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The importance of modal bandwidth in Gigabit Ethernet systems

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This article deals with the evaluation of bandwidth measurements in Gigabit Ethernet Systems using an empirical data model. It concentrates on the use of multimode fibers due to the advent of Vertical Surface Emitting Laser (VCSEL) technology that improves the performance of multimode fiber optics. Copyright © 2001 John Wiley & Sons, Ltd.

Overview

With the advent of Gigabit Ethernet Systems utilizing multimode fiber, the limiting factor in the fiber backbone is no longer the attenuation of the passive link, but rather, the bandwidth of the fiber. Due to different signal characteristics of the transmitter, new test procedures and a new understanding of the interaction between the optical fiber and the optical signal are required.

Gigabit Ethernet systems are the result of the continual evolution of networks toward higher and higher speeds. The incessant demands of end users to move large amounts of data at gigabit speeds required a new technology to handle the 10× Faster to Gigabit increase in the transmitting speed used in the network. With the introduction of such speeds, the performance of multimode optical fiber came into question, as distances thought to be achievable over standard 62.5-micron fiber were not possible using existing technology. However, new high-speed laser transmitters at 850 nm offered the necessary characteristics to make Gigabit Ethernet a reality.

To this end, the Institute of Electrical and Electronic Engineers (IEEE) 802.3z committee revised the Ethernet protocol standards for transmission for optical networks at one gigabit per second. The revised protocol standards are based upon the Fast Ethernet system protocol developed in 1995.[1] These new protocols are 1000Base-SX for 850 nm wavelength using laser-based transceivers over multimode optical fiber and 1000Base-LX for 1300 nm wavelength using laser-based transceivers over multimode or singlemode optical fibers, which are to be considered Gigabit Ethernet (GbE).

The device that was developed for high-speed multimode transmission at 850 nm was a Vertical Cavity Surface Emitting Laser or VCSEL, which uses a gallium arsenide substrate for speed.[1] Unlike light emitting diodes (LEDs), these devices are fast enough to transmit a gigabit signal. Additionally, they can be manufactured very cost effectively when compared to typical singlemode semiconductor lasers. VCSELs are the first laser devices that transmit signals in more than one mode, making them ideal for use with multimode fiber. Each type of device transmits the optical signal in a different manner; LEDs excite all the different fiber modes, VCSELs excite only a portion and the singlemode lasers excite only the fundamental mode. See Figure 1 for a representation of how LEDs, VCSELs and semiconductor lasers transmit in a multimode fiber.

Using this VCSEL source technology in Gigabit Ethernet links proved to be more complicated than merely replacing the existing technology due to the

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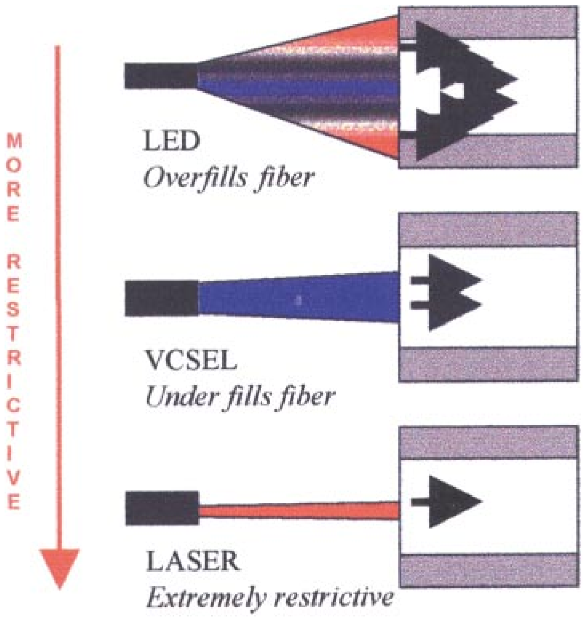

Figure 1. Depiction of the differences between overfilled and restrictive launch in multimode fibers

interaction of the source launch conditions on the effective system bandwith. An accurate bandwidth value is required for input into the GbE model to accurately estimate the system performance potential.

The Gigabit Ethernet Optical Link Model

The IEEE 802.3z committee's Gigabit Ethernet Link Model spreadsheet is available for public use, to enter assumptions for a given link configuration. This spreadsheet may be accessed via the internet address as follows: http://grouper.ieee.org/groups/802/3/10G_study/public/email_attach/All_1250.xls

The Gigabit Ethernet model is based on the concept of power budgeting or $Power_{out} = Power_{in} -$ Power Attenuation Losses − Link Power Margin.[1] The GbE link model was created by using worst-case models and extensive experimental testing, resulting in an empirical estimation of the characteristic of a fiber optic link. The multimode fiber modal bandwidth is estimated by this empirical spreadsheet. The units of measure for a multimode fiber bandwidth is expressed in MHz • km to designate the bandwidth-distance product. See Figure 2 and 3, which provide a graphical representation of the bandwidth–distance product calculated from the IEEE 802.3z GbE link model spreadsheet.

Figure 2 shows that 160 MHz • km modal bandwidth at 850 nm for 62.5 micron multimode fiber is limited to a maximum link length of 220 meters. This is due to the limiting factor of the ISI power penalty on the bandwidth-distance-product. Figure 3 shows you that 500 MHz • km modal bandwidth at 1300 nm for 62.5 micron multimode fiber is limited to a link length of 550 meters, which has been set for power budgeting. There is still approximately 1.5 db power margin left, which if this were utilized the maximum ISI limited link length would become approximately 690 meters.[1] In addition, there are other power loss and noise factors that effect the transmission bandwidth–distance product.

Power Budget Model

Within the Gigabit Ethernet model, there are essentially five power penalties taken into account. These penalties result in the allocation of link budget power that is not directly attributable to cable attenuation or connector losses. All of these penalties lead to noise and signal distortion that cause degradation in the receiver sensitivity and limit transmission distance at a given speed, thereby limiting the distance a signal can be reliably transmitted. ISI (Inter Symbol Interference) is one of five power penalties in the Gigabit Ethernet link power budget model. Other penalties included for multimode data links are modal noise, relative intensity noise (RIN), mode partition noise (MPN), and extinction ratio.

InterSymbol interference is the most dominant penalty. For a Gigabit Ethernet link budget of 8 dB (minus 2 dB for connector loss), the ISI penalty is typically maintained to below 3.6 dB, (See Figures 2 and 3). This single penalty could then represent over half of the available power budget allocated for all the different penalties. ISI is a measure of the level of interaction between adjacent bits. Data pulses that are transmitted across the link spread over the time of transmission. These bits can begin to interfere with each other causing transmission errors. The ISI penalty is a result of these bit-to-bit

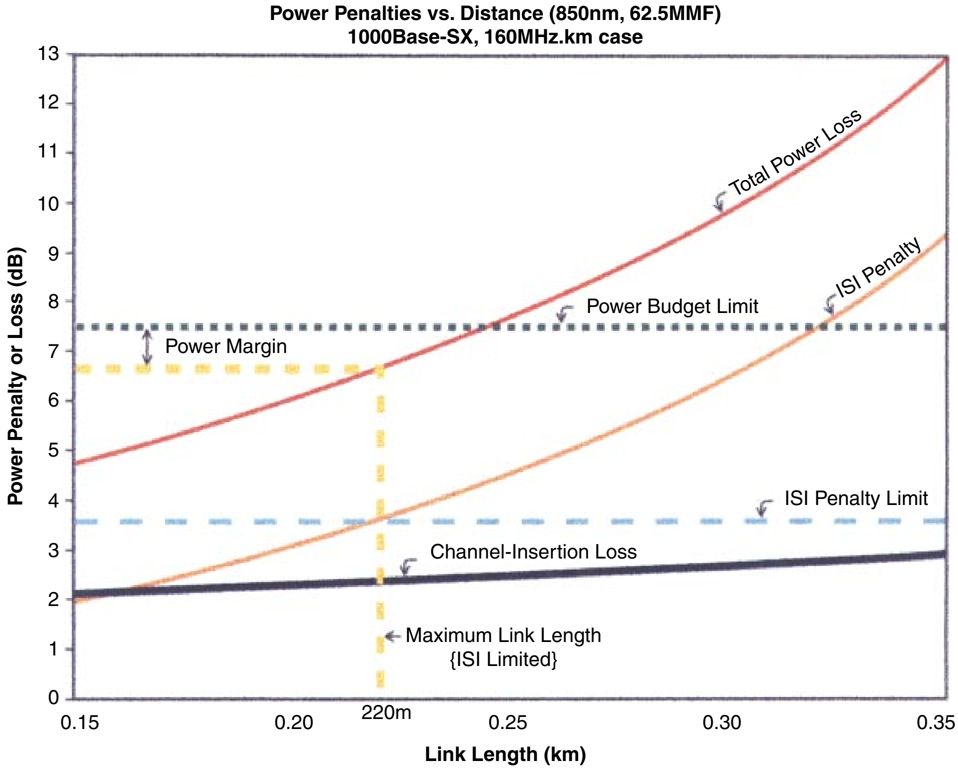

Figure 2. Power penalties versus distance (850 nm, 62.5 multimode fiber)

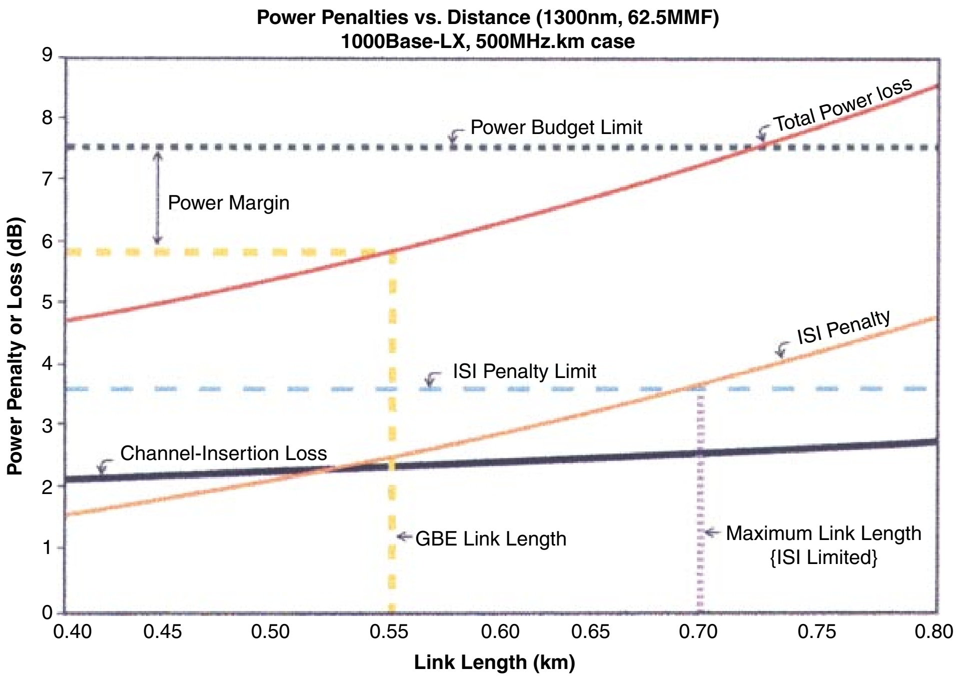

Figure 3. Power penalties versus distance (1300 nm, 62.5 multimode fiber)

interactions that are caused primarily by a limited available link bandwidth resulting from the fiber modal dispersion. In fact, the ISI penalty is exponentially dependent on the modal bandwidth of the fiber. Therefore, optimized fibers with higher overfilled bandwidths reduce the ISI penalty and allow for faster transmission speeds over longer operating distances.

Since a VCSEL transmits its optical signal in an annular or 'donut' shape, the propagation characteristics along the fiber are different from those of an LED. Although this type of launch often can improve the effective bandwidth of the fiber, it can also result in signal distortions that can effectively limit the bandwidth–distance of certain fibers. Testing showed the theoretical limits of the model could not be attained in these cases and that the overfilled bandwidth measurement is not an adequate screening method. This result forced a re-examination of the limiting factors in the Gigabit Ethernet model as they related to the fiber's capability to carry information. Unfortunately, using the overfilled bandwidth measurement as the basis for Gigabit Ethernet system performance is uncertain. As noted above, ISI is one of the factors limiting bandwidth–distance. Since ISI is related to the fiber's system bandwidth, an accurate measurement of this bandwidth is required to provide a good indication of the ISI penalty and hence a good indication of the link potential. Therefore, another measurement method was required.

Bandwidth Measurements Required to Characterize Link Performance

—A New Launch Choice for Bandwidth Measurement—

With all these limitations of the overfilled bandwidth method, why is it still used? Until the advent of a bandwidth test using an optical launch similar to a laser, overfilled bandwidth is the only information available that can be used to determine capable link length in the GbE model. Information services managers and designers, however, need an accurate method to prove transmission capability of GbE over specified distances. Figure 4 shows the relationship between link length and bandwidth as determined by the adopted Gigabit Ethernet model. Unlike attenuation measurements, which are related to a system's output power, bandwidth measurements measure the reduction

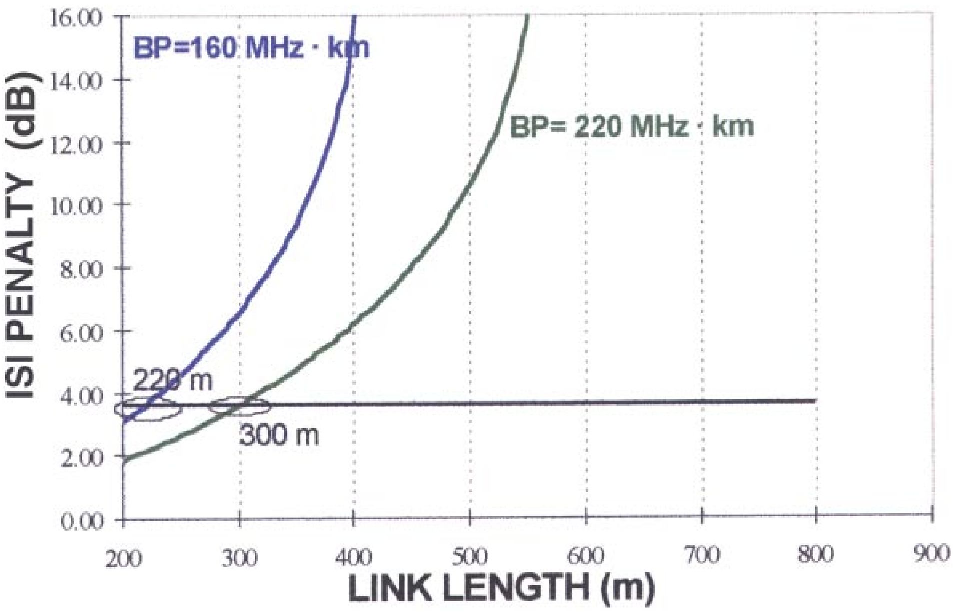

Figure 4. Measurements of overfilled bandwidth versus restricted mode launch bandwidth

in amplitude of a frequency component caused by different delay times in the arrival of the signal from each of the different modes. Unless these delay times are identical, the observed bandwidth is determined by the percentage of power being transmitted by each individual mode (restricted modes).

The outcome of this phenomenon was that the overfilled launch was initially the selected method for determining the most conservative estimate of fiber bandwidth. This was not an issue so long as LED sources, which created an overfilled launch condition, were used in the system. The use of VCSELs in Gigabit Ethernet systems results in the propagation of only certain modes in the multimode fiber, unlike LED sources used in the past (see Figure 1). The effects of an underfilling source with multimode fiber at very high speeds were not well known when the decision to use overfilled bandwidth was reached.

During the GbE modeling, the IEEE 802.3z Committee's investigation found that overfilled bandwidth is generally a conservative estimate of the performance of a multimode fiber in Gigabit Ethernet systems. This is primarily true at 850 nm. At 1300 nm, there can be other limiting factors in the bandwidth of Gigabit Ethernet systems using laser sources. Due to inconsistencies of the index of refraction (which is wavelength dependent) near the center of the core of the fiber, an offset patch cord is required. The patch cord increases the effective bandwidth of the system by insuring that the light signal transits the fiber in modes that have index of refraction profiles close to the nominal profile. Standard bandwidth characterization methods, which utilize an overfilled launch, do not accurately predict the behavior under restrictive launch conditions. Often, the bandwidth is significantly higher (up to 500%) and on occasion, it has been shown to be significantly lower. Distortions in the fiber index profile—specifically in the area at the very center of the profile—can lead to large differences in the delays of the modes in this region causing poor bandwidth performance and consequently a high ISI penalty. A measurement of fiber DMD (Differential Modal Delay) can be used to determine whether any distortions exist in the center of the profile, but this measurement technique is quite slow and tedious and therefore not a practical method for use by either fiber or fiber cable manufacturers.

—Restricted Mode Launch Bandwidth—

The TIA F02.2 Subcommittee on the modal dependence of bandwidth had to determine if additional specifications or testing methods were needed for Gigabit Ethernet using laser sources at 850 nm. The committee was initially concerned with two areas that affect bandwidth. The first issue was the wide range of VCSEL sources and how the variations in transmission characteristics would affect the fiber bandwidth. The second was the investigation of how sources and fibers interact and what the resultant system bandwidth would be when parameters were changed.

The TIA committee conducted a study among fiber manufacturers and optical cable manufacturers to determine the validity of linking the overfilled bandwidth performance as an indicator of system performance under restricted launch conditions. If a relationship could be established, legacy systems could be qualified for use with Gigabit Ethernet systems. The study was conducted using several labs and fibers of several manufacturers both domestic and international.

The end result of this initial study firmly concluded that the overfilled launch measurement of a multimode fiber's bandwidth was not an accurate portrayal of how the fiber would react when a laser transmitter was used with it. Furthermore, the laser bandwidth was not found to be consistent enough with the overfilled bandwidth to use one to predict the other (see Figure 5).

Round-robin testing qualified the limiting factors in transmission of a laser signal over a multimode fiber. Using VCSELs that have bearing on the final laser bandwidth of an optical fiber, the TIA task group found several factors affecting multimode fiber bandwidth. The first issue was that VCSEL sources existed in a very wide range of performance—varying from nearly LED-like to nearly singlemode-like in their

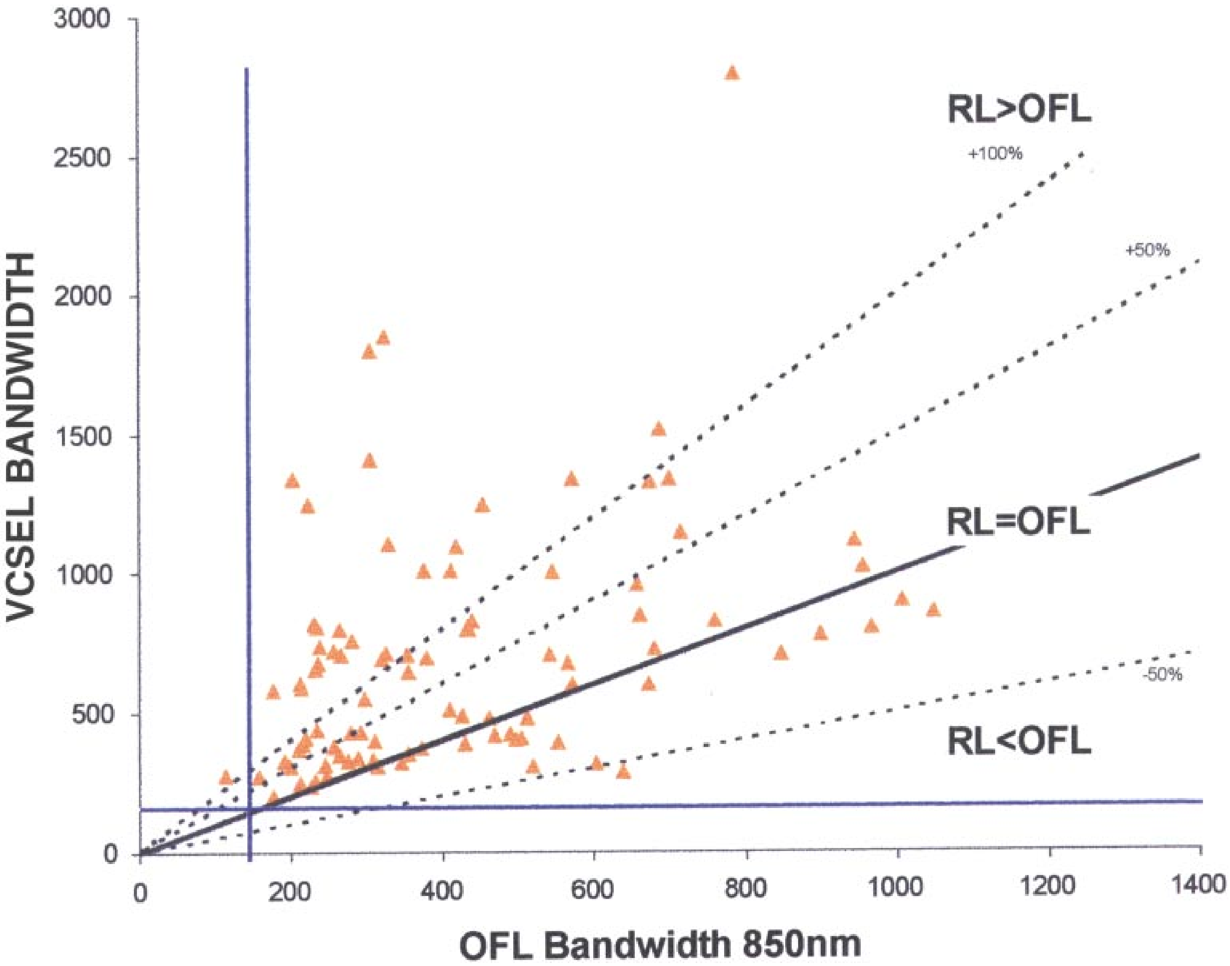

Figure 5. VCSEL bandwidth versus overfilled launch bandwidth

launch characteristics. This large variation in performance created significant difficulties in determining the system performance, as the multimode fiber bandwidth is highly dependent on the launch and the corresponding modes that are excited. Narrowing this distribution was necessary in order to achieve consistent results. Sources were characterized using a new measurement technique called Encircled Flux (EF). This measurement quantified the cumulative power distribution as a function of position. By limiting the cumulative power at two positions, namely 4.5 μm and 15 μm, the distribution was narrowed. This recommendation maximized the potential bandwidth increase, while limiting the negative effect of launching too much power into the extreme center of the profile.

—System Versus Component Bandwidth—

Narrowing the VCSEL distribution did not solve all the issues. The Committee's next area of concern was to determine if an additional test was necessary to guarantee fiber performance of Gigabit Ethernet systems. To accomplish this, the Effective Modal Bandwidth (EMB) was used to determine the system bandwidth using restrictive laser sources at the 850 nm window. This is a system measurement, as compared to a fiber component measurement. EMB characterizes a fiber's modal bandwidth under system conditions by using the system source to perform the characterization. It is called Effective Modal Bandwidth because when using a source that does not fill all the fiber's modes, the bandwidth is directly related to the number of modes, and specifically which modes that are filled. Theoretically, the bandwidth should have been higher than the overfilled bandwidth. However, as we have seen, this is not always the case. The resultant measured bandwidth can then be correlated to the ISI penalty and the system potential can be established. This particular test method, however, is not suited for a production measurement, as the sources are not designed to provide the correct type of signal for the swept-frequency bandwidth test and they also do not provide the required dynamic range to test long lengths.

The TIA group focused on defining a test method that used a launch that mimics a typical VCSEL that could be used as a standard test method on long-length fibers. A Fiber Optic Test Procedure (FOTP) for the Restricted Mode Launch Bandwidth (RML) was proposed. The Effective Modal system bandwidth measurement technique is equally suited for 62.5/125 and 50/125 fibers. However, as a VCSEL source injects light into over 60% of the modes of a 50/125 fiber, the advantages of the 'restricted launch' are minimized. Meanwhile, the issue of center profile distortions becomes less of an issue. Fortunately, there are no problems when using the proposed bandwidth measurement with either 62.5- or 50-micron fiber. The combination of source specifications and new fiber bandwidth measurement techniques has led to a better, more accurate estimation of the system performance.

Overfilled bandwidth is still the only recognized industry standard for determining the information-carrying capacity of a multimode fiber.

Conclusions

Overfilled bandwidth is still the only recognized industry standard for determining the information-carrying capacity of a multimode fiber. However, further understanding of bandwidth and the limiting factors surrounding Gigabit Ethernet System bandwidth is required to understand system performance. Until a new standard is promulgated, this bandwidth measurement can be used to predict worst case performance in GbE systems.

Restricted Mode Launch is a viable alternative for measuring bandwidth, but in this case, the actual launch condition only mimics true system VCSEL conditions. This method utilizes lasers with a modified launch to simulate those of a VCSEL. Effective Modal bandwidth is the end result of exhaustive study to determine the best method for measuring the information-carrying capacity of multimode fiber. Using this technique all multimode fibers can be measured for bandwidth and the system performance can be determined more accurately.

Finally, with the release of a measurement standard, fiber manufacturers will be able to confirm to the end-users how their fibers will actually perform under distance and power limitations as put forth by the Gigabit Ethernet model. This will enable the true bandwidth of multimode fibers to be determined with less than all modes being filled during transmission.

Definitions

Overfilled launch bandwidth—The bandwidth of a fiber when measured using a simulated LED launch. In this instance ALL the modes of the multimode fiber are excited, or filled with a light signal.

Restricted mode launch bandwidth—The bandwidth of a multimode fiber when measured using a source which mimics the transmission characteristics of a Vertical Cavity Surface Emitting Laser. In this measurement, the number of modes which are excited by a coherent light signal, are less than the total number of modes available in the fiber core.

Vertical Cavity Surface Emitting Laser (VCSEL)—Transmitting device used in Gigabit Ethernet systems for transmission at 850 nm. Required by the specification and more powerful than an LED. These devices are lasers that transmit in more than one transverse mode, which is fundamentally different from semiconductor lasers used in single-mode systems. It is important to note that these devices primarily operate at 850 nm and, therefore, with only multimode fibers.

Effective modal bandwidth—The bandwidth measurement of an optical fiber using a VCSEL laser source. This is a type of restricted mode bandwidth measurement.

Index of refraction—The ratio of the speed of light in a vacuum to the speed of light in a medium, such as glass. Typical indices of refraction for fiber are 1.45–1.48.

References

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