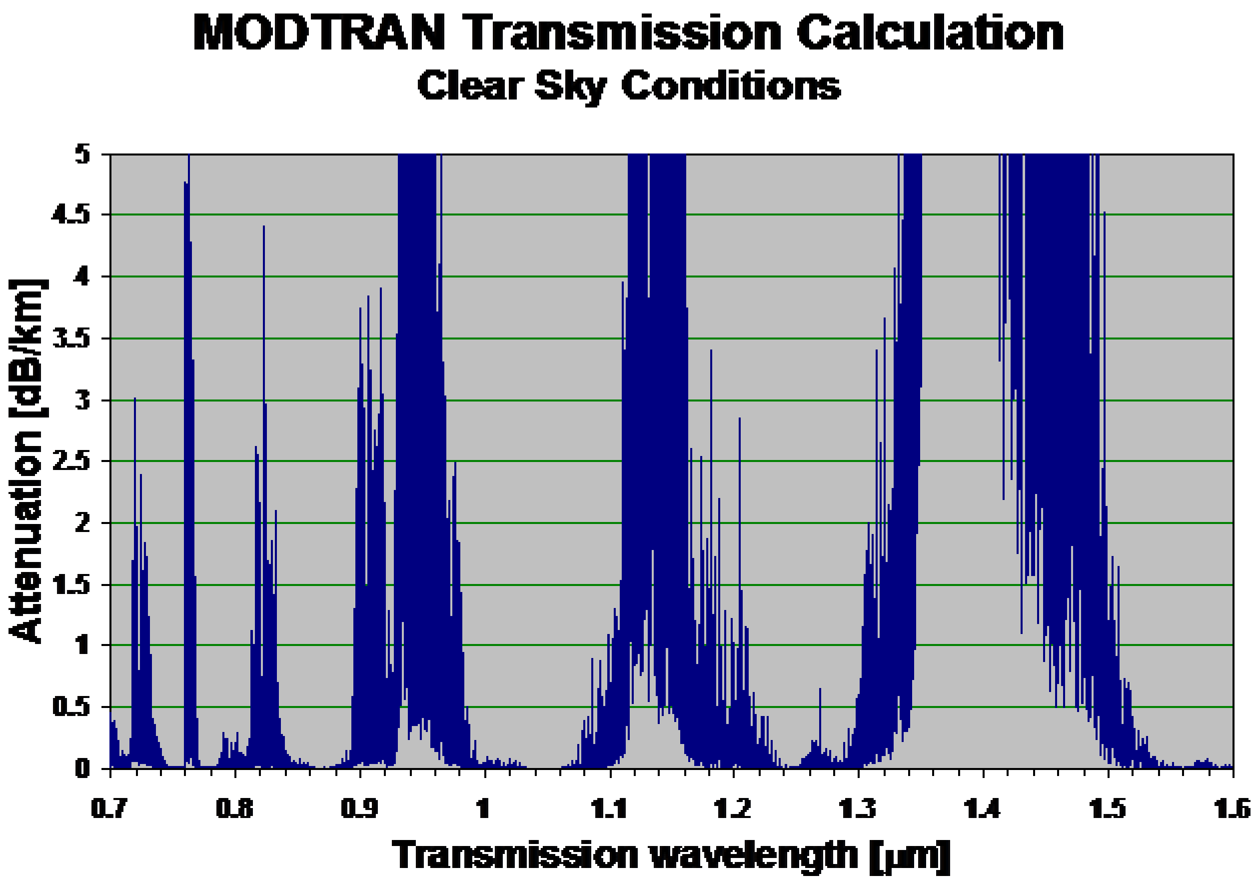


Fig. 1: *Transmission properties of the atmosphere in the near infrared wavelength range under clear weather conditions (visibility > 10 miles). The calculation was done by MODTRAN, a software program developed by the Air force Research Laboratory.*

Fig. 1 shows the transmittance of the atmosphere under clear weather conditions (visibility >10 miles) as a function of transmission wavelength in the near infrared spectral range between 700 nm and 1600 nm. The diagram was created by MODTRAN, a software program developed by the Airforce Research Laboratory to study transmission properties of the atmosphere.

The MODTRAN results provide the following conclusions:

There are several transmission windows that are nearly transparent (attenuation < 0.2 dB/km), between 800 nm and 1600 nm wavelength range. These windows are located around several specific center wavelengths:

- **850 nm**

Characterized by low attenuation, the 850 nm window is very suitable for FSO operation. In addition, reliable, high-performance, and inexpensive transmitter and detector components are generally available and commonly used in today's service provider networks and transmission equipment. Highly sensitive silicon avalanche photo diode (APD) detector technology and advanced vertical cavity surface emitting laser (VCSEL) technology can be used for operation in this atmospheric window.

- **1060 nm**

The 1060 nm transmission window shows extremely low attenuation values. However, transmission components to build FSO system in this wavelength range are very limited and are typically bulky (e.g. YdYAG solid state lasers). Because this window is not specially used in telecommunications systems, high-grade transmission components are rare. Semiconductor lasers especially tuned to the nearby 980 nm wavelength (980 nm pump lasers for fiber amplifiers) are commercially available. However, the 980 nm wavelength range experiences atmospheric attenuation of several dB/km even under clear weather conditions. Fig.2 shows the absorption bands around 980 nm in more detail.

- **1250 nm**

The 1250 nm transmission window offers low attenuation, but transmitters operating in this wavelength range are rare. Lower power telecommunications grade lasers operating typically between 1280-1310 nm are commercially available. However, atmospheric attenuation increases drastically at 1290 nm, making this wavelength only marginally suitable for free space transmission.

- **1550 nm**

The 1550nm band is well suited for free space transmission due to its low attenuation, as well as the proliferation of high-quality transmitter and detector components. Components include very high-speed semiconductor laser technology suitable for WDM operation as well as amplifiers (EDFA, SOA) used to boost transmission power. Because of the attenuation properties and component availability at this range, development of WDM free space optical systems is feasible.

Fig. 2 shows enlarged views of the low attenuation 850 nm and 1550 nm transmission windows. Attenuation under clear weather conditions is extremely low (<0.2 dB/km) and extends over more than +/- 10 nm around the center wavelengths. Even in cases where the laser transmission wavelength does not exactly match the center wavelengths, attenuation due to atmospheric absorption does not change. This is important because of manufacturing tolerances in the transmitter's lasing wavelength. A wider wavelength range of low attenuation is also desirable because the laser wavelength can drift when the laser source is not temperature stabilized. Wavelength drifts of 0.2 nm/degrees Celsius are quite common for higher power, short wavelength lasers. In the 915 nm and 980 nm wavelength range a massive amount of absorption lines can be observed. These absorption lines can cause attenuation of narrow line width transmission sources as much as 4 or 2 dB in the 915 to 980 nm wavelength range, respectively. These values are low when compared to the attenuation values in dense fog conditions and they can significantly impact the performance of FSO systems in locations that experience heavy rainfall. An "intrinsic" clear weather attenuation of 4 dB will already reduce the link budget of an FSO operating over a distance of 2 kilometers by 8dB. A difference of 8 dB in link margin roughly corresponds to a difference in rain attenuation of one inch of rain/hour. In other words a FSO system that has 8 dB more margin can withstand an additional rain attenuation of one inch of rain per hour without degradation of system performance. To make matters worse, the majority of laser manufacturers specify the lasing wavelength with +/- 5 or 10 nm, making predictability of performance of an FSO system very difficult when operating at one of these wavelength ranges. Additionally, a slight drift of the transmission wavelength due to a temperature change of the laser diode (which is quite usual for outdoor equipment operating over a wide temperature range) can cause a loss of signal in longer distance FSO systems even under very moderate rain conditions. These results clearly reveal that the operation of FSO systems within a wider atmospheric transmission window seems to be the best choice for reliable systems operation.

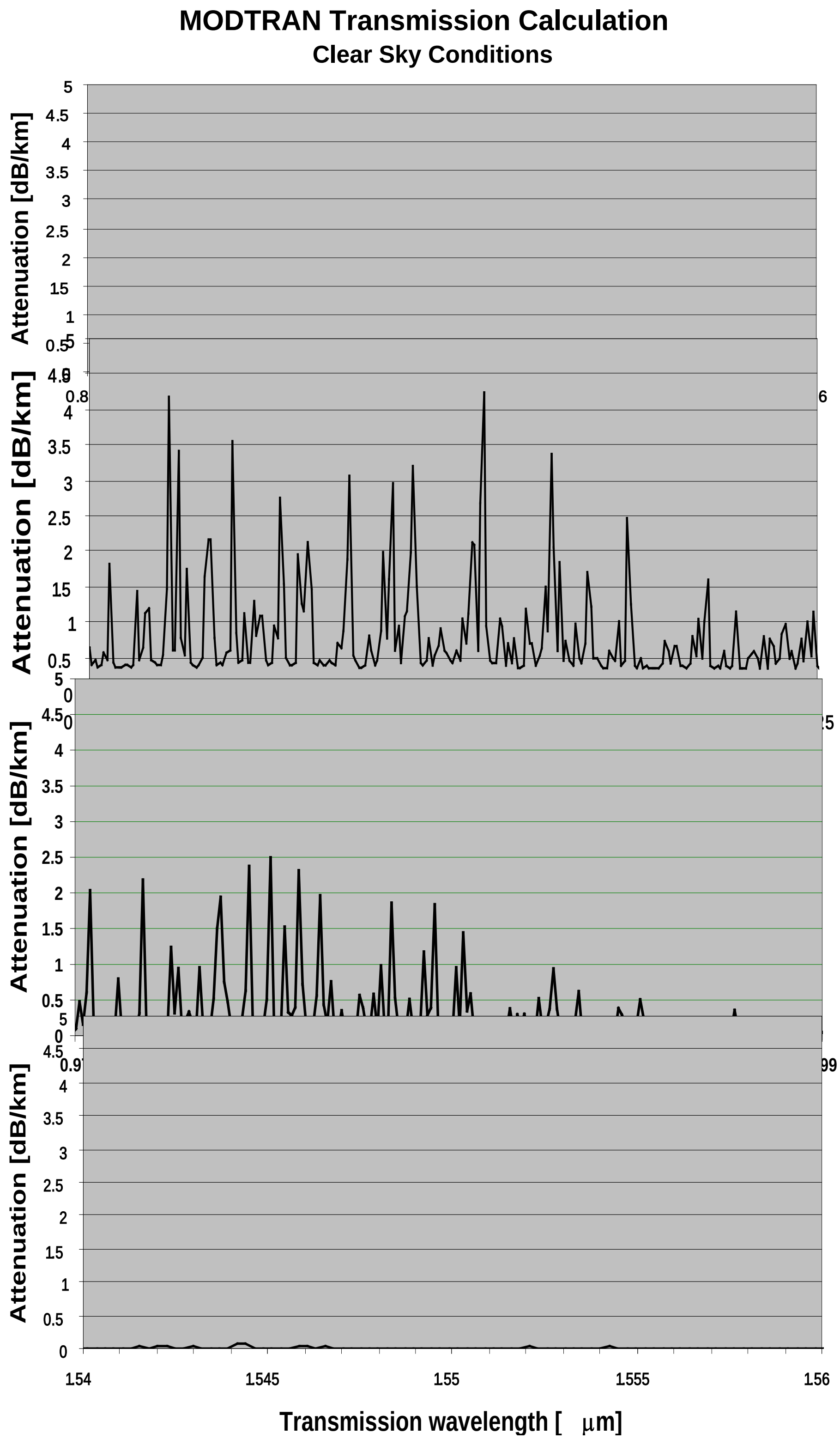


Fig. 2: Enlarged view of the two low attenuation 850 nm and 1550 nm windows (top and bottom). In comparison the 915 nm and 980 nm wavelengths are shown in the middle part to illustrate the impact of absorption lines.

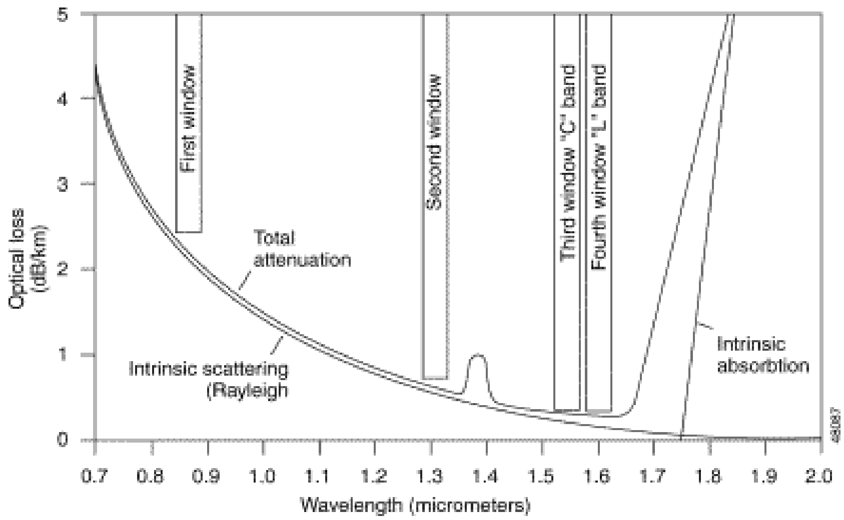


Fig. 3: Attenuation curve and transmission windows used in fiber optics communications. Very reliable and long lifetime electronic components were developed for these specific wavelength ranges to fulfill the stringent component lifetime requirements of the telecommunications industry. (Illustration from Cisco web page: http://www.cisco.com/univercd/cc/td/doc/product/mels/dwdm/dwdm_ovr.htm#xtocid629215)

It is interesting to note that three of the low atmospheric attenuation windows coincide with the standard transmission windows of optical fiber communication systems. This is of special importance for FSO system designers, who can take advantage of proven and reliable components that fulfill the stringent component lifetime requirements of carrier class equipment. As such, free space optical manufacturers can use components that operate at standard fiber optic communication system wavelengths, namely 850 nm, 1310 nm, or 1550 nm. Since the 1310nm band does not have acceptable attenuation properties for use in transmission through free space, the two remaining wavelengths to be examined are 850nm and 1550nm. Nonetheless, components operating in other wavelength ranges will be discussed when appropriate. The diagram in Fig.3 shows the transmission windows used in fiber optics communications.

FSO TRANSMITTER TECHNOLOGIES

To ensure the highest performance of an FSO system, it is important to choose a transmission wavelength within one of the two atmospheric windows that coincide with one of the fiber optics transmission windows. Within these two wavelength windows, namely 850 nm and 1550 nm, a suitable transmitter for a telecommunication grade FSO system must have the following characteristics:

- Operation at higher power levels (Important for longer distance FSO systems)
- Favorable high-speed modulation characteristics (Important for high speed FSO systems)

- Components small in footprint and low in power consumption (Important for the overall system design and system maintenance)
- Capability to operate over a wide temperature range without showing major performance decay or degradation (Important for outdoor system installation)
- Mean time between failure (MTBF) operation exceeding 10 years

For these reasons manufacturers offering carrier-class FSO equipment generally use Vertical Cavity Surface Emitting Lasers (VCSELs) in the shorter infrared wavelength range and Fabry Perot (FP) or Distributed Feed Back (DFB) lasers for operation in the longer infrared wavelength range.

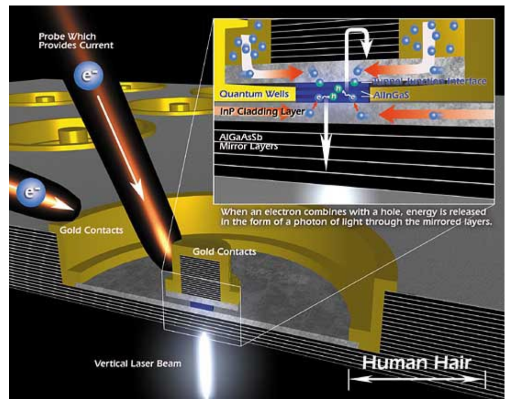
Note: Aside from general availability of high-quality components and efficient transmission window, there are several laser types that, for a variety of reasons, are not very well suited to FSO systems. At the current stage of development of these sources, solid-state lasers (e.g. YdYag lasers operating at 1060 nm) or any form of gas-based lasers fall within this category. Indeed, the majority of high power lasers operating in the near infrared spectral range cannot fulfill the MTBF requirements of carrier-grade systems. For example, high power GaAlAs lasers operating slightly beyond 800 nm or slightly above 900 nm, though generally available from many vendors and at very low cost, do not normally qualify as telecommunication grade due to insufficient MTBF values.

LONGER WAVELENGTH FP AND DFB LASERS

FP and DFB lasers based on InGaAs/InP semiconductor technology with operating wavelengths around 1550 nm were developed specifically for fiber optics communications systems due to low attenuation characteristics of optical fiber in this wavelength range. The development of these lower power laser sources created high modulation speed, wavelength stability, reliability and long lifetimes. Today's lower power 1550 nm DFB lasers show excellent lifetime performance that satisfies the stringent requirements of the telecommunications industry. Higher transmission power DFB lasers are a relatively new technology. Two technologies, erbium-doped fiber amplifier (EDFA) and semiconductor optical amplifier (SOA), are used to boost the power of lower power laser sources. In addition to boosting the output power, EDFA and SOA technologies can amplify multiple, closely spaced wavelengths simultaneously (i.e. Wavelength Division Multiplexing or WDM). This technique has enabled the fiber optic capacity revolution. EDFA technology with power outputs of 2 Watts in the 1550 nm wavelength range are commercially available today and can be incorporated in high capacity FSO systems.

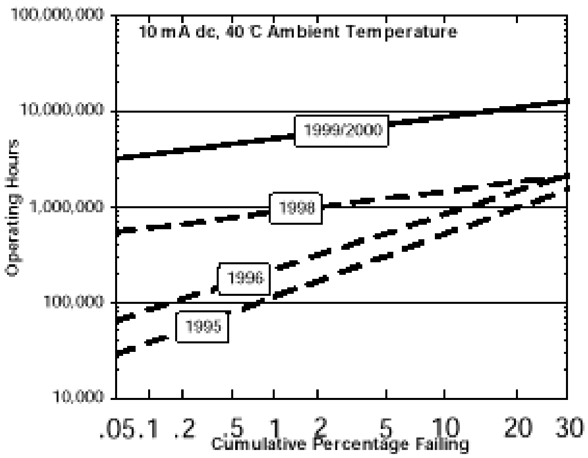
Higher power DFB lasers with output powers beyond 100 milliwatts (mW) are also commercially available. However, these lasers require a considerable amount of driving current during operation and their high-speed capabilities are somewhat limited. Commercially available high-speed laser drivers operating beyond 1 gigabits per second (Gbps) are available with driving currents up to roughly 100 millamperes (mA). High driving currents translate directly into high thermal power dissipation. Consequently, these lasers require cooling systems to reduce the junction temperature directly related to the diode lifetime and the MTBF value. The thermal stress on the complex compound layer structure of a DFB laser that is caused by the high temperature gradient between the active transmission region and the surrounding cooling surface provided by the thermoelectric (TE) cooler can still significantly impact the diode lifetime.

VCSEL LASERS



Over the last decade, VCSEL structures have gained a massive amount of popularity in the communications industry. In addition, laser lifetime, transmission power performance and modulation characteristics have shown dramatic improvements in the shorter 850 nm and 980 nm wavelength range. VCSELs clearly established a milestone and revolutionized the transmission component market due to the exceptional and dramatic cost/performance advantage over previously available technology. The success of VCSEL technology has been so tremendous that many VCSEL laser manufactures can produce shorter wavelength 850 nm laser structures with direct modulation speeds beyond 3 Gbps at power levels in excess of 10 mW. Direct electrical modulation of VCSEL lasers beyond 10 Gbps have been demonstrated and commercialized for OC-48 (STM-16) and 10 gigabit Ethernet (GbE) operations. VCSEL lasers can operate at very low threshold currents (a few milliamperes) and the electro-optic conversion efficiency of these special semiconductor laser cavity structures is extremely high. Power dissipation is not typically an issue and active cooling of the VCSEL structure is not required. In addition, VCSELs emit light in the form of a circular beam instead of an elliptical beam shape found in hetero-junction DFB lasers. The round shape of the beam pattern perfectly matches the round core of an optical fiber strand. Therefore, the coupling process is far easier and coupling efficiency is much higher when compared to a standard DFB laser.

Nonetheless, the most remarkable success in VCSEL technology is certainly related to MTBF: Some tests have measured and extrapolated failure rates below 1 FIT (1 failure in 1 billion hours) at 35 degrees Celsius junction temperature for the first 4000 years. This corresponds to a MTTF value of more than $4*10^7$ hours! Even in environments that are exposed to high ambient temperature (such as outdoor FSO equipment) where the junction temperature can reach 90°C for extended periods of time, a MTTF value of $3.9*10^5$ hours or 44 years was estimated. An example of short wavelength VCSEL laser lifetime improvement since 1995 is shown in Fig. 5. Initial VCSEL laser production showed lifetime cycles around 50,000 hours. Through constant improvements in the fabrication process this value has been pushed beyond 5,000,000 hours for the Honeywell VCSEL product line.



In summary, choosing the right transmitter is an important component of a free space optics system, critical to satisfying telecommunications equipment requirements. Besides the transmitter, the receiver is another important electronic component that has to be picked carefully. The following section focuses on suitable receivers for high performance FSO systems.

Fig. 5: *Comparison of lognormal reliability distribution fits over the development cycle from 1995 to1999/2000. The plot shows the significant improvement in reliability for low failure rates. (Honeywell 850 nm VCSEL Products Optoelectronics Reliability Study)*

FSO DETECTOR TECHNOLOGIES

Detector choices are much more limited when compared to the variety of wavelength options available. This is due to vast amounts of different semiconductor laser compound structures. The two most common material systems used to detect light in the near infrared spectral range are either silicon (Si) or indium gallium arsendide (InGaAs). Detectors are based either on PIN or APD technology. A thorough discussion of these technologies is not within the scope of this paper. More detailed information on PIN and APD technology and their use in FSO systems can be found in the book "Free Space Optics: Enabling Optical Connectivity in Today's Networks" authored by H. Willebrand and B. Ghuman and published by Sams Publishing.

Silicon is the most commonly used detector material in the visible and near infrared wavelength range. Silicon technology is very mature and silicon receivers can detect extremely low levels of light. Detectors based on silicon typically have a sensitivity maximum or spectral response around 850 nm. Therefore silicon detectors are ideal candidates for light detection in conjunction with short wavelength 850 nm VCSEL laser. Silicon drastically loses sensitivity toward the longer infrared wavelength spectrum; for wavelengths beyond 1 micrometer. 1100 nanometers defines the cutoff wavelength for potential light detection and therefore silicon cannot be used as detector material beyond this range. Silicon detectors can operate at very high bandwidth. Recently, operation at 10 Gbps has been commercialized for use in short wavelength 850 nm 10 GbE systems. Lower bandwidth (1 Gbps) silicon PIN and APD detectors are widely available in a variety of mechanical packages such as TO-46 cans. Very common are also Si-PIN detectors with integrated trans-impedance amplifiers (TIA). The sensitivity of which is a function of the signal modulation bandwidth – decreasing as bandwidth increases. Typical sensitivity values for a Si-PIN diode are around –34 decibel milliwatts (dBm) at 155 megabits per second (Mbps). Si-APDs are far more sensitive due to an internal amplification (avalanche) process. Therefore Si-APD detectors are very useful for low light level detection in free space optics systems. Sensitivity values for higher bandwidth applications can be as low as –50dBm at 10 Mbps, -45dBm at 155 Mbps, or –38 dBm at 622 Mbps. Silicon detectors can be quite large in size (e.g. 0.2 x 0.2 mm) and still operate at higher bandwidths. This feature minimizes loss when light is focused on the detector by using either a larger diameter lens or a reflective parabolic mirror.

For longer wavelength radiation, InGaAs is the most commonly used detector material. The performance of InGaAs detectors has been constantly improved in terms of sensitivity and bandwidth capabilities as well as the development of 1550 nm fiber optic technology. The vast majority of longer wavelength fiber optics systems use InGaAs as detector material. Commercially InGaAs detectors are either optimized for operation at 1310 or 1550 nm. Due to the drastic decrease in sensitivity towards the shorter wavelength range, InGaAs detectors are typically not used in the 850 nm wavelength range. The main benefit of InGaAs detectors is higher bandwidth capability. The majority of InGaAs receivers are based on PIN or PIN-TIA technology. Typical sensitivity values for InGaAs Pin diodes are similar to those of Si-PIN diodes (e.g. –33dBm at 155 Mbps). InGaAs diodes operating at higher speed are typically smaller in size than Si-PIN diodes. This is because most high-speed InGaAs receivers are designed for fiber optic transmission in conjunction with 9-micrometer core diameter, single mode (SM) fiber, and the small SM core diameter doesn't require a large detection surface. This makes the light coupling process a more challenging task and overall losses that occur when the light is coupled from free-space onto the detector surface are higher, thus impacting the link budget of the systems. The conclusion is that both Si and InGaAs detectors are capable of fulfilling the stringent service provider systems standard requirement since both detector technologies are already used in carrier class fiber optic communication systems.

COMPONENT RELIABILITY AND FSO SYSTEMS

Overall component reliability is an important factor to ensure the proper operation of service provider grade transmission equipment. MTBF values of components are especially important, as the basic requirement is to guarantee a lifetime cycle of the installed equipment well beyond its anticipated use in the network. Active components such as laser sources have to be chosen very carefully as they are exposed to the highest stress factors due to their inherent and complex internal electronic structure. Shorter and longer wavelength VCSELs as well as longer wavelength, lower power DFB lasers are among the highest lifetime laser components in the industry and therefore are highly recommended for use in FSO systems. As stated above, these lasers are designed to perform without significant failure for more than 1,000,000 hours without degradation and even under difficult operating conditions such as high temperature environments. The manufactures of carrier grade transmission equipment must perform a detailed and complete MTBF analysis and constantly check the predicted performance with the actual data generated by equipment at the actual customer site.

EYE-SAFETY CONSIDERATIONS

Eye safety, and laser safety in general, are studied extensively in the FSO user and FSO system designer community. The IEC (TAG TC 76) team finalized an internationally recognized standard in the IEC60825-1 (Amendment 2) in March 2001. This standard unifies the previous European position established under IEC60825-1 and the North American laser safety regulation as defined by FDA/CDRH.

Under the new standard, specific laser classes were generated and each class has specific labeling and warning instructions. Depending on the amount of power launched, the document outlines certain installation requirements that must be fulfilled to comply with the standard. The standard also contains definitions for specific hazardous zones in front of a laser power emitting system area that must be cleared for eye-safe viewing. The document also restricts installation of certain high power laser systems in areas easily accessible to the public. Within the new classification scheme class 1 and class 1M systems are totally eye-safe for viewing without or with an optical instrument such as binoculars. Higher power laser systems such as class 3R or class 3B have additional mounting restrictions over them, leading to an extended hazardous zone.

Nevertheless, the document states that there are no laser systems that are inherently safe or unsafe. It is fundamentally possible to design an eye-safe laser system operating at any given wavelength - output power levels (and not the wavelength itself) determine the laser class specification. It is important to understand that the new regulation refers to power density in front of the launch aperture rather than the absolute power created by a laser diode inside the equipment. For example, the laser diode inside the FSO link head can actually be classified as a class 3B diode while the system can easily be a class 1 or class 1M when the light is launched from a large diameter lens that spreads out the radiation over a large area before it enters the free space in front of the link head. The new regulation also states that a class 1M laser system operating at 1550 nm can roughly launch 100 times the power thru the same sized aperture lens when compared to a system operating in the shorter infrared wavelength range such as 850 nm. Indeed, it is possible to increase the lens aperture size to allow higher laser power emission at a shorter wavelength. Another method of maintaining preferable class 1/1M laser safety classification is to use multiple large size transmission apertures to launch power into free space. Many FSO vendors already use this technique for this purpose. This approach is also very beneficial in overcoming scintillation (heat shimmer) that can cause bit error rate (BER) degradation, especially in hot or desert-like environments.

A SIMPLE PROPAGATION MODEL – LINK EQUATION

When taking a closer look at an 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 (see Fig. 6). Internal parameters are related to the design of a specific FSO system and can be impacted by the system designer or engineer. Examples are: optical power, transmission bandwidth or divergence angle on the transmitter side and receiver sensitivity, receive lens diameter or receiver field-of-view on the receive side. Other important parameters that determine system performance are related to external or non-system specific parameters and all of them are related to the climate under which the system has to operate. Typical examples are the deployment distance and visibility.

It is important to understand that many of these parameters are linked and not independent of each other. Two examples: 1) System availability is not only a function of the deployment distance but also a function of the inherent atmospheric attenuation coefficient and 2) Increasing the modulation bandwidth on the transmitter side will impact the sensitivity figure and the BER performance of the receiver side. In general, the focus on the improvement of one system parameter (e.g. increase of transmission power) does not lead to an overall improved system performance. The next section demonstrates that the ability to launch a high amount of power is certainly beneficial within the overall link budget calculation. However, it becomes obvious that simply launching higher power levels will not automatically result in a better performing FSO system. Many other factors have to be considered. These factors can actually outperform the advantage of being able to launch higher power levels. A professional FSO system designer must balance all of these parameters.

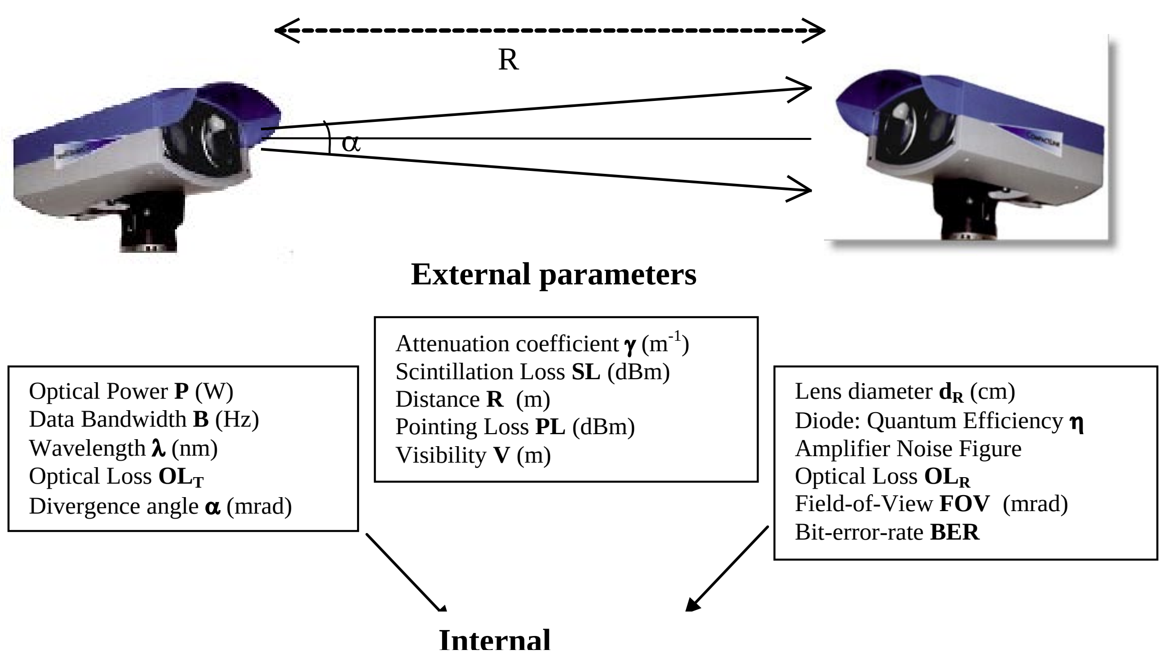


Fig. 6: *Schematic explanation of internal and external FSO system design parameters.*

Under the assumption that the transmission source can be seen as a point source, the simple link equation (1) below shows the impact of various system parameters on the power received at the receiving station. The climate/weather impact on FSO system availability is solely contained in the last part of the equation. In particular, and as can be easily seen from this equation, the value of the atmospheric extinction coefficient σ is extremely important due to the exponential dependency on the receive power level.

$$P_{received} = P_{transmit} \cdot \frac{A_{receiver}}{\left(\alpha_{mrad} \cdot Distance\right)^2} \cdot \exp(-\sigma \cdot Distance) \qquad (1)$$

ATMOSPHERIC LOSSES

There are several mechanisms that negatively impact the fade margin and consequently the performance or availability of a Free Space Optics system. While some of them are climate related (eg. rain, fog, snow), others are related to atmospheric constituents (e.g. gaseous molecules) that are inherently present in the atmosphere. Earlier in this paper the importance of operating an FSO system within one of the atmospheric transmission windows was discussed. Molecular and gaseous absorption of the atmosphere add to the value of the extinction coefficient σ (see Eq.1). Besides these, most of the factors that impact the performance of FSO systems are related to scattering. The general expression for the transmission $T_{(x)}$ defined as the ratio of the light intensity $I_{(x)}$ received at location *x* and the launched light intensity I_0:

$$T_{(x)} = \frac{I_{(x)}}{I_0} = \exp(-\sigma\, x) \ , \qquad (2)$$

where σ is again the extinction coefficient (see Eq.1) and *x* is the distance the beam traveled through the atmosphere. σ is a rather complex parameter that, in more general terms, depends on absorption and scattering mechanisms observed at the specific transmission wavelength.

There are different forms of light scattering and the main factor that determines the specifics of the scattering process is given by the ratio of the transmission wavelength compared to the size distribution of the scattering particles. In general terms, literature distinguishes between Rayleigh (particle size << wavelength), Mie scattering (particle size ~ wavelength), and geometrical scattering (particles size >> wavelength). For all practical purposes Rayleigh scattering can be neglected for FSO systems operating in the near IR wavelength range.

In the case of near infrared radiation fog particles are the most natural occurrences in nature that provide high Mie coefficients. Due to the fact that fog is generally measured and recorded by climate research institutions and international weather service centers in terms of visibility, visibility is the most natural choice in estimating FSO system availability. However, in this model it is important to understand the linkage between visibility and the underlying mesoscopic physics of the scattering process because the physics of scattering is actually better understood in terms of size of scattering particles, particles density distribution or in more general terms the liquid water content (LWC) of the atmosphere. This process is somewhat similar to the procedure used in microwave availability calculations where the rain rate, not the actual size of raindrops, and the raindrop density distribution are used to calculate the overall system availability. Another aspect that has to be considered is the relationship between the actual transmission wavelength and the wavelength used in the visibility measurement instrument. Since most commercial visibility meters operate in the visible spectrum around 550 nm, the understanding of this relationship under different visibility conditions is very important. As it turns out, the difference is small for near infrared wavelengths and within the visibility range of interest. However, differences can become quite significant in the longer infrared wavelength range. Table 1 shows the International Visibility Codes for weather conditions and precipitation. As expected, the path attenuation (last column) is extremely high under dense fog conditions in the near infrared wavelength range due to the high Mie scattering coefficient. Attenuation due to larger size rain particles is far less.

Weather Condition	*Precipitation*		*Amount mm/hr*	*Visibility*	*dB Loss/km*
Dense fog				0 m, 50 m	–271.65
Thick fog				200 m	–59.57
Moderate fog	snow			500 m	–20.99
Light Fog	snow	Cloudburst	100	770 m	–12.65
				1 km	–9.26
Thin fog	snow	Heavy rain	25	1.9 km	–4.22
				2 km	–3.96
Haze	snow	Medium rain	12.5	2.8 km	–2.58
				4 km	–1.62
Light haze	snow	Light rain	2.5	5.9 km	–0.96
				10 km	–0.44
Clear	snow	Drizzle	0.25	18.1 km	–0.24
				20 km	–0.22
Very Clear				23 km	–0.19
				50 km	–0.06

Table 1: *International Visibility Codes for weather conditions and precipitation. Typical path losses are shown for the near infrared wavelength range.*

SCINTILLATION

Scintillation is one of the effects related to turbulence. Scintillation cannot be characterized using visibility. Turbulence is caused when temperature differentials change the air particle density. Cells or hot pockets of air are created that move randomly in space and time thus also changing the refractive index of the air media. Turbulence affects laser beams propagating through the atmosphere in three different ways. First, beam wander occurs when the refractive index changes and acts like a lens, deflecting the beam from its given path. Second, turbulence results in a beam spread greater than diffraction theory predicts. Third, scintillation or intensity variations (peaks and troughs across the face of the beam) can occur that consequently change the amplitude of the beam at the receiver side.

Scintillation mainly causes a sudden increase in BER during very short time intervals (typically less than a second). During hot summer days and around midday and/or in the very early morning hours scintillation effects can be best observed. Depending on the specific system configuration, the variation in the signal strength both in time and across the cross section of the beam can reach levels in signal variation beyond 10 dB. Scintillation can act in both ways: Troughs can cause the signal to disappear, while peaks in amplitude can saturate the detector. Scintillation is distance dependent and in general the system designer has to reserve more link margin for scintillation effects over longer distances.

Research has revealed that there are several very successful geometric solutions that can decrease the effect of scintillation significantly. One of these strategies involves the use of multiple transmission beams that are sufficiently separated in space when they leave the transmission aperture plane. In this way they pass through different air (refractive index) cells, experiencing different intensity variations. The variations are averaged out when the signals are added together at the receiving terminal where they overlap in space. By separating multiple transmitters and by making the receiver optics sufficiently large (or sufficiently separating smaller receiving lenses), different parts of the receiver lenses are illuminated when the beam propagates through different air cells. As a statistical result as this approach signal amplitude variations are averaged out at the receiver. Even though scintillation is not physically correlated with visibility, scintillation under low visibility conditions, usually involving wet, cooler weather, can be neglected. For high visibility conditions that typically occur on hot and sunny days, one has to reserve the maximum loss for scintillation in the link budget analysis.

STATISTICAL AVAILABILITY CALCULATIONS BASED ON VISIBILITY MEASUREMENTS

Similar to rain fall data, visibility data is available from climate research organizations worldwide. Visibility data from a large number of airports all over the world is recorded at hourly intervals. Some weather services increase the sampling rate in case visibility changes quickly within the standard sampling frame. Most hourly visibility data that is available in electronic format has been recorded over a period of ten years.

A typical hourly visibility data set over a period of one month is shown in Fig. 7 for the city of Boston. Although the visibility at a specific airport may not characterize the exact visibility at a site in the middle of the city, it is the most consistent data available to predict overall FSO system availability. However, microclimate effects that can impact the visibility do exist and are more difficult to quantify. Major metropolitan cities very often have multiple airports and in this case data can be cross-correlated to improve the statistical availability prediction. The hourly resolution of the sampled data allows for a best path availability prediction between 99.9 % – 99.99%. Higher values of availability such as 99.999% cannot be calculated directly from the available raw data, but must be extrapolated from the available data sets. However, the error bars are quite high.

Another limitation of the available visibility data is related to the coarse distance resolution. Visibility measurement values are not provided in a continuous format, but are presented as discrete values. For example, possible visibility values within a typical data file are 0.0, 0.25, 0.5, or 0.75 miles and no values in between are given. The discrete nature of these values in both, distance and time, introduce errors. However, statistical averaging over a longer period of time (e. g. 10 years) and for a specific time interval within a year minimizes the uncertainty of a statistical availability model.

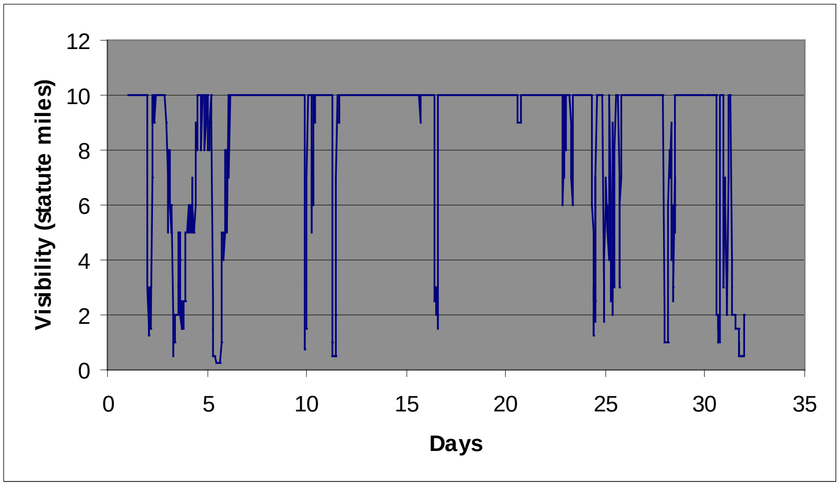


Figure 7: *Hourly visibility for January 1997 in Boston, Massachusetts.*

SUMMARY

This paper discussed some basic design criteria that are import to improve the reliability of FSO systems. With respect to transmission performance, availability and reliability of components, the 850 nm and the 1550 nm wavelength ranges are the most economical and best performing wavelength ranges for operating FSO systems. These two wavelength windows offer the lowest atmospheric attenuation and overlap with two of the most commonly used transmission windows in fiber optic communications. Therefore, the designer has access to a vast variety of commercially available and high-grade system components within carrier class system designs. Independent of the wavelength, any FSO system can be designed to operate according to international eye-safety standards. Scattering by fog particles can severely impact the availability of FSO systems in dense fog environments. Over the typically shorter distances of operation, rain is not a major factor impacting FSO availability. Current FSO availability models are based on visibility data. For most cases these models allow a statistical prediction of availability between 99.9 and 99.99%.

About LightPointe

LightPointe was founded in 1998 and has become the global market leader for high capacity wireless outdoor bridges with over 5000 systems deployed in over 60 countries worldwide and in vertical markets such as Health Care, Education, Military & Government networks, large and small campus enterprise networks, Wireline and Wireless Service Provider networks. Over the last 10 years the company has established a unique diversified product portfolio based on high capacity Free Space Optics (FSO) and Millimeter Wave (MMW) technology. With more than 10 patents granted in the FSO, RF/MMW and in the hybrid bridging solution space LightPointe has established a strong IP and patent portfolio position manifesting the company's technology leadership position.

LightPointe has a long list of global customers including but not limited to Wal-Mart, DHL, Sturm Foods, Siemens, Sprint, AOL, FedEx, BMW, Lockheed Martin, Dain Rauscher, Barclays, Nokia, Deutsche Bank, IBM, Corning, Cisco, Huawei just to mentioned a few. For more information please visit the Lightpointe website at www.lightpointe.com