fSONA Communications
T 604.273.6333
Toll-Free
1.877.Go.Fsona
info@fsona.com
www.fsona.com

Defining a Common Standard for Evaluating and Comparing Free-Space Optical Products

Abstract

The fundamental concepts that describe how a Free-Space Optics (FSO) link works are not too complicated. As usual, however, there is a difference between theory and practice. It is one thing to describe an FSO system on paper (or in a brochure), and quite another to have a robust and reliable system working in the field. This basic problem is made worse in this emerging market by various claims that are confusing or, quite frankly, hard to believe. A parameter as straightforward as “output power” may not be what you think. The key concept of “link margin” is defined differently for different products. Understanding some of the subtleties involved in achieving optimal performance will help network builders and buyers of FSO products make intelligent decisions about FSO, and can help differentiate product performance from product hype.

It has been proposed by some vendors in the field that a standard set of definitions be used when describing certain key performance parameters of an FSO system. This is a good first step. However, because the performance of any FSO link is a function of that particular link’s configuration (e.g. weather conditions and distance), there is still room for confusion. Even a common set of definitions needs to be explained within the context of a particular link installation. What is really needed is an overall measure of system performance that compares one FSO product to another on completely impartial grounds, independent of any installation or application. Such a performance metric is proposed and defined in this paper.

Shedding Light on the Subject

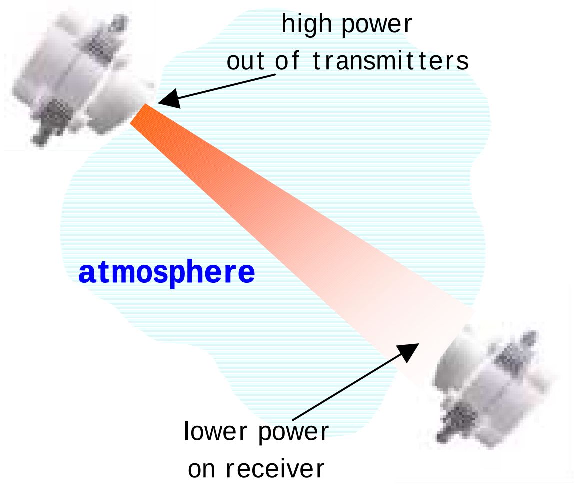

Figure 1 *Atmospheric Attenuation*

The key to a reliable free space optics link is getting as much light as possible from one transceiver terminal to the other. For a given distance between terminals and set of weather conditions, there are two simple yet fundamental questions to ask; how much light is being transmitted from one end, and how much of that light is being received at the other end? The two questions have different answers because the light gets attenuated to some degree in the atmosphere, as shown in figure 1. This can be easily understood by imagining how far one can actually see in different weather conditions. Just as a person can see buildings several kilometers away on a clear day, so can an FSO transceiver. On a foggy day, however, when it is difficult to see the house in front of you, an FSO link will similarly have a harder time “seeing,” or reaching, the opposite terminal. The light being transmitted in an FSO link, which is in the far-infrared part of the spectrum, will generally go a few times further through the atmosphere than visible light, but the same basic principle applies.

As the example above suggests, fog presents the single greatest challenge for FSO technology. In general, a system is selected for a particular application to provide a certain level of performance in worst-case atmospheric conditions. This worst-case condition almost invariably refers to fog.[1] Unlike RF transmission, however, FSO links are relatively unaffected by rain or snow. Also, there is no variation in performance or throughput as weather conditions change; as long as the link is running, an OC3 link always transmits and receives data at OC3 data rates. This is an important factor to keep in mind when discussing the “availability” of an FSO link.

Availability refers to the amount of time a link remains operational, and is expressed in terms of a percentage of time. For example, an availability of 99.9% (often referred to as “three nines” availability) means that the link is down 43 minutes each month, or 8.6 hours each year. An availability of 99.99% (“four nines”) means that the link is down only 4 minutes each month, or 52 minutes each year.

The Big 5 in FSO

In any FSO system there are five fundamental parameters that determine how much light gets from one terminal to the other, and therefore the general performance of the link…

Transmit Power

Obviously, the more power you start off with the better. If the light beam comes out of the terminal with more power in the first place, then it can afford to lose more of this power to the atmosphere on its way to the opposite terminal. More power, then, means you can penetrate further through the atmosphere to get longer link ranges. Or conversely, for a given range, higher power increases the availability of the link (the amount of time the link stays up) because it can handle more difficult weather (e.g. thicker fog).

Transmit Beam Divergence

The light beams exiting the terminal are not perfectly collimated laser beams; they have a cone angle, or “divergence” angle, as shown in figure 2. Because of this, the light gets more spread out as it gets further from the terminal, so that the beam cross-section may be as much as several meters in diameter by the time it gets to the receiving terminal. Consequently, not all of the light in the beam actually hits the receive aperture, and much of it gets wasted around the sides of the terminal. By minimizing the beam divergence, more light can be concentrated onto the opposite terminal’s receive aperture.

---

[1] In some areas, extreme rain or snow conditions may prove more severe than fog (e.g. torrential rains in tropical climates or white-out blizzards in northern climates). However, because of FSO’s general lack of sensitivity to rain and snow, this unconcern with fog is the exception to the rule.

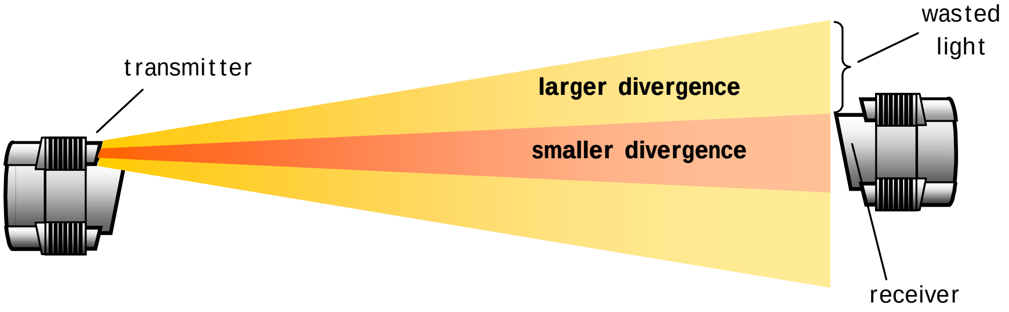

Figure 2 *Beam Divergence*

On paper this idea is fairly straightforward, and in fact is easily demonstrated in the lab. In real-world applications, however, reducing the beam divergence introduces other problems. In particular, the smaller the divergence the more difficult it is to keep the beam aligned with the line of sight (LOS) between the two terminals. External disturbances, such as building motion, mount vibrations, and wind gusts, cause the terminal to move relative to the LOS and mispoint the transmitted beam. These motions can cause errors in the transmission, and if sufficiently large could conceivably move the beam off the opposite terminal completely, resulting in a loss of link. If the beam divergence is wide enough, it can accommodate a certain amount of motion without sacrificing performance, as shown in figure 3.

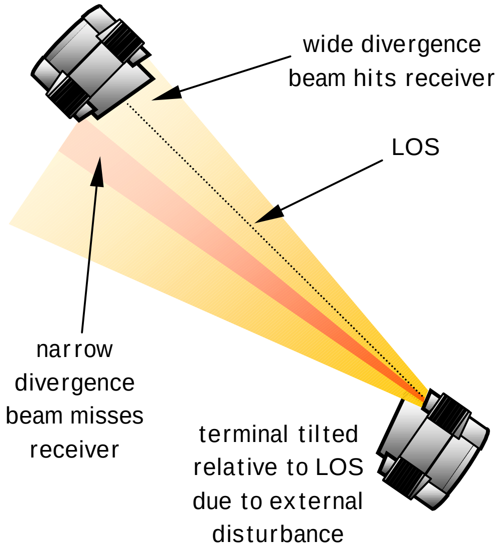

Figure 3 *Beam Mispointing*

Receive Aperture Area

As explained above, because the transmitted beam has some divergence angle, much of the light actually misses the receive aperture of the opposite terminal. It is therefore beneficial to have a larger receive aperture to "catch" as much of the incident light as possible. The trade-off is obviously that larger receive optics are more expensive and add unwanted weight.

Receiver Sensitivity

Regardless of how much light actually reaches the receive aperture, the receiver itself should be capable of measuring as low a signal as possible. The "sensitivity" of a receiver is defined as the minimum power level that can be detected while maintaining a specified bit error rate (BER).

Optical Losses

As well as traveling through the atmosphere, the light beam must go through the optical system of each terminal before finally reaching the receiver. In some cases this may involve an external window as well. Each optical component can absorb, reflect, or scatter some portion of the light, reducing the total received power. It is therefore important to design an optically efficient transceiver system.

SONA
OPTICAL WIRELESS

What is Link Margin?
(dB or not dB… or dBm?)

Historically, the single most significant parameter in describing the performance of an FSO link has been the link margin. Basically, this is the amount of light received by a terminal over and above what is required to keep the link active (hence the term “margin”). This is usually expressed in dB (decibels), where…

$$\text{dB} = 10 \bullet \log\left(\frac{\text{power}}{\text{min. power}}\right)$$

ratio of $\frac{\text{power}}{\text{min. power}}$	Link Margin (dB)
2	3
4	6
10	10
100	20
1000	30

For example, suppose the receiver must see a minimum of 5 nanoWatts of optical power in order to keep the link active. If the link conditions are such that the receiver actually sees 500 nanoWatts, then the link margin is 20dB (one-hundred times the power required to keep the link active). This means that up to 99% of the power in the transmitted beam can be attenuated in the atmosphere before the link goes down.

As straightforward as this definition is, it can be manipulated to yield somewhat misleading results. Some vendors, for example, define link margin using the power coming directly out of the transmitting terminal, rather than the power being received at the other end. This number will generally be larger (due to the atmospheric attenuation of the signal), yielding a more attractive-sounding link margin. “Transmit power” may refer to the light measured at the terminal exit aperture or that measured at the laser itself within the system. Because of optical losses, the former may be significantly less than the latter. Consequently, the real link margin (according to the above definition) could be different than the value stated.

One should also be careful not to confuse values expressed in “dB” with values expressed in “dBm.” dBm is defined as follows…

$$\text{dBm} = 10 \bullet \log\left(\frac{\text{power}}{1\ \text{mW}}\right)$$

Unlike dB, which is a relative measurement between two values, dBm is an absolute power measurement relative to one milliWatt. For example, a value of 3 dBm means a power level twice as large as 1 mW, which equals 2 mW. Similarly, negative dBm values refer to power levels *less* than one milliWatt. –3 dBm means a power level half as large as 1 mW, or .5 mW. Receiver sensitivity and transmitter output power are often expressed in dBm (-dBm for the former, +dBm for the latter). While these values contribute to the total link margin of an FSO system, they are not themselves measurements of the link margin.

Power in mW	Power in dBm
.1	-10
.5	-3
1	0
2	3
4	6
10	10
100	20

An important concept related to that of link margin is the "dynamic range" of an FSO system. This is defined as the difference between the maximum and minimum power levels that a system can accept. While it is clearly important to detect small signal levels, too much power can also cause problems by saturating the receiver. This is of concern particularly for shorter-range links, where less light is attenuated in the atmosphere. Like link margin, dynamic range is typically measured in dB, as it is effectively a comparison of two values. For example, a dynamic range of 30 dB means that the maximum detectable signal (receiver saturation) is 1000 times greater than the minimum detectable signal (the receiver's sensitivity). The larger the dynamic range, the more versatile and robust an FSO system is, in the sense that it can handle a wider range of atmospheric conditions.

It is important to understand that the link margin of a particular FSO link is a direct function of the atmospheric conditions as well as the distance (i.e. range) between the terminals. The transmitters may be capable of outputting a certain maximum amount of power, regardless of weather or range, but the amount of light actually received by the receiver will vary. For example, a link in Tucson, AZ, where the worst-case atmospheric attenuation is generally low, may have a link margin of 30dB. That same link in foggy London, however, would have a considerably lower margin. Similarly, a 2-km link will have a lower link margin than a 1-km link in the same location, because of the greater atmospheric attenuation over the longer range. Therefore, it is not enough to simply state a link margin for a particular system. It is necessary to specify the range and the current or worst-case weather conditions as well.

Using a Common Language

It has been suggested by some[2] in the industry that a standard set of definitions is needed to describe the key performance parameters of an FSO system. This would indeed go a long way toward simplifying comparisons between different products and applications. In accordance with this line of thought, therefore, the following standard definitions are used in this paper…

Transmit Power

Because the output power of a laser is typically given as a property of the laser itself, the transmit power is defined as the total maximum (peak) power measured at the output of the laser. If more than one laser is used, the sum of their outputs is the total power. It is therefore necessary to take into account any optical losses in the transmitting system itself.

Transmit Beam Divergence

The power profile that defines the beam is not constant across the beam's cross-section but is in fact a gaussian distribution, as shown in figure 4. How one defines the actual width of this gaussian beam is somewhat arbitrary. Because it is generally more intuitive to understand, the width measured half-way to the peak of the profile is considered here to be the beam divergence. This is called the full-width half-maximum (FWHM) divergence angle of the beam.

---

[2] *Understanding the Performance of Free-Space Optics*, presented by representatives from AirFiber, LighPointe, and Terabeam at the WCA Technical Symposium, Jan. 14, 2003.

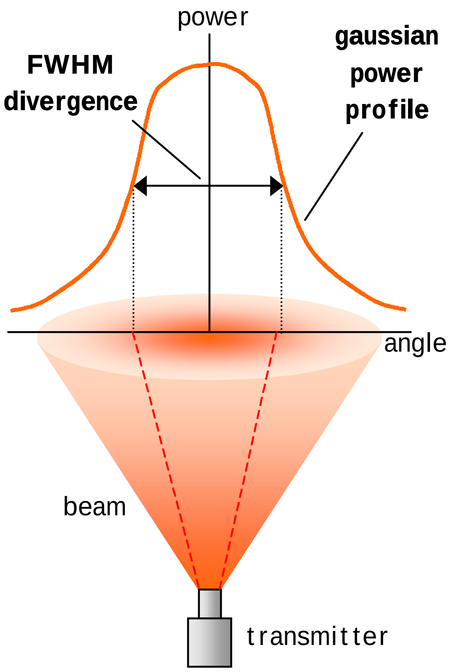

Figure 4 *FWHM Beam Divergence*

Receiver Sensitivity
Similarly to transmit power, the sensitivity is measured directly at the receiver itself, not at the receive aperture of the terminal. This is mainly for reasons of simplicity, as the sensitivity is a standard property of the receiver, similar to output power for a laser. This means that the efficiency of the receive optical path must be defined as well to take into account those losses between the receive aperture and the receiver itself.

The sensitivity is defined as the minimum power level detectable by the receiver while maintaining a BER of at least $1 \cdot 10^{-6}$. This is the standard BER specification for satellite communication, and has generally been carried over to the FSO industry as a rule of thumb.

Comparing Performance: The Generalized Link Margin (GLM)

Even with a common set of standard definitions, the task of judging link performance and comparing FSO products is not very straightforward. The above section discussing the subtleties of link margin, dynamic range, dB, and dBm testifies to this fact. The basic problem is that the overall system performance is still defined in terms of the link range and weather conditions for each application. For example, some vendors publish link margins for their products without mentioning that this value applies to clear weather (called the "clear-air link margin"). This can be misleading for an application that will almost surely involve some amount of atmospheric attenuation. A complete picture of product performance would involve plots of attenuation vs. range and/or link margin vs. range. But this can be confusing for a customer who simply wants to decide which product he/she likes better, and it allows too much room for different vendors to inject a certain marketing spin into the data. A direct comparison between FSO products will not be possible as long as each product must be evaluated in the context of a particular application.

What is needed is a standard metric that takes into account the five fundamental performance parameters without applying them to any particular link conditions as the concept of link margin does. This would effectively give an indication of how various different products would perform under exactly the same link conditions, regardless of what those conditions actually are. In an effort to accomplish this, let us take a look at the basic equations for calculating link margin.

The power received by a terminal at one end of an FSO link can be calculated with the following equation…

$$P_{\text{received}} = P_{\text{transmitted}} \bullet \frac{L \bullet D^2}{d^2 \bullet R^2 \bullet 1e6} \bullet 10^{(-a \bullet R/10)}$$

P = power (mW)
L = transmit and receive optical losses (%/100)
D = receive aperture diameter (m)
d = beam divergence (radians)
R = range (km)
a = atmospheric attenuation (dB/km)

The ratio of this received power to the minimum required power (i.e. the receiver sensitivity, s), expressed in dB, is the link margin…

$$\text{Link Margin} = 10 \bullet \log\left(\frac{P_{\text{received}}}{s}\right)$$

It can be seen from these equations that the link margin is a fairly complex function of the link range and atmospheric attenuation (i.e. weather conditions). However, this dependency on specific link conditions can be separated from those parameters that pertain to the FSO system hardware itself…

$$\text{Link Margin} = 10 \bullet \log\left(\frac{P_{\text{trans}} \bullet L \bullet D^2}{s \bullet d^2} \bullet \frac{10^{(-a \bullet R/10)}}{1e6 \bullet R^2}\right) = \underbrace{10 \bullet \log\left(\frac{P_{\text{trans}} \bullet L \bullet D^2}{s \bullet d^2}\right)}_{\substack{\text{system-related} \\ \text{parameters}}} + \underbrace{10 \bullet \log\left(\frac{10^{(-a \bullet R/10)}}{1e6 \bullet R^2}\right)}_{\substack{\text{link-related} \\ \text{parameters}}}$$

The link margin, therefore, can be thought of as the sum of two completely independent factors; one involving the specific conditions of the link itself, and the other involving only the five fundamental performance parameters of the FSO system that were defined earlier. The former term, involving the link-related parameters, is essentially a measure of the attenuation that the FSO system must overcome for that particular link. The latter term, however, involving only system-related parameters, is a direct measure of the system's ability to overcome this attenuation. It is this term that satisfies our goal of defining an FSO system according to it's own inherent merits, distilling the various plots and measures down to a single, straightforward, comprehensive performance metric. Because it is independent of specific range or weather conditions, and because it is naturally expressed in dB, we call this metric the Generalized Link Margin (GLM).

$$\textbf{Generalized Link Margin} = \mathbf{10 \bullet \log\left(\frac{P_{\text{trans}} \bullet L \bullet D^2}{s \bullet d^2}\right)}$$

The GLM provides an objective and unbiased way of comparing one product to another based solely on the merits of each product's design. It can be thought of in precisely the same way as the already accepted and well-worn concept of link margin, but without having to worry about specific range or weather conditions. For example, if product A has a GLM of 10dB and product B has a GLM of 13dB, product B will *always* have 3dB more link margin than product A when placed in any link together (refer to figures 5-a and 5-b) – in other words, product B has twice the performance capability as product A (3dB = factor of 2). This in turn translates into higher availability and more reliable performance.

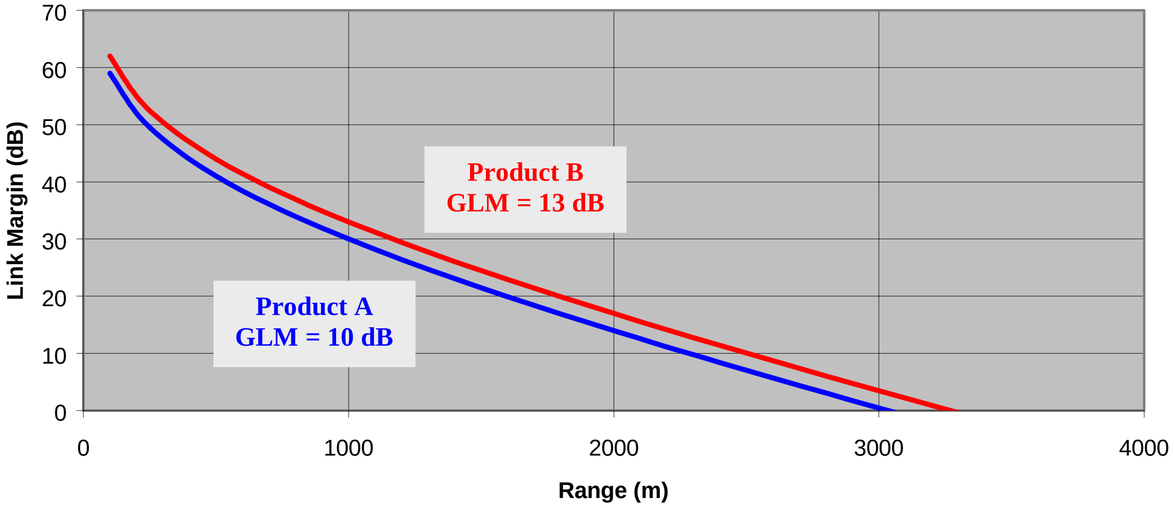

Figure 5-a *Link Margin vs. Range for 10 dB/km Attenuation*

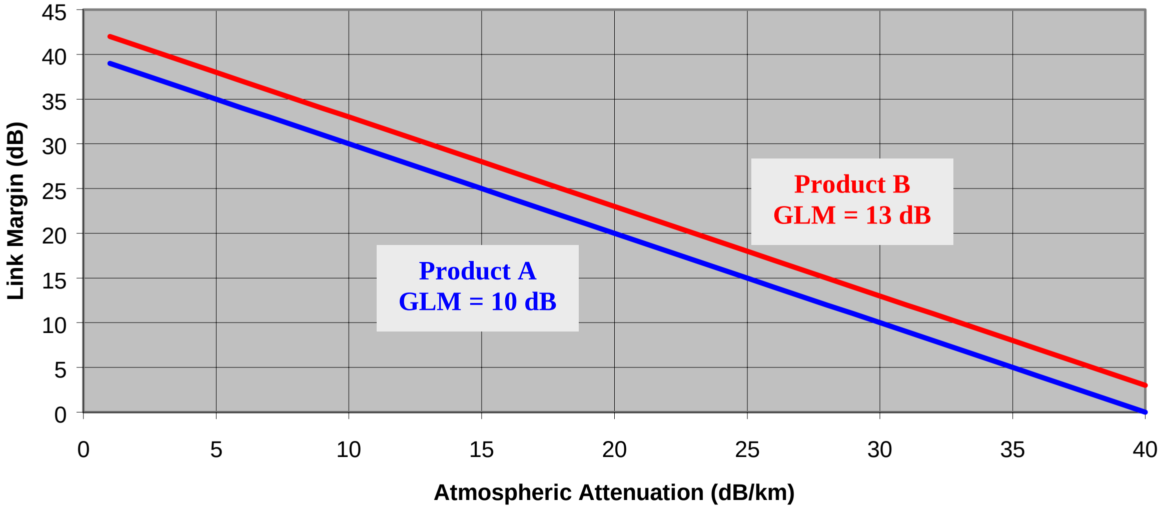

Figure 5-a *Link Margin vs. Attenuation for 1 km Range*

A representative matrix of GLM values is shown in figures 6-a and 6-b below for a set of products addressing similar markets. These are real products available on the market today, and the data was collected from various web sites and spec sheets. This matrix demonstrates how simple the Generalized Link Margin is to use, and for the first time gives a clear and concise picture of how some leading FSO products really compare.

Figure 6-a *GLM Calculations for Various FSO Vendors*

	Product A	***Product B***	***Product C***	***Product D***
Tx Power (mW)	640	30	345	16
Divergence (rad)	2e-3	1e-3	5e-3	2e-3
Rx Clear Ap. (m)	0.2	0.13	0.15	0.15
Rx Sensitivity (mW)	5e-4	1e-4	1e-4	5e-5
GLM (dB)	**101**	**97**	**95**	**93**

* Because reliable values for optical losses are difficult to obtain from various sources, all products in this comparison are considered to have 100% optical efficiency.

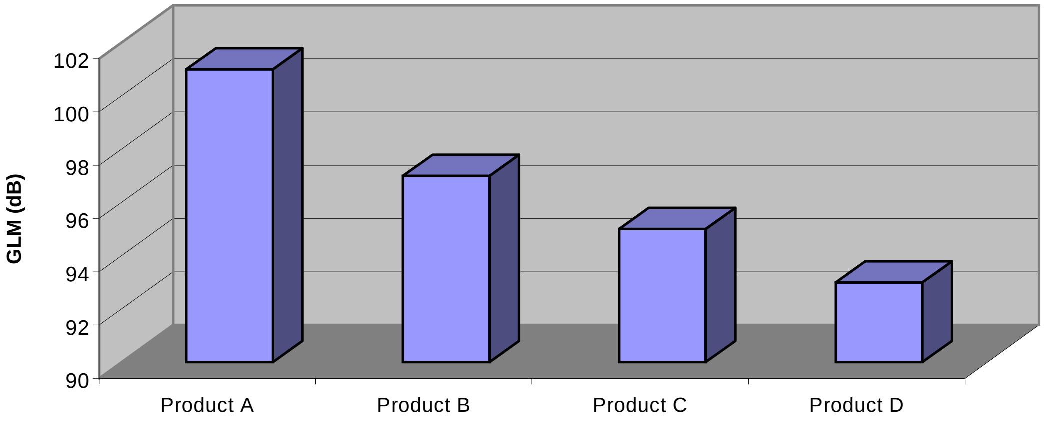

Figure 6-b *Graphical Comparison of GLM*

Comparing Value: Performance / Price

Up to now this paper has been discussing FSO technology in terms of performance. But when a customer is comparing different products for use in his/her application, what ultimately matters is not just performance but value. In other words, how much performance can I get *for my money*? The various product lines offered by different FSO vendors today (and this is only the beginning) make it difficult to answer this question, as products can be geared toward a particular range, data rate, or market sector. For example, product A may be the Cadillac of the FSO industry and have the best performance (i.e. the highest GLM), but are you willing to pay for a Cadillac for this application? Or conversely, product B has the most attractive price, but if the link is going to go down in even the lightest fog, how much will you really save? Performance is obviously the #1 priority; if the product does not satisfy the performance requirements, how much it costs is irrelevant. But once a set of feasible products has been identified, the selection criterion is value.

The Generalized Link Margin offers a quantitative yet intuitive way of comparing the actual value of each product. Because the GLM is a measure of inherent performance capability, one can divide a number proportional to GLM by the price of the product to arrive at a direct measure of the performance/dollar for that product, otherwise known as "bang-for-the-buck." Exactly what GLM-related number to use in this ratio is somewhat arbitrary, since actual "value" may mean different things to different people. Simply dividing the GLM itself by price yields misleading results. For example…

Product X has GLM = 90dB and costs $20,000 ➔ 90/20,000 = .0045
Product Y has GLM = 96dB and costs $20,000 ➔ 96/20,000 = .0048

This would suggest that the value of product Y is only slightly better (6.7%) than that of product X. But for the same price, product Y has 4 times the effective power (6dB more margin), which is a significant difference for most applications. This value calculation, then, seems rather unfair.

Despite the relative subjectivity of any value calculation, a basic common standard can be defined that references absolute value to an average or typical application. As long as this standard is applied consistently to each product, the calculation should yield a fair and useful indication of a product's value. Keeping this in mind, the fundamental assumption made in this paper (and proposed for future use elsewhere) is that a *10dB difference in GLM* equates to a *factor of two difference in the actual value* of the product. This assumption is derived from the fact that a typical adverse weather condition for most developed areas of the world involves an atmospheric attenuation of about 10dB/km. Consequently, a product that provides 10dB more link margin will penetrate about 1km further through typical adverse weather. Considering that the average range of an FSO link in most applications is around 1km, adding another km of range would seem to suggest a doubling of value.

Once this basic definition of absolute value is set down, the actual calculation is straightforward…

$$\mathbf{Value} = \frac{\mathbf{Performance}}{\mathbf{Price\ (thousands\ of\ \$)}} = \frac{\mathbf{1.072^{(GLM)}}}{\mathbf{\$K}}$$

By plugging the GLM value into this simple equation, a direct measure of that product's value can be obtained. Any product that has a GLM of 10dB higher than another product is justified in charging twice as much. For example…

$$\left.\begin{array}{l}\text{Product X has GLM = 90dB and costs \$20,000} \Rightarrow \text{Value} = 1.072^{90}/20 = 26 \\ \text{Product Y has GLM = 100dB and costs \$40,000} \Rightarrow \text{Value} = 1.072^{100}/40 = 26\end{array}\right\}\ \text{same total value}$$

Product Z has GLM = 100dB and costs $20,000 ➔ Value = 1.072^{100}/20 = 52

In this example, it would be quite valid to simply say that product Z is twice as good as product X, with no further analysis or explanation required.

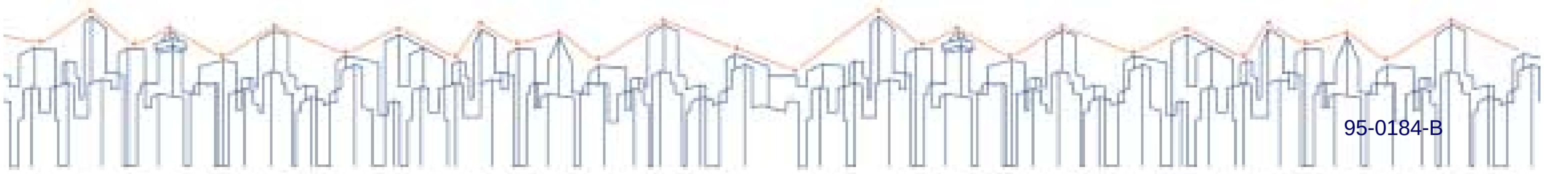

Figure 7 shows an example of the difference between comparing performance (GLM) and comparing value (performance/price). Again, these values were calculated from real products currently on the market.

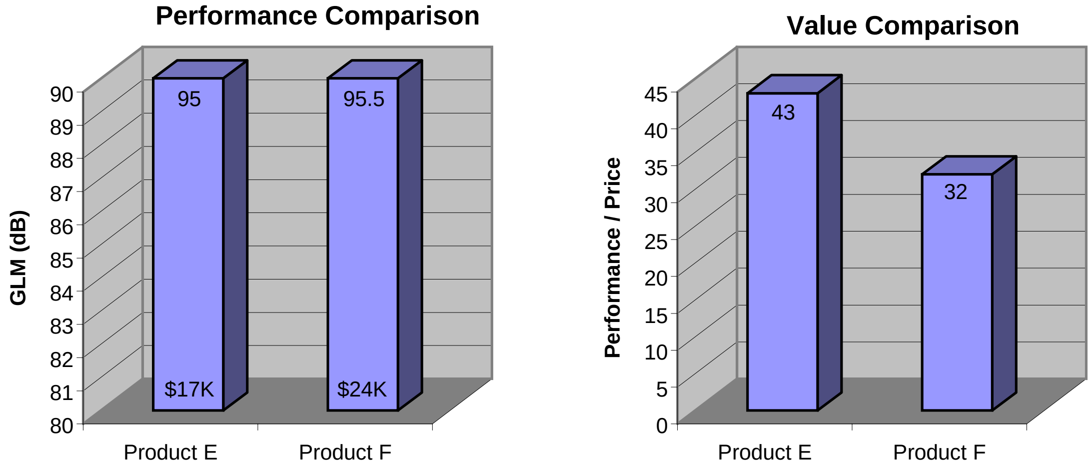

Figure 7 *Comparing Performance vs. Comparing Value*

Conclusion

Free Space Optics is now generally accepted as a viable and economical technology in the telecommunications industry. Yet as awareness increases, and FSO vendors multiply, so do the chances for misunderstanding and confusion. Currently used concepts such as link margin and dynamic range are useful for understanding how FSO works, but are cumbersome as measures of system performance. This makes it difficult for the average buyer to compare products, and allows different vendors to present the data according to their own marketing slants. This will be true as long as system performance is tied to individual link conditions.

The Generalized Link Margin (GLM) provides a standard metric for evaluating and comparing FSO products, independently of link range or weather conditions. It is effectively a “link-independent” link margin, and works mathematically the same way as the usual link margin. Far from being an arbitrary number, the GLM is derived from the link margin calculation, and takes into account all significant parameters that define the performance of an FSO system. It therefore represents a fair, unbiased, and comprehensive measure of the quality of an FSO product. Moreover, dividing a value proportional to GLM by the price of the product yields a direct and easily understandable measure of the actual *value* of a product, in terms of performance per dollar. Ultimately, marketing material from all FSO vendors should include GLM as *the* standard performance spec for their products.