Fiber Optic
Technical Training Manual

Agilent Technologies
Innovating the HP Way

Acknowledgements

Contents

Introduction

Welcome to the **FIBER-OPTIC TECHNICAL TRAINING MANUAL.** This manual is intended for readers with knowledge of electronics but either little or no experience with fiber optics.

The manual is divided into six sections:

- Fiber Optic Technology,
- Networking Technology,
- LAN Standards,
- Types of Fiber and Optical Transmission,
- How to Use the Fiber Optic Section of the Catalog,
- Glossary (of fiber-optic and related terms).

How to use the Manual

Basic information is in a larger type with a clear background. Information that is more detailed or technical is in smaller type with a dark background and is separated from the basic text by a row of magnifying lenses with a bold black line above them. An example is shown below:

Bit Error Rate

In an actual transmission system, various electronic noise sources, such as the shot (random) noise of the first transistor in the PIN-photodiode preamplifier or noise on the power-supply line of the host digital system, can change or corrupt the stream of data bits. The number of these corrupted bits divided by the total number of received bits within an arbitrary time period is the bit error rate (BER). The lower the BER value, the fewer the number of errors in the transmission.

The bit-error ratio is usually given by a number such as 10^{-6}. This means that on average, one error occurs for every million pulses sent. Typical error ratios for optical fiber systems range from 10^{-9} to 10^{-12} (local-area networks require a BER as low as 10^{-12}). The BER can be measured by repeatedly transmitting and receiving a suitable length of a pseudo-random bit sequence (PRBS) data. The necessary optical power to achieve a given signal-to-noise ratio, and therefore a certain BER, is called the receiver's sensitivity.

If you want or need only the basic information you can skip these sections.

Fiber Optic Technology

Introduction

A communication link can be made with a variety of media, including twisted-wire pair, coaxial cable, RF (radio frequency) or IR (infrared) wireless signal transmission, or fiber-optic cable.

Fiber-optic systems use pulses of light traveling through an optical fiber to transmit data. This method offers many advantages over copper wire, some of which are not available with other technology:

- Complete input/output electrical isolation,
- No electromagnetic interference (EMI) susceptibility or radiation along the transmission media,
- Broad bandwidth over a long distance,
- Light-weight, small-diameter cables
- Equal to the cost of copper wire and connectors (except when copper wire is already installed).

Feature	Benefit
Electromagnetic Interference (EMI)	Because optical fiber transmits light rather than electrons, it neither radiates EM (electromagnetic) fields nor is it susceptible to any EM fields surrounding it. This is important in a number of applications: - Industrial control, where cables run along factory floors in proximity to electrically noisy machinery. The optical medium permits the control signals to be carried error-free through the electrically noisy environment. - Telecommunications equipment manufacturers use optical fiber because it eliminates cross talk between the telecommunication lines. - Financial institutions and gaming equipment manufacturers require data security. Tapping into a fiber cable without being detected is extremely difficult.
High Bandwidth	Optical fiber has a relatively high bandwidth in comparison to other transmission media. This permits much longer transmission distances and much higher signal rates than most media. For example, all undersea long-haul telecommunications cable is fiber-optic. This technology is allowing worldwide communications (voice, video and data) to be available mainstream. With new technologies, such as VCSEL transmitters, parallel optics and wavelength division multiplexing (WDM), services such as video-on-demand and video conferencing will be available to most homes in the near future.
Voltage Isolation Voltage Insulation	Fiber isolates two different voltage potentials. and insulates in high-voltage areas. For example, it will eliminate errors due to ground-loop potential differences and is ideal for data transmission in areas subject to frequent electrical storms, and presents no hazard to the field installer.
Weight and Diameter	A 100 meter coaxial cable transmitting 500 megabits of data per unit time is about 800 percent heavier than a plastic fiber cable and about 700 percent heavier than a hard-clad silica cable, all of equal length and transmitting at the same data rate. The relative diameters of various types of fiber cable and coaxial copper cable for the same distance and data rate are shown in the illustration at the right. 200/230-μm diameter hard-clad silica (HCS) 62.5/125-μm diameter multi-mode glass 9/125-μm diameter single-mode glass 5-mm diameter coaxial copper wire (with 2-mm diameter jacket) 1-mm diameter plastic optical fiber (POF)

The Fiber-Optic Link

A basic link has three main components, each with a specific function. The transmitter contains a light-emitting diode (LED), laser diode (LD), or vertical cavity surface-emitting laser (VCSEL) that converts an electrical current into an optical signal. The receiver contains a photodiode that converts the light back into an electrical signal and an amplifier that makes the signal easier to detect. The fiber-optic cable carries the optical signal between them.
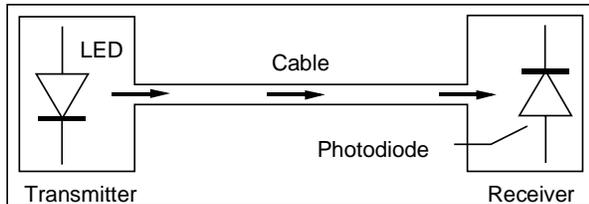
Emitters

The two major groups of optical emitters for communication links are light-emitting diodes (LEDs) and lasers. The VCSEL (Vertical Cavity Surface-Emitting Laser) is often categorized separately because of its similarities to both lasers and LEDs.

Emitters are made from semiconductor compounds. Elements in the third column of the periodic table combined with elements in the fifth column (known as "III-V" compounds--GaAs is one example) emit particles of light (photons) when subjected to an electric current.

Using the right combination of elements, and the right processing parameters, engineers can produce a variety of different wavelengths, brightness, and modulation speeds (how fast the emitter can be turned on and off) of the emitted light.

By optimizing its wavelength, the light can be efficiently coupled into the appropriate type of fiber when combined with an optimally designed optical sub-assembly (OSA). The wavelengths span the visible and infrared spectrums up to 1550 nm. Typically, wavelengths 1300 nm and above are considered to be long wavelength (LWL) and those below 1300 nm are considered to be short wavelength (SWL).

LEDs

LEDs are diodes made of III-V material, which emit light. As electrons pass through an active region of semiconductor material, they cause photons to exit. The light produced by an LED has a pure spectrum and is relatively brighter than a standard light-bulb emitter. The LED can be turned on and off at speeds which make data communications possible.

The most common wavelengths for LED emitters are 650 nm for plastic fiber; 850 nm and 1300 nm for multi-mode glass fiber. Surface-emitting LEDs (SLEDs) are inexpensive to manufacture because they emit light from their surface and so require no precision cleaving. LEDs can also be made to emit light from the edge, producing a more narrow, collimated beam that can launch into single-mode fiber. Edge-emitting LEDs are called ELEDs.

Lasers

Lasers are devices that efficiently convert electrical power to optical power due to a process called stimulated emission. Photons produced by a semiconductor laser are initially trapped in a cavity and bounce off reflective surfaces at each end. They then repeatedly pass through an active gain region, where on each pass they stimulate the production of additional photons. Eventually the power in the cavity increases enough so that a very bright, coherent, collimated beam of light is emitted from one end of the cavity.

The gain medium determines the properties of the output light, including wavelength, output power, and whether the light exits in pulses or in a continuous wave.

Semiconductor lasers are devices with a unique structure that makes them more efficient.

1. Laser Diodes
   In Laser diodes, the active gain material is a III-V semiconductor compound. Because the active region is very small and the input current is relatively low, laser diodes output optical power in milliwatts. By contrast, some medical lasers and industrial lasers output power in megawatts.

Because laser diodes emit light from the edge of the die, they are more difficult to manufacture and handle than LEDs. These devices must be cleaved, and mounted on their sides. Furthermore, it is more difficult to align the laser to the connector ferrule than it is to align an LED to the connector ferrule. For these reasons, lasers are more expensive than LEDs. Laser diodes are commonly found in 1300 nm and 1550 nm wavelengths for communications, and 980 nm and 1480 nm for pumping lasers.

2. VCSELs

A type of laser that has recently emerged in the communications market is the vertical-cavity surface-emitting laser (VCSEL). This laser behaves as a laser diode, but can be manufactured similarly to an LED, because it emits light from the surface. This makes the VCSEL very attractive to the market due to its performance/price ratio. VCSELs are being produced at 650 nm and 850nm, with 1300 nm to be produced in the near future.

LED Operation

Light-emitting diodes operate in the same way as diodes made from silicon or germanium: they allow current to flow in the forward direction and block current from flowing in the reverse direction. Current flowing through the diode in the forward direction generates a near-constant voltage across the diode, which is primarily determined by the material from which the diode is made. For example, diodes made from silicon have forward voltages of about 0.7 V and LEDs have forward voltages of around 1.3 V to 2.5 V. The forward current flowing through the LED generates light.

The light output of an LED is nearly proportional to the magnitude of its forward current. Therefore, controlling the forward current controls the light output of the LED.

The circuit at the right shows one of the simplest ways to drive an LED. The LED current is determined by the difference between the input voltage and the forward voltage of the LED, divided by the series resistance. It is the current through the LED that controls the light output.

$$I_F = \frac{V_{in} - V_F}{R}$$
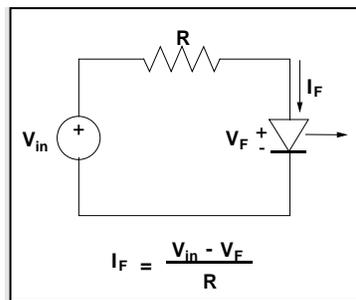
LED Materials

Numerous elements and compounds can produce light, from the ultraviolet to the infrared. Very few, however, are practical for LED devices. At the present time, most commercially available LEDs are made from combinations of gallium (Ga), arsenic (As), phosphorus (P), Aluminum (Al), and Indium (In).

Certain materials can be made to produce a range of wavelengths by adjusting the relative proportions of the constituent elements. It should be noted that LEDs actually emit light over a narrow range of wavelengths, not just at a single wavelength. For example, an 820 nm LED might actually emit light from about 800 to 840 nm, with the peak intensity at 820 nm.

The material used depends on the application. For example, plastic optical fiber has a minimum loss of transmitted light at wavelengths around 650 nm. Therefore, an LED made from GaAsP would be best suited for use with plastic fiber. AlGaAs is also a good material for use with glass optical fiber. Glass fiber loses a minimum of light at wave-lengths around 1350 nm, which is within the spectral band of an InGaAsP LED.

Laser Operation

A laser (Light Amplification by the Stimulated Emission of Radiation) operates in a manner similar to an LED. The difference is that the LED has spontaneous output only when forward biased. The laser begins with spontaneous output at low forward currents, increased to a point known as the Threshold Current level. Biasing above the threshold current causes the device to reach the stimulated emission region of operation.

The advantage of the laser is that it's stimulated emission output optical power launched into a small-core optical fiber is typically far higher than that of an LED. Typically the laser also has a narrower output optical spectra, thus providing better performance at high bit rates over long distances. The disadvantage is that the threshold current is temperature dependent and circuit designers must take this into account. The added circuit complexity increases the cost of the laser transmitter.

Fabry-Perot Lasers

A FP laser has two parts: a semiconductor optical amplifier that provides gain and mirrors to form a resonator around the amplifier. The semiconductor optical amplifier is formed by applying current to a lower-bandgap active layer surrounded by higher-bandgap materials. The low-bandgap and high-bandgap layers form an optical waveguide to direct the light that is produced. Light radiates from the laser in a narrow-angled cone.

As the current increases, the optical amplifier gain increases. When the amplifier gain equals the mirror loss,

the lasing threshold is reached; the laser begins to oscillate above threshold current. FP lasers can produce many mW of output optical power and can be modulated to very high rates by varying the current to the laser diode.

VCSELs

Vertical cavity surface-emitting lasers (VCSELs) emit light perpendicular to the top plane of a semiconductor wafer. The VCSEL uses a Bragg reflector, a multi-layer dielectric mirror composed of alternate layers of high and low index of refraction material. For data communication applications, the diameter of the laser is made large enough to support multiple modes. This causes the central lasing peak to spectrally broaden. The wider spectral width is often designed into VCSELs to avoid mode-selective loss in multi-mode fiber applications.

The major advantage of the VCSEL design is ease of manufacture, simplified on-wafer testing, and simple packaging, resulting in lower costs. The device has higher output power and higher modulation rates than SLEDs (Surface Light-Emitting Diodes.

Detectors

Detectors are typically PIN photodiodes that function exactly the opposite of an emitter diode: they absorb photons and convert them into electrons. Photodetectors can be made of either pure silicon, or a III-V compound, depending on the wavelength requirements. The detector must be able to detect the same wavelength emitted by the transmitter, or the link will not operate. The detector is always followed by a pre-amplifier (preamp) that converts the current coming from the diode to a voltage, which is used by most amplification schemes.

Other detectors include avalanche photo-diodes, which are more complex to operate due to their control circuitry, and silicon photo-detectors, such as photo-transistors or photo-FETs.

One important property of a receiver is its sensitivity. This property defines how small a signal the receiver is able to detect. The receiver must be able to detect a signal over the top of any electromagnetic noise that may be interfering with the system. A careful design of the preamp and following circuitry, plus metal shielding around the receiver, can improve the sensitivity.

The importance of understanding this technology lies in how it relates to two important specifications of a fiber-optic link: distance and data rate. The first step is to determine the distance over which the data needs to be transferred and the data rate at which it is being sent. Some applications will be defined by industry standards, which clearly state specific distances and data rates. Other applications will be proprietary, and you will have to work closely with the customer to determine the details.

Fiber as an Optical Waveguide
Reflected light

The most basic optical waveguide is the step-index fiber, which consists of two layers, a core and a cladding. These layers are made of materials that have different optical transmission properties. One important property of these materials is the index of refraction (n), a material constant that determines the direction of the light through the material.
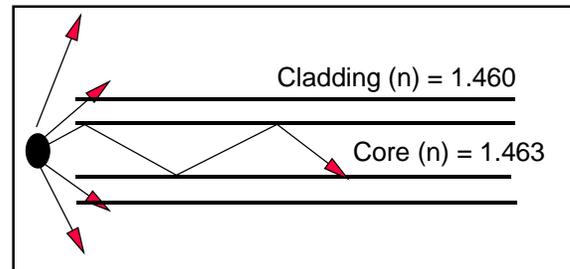

The index of refraction of the core must be larger than that of the cladding for the light to travel through the waveguide:

$(n_{core} > n_{cladding}$ provides total internal reflection).

For some glass fibers, the cladding is SiO_2 (glass) and the core has dopants (such as germanium) to increase the index of refraction.

The light travels through the waveguide in paths called modes. Each ray of light has a different mode, which creates a crowded waveguide. Not all of the modes that exit a light source are transmitted through the waveguide. A specific angle, the acceptance angle, serves as a cutoff for the light modes.
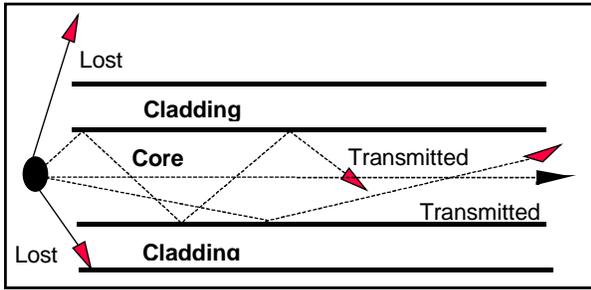
All light rays that enter the fiber at an angle greater than this critical angle, α, exit through the cladding and are lost. This angle can be calculated based on the value, n, of the core and cladding, and is usually represented as the numerical aperture, NA, a standard specification of any fiber. The NA is defined in the following illustration.

$$NA = \sin \alpha = \sqrt{n_{core}^2 - n_{clad}^2}$$
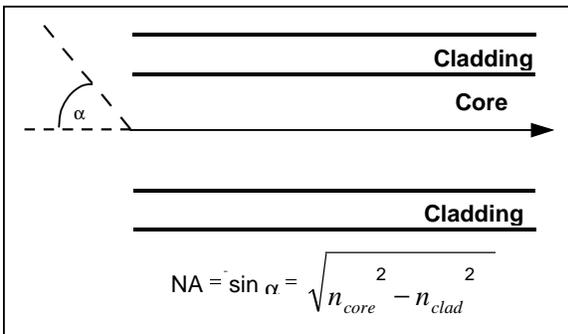
Bandwidth

Bandwidth determines how much information can be transmitted through a waveguide at one time. An analogy would be the speed of a fluid flowing through a pipe and, in fact, optical fibers are often called "light pipes." One of the reasons that optical transmission is more desirable than electrical transmission is because optical offers a much wider bandwidth. This is due to the properties of light versus electricity.

The bandwidth of a transmission medium is limited by an effect called dispersion. This means that the input signal is spread out or distorted as it passes through the medium and has a wider or different shape at the receiver. The more dispersion in a signal, the shorter the time between the unique data bits. If they get close enough to each other, they can overlap, causing errors in the signal, as illustrated at the top of the next column.


Dispersion

In an optical medium, such as fiber, there are three types of dispersion, chromatic, modal, and material.

Chromatic dispersion results from the spectral width of the emitter. The spectral width determines the number of different wavelengths that are emitted from the LED or laser. The smaller the spectral width, the fewer the number of wavelengths that are emitted. Because longer wavelengths travel faster than shorter wavelengths (higher frequencies) these longer wavelengths will arrive at the end of the fiber ahead of the shorter ones, spreading out the signal.

One way to decrease chromatic dispersion is to narrow the spectral width of the transmitter. Lasers, for example, have a more narrow spectral width than LEDs. A monochromatic laser emits only one wavelength and therefore, does not contribute to chromatic dispersion.

Modal dispersion deals with the path (mode) of each light ray. As mentioned above, most transmitters emit many different modes. Some of these light rays will travel straight through the center of the fiber (axial mode) while others will repeatedly bounce off the cladding/core boundary to zigzag their way along the waveguide, as illustrated below.
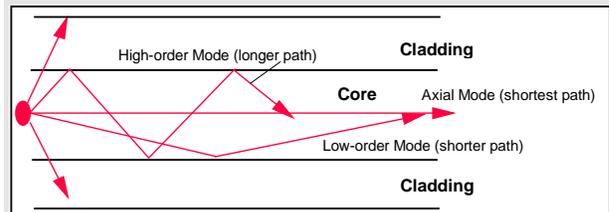
The modes that enter at sharp angles are called high-order modes. These modes take much longer to travel through the fiber than the low-order modes and therefore contribute to modal dispersion. One way to reduce modal dispersion is to use graded-index fiber. Unlike the two distinct materials in a step-index fiber, the graded-index fiber's cladding is doped so that the refractive index gradually decreases over many layers. The corresponding cross-sections of the fiber types are shown at the top of the following page.
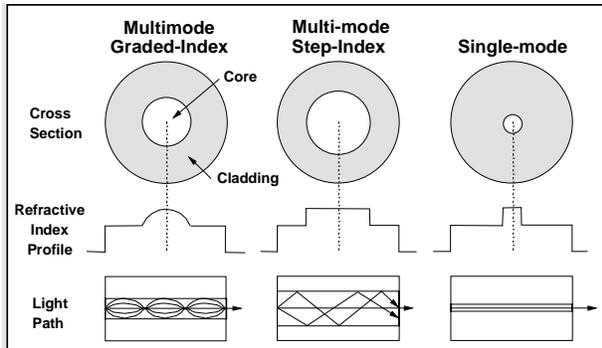
Note: Shading is used only to make the illustration clearer

With a graded-index fiber, the light follows a more curved path. The high-order modes spend most of the time traveling in the lower-index cladding layers near the outside of the fiber. These lower-index core layers allow the light to travel faster than in the higher-index


Graded-index Fiber
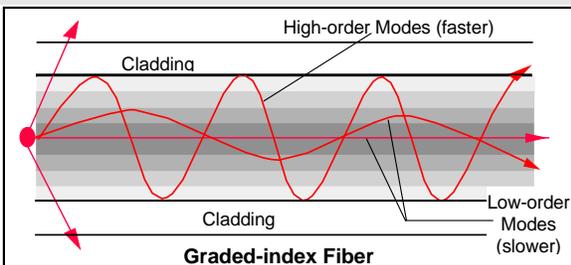
Note: Shading is used only to make the illustration clearer

center layers. Therefore, their higher velocity compensates for the longer paths of these high-order modes. A good waveguide design appreciably reduces modal dispersion.

Modal dispersion can be completely eliminated by using a single-mode fiber. As its name implies, single mode fiber transmits only one mode of light so there is no spreading of the signal due to modal dispersion. A monochromatic laser with single-mode fiber completely eliminates dispersion in an optical waveguide but is usually used in very long distance applications because of its complexity and expense.

The amount of information that an optical waveguide can transmit is usually specified by the bandwidth-distance product in MHz-km. For a step-index multi-mode fiber, distortion effects tend to limit the bandwidth-distance product to about 20 MHz-km. In graded-index fibers, pulse broadening is minimized at a specific operating wavelength.

The attenuation of the fiber that you choose may limit the distance over which the data can be sent. The dispersion effects of the link can limit both the distance and the data rate. It is generally a compromise between the two: the longer the distance, the lower the data rate that

can be sent, and vice versa. A typical distance versus data rate plot appears as shown below.
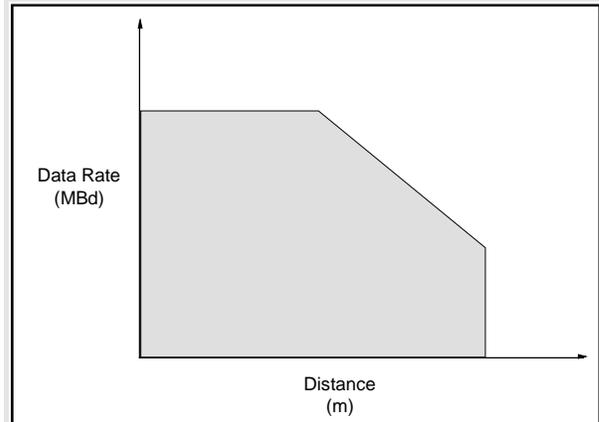
The flat line is where the fiber does not contribute to any limiting effects. The sloping line is where the data rate decreases as the distance increases. Finally, there is a cut-off point, the vertical line, at which the receiver can no longer detect the signal.

Different types of fiber and different emitter wavelengths and properties will change the shape of this curve, so you must take all components of the link into account when determining a solution. Generally, distance versus data rate graphs and tables are available for most Agilent general-purpose fiber-optic components.

The following table compares the major specifications of fiber-optic cable.

Specification	Core/Cladding		
	Plastic/ Plastic	Glass/ Plastic	Glass/ Glass
Bandwidth-Length-Product (MHz-km)	3	20	300 - 1500
Core Diameter (μm)	350 - 000	125 - 600	50 - 100
Transmission Dist.	Short	Medium	Long
Attenuation (dB/km)	250	6	4
Numerical Aperture	0.50	0.37	0.30
Wavelength (nm)	650	800	1300 - 1550

Attenuation

As light pulses travel through the fiber, they lose some of their photons, which decreases their amplitude. This is know as attenuation, the other major factor that limits signal transmission (light output power) and consequently, reduces the length of the fiber. Attenuation is usually specified in decibels per kilometer or per meter (dB/km or dB/m). Attenuation of optical power in a fiber has three main

causes: scattering, absorption, and bending. Attenuation varies over the light spectrum.

Rayleigh Scattering
A ray of light is partially scattered into many directions by microscopic variations in the core-cladding interface. The angle of some of the light rays impinging at these variations is changed enough so that they are refracted onto different paths and do not experience TIR (see Snell's Law). For this reason, some light energy is lost. Scattering is responsible for up to 90 percent of the total attenuation. Rayleigh scattering causes about a 2.5 dB/km loss at 820 nm but less than 1 dB/km in wavelengths over 1000 nm.

Absorption
Impurities in the glass, which absorb light energy and turn photons into phonons (heat), include ions of copper, iron, cobalt, chromium and the hydroxyl (OH⁻) ions of water. The OH-ions of water and the molecular resonance of SiO_2 are the principal reasons that light energy is absorbed by the fiber.

Bending
Two types of bending exist: micro-bending and macrobending. Micro-bending is microscopic imperfections in the fiber geometry, such as, rotational asymmetry, variations of the core diameter, and course interfaces between the core and cladding caused by pressure, ten-sion and twist. Macro-bending is due to fibers curved around diameters of about a centimeter, causing less than total reflection at the core-to-cladding boundary. Bending loss is usually unnoticeable if the diameter of the bend is larger than 10 cm.

In multi-mode fibers, a large number of modes is always present; and each mode in a fiber is attenuated differently (differential-mode attenuation). In single-mode fibers this effect is not as much of a problem.

Other Factors
Optical power loss in a fiber can also be caused by
- light reflected off the ends of the fiber by differences in the refractive indices of the core and air at the interfaces (Fresnel reflection);
- poor finishing of the fiber ends, which scatters a portion of the light; and
- variations in the diameters and cross sections of the core and cladding along the length of the fiber.

Propagation Delay
Propagation delay is the length of time it takes the output of a device to go from one state to another state, either low to high or high to low, after having been stimulated to change at the input. It is also a measure of the time required for a signal or pulse to travel through a medium. The following table lists the typical propagation delay times in ns/m for various media.

Medium	Delay (ns/m)
Copper Wire	4.0
Plastic Fiber	4.8
Glass Fiber	5.0

The extra delay in travel time through a fiber (compared to copper) does not necessarily reduce the bandwidth; however, failure to allow for it in system design can have an adverse effect on message protocol.

When there are parallel logic paths using individual parallel links, the signals can arrive at the other end of the links at different times because the transit time for each link is different. If this happens, individual link delays might affect the performance of the circuit when all parallel paths are strobed at once. The strobe edge should be timed to just follow the longest individual transition delay and to precede the shortest individual transition delay.

Pulse-Width Distortion (PWD)
Pulse-width distortion refers to the time difference between the delay of a low-to-high edge and the delay of a high-to-low edge of the output signal waveform. Ideally, low-to-high and high-to-low transitions should have exactly the same time delay. The time difference between them is distortion, and this can limit the signal rate.

Wavelength Division Multiplexing (WDM)
The data rate for a single optical channel eventually reaches a limit due to chromatic and other types of dispersion (see above). The available bandwidth can be increased by adding multiple wavelength channels. A wavelength multiplexer combines the laser wavelength channels onto a single fiber with low loss, then later separates them at the receiver end of the link.
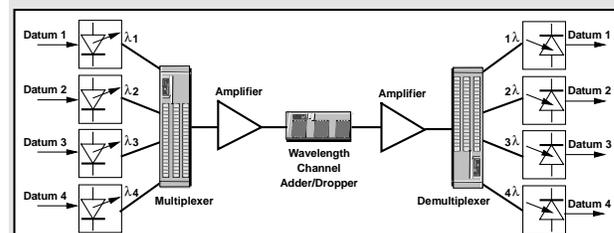

Wavelength division multiplexed fiber-optic link

In the past, when signals needed to be routed to a specific location, the optical signal was detected and routed electronically. WDM systems allow the optics to route the optical signal. These systems can also add and drop certain wavelength channels from a fiber while simultaneously sending on other channels.

Each type of fiber has a different attenuation versus wavelength curve, none of which is linear or exponential, but rather a complicated series of peaks and valleys.

The attenuation of the light through a glass optical waveguide has been decreased over the last 25 years to less than 0.02 db/km and scientists are trying to decrease the attenuation even more.

The following graph depicts the attenuation for a specific type of plastic optical fiber. As the graph shows, certain wavelengths are ideal for transmission because they fall in the valleys of the curve. For this type of plastic fiber, the best suited wavelengths are 570 nm and 650 nm. For most glass fibers there are valleys around 850 nm, 1300 nm, and 1550 nm. For other types of fiber, such as HPCS (Hard Plastic Clad Silica) fiber, the attenuation curve is relatively flat over a wide spectral range.
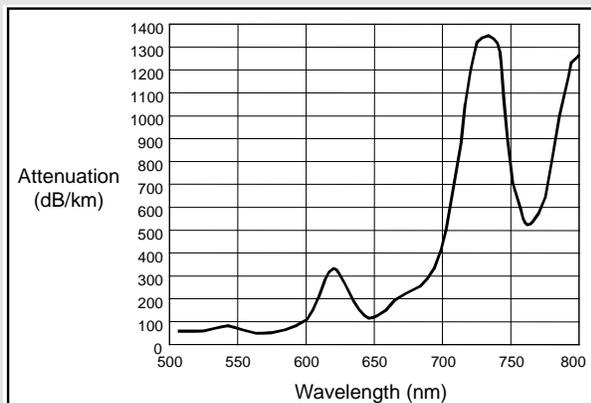
This feature makes these types of fibers useful for a variety of applications.

Attenuation loss in a fiber can be calculated by taking the logarithmic ratio of the output power (P_o) to the input power (P_i):

$$dB = 10 \log_{10} \frac{Po}{Pi}$$

Indirect Measurements
Cutback Method
The attenuation of a fiber can be measured by transmitting a signal through it and measuring the power at the opposite end. The fiber is then cut near the input end without changing the launch conditions and the power is measured again. The loss per unit length can be calculated from the difference between these two values.

Substitution Method
A short length of reference fiber is compared with the attenuation of the fiber being tested.

Both the cutback and substitution methods have drawbacks. The attenuation measured by the cutback method varies according to the numerical aperture and the spectral bandwidth of the source. In the substitution method, the coupling losses of the fiber being tested and the reference fiber may be different, so the value derived may not be correct.

Direct Measurement
A more reliable technique for measuring attenuation in a fiber is optical time-domain reflectometry (OTDR). In this method, a brief signal (a short burst of optical power) is introduced into the fiber. When this signal encounters imperfections or discontinuities, some of the light is reflected by a beamsplitter (a glass plate at a 45 degree angle to the incident light or two prisms cemented together with metal-dielectric film between their faces) onto a detector, where it is amplified and displayed on an oscilloscope.

The ODTR display is a smooth curve for a continuous length of fiber and an irregular curve if discontinuities or splices exist. The advantage of OTDR is that it yields more accurate results.

Bit Error Ratio
In an actual transmission system, various electronic noise sources, such as the shot (random) noise of the first transistor in the PIN-photodiode preamplifier or noise on the 5-volt power-supply line of the host digital system, can change or corrupt the stream of data bits. The number of these corrupted bits divided by the total number of received bits within an arbitrary time period is the bit error ratio (BER). The lower the BER value, the fewer the number of errors in the transmission.

The bit-error ratio is usually given by a number such as 10^{-6}. This means that on average, one error occurs for every million pulses sent. Typical error ratios for optical fiber systems range from 10^{-9} to 10^{-12} (local-area networks require a BER as low as 10^{-12}). The BER can be measured by repeatedly transmitting and receiving a suitable length of a pseudo-random bit sequence (PRBS) data. The necessary optical power to achieve a given

signal-to-noise ratio, and therefore a certain BER, is called the receiver's sensitivity.

Receiver Threshold-to-Noise Ratio vs. BER
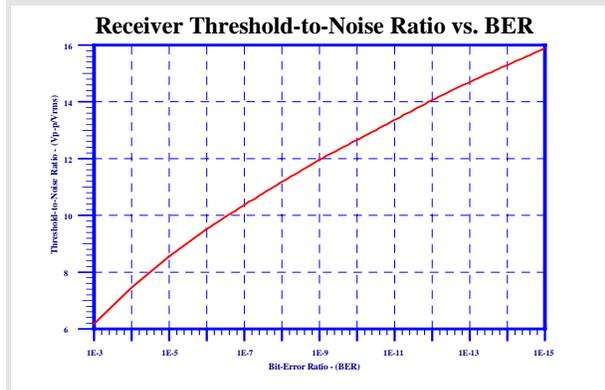
At any fixed temperature the total value of the receiver's random noise plus the host system's noise can be assumed to be a constant. So, the most obvious way to reduce the probability of error is to increase the amplitude of the optical signal applied to the receiver.

Another technique for lowering the error rate is to improve the receiver's ability to reject electrical noise from the system it is in. One method is to use small PIN diode pre-amps in the receiver's first stage that do not function as efficient antennas. A second method, for extremely noisy applications, is to use PIN diode pre-amps in electrically conductive plast5ic or all-metal packages.

The worst source of noise is usually the host system's power (usually +5 V) supply. The host system's +5 volt supply normally powers the fiber-optic receiver, the fiber-optic transmitter and an entire system comprised of relatively noisy digital circuits. Simple and inexpensive power supply filters have been proven to work in a wide range of system applications. Simple, third-order pi power-supply filters are normally sufficient to protect the fiber-optic receiver from very noisy host systems, but in extremely noisy applications, additional power supply filtering might be needed.

Receiver sensitivity is specified at a BER; however, in practice, the BER is too low to be directly measured in a useful time period. For this reason, the transceiver is usually tested during an artificially shorter time at a much higher BER. The resulting data is then fitted to a curve and the optical input power at the required BER is extrapolated.

Note: The receiver's signal-to-noise ratio determines the probability of error; small increases in this ratio will sharply reduce the probability of error. Optical budgeting is a design technique that takes system- and component-level parameters into account.

System-level parameters include:

- transmitter output power (P_T dBm avg.),
- receiver sensitivity--the minimum optical power that the receiver requires to operate at the specified data rate and bit error ratio (P_R dBm avg.),
- fiber losses (caused by attenuation, bandwidth and insertion losses from connectors and are dependent on the type of fiber) and
. - dynamic range.

Component-level parameters include:

- data rate,
- bit-error ratio (BER), and
- data pattern.

These two sets of parameters allow a designer to determine the distance and power budgeting for the fiber link.

Optical Power Budget
Power budget is the difference between the minimum output power of the transmitter and the minimum sensitivity of the receiver. If optical power losses are greater than the worst-case power budget, the BER increases and the reliability of the link decreases.

Optical power expressed in µW or dBm, and optical attenuation is expressed in dB/m. the total loss budget is derived from the individual losses contributed by attenuation and other possible losses in the link.

The Optical Power Margin is

$$\phi_{M =}(\phi_T - \phi_R) - (\alpha_O \ell + \alpha_{CC}).$$

Optical Power Margin =

Optical Power Ratio - System Losses.

Note: For the fiber-optic cable to transmit and receive, the flux margin must be positive.

Each of these losses is expressed in decibels (dB) as

$$\text{Loss} = 10 \log \frac{\text{Pout}}{\text{Pin}}$$

where Pin and Pout are the optical powers into and out of the loss element.

Note: dBm is a unit used to describe optical power with respect to one milliwatt. For example, if $P_{IN} = x\mu W$), then

$$P_{IN} = 10 \text{ Log} \frac{X}{1000 \, (\mu W)} \text{ dBm.}$$

The link loss budget considers the total optical power loss allowed between the light source and the photodetector, and allocates this loss to cable attenuation, connector loss, splice loss, and system margin.

The optical power budget is $P_T - P_R$, where P_T is the power launched by the transmitter and P_R is the power required by the receiver for proper operation. These values are usually expressed in dBm, so the difference is expressed in dB. If the losses between transmitter and receiver exceed the power budget, then the power at the receiver will not be adequate to assure proper operation.

In the following example, $P_T = -12$ dBm and $P_R = -24$ dBm. Substituting these values into the equation:

$$P_T - P_R = -12 - (-24) = -12 + 24 = +12 \text{ dB},$$

and so, the receiver has sufficient power to operate.

Eye Diagrams

An oscilloscope display of a long stream of random bits (light pulses) is used to determine transmitter and receiver performance. Due to distortion of the waveform (by a variety of factors), the displayed light pulses do not align, but instead overlay one another and appear blurred, as shown below.
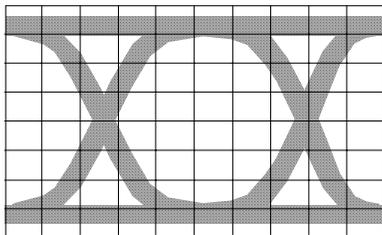
The important point is that the center of the pattern formed by these pulses must be open: the wider the opening, the less the distortion and jitter.

Much information about system performance can be gathered from the eye pattern:

- The width of the eye defines the time interval during which the received signal can be sampled without error from inter-symbol interference.
- Amplitude distortion in the data signal reduces the height of the eye opening. The smaller this dimension, the more difficult it is to detect the signal without error.
- The height of the eye opening at the specified sampling time shows the noise margin or immunity to noise. Noise margin is derived from the following equation:

$$\text{Noise margin (percent)} = \frac{V_1}{V_2} \times 100 \text{ percent}$$

where V1 is equal to peak signal voltage and V2 is equal to the ideal signal voltage.
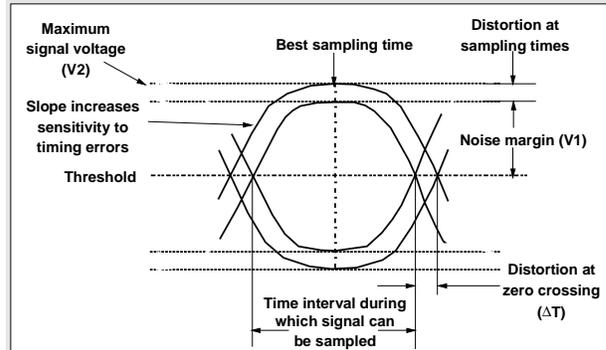
- Timing jitter is caused by noise in the receiver and pulse dispersion in the fiber. If the signal is measured at its midpoint, then this time-width indicates the amount of jitter.
- The lower the slope of the signal's transition time, the more that the eye closes and the greater the increase in timing errors. As the slope approaches the horizontal, the possibility of error increases.
- If a truly random data stream passes through a linear system, all eye openings will be identical and symmetrical. Any non-linearities will produce asymmetry in the eye pattern.

Parameters such as rise- and fall-times, extinction ratio, overshoot, undershoot, and pulse-width distortion can be observed.

When an oscilloscope is triggered by the clock, the result is the classical "eye" pattern, as shown on the preceding page. Data are recoverable if the "eye" is "open" above and below the threshold for a period of time greater than the "set-up" and "hold" time needed for subsequent decision devices or circuits.

Most serial communications standards now define a minimum condition on eye-pattern opening (template) for the serial data stream. The area from which the waveform is excluded is the mask.

The mask limits that specify the eye-pattern opening are an improvement over the older technique of specifying pulse parameters individually. It is compact, conveying important information without placing undue restrictions on the data pulse. Limiting rise and fall times, pulse-width distortion, overshoot, damping, undershoot, and so forth, is unwieldy and insufficient by comparison.

Mask region 1

1.0

Mask region 2

0.0

Mask region 3

Absolute Amplitude (V)

Relative Amplitude

0.0   Relative Time (Unit Interval)   1.0

Absolute Time (s)
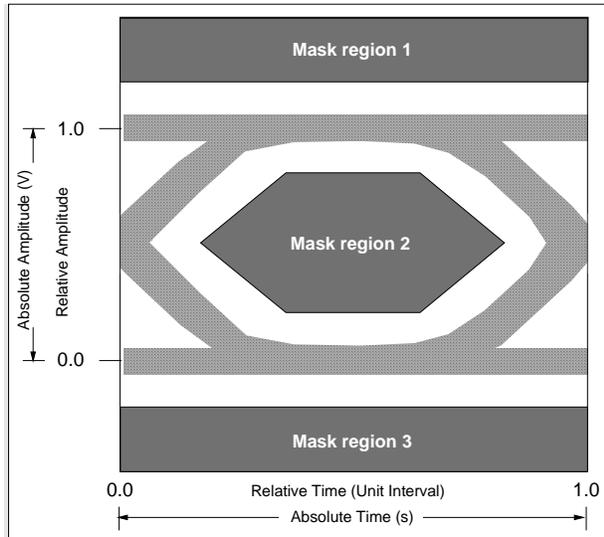
As shown by the preceding diagram, a mask consists of two parts:

  - defined regions on the oscilloscope screen where the waveform is not permitted to appear.
  - definitions of the time and amplitude scales.

TTL and PECL

ECL (Emitter Coupled Logic) is a non-saturating digital logic, characterized by high speed, low noise, and the ability to drive low-impedance circuits. ECL uses a negative power supply. PECL (Positive Emitter-Coupled Logic) is the standard ECL device powered by a positive power supply.

A typical application for ECL (Emitter Coupled Logic) is a subsystem that requires very fast data transmission, such as fiber-optic links. In this application, parallel data is serialized into a high-bandwidth PECL data stream. At the other end of the link, the signal is converted back to relatively low-speed parallel data for further processing. This system of translating parallel to serial then serial to parallel minimizes the number of transmission lines required for interconnecting the subsystems.

The gigabit rate performance of current fiber-optic link designs demands the use of PECL circuits.

In the following block diagram, the high-speed serial data from the SerDes (serializer-deserializer) IC is PECL-compatible with the Optical Transceiver. The low-speed Signal Detect output from the Optical Transceiver is PECL. The Host Protocol IC, which uses signal detection, operates with TTL logic levels. It is converted from PECL to TTL using the Converter IC. The parallel data interface between the Host Protocol IC and the SerDes IC is TTL.

**Simplified Gigabit Ethernet Network Interface Card**
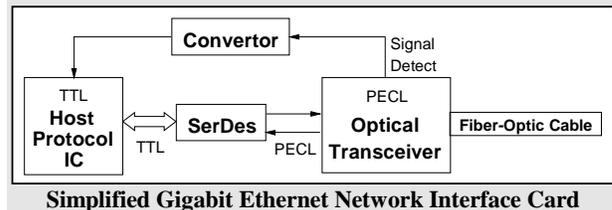
Data Communication Links

A data communication link transfers information from one piece of electronic equipment to another. These links interconnect computers, peripherals, servers, and other individual devices. Busses inside these devices distribute the parallel data between the internal components (memory chips, the micro-processor, logic devices, and so forth). To send this parallel data across a data-communication link, it must first be transformed into a serial bit stream.

To do this, the transmitter, receiver and the supporting ICs must do more than merely convert current into light. Sometimes the manufacturer, for

example, Agilent, builds additional cir-cuitry into the fiber-optic transmitter and receiver and some-times it is instead the responsibility of other equipment designer and the integrated circuit ven-dors. The level of integration is different, de-pending on factors that will be discussed later.
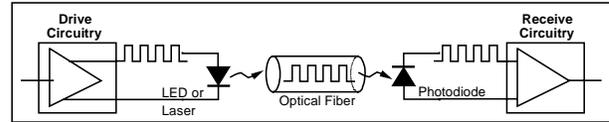
A number of steps are needed to prepare this serial bit stream from the parallel word data and transmit it.
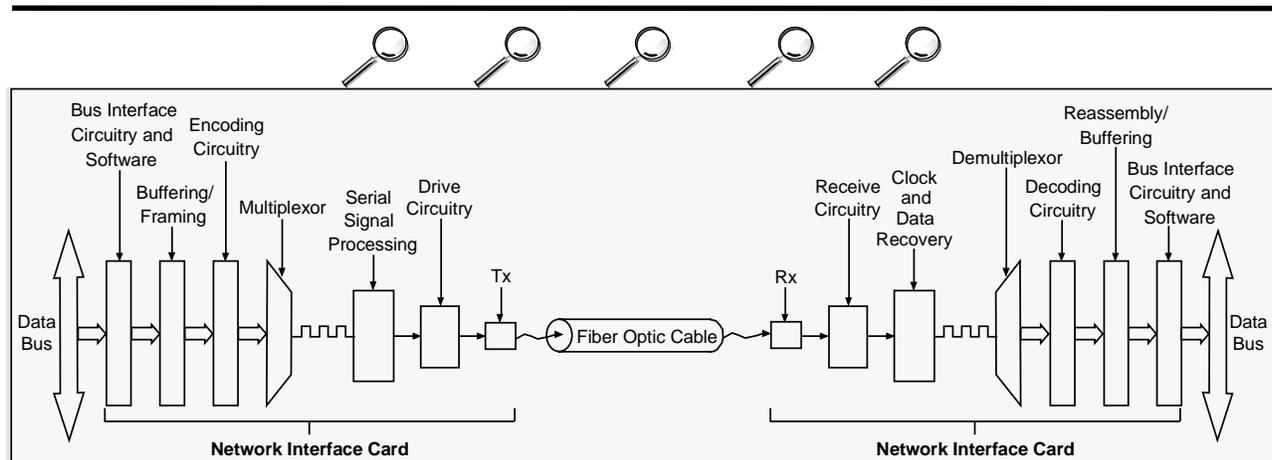
Block Diagram of a Generic Fiber-Optic Data Communication Link

Block	Description
Bus Interface	Interfaces directly with the data bus, recognizes requests to send data, pulls the data off the bus, and maps the data from the bus format over to the data communication link format. When the data link is receiving data, the bus interface notifies the local bus that information has been received and is going to be put on the bus. It then maps the data from the data link format to the specific bus format.
Buffering / Framing	Stores the parallel data from the bus in local memory. Partitions this large block of data into frames (small blocks); overhead (additional frames) may be inserted. These overhead frames include address error tolerance, and LAN management information. All frames are then sent sequentially to the transmitter-encoding circuitry. When receiving data, this procedure is reversed and the original data is restored and placed in local memory. It remains here until the bus interface circuitry places it on the resident data bus.
Encoding / De-coding	Converts the data from an original value to a prescribed value, which when serialized, ensures that the link will function properly. Since this conversion is "prescribed," the receiver side of a data communication link can convert the received signal back into the data's original form.
Multiplexor/ Demultiplexor	Serializes the parallel data (a data communication link can transmit only one data bit at a time along the same cable). The serial bit stream goes to the Serial Signal Processing circuitry. On the receiver side of the link--once the serial bit stream has been recovered--this data is converted back into parallel data words by the demultiplexor (DeMux)..

(Continued on the following page)

Block	Description

Serial Signal Processing	Changes the digital serial bit stream, if necessary, into a form appropriate for the transmission medium.
Drive Circuitry	Drives the transmitter to send the serial signal, which is usually amplified. The drive circuitry may convert an input voltage signal to a current drive signal, which is sent to an LED or laser diode (both of which are current driven).
Transmitter	Converts the electrical signal into a form appropriate for propagation through the transmission medium. For fiber optics, the signal is converted into light, which is launched into the fiber-optic cable.
Transmission Medium	Carries the signal from the transmitter to the receiver. The medium can be twisted-wire pair (TWP), coaxial cable (coax), fiber-optic cable (glass or plastic) or wireless (does not require a medium).
Receiver	Detects the incoming signal and converts it to an electrical signal, which can be processed by the receive circuitry.
Receive Circuitry	Processes the signal from the receiver into a more useable form. Frequently the signal is converted from current to voltage (by a trans-impedance amplifier) or amplified (by fixed and variable gain amplifiers) or wave-shaped (by an equalizer for copper cable transmission or quantizer for some fiber-optics transmission) or can undergo any combination of these procedures.
Clock and Data Recovery	Reconverts the received and processed serial signal into the original serial bit stream. For this to happen, the clock and data recovery must first lock onto the frequency and phase of the incoming signal and extract the clock (by a phase-locked loop, or some other method). This clock is then used to check the incoming signal at every clock period. In this way, the original digital serial bit stream is recovered along with the clock (data rate at which the serial bit stream was sent).

Encoding

Encoding allows the data transmission link to be more efficient. Encoding merges the data and clock signals in a manner that allows a timing recovery circuit to reconstruct the clock and data signals at the receiver end of the data link. Without encoding, a clock signal would have to be sent via a second fiber link. Increased cost and possible timing skew problems could arise if an additional clock link were to be established. A number of encoding schemes are shown in the following table.

The basic unit of information in a digital system is the bit: a logical "one" or "zero." A logical one is represented by a high voltage; a logical zero by a low voltage. In binary signaling, a "symbol" is either a high of low signal level that is held for a period of time. When a string of identical bits is transmitted, the voltage remains at the same level. Unencoded data has dc voltage offsets because this data can remain in the "logic 0" or "logic 1" state for an indefinite period. Digital systems use a clock to define the bit period in a constant-voltage transmission.

Data rates are often expressed in bit per second. The terms, megabits per second (Mb/s), megahertz (MHz), and megabaud (Mbd) are related as follows: the translation from bits per second to baud depends on the encoding scheme. If there is no encoding, bits per second equals baud. Baud is expressed in symbols/second. In binary transmission systems, the maximum fundamental frequency (Hertz) of the data is half the baud rate.

Type	Description	Mb/s	Mbd	MHz	Efficiency
Manchester	Replaces each bit with 2 symbols	100	200	100.0	Less
4B5B*	Replaces 4-bit group with 5 symbols	100	125	62.5	More
5B6B	Replaces 5-bit group with 6 symbols	100	120	60.0	More

*Another type is 8B10B, which replaces 8 bits with 10 symbols. The relationship between Mb/s, Mbd, and Mhz remains the same for this encoding as well.

At the transmitter end of the link, serial binary data is coded to a signal suitable for transmission. At the receiver end of the link the digital signal is demodulated by a phase-lock loop (PLL), a circuit that synchronizes a local oscillator with the incoming signal. A PLL has three basic elements: a phase detector (PD), a loop filter (LF), and a voltage-controlled oscillator (VCO), as shown in the following circuit diagram.
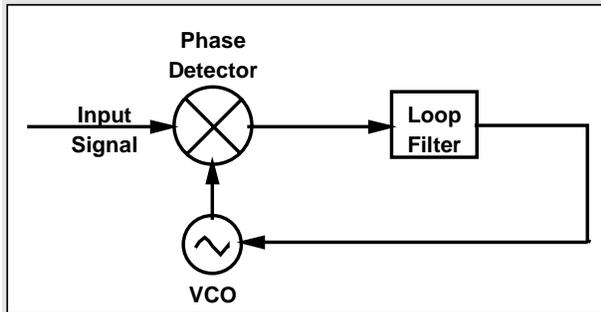
The phase detector compares the phase of a periodic input signal to the phase of the VCO. The voltage output of the PD is the difference in phase between the two inputs. This voltage is filtered by the LF and applied to the VCO. Control voltage on the VCO changes the frequency to reduce the phase difference between the input signal and the VCO. When the loop is locked, the VCO is exactly equal to the average frequency of the input signal. Each cycle of input has only one cycle of oscillator output.

The number of symbols per second is expressed in baud. Although bit rate and baud may coincide, they are not the same. The fastest baud is defined as the reciprocal of the narrowest pulse width. Data rate is influenced by format, which is the method of encoding bits for transmission. Baud is a true measure of a system's signaling speed because it is not dependent on the data format.

The following table describes the various modulation codes used in data transmission.

Standard Modulation Codes

Code	Description
NRZ	A logic-level code for serialized data. A "zero" is a low logic level and a "one" is a high logic level that does not return to zero between successive "ones."
RZ	A code in which "ones" are represented by a high logic level that returns to zero between successive "ones." For this reason, the code requires a channel that can signal two symbols (high and low) per bit. Its main advantage is that it conserves power because energy is needed only for transmitting "ones."
NRZI	A code in which a "zero" is represented by an edge and a "one" is represented by the absence of an edge. Because the edges may be either rising or falling, inversion of the signal does not change the meaning of the code and it is therefore invertible.
Biphase-Mark	A code requiring a channel capability of two symbols per bit. Each bit cell begins with an edge: then, for a "one" an additional edge occurs during the bit cell; for a "zero" there is no edge during the bit cell. Because there is always an edge at the beginning of the bit cell, clock recovery from this code is possible by either phase-lock or one-shot techniques. It is also invertible and has a duty factor exactly 50%.
Biphase-Space	An invertible, self-clocking code, differing from biphase-mark only in that 'zeroes' have the additional edge during the bit cell. Both biphase codes are sometimes called "f/2f" because the additional mid-cell edge may be regarded as a cycle of a frequency that is twice that for the absence of the mid-cell edge. Duty factor = 50%.
Manchester	A code in which a "one" has a high logic level at the beginning of the bit cell with high-to-low transitions at mid-cell; a "zero" starts at a low level with low-to-high transition at mid-cell. This code also requires a channel capability of two symbols per bit. Because there is a mid-cell transition in each bit, clock recovery is possible by either phase-lock or one-shot techniques. It is not invertible; the duty factor is 50%.
Miller	An edge-type code in which each "one" in the serial data is encoded as a mid-cell edge. The "zeroes" either have no edge or are encoded as edges at the beginning of the bit cell. Because no edges occur at intervals less than one bit time, the channel capability required is only one symbol per bit. With edges occurring regularly at integral multiples of half of a bit time, clock recovery is possible with a phase-locked oscillator running at a frequency that is twice the data rate. The duty factor is generally 50%.
MFM*	A code similar to Miller: impulses occur at intervals of 1.0, 1.5, or 2.0 bit times. For this reason, clock recovery is possible .. Because impulse duration is much less than bit time, the duty factor approaches zero but cannot exceed 50 percent.

*Modified Frequency Modulation

Electromagnetic Compatibility—EMC

EMC refers to the capability of electronic equipment or systems to be operated in the intended operational electromagnetic environment at their designed levels of efficiency. Specifically, EMC describes how the product behaves in terms of radiated emissions, commonly known as electromagnetic interference (EMI), and also how the product's performance is affected by immunity (sus-ceptibility to radiated energy), electrostatic discharge (ESD), and conducted power supply noise.

1. EMI

The first EMC area is radiated emissions, sometimes called electromagnetic interference or EMI. A radio or TV broadcast is an example of intentionally radiated electromagnetic energy. A computing device also radiates electromagnetic emissions, although it is not intended to (the radiation is an inherent by-product of the switching currents flowing in its conductors). Electromagnetic interference (EMI) describes the effect of unwanted radiation interfering with another (intentional or unintentional receiver) circuit's operation. Electromagnetic radiation occurs when a changing current flows in a conductor. The area near the conductor (antenna) is where either the electric or the magnetic field dominates the total radiated field.

Government agencies around the world regulate the amount of radiated electromagnetic energy emitted by various sources. Their intent is to allow any purposely transmitted radiated energy to be received without being interfered with by some other radiation source at around the same frequency.

Most manufacturers want their systems to meet all of the home environment radiated emissions specifications used around the world so that they can be sold in the US, in Europe or in Japan, without restrictions. Government agencies usually set their radiated emissions regulations to distinguish between two types of applications. One is factory or office (Class A) where a higher level of radiation can be tolerated; the other is the home (Class B) where there are more TVs and radios and therefore less electromagnetic radiation can be tolerated.

Any product that does not meet the pertinent emissions requirement for a particular country cannot be legally sold in that country. Any manufacturer who sells equipment that is found to violate the regulations can, if caught, face large fines and penalties. Also the manu-

facturer may be forced to withdraw the product from the market until the regulating government agency, for example, the FCC (Federal Communications Commission) in the United States is convinced that the radiated emissions of the modified product meet the required specification limits.

System design can affect radiated emissions in three ways. The first way is in the choice of circuit components. Some generate more high-frequency energy than others do. The second way relates to the effect of the antennas (that is, the circuit interconnections) that the high-frequency energy sources are connected to. The third way is by the shielding that the chassis box provides and by the cable shields that effectively reduce the amount of radiation that the antennas leak to the outside world.

An actual communication system contains various antennas formed by circuit interconnections and by the other metal bodies in the circuitry that create the Vcc-to-ground-current loops. These antennas are then driven by various energy sources within the system circuitry. Keep these antennas as small as possible. If they are long enough to be treated as transmission lines, then it is important that the line is terminated in its characteristic impedance. Antennas can also be formed by long traces that are driven by ground voltage noise and therefore radiate. Even a ground plane, when driven by a ground noise source can radiate. Often, cables can radiate energy when high-frequency currents flow through them. Because cables are often the largest antenna around, they are usually the dominant source of radiation. Chassis and cable shields can also radiate if ground noise current or voltage drives them.

Fiber-optic cables do not, however, radiate energy as wire cables do. Therefore, fiber-optic cables can help reduce radiated emissions if using wire cables is a problem. At FDDI and ATM data rates, the encoding/ decoding schemes, and the consequent additional circuitry needed to reduce the bandwidth and the emissions on a twisted pair wire cable, are not needed if a fiber-optic cable is used.

If an antenna is completely enclosed in a sufficiently thick metal box, then no radiation will escape. If the box has an aperture, then some radiation will escape through it; the bigger the opening and the higher the frequency, the more radiation that escapes.

More accurately stated, the leakage through a single aperture in a metallic chassis is related to the longest dimension of the opening (d) and the wavelength (λ) of the radiating frequency. When wavelength is less than

or equal to twice the longest aperture dimension, the attenuation of the aperture is 0 dB. The cutoff frequency of a solitary aperture occurs when $\lambda = 2d$. At frequencies less than cutoff, the attenuation of the aperture increases at a linear rate of 20 dB per decade. If the metal chassis box has multiple openings with identical longest dimensions d, then the attenuation of the shielding decreases by 10 log (N), where N equals the number of apertures. The preceding relationship holds true until N becomes large enough to reduce shield attenuation to 0 dB.

2. Electromagnetic Susceptibility

Electromagnetic susceptibility (or immunity) of a product is defined as the effect of external electromagnetic fields on the performance of that product. The performance is measured in the presence of an external electromagnetic field relative to the performance with the electromagnetic field absent.
Immunity and susceptibility refer to the same characteristics (immunity is the inverse of susceptibility).

What is meant by immune, however, is left to be negotiated between vendor and customer. Based on some of Agilent's customer inputs, Agilent has standardized on a 10 V/m field strength to test fiber-optic transceivers.

Usually an antenna in the circuit will pick up the external field and then couple it into a critical circuit node where it appears as a noise signal. The susceptibility will depend on the frequency of the field because the receiving antenna gain varies with frequency and because the circuit noise rejection varies with frequency. The noise can be picked up directly at the sensitive node itself or can be conducted from another node (such as Vcc) that has a larger gain antenna connected to it.

The usual effect of an external field on a fiber-optic receiver is to degrade the received bit error rate. The fiber-optic receiver (Rx) is usually the most sensitive analog circuit in the entire communication network product. An external field can induce a signal on the antennas formed by the interconnections in the fiber-optic Rx circuitry. Antennas are bi-directional devices. The same phenomenon that causes an antenna to radiate an electromagnetic field when a voltage/current signal is applied to its inputs, will generate the same voltage/current signal at those inputs, (now really the outputs), if the same antenna is placed within an identical, but externally generated, electromagnetic field. The antenna, formed by the Rx circuit inter-connections, picks up the external field and generates a signal. If the generated noise signal is conducted to a sensitive circuit node, the node then experiences a lower signal-to-noise ratio, which increases the bit error rate. (In a perfect fiber-optic Rx,

the signal-to-noise ratio and the bit error rate are directly related). So the external electromagnet-ic field can inject noise into the fiber-optic Rx and thus degrade the bit-error rate (BER).

3. Electrostatic Discharge

Certain non-conductive materials can either donate charge (electrons) or acquire charge when in contact with other materials. A material with a net charge can then transfer it to a conductive material either by direct contact or by inducing the opposite charge in the conductor. If this charged conductor contacts an earth ground (or any conductive body with a very large amount of stored charged available), a current will flow until that conductor's net charge becomes zero. For example, if your skin is charged from walking across the carpet on a cold dry day and you then touch a grounded or large conductor, you may see a spark as your skin discharges, and feel a tingle in your finger, as the current flows. The characteristics of the ESD current depend on the amount of charge stored and on the impedance of the circuit that discharges it (to ground).

ESD can affect a product during its manufacturing or during its operating lifetime. If all the ESD events are controlled during manufacturing so that they lie safely within the limits of the most ESD-sensitive components, then the system can be manufactured without ESD damage.

In a finished system, ESD can still cause permanent product damage. Often, however, a more important problem is ESD disturbances to the system performance. An ESD performance disturbance could include lines on a CRT display, logic stuck in a locked state, or a larger number of bit errors than usual. These ESD disturbances can be accounted for in the system design to ensure that the product's end user does not notice any drastic performance differences when an ESD occurs.

If the components are enclosed inside a conductive or static-dissipating chassis box in the end product, ESD is more likely to go to the conductive box than to some other non-conductive component. For example, if a plastic-nose, fiber-optic module is protruding from the chassis box, then ESD is more likely to be conducted to the section of the chassis box that is near the module nose than it is to be conducted to the insulating transceiver's plastic-nose itself. If the chassis grounding is such that the ESD currents to ground flow on the chassis and do not flow inside the PCB component grounds, then ESD damage or ESD problems due to radiated fields caused by the ESD pulse will be reduced.

4. Conducted Noise

The fourth EMC area is conducted noise. Ideally a conductor will carry only the desired signal. Practically, however, there is always some component of the actual signal on the conductor that is undesirable. This component is defined as noise. Conducted noise emanates from one section of the product's circuitry and is conducted to the section of the circuitry being observed.

There are three main components of conducted noise:
  1. the conducted noise generator,
  2. the path that the noise takes to conduct from the generator circuit to the receiving circuit, and
  3. the sensitivity of the receiving circuit to this noise.

So, conducted noise problems could be eliminated by eliminating the noise source, removing the conductive path, or by using circuitry that is insensitive to the effects of conductive noise.

Since an actual fiber-optic communication network has many different types of circuitry, all operating at once, it is important that potential conducted noise problems be minimized to allow all the circuitry to operate without any section of it being adversely affected. In addition, most computing products have limits on how much conducted noise they are allowed to generate on the 120 Vac power lines to prevent them from disturbing other devices connected to the same ac power line.

Networking Technology

This section gives a generic summary of networking technology. Several very informative documents on LANs and Networking are accessible via the following URL

www.semiconductor.Agilent.com

on the Internet.

Depending on the distance and type of equipment, a network is segmented into LANs, MANs and WANs, as shown in the following table.
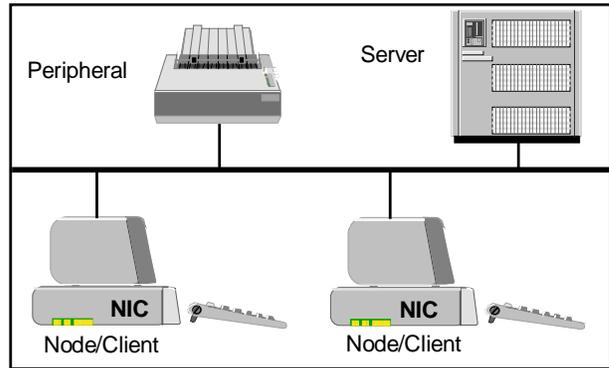
Typical local-area network (LAN)

Network	Acronym	Description
Local Area	LAN	A group of computers, peripherals and other devices that inter-operates, typically connected by no more than 1,000 feet of cable, and which allows people to share resources.
Metropolitan Area	MAN	Several LANS linked within a metropolitan area or campus. Usually fiber-optic networks installed and operated by the local telephone company or cable company.
Wide Area	WAN	Several LANs linked beyond the metropolitan area where service is generally provided by leased circuits from suppliers such as long-haul telephone carriers (AT&T, MCI), specialized companies (Tymnet, Telenet), or satellite system providers (GTE).

The following table shows the standard model for data communication systems, each layer having a specified task. More detail will be given about this model in the Ethernet standard section.

Open System Interconnections

	Layer	Description
7	Application	Provides clean interface-to-user application
6	Presentation	Monitors that all bits conform to specific digital language code
5	Session	Establishes and reserves resources via software link-by-link error control ("handshaking")
4	Transport	Error control and acknowledgement
3	Network	Routing information
2	Data Link	Error control, retransmission (Ack/Nack)
1	Physical	Encoding, serialization, clock generation and recovery Places bit onto the link

LAN Components

Device	Description
Network Operating System	A family of programs that run on both clients and servers on the network. It can be either a separate program loaded (LANtastic) or part of the operating system (Microsoft).
Clients (also referred to as nodes or users)	Computers that request to use files, send print jobs, and request other shared resources on the network. Client software (part of the network operating system) contains a redirector that captures requests from the PC application program (such as Amipro) and routes them out of the PC and across the network.
Servers	Computers that share their resources (hard disk drives, attached peripherals, communication circuits) with clients and other servers.
Networked Peripherals	Peripheral equipment has specialized processors to run networking server software. They may be attached to a computer or attached directly to the LAN.
Network Interface Card (NIC) or LAN adapter card (located in the PC)	Links the PC to the network via a cable. The NIC amplifies and encodes the data to be transmitted over the network. Software drivers are located between the NIC and the network communication software. The network communication software makes it possible to use the devices as if they were attached to the user's own computer.
Backbone	A network that connects smaller LANs. Only bridges, routers, hubs/concentrators, and possibly, company-wide servers should be connected to the backbone. End-users are not connected to the backbone. Backbones are usually high speed and use fiber-optic cables. LAN 1 — Backbone — LAN 2, LAN 3
Hub[1]	Stand-alone equipment with up to 24 physical interfaces that connect the nodes to the server. An active hub regenerates the signal using a repeater. Hubs function as a junction box and can also be stacked.
Concentrator[1]	A chassis-mounted rack where hubs are stacked. The advantage of a concentrator is its ability to accommodate large numbers of nodes.
Bridge	A "store and forward" device that segments shared LANs. Segmenting of shared LANs reduces the number of nodes that the hub services and is useful for increasing the average bandwidth per node. LANs connected by bridges must be of the same type, for example, Ethernet, because a bridge does not have the ability to translate between different protocols. They also do not have the ability to open the message, read its intended address, and forward it. Instead, a bridge will forward any message it receives from one segment of the LAN to another.
Router	An intelligent "store and forward" device similar to a bridge except for the following important differences: - LANs connected by traditional routers must be of the same type, for example, Ethernet, because a router does not have the ability to translate between different protocols (at one time, gateways were the only devices that could perform this translation). Over the past several years, however, routers have incorporated the functions of gateways and many can now perform protocol translation. - Unlike bridges, routers have the ability to open the message, read its intended address and forward it accordingly (some have error correction). The router functions as a "firewall," that is, it prevents unauthorized users from gaining access to the network. The router strips the outer envelope information off the data packet, permitting networks built with routers to transfer data more efficiently.

[1]An active hub or concentrator contains a management module that can answer queries from a management console.

Network Topologies

| Topology	Advantages	Disadvantages	Diagram
Star Central hub connected to all devices	- Cable layouts easily modified - Additional nodes easily added - Centralized management	- Large amounts of cable needed - More expensive - Single point for network failure	
Ring Wired in a circle	- Less cable needed - Lower costs - No wiring closet	- Network configuration modification more difficult	
Linear Bus Nodes attached to common cable	- Uses least amount of cable - Simple layout - Reliable - Easy to extend	- Fault diagnosis and isolation difficult - Bottlenecks occur when traffic heavy with increased number of nodes	
Star-Wired Ring Circular hub with nodes radiating from it	- Fault diagnosis and isolation easy - Easy to expand - Network does not fail if one node fails	- Network topology complicated - Cabling is complicated	
Tree Several daisy-chained linear buses	- Easily extended - Simplifies fault isolation - Network does not fail if one node fails	- If primary bus fails, network fails	
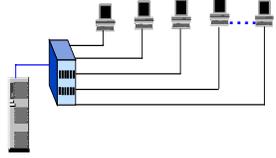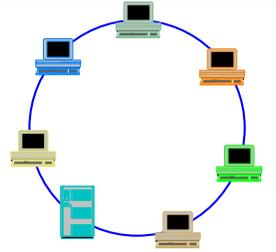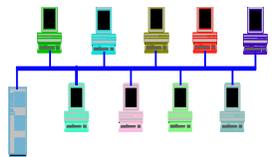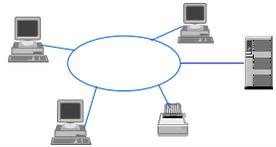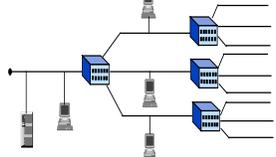
LAN Architecture Evolution

At first, all LANs were shared, allowing only one transmission at a time. In this arrangement, each device waits for access to the LAN before transmitting. Bandwidth is shared among the nodes.

As the number of nodes increases, the bandwidth for each node decreases. To alleviate the problem of shared LANs, bridges and routers were created to segment traffic into smaller LANs. This permitted fewer devices to be connected to each hub, in effect, increasing the bandwidth on it.

When do you use a bridge and when do you use a router? As shown below, if two different networks are to be joined, use a router. If two similar networks are to be joined use a bridge.
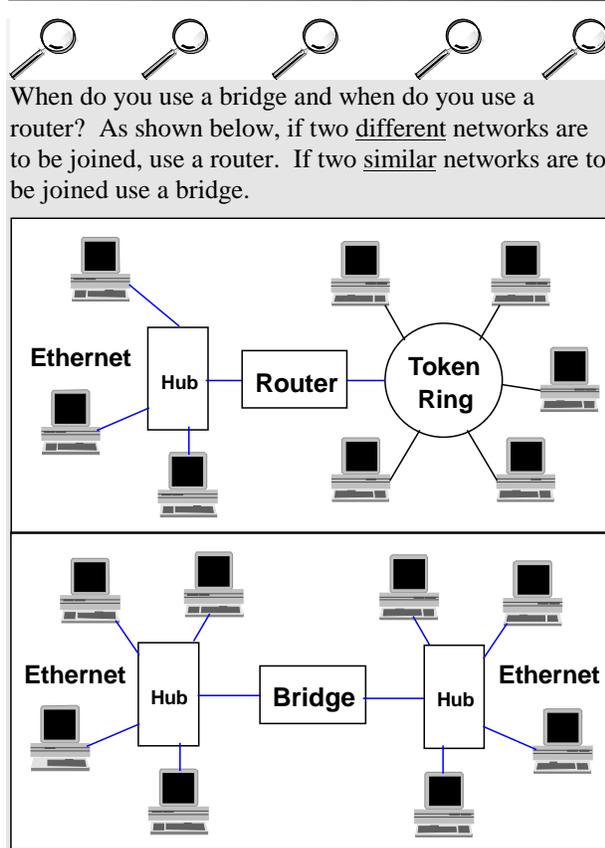
The problem with lack of bandwidth led to the development of switches. A switch is basically a multi-port bridge. Switched LANs allow a virtual dedicated point-to-point connection between multiple devices on the LAN, allowing access to full bandwidth for each connection (similar to a phone system experiencing many simultaneous phone calls). With a switch, each node has access to the full bandwidth. Switches work best in a uniform traffic flow, for example, 10 to 20 desktop computers communicating with each other, as opposed to one device receiving most of the traffic.

In full duplex switching, each node has equal bandwidth both transmitting and receiving, which can be exercised simultaneously, effectively doubling the bandwidth requirement. The node can "talk" and "listen" at the same time as in a telephone call. In this situation, special NICs, hubs and a high through-put backplane are required.

The following table compares routers and switches.

Routers Support	Switches Support
- Software-based route determination and packet processing - Network node-address resolution - Traffic isolation and filtering - Network management - Protocol conversion and mismatch resolution	- Hardware processing (provides higher throughput) - Full-duplex switched links between NICs (reduces latency) -Bandwidth management -Lower cost

Access Methods

Access methods determine how data shares a common network path.

Carrier Sense Multiple Access with Collision Detect (CSMA/CD)

In this method, a node's NIC can continually sense the traffic on the network. When the node has a frame to send, the NIC checks to see if the network path is clear. If it is, it sends the data. If data "collides" because two nodes send at the same time, each node will sense it, stop sending and wait for a random time before trying to put its data on the network again. Collisions represent only about 1 to 10 percent of active time in networks. Equal access is guaranteed only on a probabalistic basis. Ethernet uses CSMA/CD.

Token passing

Token Ring networks and FDDI networks use token passing. A node can transmit on the network only when it has the token. The token travels around the ring and stops at each node to see if it has anything to send. When a node is ready to send data, it marks the token frame as busy, attaches its data and destination information, and passes the token on. The token continues to travel around the network until it reaches its destination.

At this point the recipient removes the information and indicates on the token frame that the information has been received. The token returns to the originator where confirmation is acknowledged, the token is then released as "un-busy."

Token Ring requires a "manager" or active monitor for the ring. The active nodes negotiate, using their serial numbers, to determine which node is the active monitor. The monitor initiates the first "free" token and does general ring operation maintenance. This method guarantees equal access to the network.

A comparison between CSMA/CD and token passing are shown in the table.

Uses	CSMA	Token Passing
Light/moderate traffic	x	
Consistent heavy traffic		x
Office Applications	x	
Medical Imaging		x
Monitoring		x
Cheap, easy flexible	x	

Demand Priority

Demand Priority is a deterministic access method similar to token ring passing. The hub successively scans the ports to determine which one is ready to transmit data. This avoids the collisions that can occur with CSMA/CD.

23

LAN Standards
Ethernet

Overview

Ethernet, an established standard since the mid 1980s, is the most widely used local-area network (LAN) transport protocol in the world today. The following table summarizes its data rates (the structure and protocol are identical for all three).

	Data Rate	
Standard	**Mbps**	**MBd**
Ethernet	10	20
Fast Ethernet	100	125
Gigabit Ethernet	1000	1250

Ethernet is a shared bus network with a CSMA/CD (Carrier-Sensing Multiple Access with Collision Detect) access scheme. The encoding scheme for 10 Mbps Ethernet is Manchester; Fast Ethernet uses 4B/5B, and Gigabit Ethernet uses a 8B/10B encoding scheme.

Most Ethernet configurations today use a central Hub specified by the LAN standard. The ring architecture is hidden inside the Hub, and the LAN management is centrally located. The 10BaseT, 10BaseFB, and 10BaseFL versions of the Ethernet standard specify a Hub-based Ethernet structure.
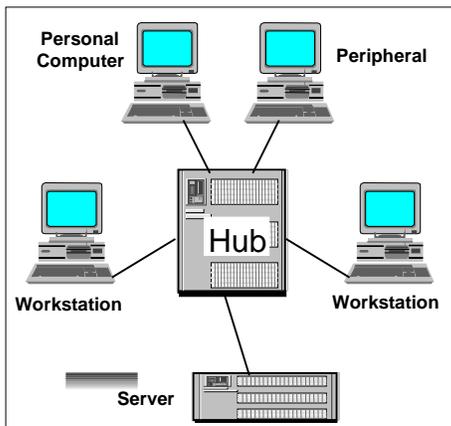
Ethernet today accounts for approximately 90 percent of the installed copper and fiber networking nodes. Most network designers prefer to work with Ethernet because it is a stable, well-understood LAN standard; and network standards that emerged after Ethernet have not succeeded in replacing it. Standards such as Token Ring and FDDI have been adopted by some companies in niche markets, but have not acquired the same market share.

Ethernet's ability to quickly adapt to faster signaling rates is one reason why it has remained popular. Because Ethernet is familiar to the standards committees, adjusting the standards to meet new data rate requirements is a lot easier than adopting a completely new standard. With the introduction of Fast Ethernet and the emergence of Gigabit Ethernet, IEEE 802.3 is not likely to be replaced in the near future and is in a good position to remain the most-used LAN standard in the world.

As speeds continue to increase, the market has shifted from 10 Mbps Ethernet to Fast and Gigabit Ethernet and eventually to 10 Gbps. One way that equipment manufacturers are making this transition easier for their customers is by offering them 10/100 hubs, which have both 10 Mbps and 100 Mbps connections. These hubs are popular today, but the market will probably shift to 100/1000 hubs within the next few years.

The main points to keep in mind when selling into Ethernet applications are

- Although 10 Mbps is still the majority of installed networks, it will be phased out over the next few years as Fast and Gigabit Ethernet takes over.
- Fast Ethernet is growing at a very high rate and is also the biggest network standard at that speed, which includes ATM and FDDI.
- 10/100 hubs are very popular today among OEMs.
- Manufacturers are very interested in Gigabit Ethernet and will begin using it for backbone connections as soon as the standard is approved (customers are designing with it now).
- Ethernet is a shared network, not a dedicated network, so most telecommunications applications will be more in favor of the ATM standard, which can handle voice, video, and data simultaneously.

Standards
Ethernet, whose base identification is IEEE 802.3, is a LAN standard of the IEEE. The tables on the following page show the various standards and the major specifications that all Ethernet networks must follow.

Ethernet (10 Mbps/20 MBd) IEEE 802.3

IEEE 802.3 Specification	Other Terms	Transmission Medium	Signal Type	Maximum Link Length
10Base2	CheaperNet	Coaxial	Electrical	200 meters
10Base5	ThickNet	Coaxial	Electrical	500 meters
10BaseT	- - - - - - -	Twisted Wire Pair	Electrical	100 meters
10BaseFB[1]	- - - - - - -	Multi Mode Fiber	820 nm Optical	2 km
10BaseFL(FA)[1]	- - - - - - -	Multi Mode Fiber	820 nm Optical	2 km
10BaseFP[2]	Fiber Passive	Multi Mode Fiber	820 nm Optical	500 meters
FOIRL*	- - - - - - -	Multi Mode Fiber	820 nm Optical	1 km

*Fiber Optic Inter-Repeater Link: a fiber-optic link that connects two separate Ethernet LANs.

[1]Active - repeater used (more components)

[2]Passive - repeater not used (fewer components)

Fast Ethernet (100 Mbps/125 MBd) IEEE802.3u

| IEEE 802.3u Specification	Transmission Medium	Signal Type	Maximum Link Length
100Base-T	UTP[1]	Electrical	100 meters
100 Base-FB	Multimode Fiber	1300nm Optical	2km
100Base-FL	Multimode Fiber	1300 nm Optical	2 km
100Base-FP	Multimode Fiber	1300 nm Optical	500 meters

[1]Unshielded Twisted Pair

Note: For Ethernet and Fast Ethernet, there is no single-mode specification.

Gigabit Ethernet (1000 Mbps/1250 MBd) IEEE802.3z

Transmission Medium	Signal Type	Maximum Link Length
UTP[1]	electrical	25 meters
62.5/125 µm fiber	850nm optical	220/275 meters
50/125 µm fiber	850nm optical	500/550 meters
50/125 µm fiber	1300nm single-mode	550 meters
62.5/125 µm fiber	1300nm single-mode	550 meters
9/125 µm fiber	1300nm optical	5 km

[1]Unshielded Twisted Pair

The various layers in the following illustration are described at the right and explanations of abbreviations used are given in the table on the following page.
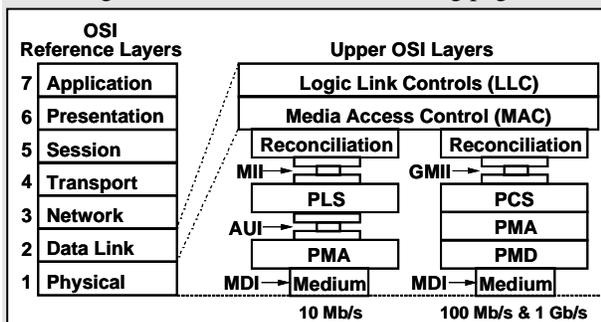
IEEE 802.3 Ethernet Physical Layers versus Data Rate

OSI Layers
- Layers 5, 6, and 7 support InterOperability
- Network (3, IP) and transport (4, TCP) support InterNet-working
- Physical (Level 1) and data link (Level 2) are specified for the LAN

Network (Level 3) Routers and Switches
- Utilize IP Protocol for routing and packet segmentation
- Packets are routed end-to-end using the Level-3 source and destination logical addresses located in the IP header
- Packets are transported point-to-point between network nodes using the Level-2 universal MAC addresses

Data Link (Level 2) Bridges and Switches
- Utilize MAC Addresses only and cannot scale to larger networks

| Abbrev.	Explanation	Abbrev.	Explanation
AUI	Attachment Unit Interface	OSI	Open System Interconnections
GMII	Gb/s Media Independent Interface	PCS	Physical Coding Sublayer
IP	Internet Protocol	PMA	Physical Medium Attachment
MAC	Media Access Control	PMD	Physical Medium Dependent
MDI	Medium Dependent Interface	PLS	Physical Layer Signaling
MII	Media Independent Interface	TCP	Transmission Control Protocol
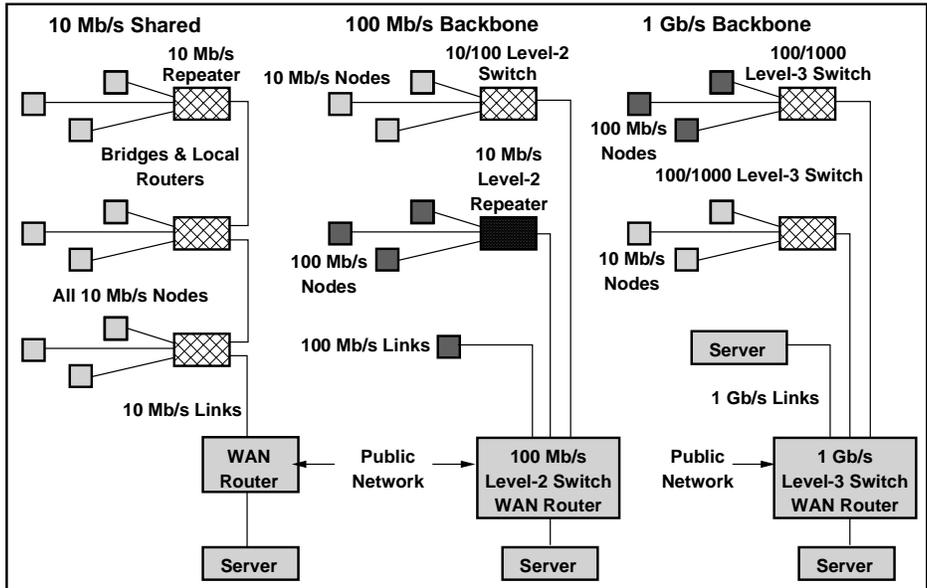
Ethernet LAN Collapsed Backbone Network Evolution
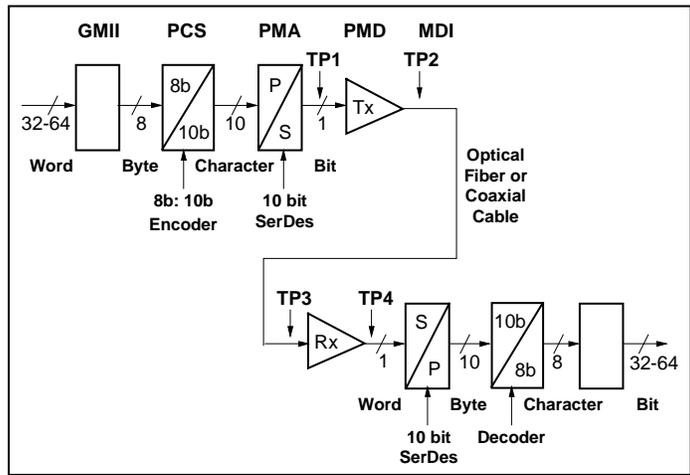
Gb/s Ethernet (GbE) Physical Link Interfaces

27

The Ethernet Link

The structure of an Ethernet link depends on the transmission medium. As shown in the following block diagram, the Ethernet Controller chip is common to all Ethernet adapter cards; and depending on the network speeds, it has different functions.
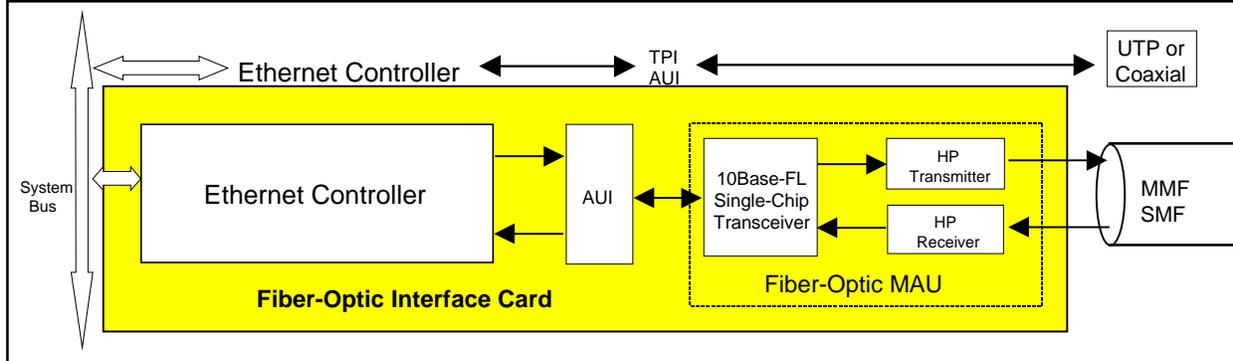

10 Mbps Ethernet

The gray box is the fiber-optic interface card; above it is the corresponding copper interface. The functions of the interface card component's are described in the following table.

| Block	Description
Ethernet Controller Chip[1]	Performs all functions concerning bus interfacing, buffering/framing, multiplexing/demultiplexing, encoding/decoding, and clock and data recovery[2].
TP Interface	Interfaces directly to the twisted-pair wire cable.
AU Interface	Interfaces directly to the coaxial cable or the fiber optic MAU.
10Base-FL Single-Chip Tranceiver	Converts data from the AUI into format required by the optical transmitter and receiver. Contains the drive and receive (quantizing) circuitry. Also monitors functions for transmission, reception, collision and error.
Transmitter	Contains the LED or ELED.
Receiver	Contains the pin photodiode and transimpedance amplifier.

[1]Available from several IC vendors.
[2]Clock and data recovery is included in most Ethernet Controller Chips.
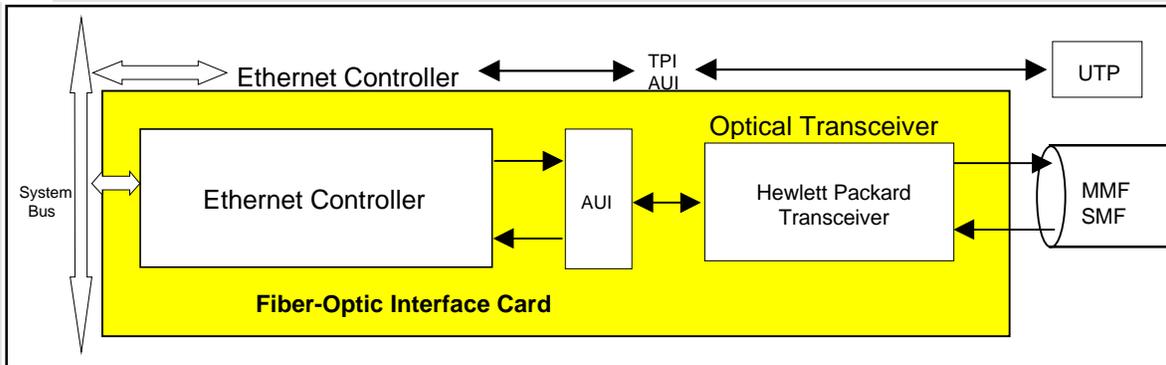
100 Mbps Fast Ethernet

Block	Description
Ethernet Controller Chip	Performs all functions regarding bus interfacing, buffering/framing, multiplexing/demultiplexing, encoding/decoding, and clock and data recovery.
TP Interface	Interfaces directly to the twisted-pair wire cable.
AU Interface	Interfaces directly to the fiber optic transceiver.
Optical Transceiver	Includes LED or laser, PIN/preamp, drive, and quantizing circuitry.

28

1000 Mbps Gigabit Ethernet
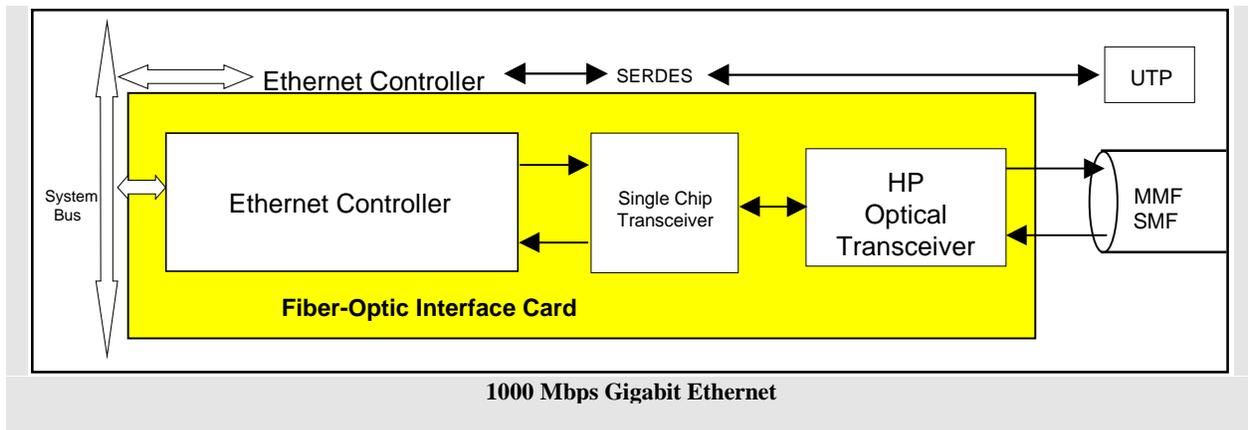
Block		Description
Ethernet Controller Chip		Includes bus interfacing, buffering/framing, encoding/decoding, and clock and data recovery.
SERDES chip		Interfaces to the fiber-optic transceiver or directly to the UTP, includes serializing/deserializing function.
Optical Transceiver		Includes VCSEL or Fabry-Perot laser emitter, PIN/preamp, drive and quantizing circuitry.

Gigabit Ethernet

As new and existing network applications evolve to embrace high-resolution graphics and high-volume data, for example, video, medical and data warehousing, demand is increasing at the desktop, the server, the hub, and the switch for increased bandwidth. The simple migration and support offered by Ethernet, combined with the scalability and flexibility to handle new applications and data types, makes Gigabit Ethernet the strategic choice for high-speed, high-bandwidth networking.

Gigabit Ethernet is an extension of the highly successful 10 Mbps and 100 Mbps IEEE 802.3 Ethernet standards. It offers a raw data bandwidth of 1000 Mbps, while maintaining full compatibility with the huge installed base of Ethernet nodes.

The Gigabit Ethernet standard has the following attributes:

- allows half- and full-duplex operation at speeds of 1000 Mbps,
- uses the 802.3 Ethernet frame format,
- uses the CSMA/CD access method with support for one repeater per collision domain, and
- addresses backward compatibility with 10Base-T and 100Base-T technologies.

Distance Specifications for Fiber Optic Media

As the bandwidth of the fiber increases, the minimum range for multi-mode fiber increases up to 550 meters. The longwave length transceiver (1000Base-LX) reaches 550 meters for all media types. For single-mode fiber with 1000Base-LX, the distance is specified at 5 km. The link distance for the lowest bandwidth multi-mode fiber was specified at 220 meters. Other fiber types can go farther.

Three features of the Gigabit Ethernet link distances are

- a multimode fiber-optic link with a maximum length of 550 meters,
- a single-mode fiber-optic link with a maximum length of 5 kilometers, and
- a copper-based link with a maximum length of at least 25 meters.

## Full- and Half-Duplex over Fiber Today, UTP in the Future

Gigabit Ethernet supports new full-duplex operating modes for switch-to-switch and switch-to-end-station connections. Initially operating over optical fiber, Gigabit Ethernet will also be able to use Category 5 UTP (Unshielded Twisted Pair) cabling.
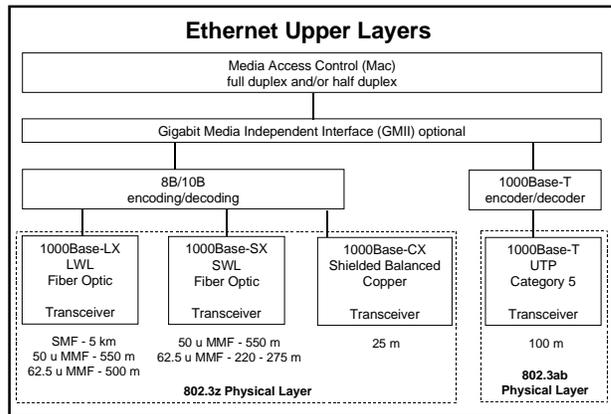
Gigabit Ethernet adheres to a physical-layer standard. In general, the PHY or physical layer is responsible for defining the electrical and procedural characteristics for establishing, maintaining and deactivating the physical link between network devices. Two PHYs provide Gigabit transmission over fiber-optic cabling. 1000BASE-SX is targeted at lowest-cost multi-mode fiber runs in horizontal and shorter backbone applications. 1000BASE-LX is targeted at longer multi-mode building fiber backbones and single-mode campus backbones. For multimode fiber, these standards define gigabit transmission over maximum distances ranging from 220 m to 550 m. Single-mode fiber, which is covered by the long-wavelength standard, is defined to transmit up to 5 km; some transceivers, including Agilent's, are defined to transmit up to 10 km.

Gigabit Ethernet Products

Because Gigabit Ethernet is Ethernet, Gigabit Ethernet product types are quite straightforward: Layer 2 switches, Layer 3 switches (or routing switches), uplink/downlink modules, NICs, Gigabit Ethernet router interfaces, and buffered distributors. There are pure multi-port Gigabit Ethernet switches with high-performance backplanes, as well as devices that have both Gigabit Ethernet and Fast Ethernet ports in the same box. Gigabit Ethernet uplinks have appeared as modular upgrades for fixed-configuration Fast Ethernet devices or modular, chassis-based hubs to provide a high-speed connection to the network.
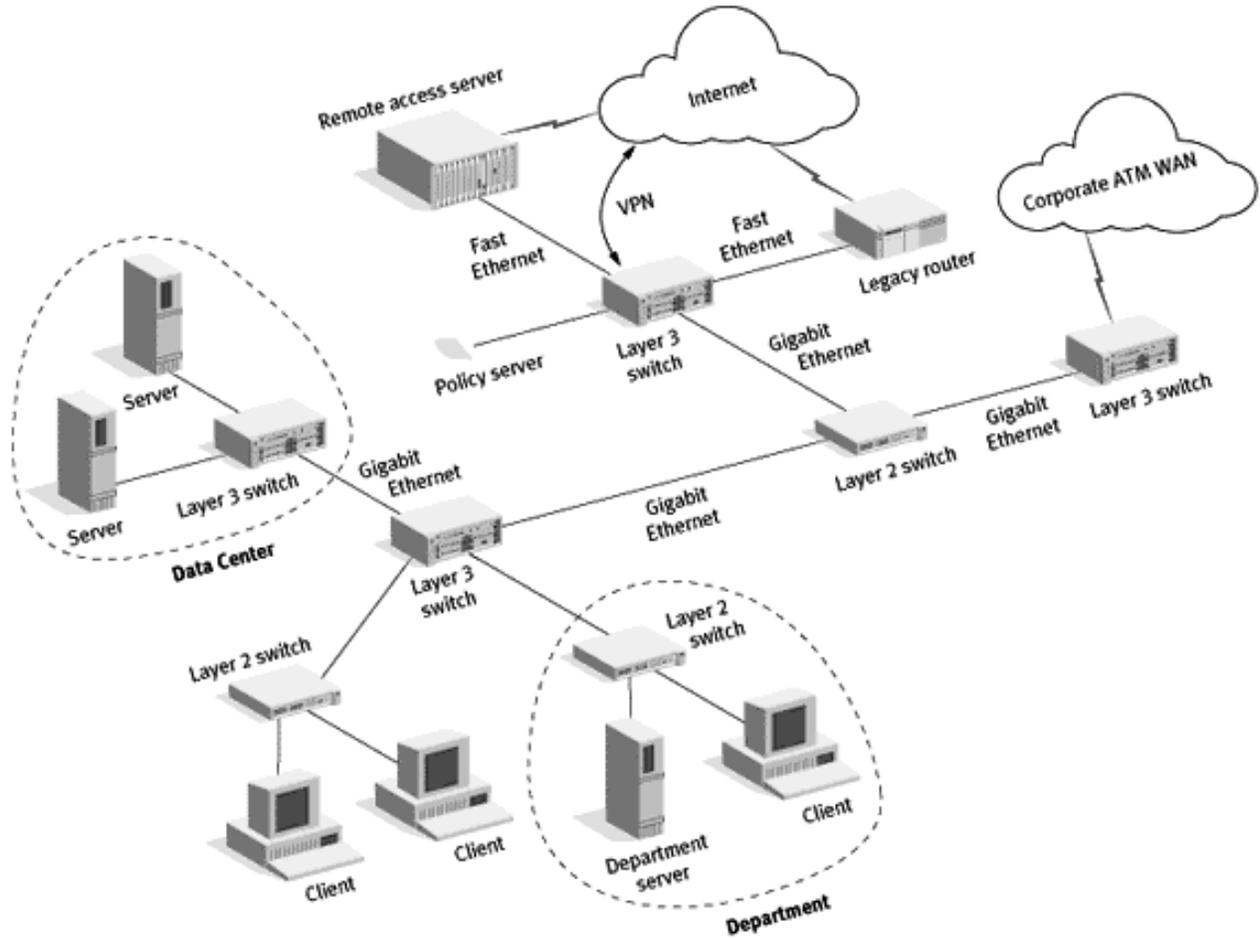
Token Ring

Overview
Token Ring (IEEE 802.5), originally developed by IBM, has two versions: 4 Mbps and 16 Mbps. The faster version is generally used as a backbone.

Topology
Token Ring access was discussed in the Networking Section. In a Token Ring LAN, the devices (nodes) are connected in a ring that forms a shared LAN; information is passed in only one direction.

The token-passing scheme for LAN allocation deterministically ensures that each device has equal access to the LAN over both short and long intervals of time. In comparison, equal access to an Ethernet LAN is ensured on a probabalistic basis only over long periods of time. In cases where guaranteed timely access to the LAN is needed, Token Ring is preferred.

Token Ring also has more complex LAN management, which provides additional services for the LAN, including information on routing and connection problems. This additional complexity, however, results in a slightly higher cost per node.

Structure
Most installations today consist of a central Token Ring hub (or Multi-Station Access Unit, MSAU). The wiring for the LAN is in the form of a "star" network, as shown below.
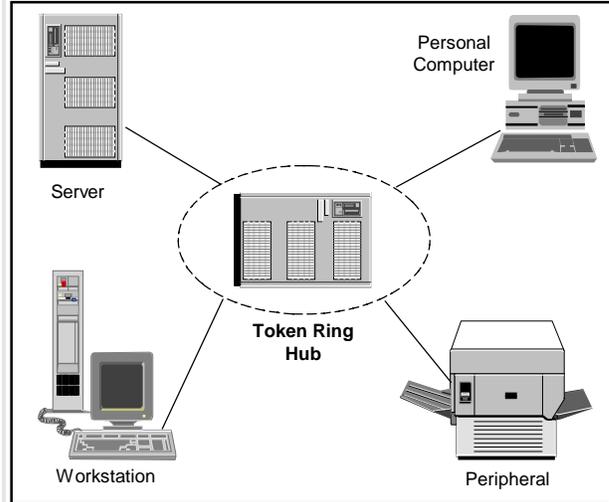
The Token Ring standard specifies a hub-based wiring structure. The hub, which is centrally located, manages the LAN. The Token Ring LAN does not appear to be a ring because the wiring is hidden inside the hub.

The structure of a Token Ring link depends on the transmission medium. As shown in the block diagram, below, the Token Ring controller chip is common to all Token Ring adapter cards. The serial transmit and receive circuitry and media interface depends on which transmission medium is used. This circuitry must be composed of discrete components. These components are described in the table on the following page.

Token Ring Media Access Unit

Block	Description
Token Ring Controller Chip	Bus Interface, Multiplexing/Demultiplexing, Encoding/Decoding, Buffering/Framing, Clock and Data Recovery[1]
TP Interface	Interfaces directly to the twisted-pair wire cable.
AU Interface	Interfaces directly to the coaxial cable or the fiber optic MAU
Transmitter	HFBR-1414 - Contains the LED
Receiver	HFBR-2416 - Contains the pin photodiode and transimpedance amplifier.

[1]Available from several IC vendors.

Fiber Distributed Data Interface

Fiber Distributed Data Interface (FDDI) Network Overview

Fiber Distributed Data Interface (ANSI X3T9.5), developed in the ANSI Standards Committee throughout the 1980's, is a Local Area Network standard designed for transmission over both single-mode and multi-mode fiber-optic cable. "Backbone" applications use this LAN standard because it provides 100 Mb/s bandwidth (Ethernet runs at 10 Mb/s and Token Ring runs at 16 Mb/s).
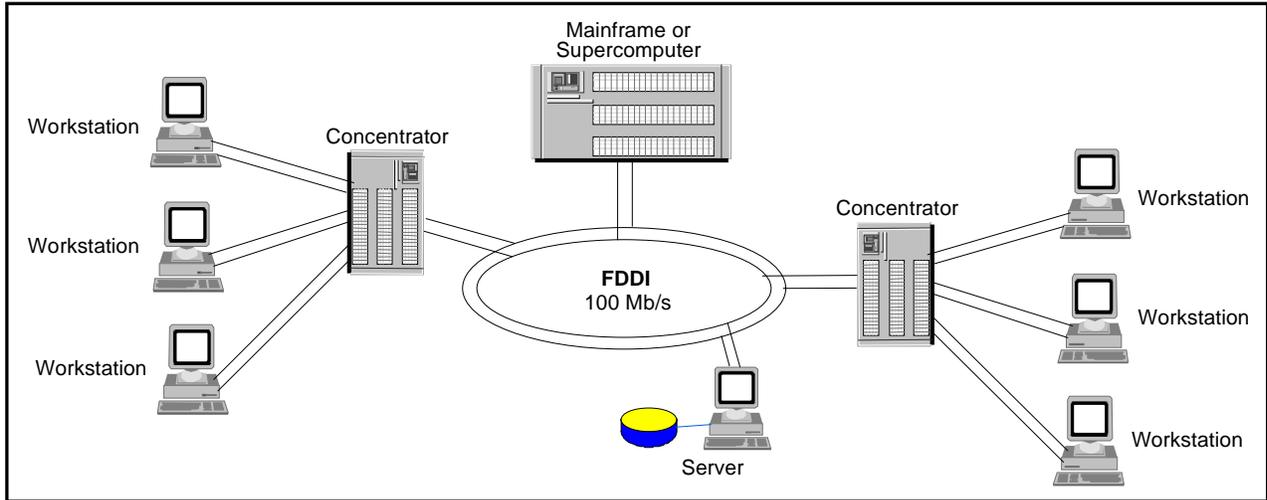


Typical FDDI Network

Topology

As shown above, FDDI is a redundant-ring, token-passing network that provides high-speed connections between groups of slower network devices. The FDDI "back-bone" refers to the central dual-ring structure. The outer ring is usually referred to as A and the inner ring as B. Only the A ring is used for primary network transmission, and the information (as with Token Ring) is transmitted on this ring in only one direction. The second, or redundant ring, B, transmits information in the opposite direction and is used for fault tolerance.

Should the primary ring develop a discontinuity due to a break in the fiber cable or a device shutting down, the secondary ring is activated. The network then detours the transmission onto the B ring avoiding the discontinuity. As shown by the illustration below, this scheme provides fault tolerance by maintaining an intact ring structure.

Protocol

As with the Token Ring LAN, FDDI allocates access to the LAN using the Token Passing method. For a description of how this LAN allocation scheme works, please refer to the Networking section.

As with Ethernet and Token Ring, FDDI is a shared LAN. The total bandwidth of the LAN is equally divided between the devices connected to it. The more devices that are added, the less bandwidth each device gets.

Break in Cable
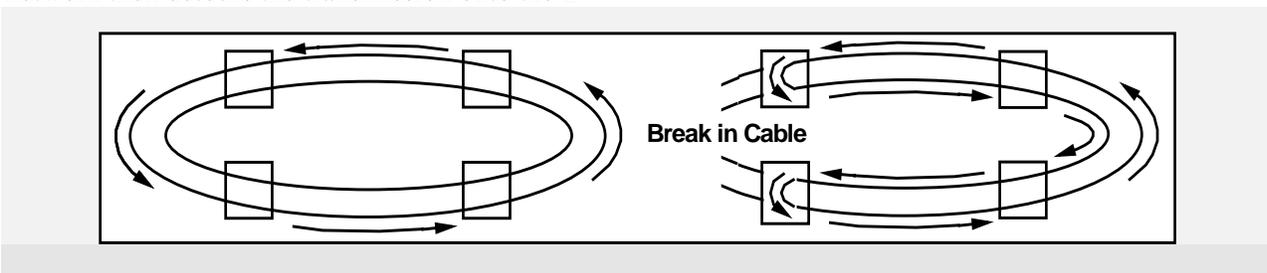
Most networks today use concentrators, which connect multiple devices to the central FDDI backbone. It is possible to "stack" these concentrators to connect numerous nodes (or desktops) to the network. As the following illustration shows, the number of connections to the desktop is much greater than the number of connections to the FDDI backbone.

Encoding Scheme
An FDDI LAN uses a 4B/5B encoding scheme that is 80 percent efficient. This means that for every 4 bits of raw (useful) data being sent, 5 signal elements are actually transmitted. This encoding scheme requires a serial signal rate of 125 MBd to transmit 100 Mb/s. The resulting serial signal for an FDDI link is 125 MBd.
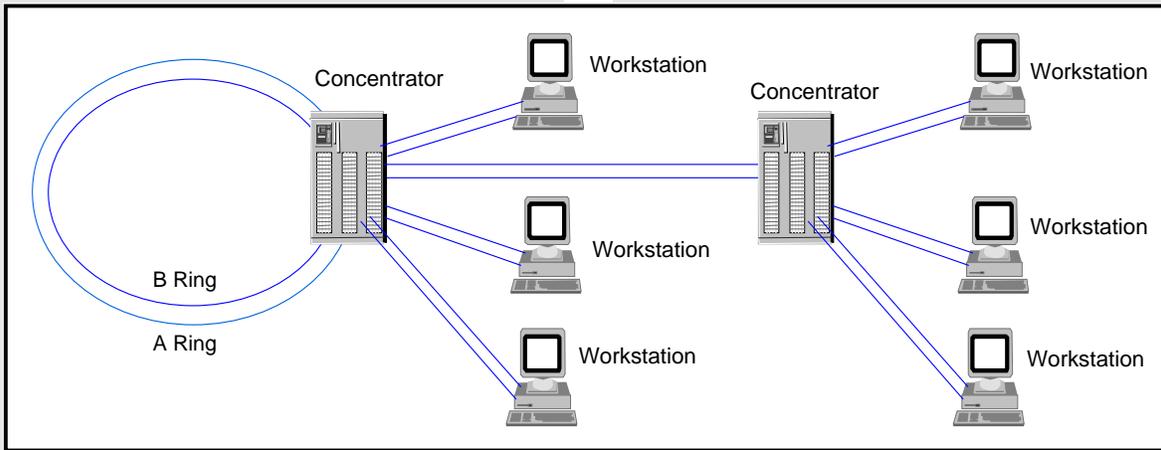

Standards
The MIC (Media Interface Connector) standard was defined specifically for use in the FDDI network. To decrease the possibility of simple wiring errors (for example, connecting the A-ring cable into the B-ring transceiver of the box) the standards committee designed special keys for each connector/port mating.
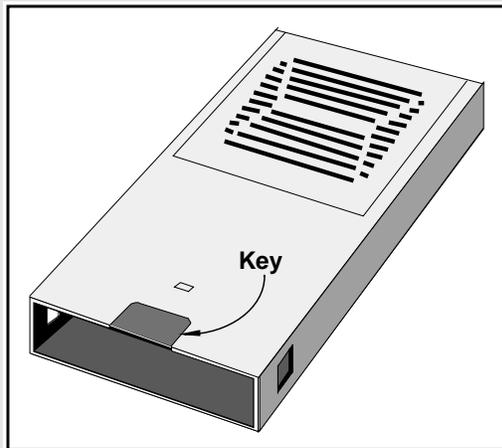

The keying options are based on the specific part of the FDDI LAN that the data communication link fits. The link from a concentrator to a device was defined as a "master-slave" link, while the two redundant rings (described earlier) were called the A ring and B ring. The keying options, shown in the following table, were then defined.

Key Type	Location	Purpose
A	Any device connected to the backbone	Connect to A ring
B	Any device connected to the backbone	Connect to B ring
M	Non-backbone side of a concentrator	Connect to end device
S	End Device connected to the concentrator	Connect to concentrator

Other connector styles accepted by the standards committee for FDDI are the ST (a registered trademark of AT&T) connector and the SC connector, shown below.
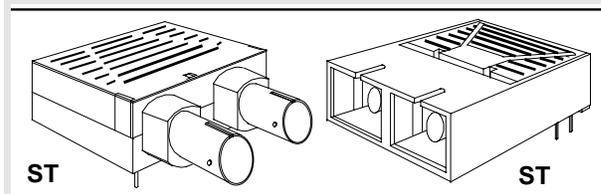
CDDI (Copper Distributed Data Interface, which is FDDI over twisted-wire pair) has emerged as low-cost technology link with a maximum length of 100 meters. The back-bone of an FDDI network, which has a maximum link length of 2 km between devices, will continue to use fiber optics.
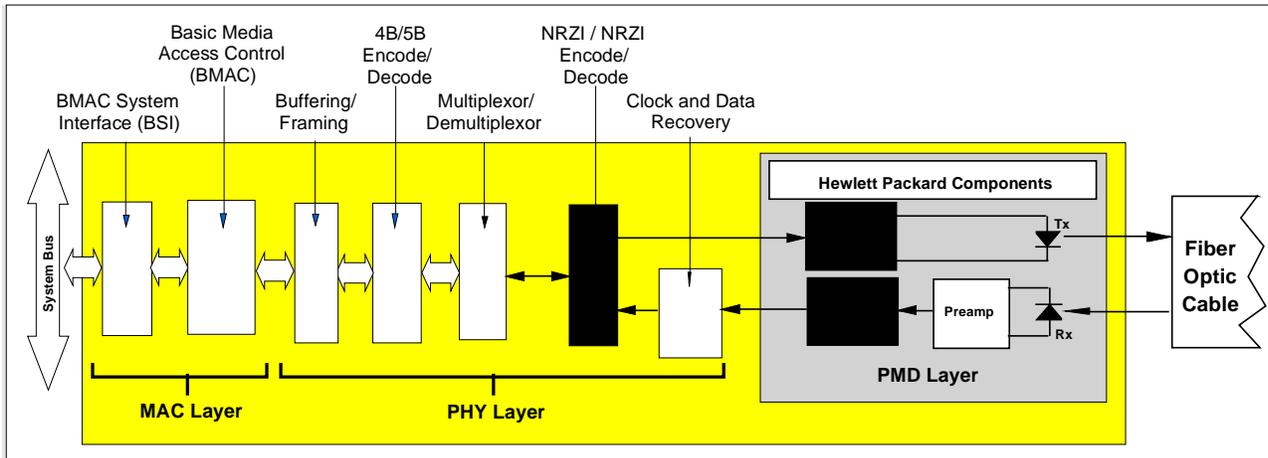
FDDI Adapter Card

FDDI Structure

The standard FDDI link is composed of four distinct layers: the MAC (Media Access Control) layer, the PHY (Physical) layer, the PMD (Physical Media Dependant) layer, and SMT (Station Management). These layers are described in the following.

To promote the development of FDDI products, Agilent, AT&T and Siemens formed a multi-sourcing agreement specifying a common electrical footprint. These products had a MIC connector as their optical interface and 2 rows of 11 pins for their electrical, board interface.

Subsequently, products introduced by other companies, for example, Sumitomo, which had a smaller footprint (1 row of 13 pins) were offered at a lower price. As time passed, this pin configuration became more popular. Then, even smaller products (1 row of 9 pins, with a dual SC connector) were introduced to compete for

these PMD low-cost fiber design-ins. (Products compliant with the FDDI LCF PMD standard, which has less stringent specifications than the original PMD standard, can be low-cost options for fiber-optic data links.) These products are available in both multi-mode and single-mode versions. Customers of FDDI MIC transceivers are using the 1 X 9 foot print products due to limited board space and lower cost.
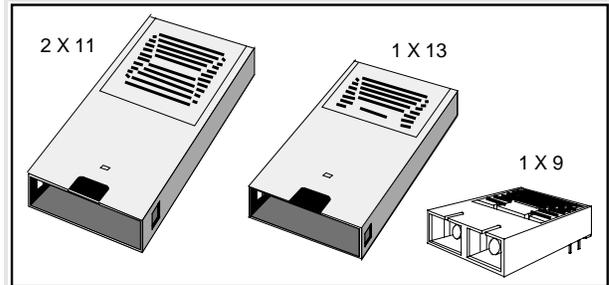
Layer	Description
MAC (Media Access Control)	Controls flow of signals to and from the bus interface.
PHY (Physical Layer)	Performs all functions related to buffering/framing, multiplexing/demultiplexing, encoding/decoding, clock and data recovery.
PMD (Physical Media Dependant)	Controls the transmitter drive circuitry, transmitter (1300nm LED or Laser), receiver (1300nm PIN photodiode), receive circuitry (quantizer).
SMT (Station Management)	Manages the configuration of the network and reconfigures it if a discontinuity occurs, for example, a break in the fiber or a device shutting down.

ATM (Asynchronous Transfer Mode)/SONET Network

Overview

ATM is a network technology that provides voice, video and data capabilities at the desk-top level. For this to happen, the user needs a dedicated (uninterruptible) high-speed data-communication link. To provide these "dedicated" connections, the ATM standards committee chose a "Switched Network," illustrated below. This arrangement allows multiple users to have full access to the bandwidth of the network without having to wait until the network is available.

The switch establishes a virtual connection between a device and its requested counterpart, unless the requested counterpart is already part of another data communication link. This is similar to the current phone network: if you dial someone's number, you are given a dedicated link for your conversation, provided that the person you are calling is not already on the phone. The ATM switch then routes the "call" to its proper address.
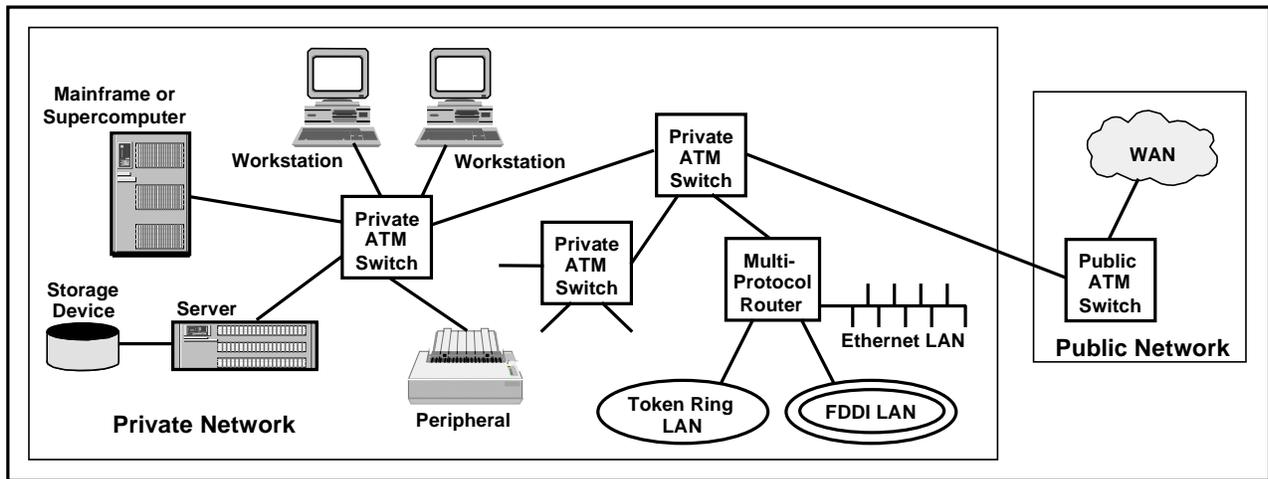
ATM / SONET End-User Products

Product	Description
ATM Switch	At the center of the ATM network, it directs the requests and establishes the virtual, dedicated connections between the two distinct devices (nodes). Connected to the switch are all the separate units that are tied into the network. Each unit is connected to the switch via a bi-directional data-communication link, based on the SONET standard. ATM Switches are of two different kinds: 1. The Private ATM Switch: For interconnecting multiple ATM Switches in the Private Network, as well as connecting to the desktop. 2. The Public ATM Switch: For interconnecting multiple private ATM switches, as well as multiple public ATM switches. It is expected that there will be a network of public switches in the WAN.
ATM Adapter Card	Inserted into a workstation or PC to connect it to the ATM Switch, and hence into the ATM Network. Each adapter card has a duplex ATM Interface link. The next page shows a simple block diagram of an Adapter Card.
Multi-Protocol Router	An important part of the first implemented ATM Networks. It allows users on existing LANs access to the ATM Network. It forms the "bridge" between the two LAN standards and maps the data from one format to another format.

**The ATM Standard and Architecture Model**

As shown below, the ATM standard separates its links into two catagories: UNI (User-to-Network Interface) and NNI (Network-to-Network Interface). The majority of Agilent FCD products are used in private UNI links.

UNI   User-to-Network Interface
NNI   Network-to-Network Interface
CPE   Consumer Premises Equipment
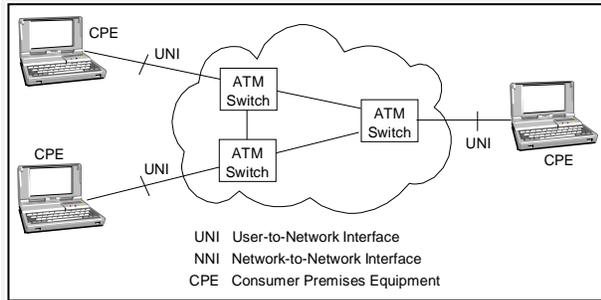
Public B-ISDN Network

SONET Protocol for ATM Transmission
Instead of inventing a new high-speed, point-to-point data communication link, the ATM Committee adopted an existing standard: SONET (Synchronous Optical Network). The international SONET standard is SDH

(Synchronous Digital Hierarchy). Occasionally, the two are used together: SONET/SDH. The ATM architecture is above the SONET physical layer specifications. Agilent designs its optical products to conform to SONET specifications.

The choice of SONET as the data communication structure allows:

1. An already proven and understood technology for the high-speed datacom links. SONET link speeds are scalable: 155 Mb/s, 622 Mb/s, 2.488 Gb/s.
2. Potentially seamless connections to the Wide Area Network (WAN) because SONET is a telecom standard.

The SONET standard specifies a 100 percent efficient technique for encoding the date: for example, the serial rate for a 155 MBd link is 155 Mb/s.

SONET Physical Layer Specifications for 1300 nm MLM Lasers

	OC-1	OC-1	OC-1	OC-3	OC-3	OC-3
Specification	SR *	IR	LR	SR	IR	LR
Data Rate	51.84 Mb/s	51.84 Mb/s	51.84 Mb/s	155 Mb/s	155 Mb/s	155 Mb/s
Distance	0 - 2 km	2 - 15 km	15 - 40 km	0 - 2 km	0 - 15 km	15 - 40 km

	OC-12	OC-12	OC-12	OC-48	OC-48	OC-48
Specification	SR	IR	LR	SR	IR	LR
Data Rate	622 Mb/s	622 Mb/s	622 Mb/s	2.488 Gb/s	2.488 Gb/s	2.488 Gb/s
Distance	0 - 2 km	0 - 15 km	15 - 40 km	0 - 2 km	0 - 15 km	15 - 40 km ?

The Agilent components shown in the illustration of an ATM/SONET implementation are described in the table on the following page. Agilent FCD supplies products for the SONET/PMD Interface block of an ATM link.

The particular Agilent product depends on the portion of the ATM standard that the user's product ad-dresses (see the previous table for a description of physical-layer specifications).
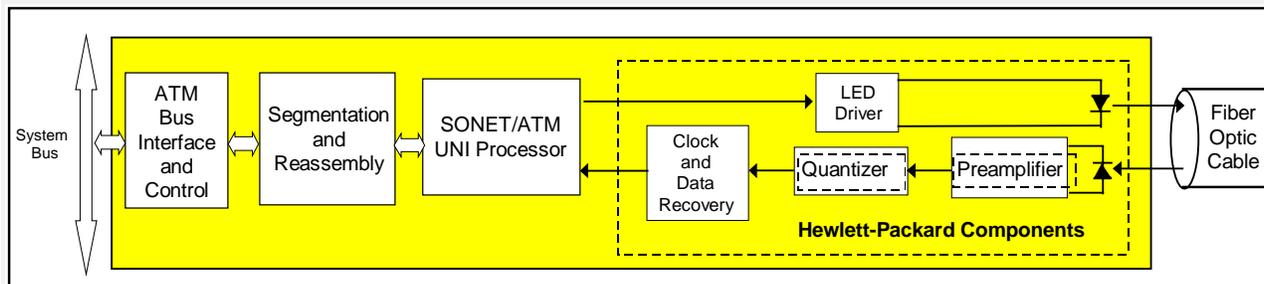
ATM/SONET block diagram

| Block	Description
ATM Bus Interface and Control	Responsible for the bus interface.
Segmentation and Reassembly (SAR)	Frames the transmitted data, multiplexes voice, video, and data.
SONET/ATM UNI Processor	Converts the data from the ATM format into the SONET format. It is responsible for the encode/decode and Mux/Demux functions
SONET/PMD Interface	The physical media dependant part of the link. 　On the transmit side it involves: 　　- the drive circuitry 　　- the transmitter (laser or LED) 　And on the receive side it involves: 　　- the receiver (pin photodiode) 　　- the receive circuitry (amplifier/quantizer stage) 　　- the clock and data recovery (CDR) circuitry

Fibre Channel

Fibre Channel Overview
Fibre Channel was developed as a high-speed interconnection to serve the needs of both channels and networks. A channel provides direct or switched point-to-point connections between devices, typically between a processor and a peripheral device, with minimal delay, and error correction in hardware. Networks, on the other hand, are more software intensive with more overhead because they provide a more extensive range of tasks, including managing unanticipated connections and commands. To meet the needs for both networking and channels, the Fibre Channel standard has defined three Fibre Channel topologies and three classes of service.

Fibre Channel Topologies
The three topologies of Fibre Channel are fabric (also referred to as switched fabric), point-to-point (direct connect), and Arbitrated Loop (FC-AL).
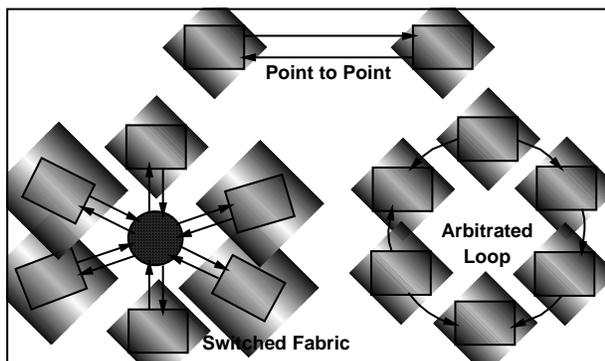

Switched-fabric topologies are used today for clustering multiple devices through a switching fabric. This fabric can be a single switch or a network of interconnected switches, as shown below.
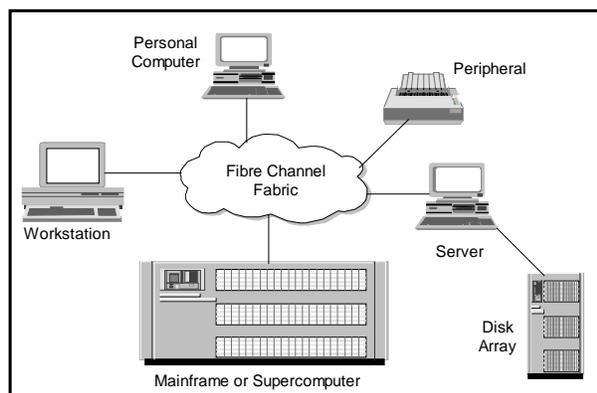
Point-to-point Fibre Channel data communication links are used today for efficient transmission of large blocks of continuous time-sensitive data and are ideally suited for mass storage applications.

Arbitrated Loop, the third Fibre Channel topology used today, defines a method of connecting three or more devices without the use of a fabric. This architecture allows several devices to be connected in a ring, forming a "virtual single device," as shown below.

Mass Storage
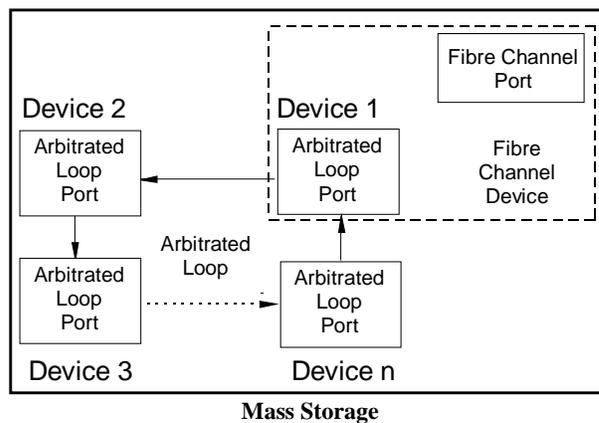
Fibre Channel Classes of Service
To accommodate the wide range of communication needs, the Fibre Channel standard has defined three classes of service:

- Class 1 connection is based on a hard- or circuit-switched connection. It is a dedicated link between two devices only, and ensures continuous, uninterrupted connections for rapid data transfer. It provides guaranteed delivery, with an acknowledgment of receipt.

- Class 2 connection is a frame-switched service without a dedicated connection. Frame switching requires the switching mechanism to read the frame header information, then decide to route the payload to its destination. As with Class 1, it provides guaranteed delivery with an acknowledgment of receipt.

- Class 3 is a connectionless service that allows data to be sent rapidly to multiple devices at-tached to a fabric. With Class 3 service, there is no acknowledgement of receipt. It is sometimes referred to as a "datagram" transfer.

Fibre Channel Efficiency

In October of 1989, the standards committee adopted a coding scheme (8B/10B) developed by IBM for data transmission via optical fiber.

Fibre Channel can be specified with different speed links, as shown in the following table.

Fibre Channel Speed	Parallel Data Rate (Mbytes/sec)	Serial Data Rate (Mb/s)	Serial Signal Rate (MBd)
Eighth	12.5	100	133
Quarter	25	200	266
Half	50	400	531
Full	100	800	1062.5
Double	200	1600	2125
Quad	400	3200	4250

Fibre Channel Standard

Fibre Channel is the general name of an integrated set of standards being developed by the American National Standards Institute (ANSI) X3T11 committee.

Included in this family of standards are the FC-PH (X3.230-1994), Fibre Channel Physical standard, and the FC-AL (X3.272-199x), Fibre Channel Arbitrated Loop standard.

The FC-PH standard consists of the three lower levels, FC-0, FC-1 and FC-2 of the segmented standard data-communication link defined in Fibre Channel (see link description diagram below).

Fibre Channel Media

The physical media defined in FC-0 are

> Optical Laser, LED
> Copper Coaxial, Twisted Pair

Fibre Channel uses a special low-cost duplex SC connector for optical fiber interfaces; and a 9-pin, D-type connector (DB-9) for shielded twisted-pair (STP) copper interface. A BNC transmitter connector and a TNC receiver connector are specified in the standard for coaxial connections.
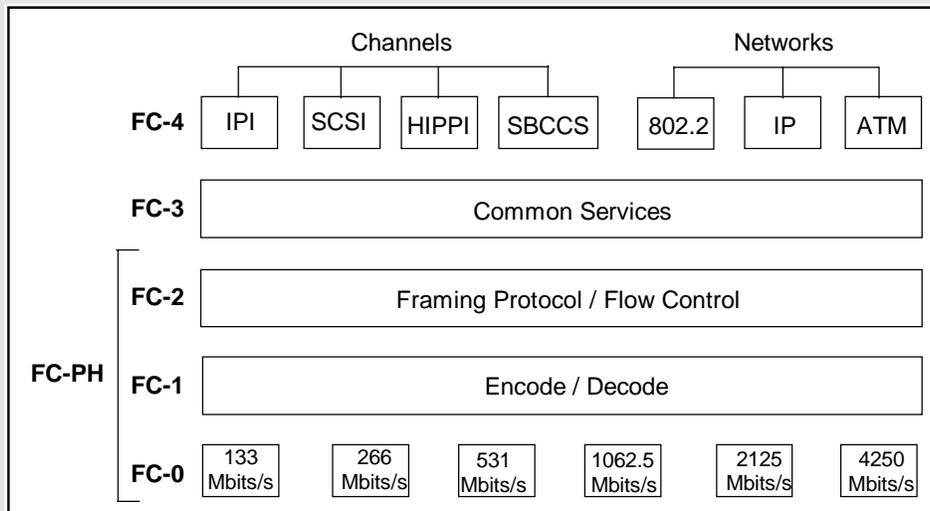
Fibre Channel Link Description:

Layer	Function	Description
FC-4	Bus Interface	Maps the data from the bus format to the Fibre Channel format.
FC-3	Common Services	Undefined in the standard and by-passed in current implementations.
FC-2	Signalling Protocol	Buffers and frames the data before transmitting it.
FC-1	Transmission Protocol	Encodes and decodes, using the 8B/10B encoding scheme.
FC-0	Physical Layer	Serialize/Deserialize, Clock and Data Recovery, PMD (Physical Media Dependent) Interface (dependent on the medium).

The Fibre Channel standards committee has segmented the standard data communication link into five distinct blocks, FC-0 through FC-4, as shown in the following illustration.
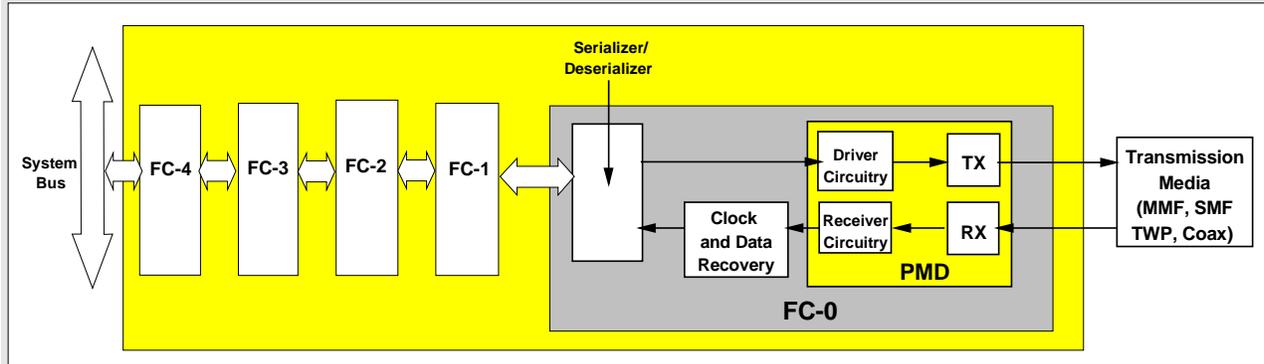
Fibre Channel Adapter Card

Physical Media Dependent (PMD) products are designed to interface with either copper or multi-mode and single-mode, glass fiber-optic cables. OEMs can design them into various equipment, such as Fibre Channel hubs, switches, or mass storage devices. OEMs can also use some of these products as part of a workstation sub-assembly

Fibre Channel Topologies
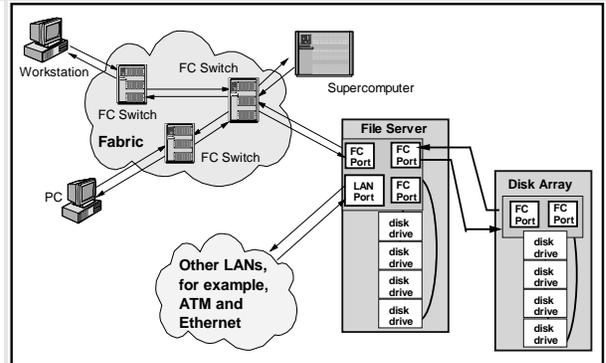
Fibre Channel Applications
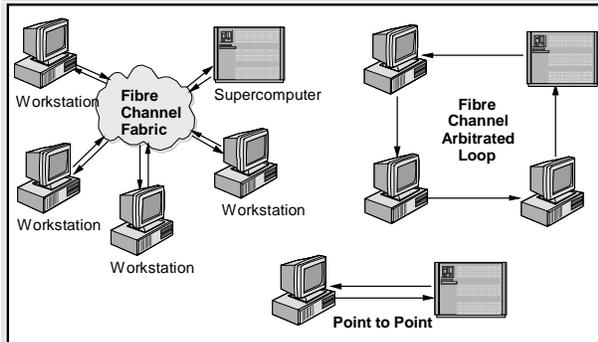
Agilent (FCD and ICBD) has the broadest product offering in the Fibre Channel industry today. In addition to the breadth of FC-0 physical layer products of optical modules, Serialize/Deserialize (SerDes) ICs and Gigabit Link Modules (GLM's), Agilent is also a recognized leader for protocol chips.

Optical Transmission and Types of Fiber

Optical Transmission

The basis for optical transmission in a fiber is governed by Snell's Law. It states that at the boundary between two media, light bends toward the normal (a line perpendicular to the surface) when it enters the optically denser medium, and bends away from the normal as it enters the optically less dense medium.

Each medium has a value called its refractive index. It is expressed as the speed of light in a vacuum divided by the speed of the light in that medium. It is given by the following equation:

$$\text{Index of Refraction (n)} = \frac{\text{Velocity of Light in a Vacuum}}{\text{Velocity of Light in a Medium}} \geq 1$$

Note: the index of refraction, n, of any
material is never less than one.

A ray of light traveling across the boundary between two different optical materials may be reflected or transmitted, depending on the relative indices of refraction of the materials. A ray in the low-index medium, n_2, always penetrates (is transmitted into) the high-index medium n_1.

A ray in the high-index medium, n_1, can penetrate into the low-index medium, n_2, ($n_1 > n_2$) only if it is incident at less than a specific angle (the critical angle) for those materials. If the angle of incidence is less than the critical angle, there is a partial reflection.
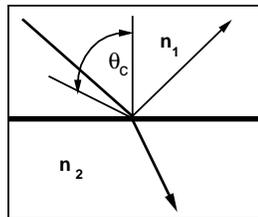

At angles of incidence greater than the critical angle, reflection is total and no fraction of the light penetrates into the second medium.
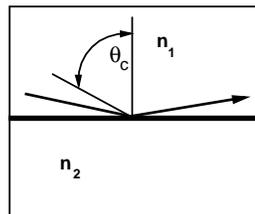
Optical fiber construction takes advantage of Snell's Law in the following manner. The fiber consists of a core with a refractive index n_1 and a cladding with a refractive index n_2. For the light to propagate through the fiber core, the refractive index of the core must be greater than the refractive index of the cladding, that is, ($n_1 > n_2$).
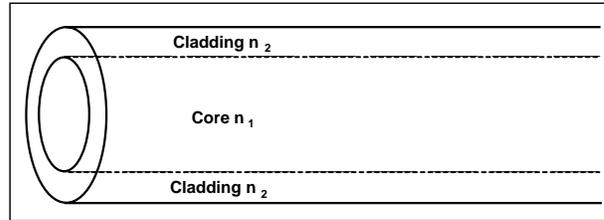
The refractive indices of a fiber's core and cladding determine its numerical aperture, NA, a term that defines the angle of the largest off-axis ray that a fiber can transmit. A fiber with a high NA can collect more light than a fiber with a low NA. The equation for numerical aperture is:

$$NA = \sqrt{n_1^2 - n_2^2}$$

As an example, if $n_1 = 1.22$ and $n_2 = 1.18$, then the numerical aperture is calculated as shown below:

$$NA = \sqrt{(1.22)^2 - (1.18)^2}$$

$$NA = 0.31$$

Rays within the core that are incident on the inner wall of the cladding at an angle greater than the critical angle will be totally reflected. They will then strike the opposite wall at the same angle and again be totally reflected. This

process continues all the way to the end of the fiber. This phenomenon is known as total internal reflection (TIR), a key principle in fiber optics. (The only loss of light is from scattering by foreign matter or by absorption).
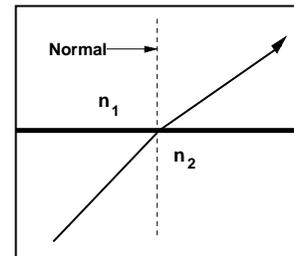
Typically, light rays enter the fiber core within a range of angles relative to the fiber axis. The maximum angle at which an entering ray experiences TIR is the acceptance angle, θ_A.

This angle, θ_A, is related to the critical angle, which is determined by the refractive indices of the core and the cladding. The smaller the critical angle, the larger the acceptance angle, so light rays at

larger angles are propagated along the fiber, as shown in the upper illustration at the bottom of this page.

When the acceptance angle is rotated 360 degrees around the fiber axis it forms an acceptance cone, as shown at the right. The larger the angle of the acceptance cone, the larger the NA. The larger the NA, the more light that the fiber can collect and transmit.

Light rays outside the acceptance cone strike the boundary between the fiber and the cladding at an angle less than the critical angle. As shown in the enlarged view in the lower illustration at the bottom of this page, these rays are not reflected along

the fiber but are absorbed by the cladding and lost. The angles that the light makes are exaggerated here to make the illustration clearer.
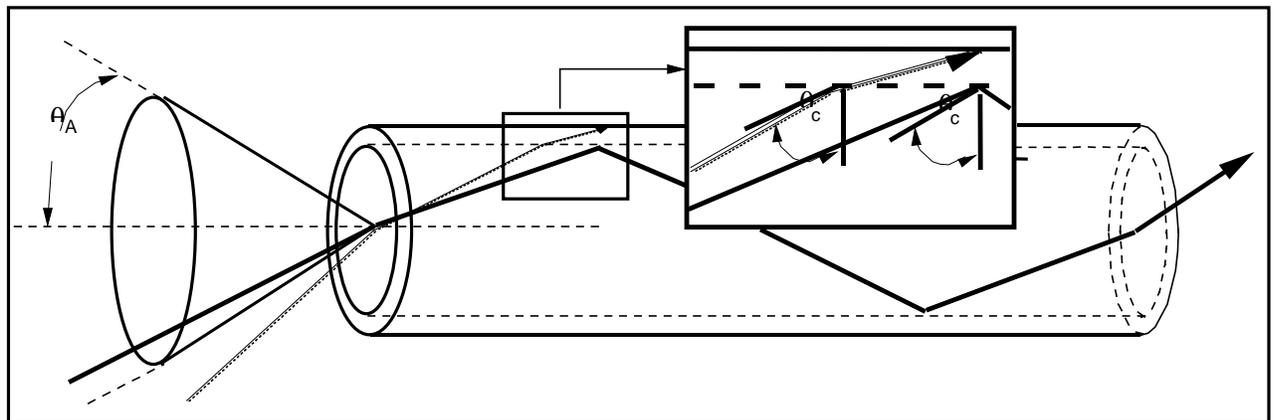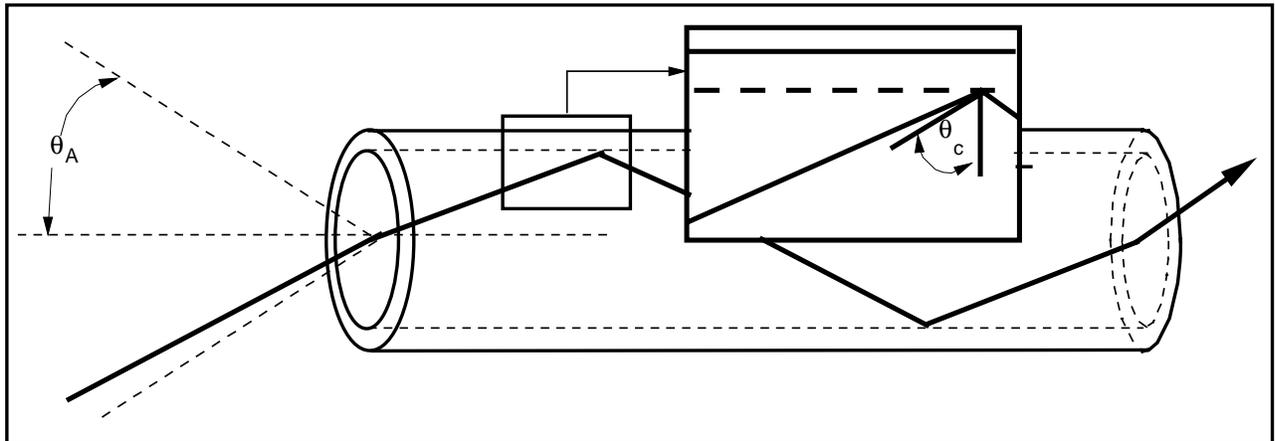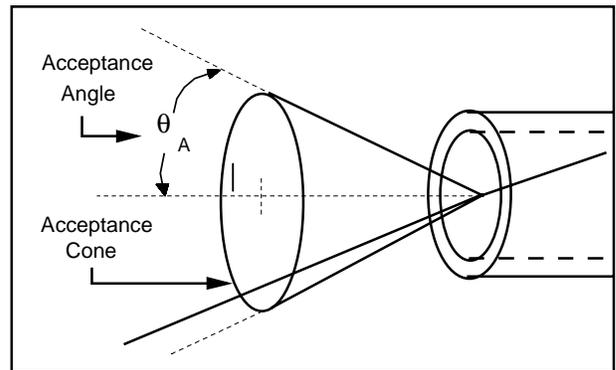
Types of Fiber
A number of fibers types are common in to-day's marketplace.

Glass Fiber

Glass fiber is the most common type of fiber avail-able, with companies such as Corning and Siecor producing billions of meters per year. Common industry-standard glass fibers are differentiated by the diameter of the core: larger cores allow more modes to propagate; smaller cores allow fewer. Glass fiber is available in three common sizes: two multi-mode fibers and one single mode fiber. Multi-mode fibers have larger cores and allow many modes to travel through the fiber. The two standard sizes for multi-mode fiber are 62.5/125 μm, and 50/125 μm, and

The first number indicates the core diameter and the second number indicates the cladding diameter. Single-mode fibers have cores so small that only one mode of light enters the fiber. Most single-mode fibers are 9/125 μm, but some have 8 μm cores.

Glass fibers are lightweight, durable, and fairly inexpensive. They make up most of the installed base of fiber-optics in the world. Single-mode fiber accounts for all of the long-haul telecommunications fiber.

Plastic Optical Fiber (POF)

Plastic fiber has been around for about 20 years and makes up only a small percentage of the total fiber in the world today. Most plastic fiber is used in Japan and Europe. The two major manufacturer of POF today are Mitsubishi in Japan and Boston Optical Fiber in the US. Several other smaller Japanese vendors also manufacture POF.

POF is easy to work with because of its large 980/1000 μm diameter. As a result, compo-nent, connector, and labor costs are all mini-mal, making a plastic fiber-optic link compa-rable to the cost of copper wire.

Hard Clad Silica (HCS)

HCS fiber has a glass core and a plastic clad-ding, giving it the qualities of both materials. This fiber is used even less than plastic fiber: SpecTran Specialty Optics Corporation is the most prominent manufacturer in the United States and Torray is the most prominent one in Japan. HCS is the most durable of fibers and is relatively easy to work with. It has a 200/240 μm diameter, and is avail-able in riser and plenum versions that meet envi-ronmental standards.

If the diameter of the fiber core is smaller than the light emitter or larger than the photo-diode detector, power coupled from the transmitter into the fiber or power coupled from the fiber into the receiver can be lost. For this reason, the transmitter and receiver must be optically matched to the fiber's di-ameter.

How to Use the Fiber Optic Section of the Catalog

Introduction

The quickest way to locate the proper fiber-optic components for your customers is to first determine the requirement of their designs. You can assist them in identifying which specifications are most critical by reviewing the following items with them.

Key Specifications

1. Signaling Rate (Link)

   Signaling rate is the number of transitions per second required for the proper data rate. Data rate is in bits per second; signal rate is in transitions per second (baud). With some codes, one symbol is all that is needed for one bit, for example, NRZ (Non-Return to Zero); other codes may require two transitions per bit, for example, Manchester, Biphase, and so forth.

2. Bandwidth (Fiber and Link)

   Bandwidth is expressed in units of Hertz (cycles/sec) and is abbreviated as Hz. The band width of a fiber is related to a phenomenon known as dispersion. The dispersion is described in terms of nanoseconds per kilometer. If a zero rise-time signal is introduced at the transmitter end of the fiber, it emerges at the receiver end with a rise time determined by the length of the fiber in kilometers multiplied by the number of nanoseconds per kilometer of dispersion. Link bandwidth includes the effects of bandwidth limitation in transmitters and receivers.

3. Launched Power (Transmitter)

   The power launched into a fiber is directly dependent on the intensity (brightness) projected onto the face of the ferrule at the cross-sectional area of the fiber core. Other factors also affect the coupled optical power into the fiber. They include the numerical aperture of the fiber, material interface differences, and so forth.

   It is important to note that the launched optical power specification is for usable optical power already inside a specified type of fiber.

4. Dynamic Range (Receiver)

   Dynamic range is the difference between the overdrive (dBm) and the under-drive (sensitivity, dBm) conditions for a fiber-optic receiver. The range depends on certain operating conditions, for example, acceptable error rate and signal-rate distortion.

5. Attenuation (Fiber)

   Attenuation describes how rapidly power diminishes from a combination of scattering, absorption, and bending losses as it travels through the fiber-optic cable. This property limits the distance that the signal can travel before the power is less than the minimum required for proper receiver operation. Attenuation is expressed in dB per kilometer, that is, it decreases exponentially as it travels through the fiber.

6. Optical Connections (Transmitter and Receiver)

   In addition to specialized connectors, such as the Agilent snap-in connector, other options are recognized as standard. These are described in the data sheet with enough detail to ensure compatibility with the connector system to be used. Some of the standard designators are FC, FDDI, MT-RJ, SC, SMA, and ST.

   For some of these, only one fiber size is used while others have options for fibers of various types and sizes.

Data Sheet

As the name implies, this document identifies, describes and specifies the performance of a particular link or its components under specific operating conditions. Package dimensions are specified also. Major features of the product and the advantages that these features yield are listed; the benefits derived from these features are explained. This information helps customers to properly design, which helps them to apply the link or the various components in the best way.

Interpreting a Fiber-Optic Data Sheet

The arrangement of Agilent's data sheets for both plastic and glass fiber-optic links is very similar. Included are the key parameters and specifications, test conditions and applications. Shown below are generic specifications for a variety of products.

1. Recommended Operating Conditions

   Lists the operating supply voltage needed for the receiver and the currents at which the transmitter should be operated.

2. Peak Forward Current

   The maximum amount of current permitted in the LED of the transmitter. The duration of time that the current is at this maximum is limited by other factors of the device, such as the amount of heat that the electrical power generates.

3. Fanout (TTL)

Indicates how many standard transistor-transistor logic device inputs can be connected to the output of the receiver.

4. Minimum and Maximum

The guaranteed limits of performance. Typical refers to the device performance when it is at room temperature (25 degrees C) and nominal operating conditions.

5. Duty Factor

A measure of the average length of time a signal is high versus low. A duty factor of 50 percent means that the signal is equally up and down in the same amount of time, over a long time. Duty factor can be adjusted to permit more peak LED transmitter current for more distance capability of a link at the compromise of on versus off time for the LED.

6. Numerical Aperture

Describes a characteristic of the optical port in the fiber, transmitter, and receiver. This characteristic is useful when using the transceiver with cable that has a different numerical aperture than the Agilent component.

7. Table of Absolute Maximum Ratings

Lists operating limits for the transmitter and receiver. Supply voltage is the major consideration and should not exceed the specified value or a receiver may fail to function or be damaged. Many links are specified to operate at 0 degrees C and above. This prevents moisture from freezing in the optical port, which might cause unpredictable excess optical power loss.

8. Short- and Long-Term Bend Radii (Table of Absolute Maximum Ratings)

States the specific limits. Having sharper bend for a long period of time will cause plastic cable to cold flow and the cross section to change from circular to elliptical. The latter shape causes higher light losses in the fiber. Long-term bend may also cause static fatigue fracture.

9. Table of Connector Mechanical/Optical Characteristics

Aids the designer in preventing damage or abuse to the cable, connectors or optical ports of the transmitters and receivers.

10. Optical Port Diameter

Measurement of the light at the plane of the glass fiber face that the LED projects through the lens system of the transmitter port. The value in the table helps determine how much of the light couples into the fiber core. This value can be used to calculate a partial amount of coupled optical power into a fiber with a different core diameter.

11. Receiver Input Optical Power Minimum (Table of Electrical/Optical Characteristics)

Eye Center indicates the sensitivity of the receiver section of the transceiver when ideal Input Optical Power timing characteristics are presented per definitions specific to the product.

12. Bandwidth-Length Product

An alternate means to describe dispersion.

$$BW*L(MHz*km) = \frac{350}{Dispersion\left(\frac{ns}{km}\right)}$$

Glossary

10base-2
An approved IEEE 802.3 standard for 200-m links using coaxial cable. The applications are a 10 Mb/s baseband-modulated LANs for HUB or concentrator-to-desktop links.

10base-5
Same as 10Base-2 but used with 500-meter links.

10base-FL
An approved IEEE 802.3 standard for 2-km links with 0.85-m LED sources and 62.5/125 um multi-mode fiber. Applications are 10 Mb/s baseband-modulated LANs using repeater links to hubs or concentrators. This standard uses the CSMA/CD protocol. With Manchester coding, the signaling rate is 20 MBd.

10base-T
An approved IEEE 802.3 standard for 100-m links using unshielded twisted-pair wire (UTP). The applica-tions are a 10 Mb/s baseband-modulated LANs for HUB or concentrator-to-desktop links.

Access LAN
The front-end LAN used to interconnect distributed stations and provide access to a backbone LAN, usually by means of bridges or routers, which are located in a wiring closet.

Acceptance Angle
The maximum angle with respect to the fiber axis at which an entering ray will experience Total Internal Reflection (TIR). See also TIR and NA.

Acceptance Cone
A right circular cone whose included angle is twice the Acceptance Angle.

Active Area
The sum of the core areas of the individual fibers in a bundle, as distinguished from the total area of the cable or bundle. See also Packing Fraction.

Alignment, Optical
Lateral and angular positioning of the central axis of a fiber terminus to an optical port to minimize coupling losses.

Ambient Light
The light from the surroundings (the sun, fluorescent and incandescent lamps, and so forth).

Ambient Temperature (T_A)
The temperature of a medium such as air, water, or earth into which the heat of the equipment is dissipated. T_A is usually room temperature and is normally assumed to be 25°C if not otherwise specified.

The temperature of the surroundings.

AM Modulation
Conveying information by altering or modulating the strength (amplitude) of a radio signal.

AM may be either analog (continuous) or digital (discrete). In digital AM, the presence of a signal sends a "1", the absence sends a "0".

AM radio is an example of a system that uses AM modulation.

American Standard Code for Information Interchange (ASCII)
A standardized set of alphanumeric fonts. The associated numeric code used to represent fonts inside a computer.

Analog
Signals which make use of electrical analogies, for example, varying voltage, frequencies, to produce a continuous signal rather than a pulsed signal (Compare to Digital).

Anode
The part of the diode that when positive with respect to the cathode causes forward current flow.
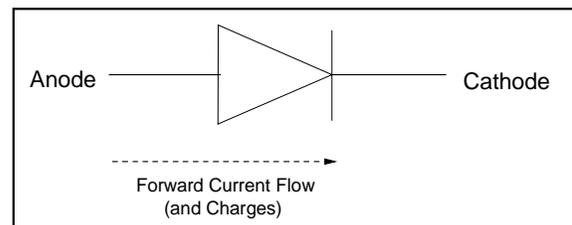
ANSI
American National Standards Institute. The coordinating organization for voluntary standards in the United States. Current ANSI standards for Fiber Optics include FDDI and Fiber Channel.

Angstrom
Unit of length formerly used to describe optical wavelengths. The preferred unit now is the nanometer, which is equal to ten Angstroms.

Aperture
The diameter of the largest beam of collimated light that can enter or leave the optical fiber, the lens or other optical device.

Note: "Aperture" and "Numerical Aperture" are not related.

Area Loss
The loss of optical power (usually in dB) resulting when optical is coupled from a large-core-diameter fiber into a small-core-diameter fiber.

Arithmetic Logic Unit (ALU)
One of the three essential components of a microprocessor (the other two are the registers and the control block). The ALU adds and subtracts; the logic unit performs operations such as ANDing the contents of two registers, or masking (blanking or inhibiting) the contents of a register.

Asynchronous
Not synchronized to a single, stable, time reference.

Asynchronous Transmission
Transmission of data through start and stop sequences without using a common clock signal.

Attenuation
The optical power loss per unit of fiber length caused by adsorption and scattering. Expressed in decibels per kilometer (dB/km) or decibels per meter (dB/m).

Avalanche Photodiode (APD)
A photodetector used in high-speed (broad band-width) fiber-optic systems. The avalanche feature results from the rush of electrons across a junction under a very high reverse-bias state. The APD has a much higher cutoff frequency and internal photo-current multiplication than a PIN photodiode; so it is more sensitive at high frequencies.

Bandwidth, Optical
The frequency at which modulated optical power is down 3 dB (1/2) relative to lower frequencies, as the signal is passed through a fiber of given length. Bandwidth varies inversely as the first power of the cable length.

Baud
A unit of measure for the rate of digital signaling, expressed in transitions per second. For modulation codes requiring only one transition per bit, the data rate in bits per second (bps) is numerically equal to the signaling rate in transitions per second (baud).

Note: The term "baud rate" is incorrect, because "baud" is the unit of measure for transitions per second or signaling rate.

Bellcore (Bell Communications Research)
Created in 1984 following the breakup of AT&T, Bellcore does R&D for the seven RBOCs (Regional Bell Operating Companies). Bellcore performs basic communications research and sets performance standards for telecommunications equipment. Most notable are Bellcore 253 (SONET) and Bellcore 983 (components reliability).

Bend Loss
Attenuation caused by bending the fiber optic cable around a restrictive radius of curvature.

Bend Radius
The radius taken by the axis of the fiber cable when it is bent. A minimum bend radius is the minimum radius to which a fiber cable can be bent without exceeding maximum stress in its fiber.

$$S = \frac{E\Delta r}{r}$$

S = Stress
E = Young's modulus = 10,000 kpsi for glass
r = fiber radius for single-fiber cable
Δr = distance from cable axis to the outermost fiber axis

Bias
The dc operating voltage or current or both applied to a component. Alternately, bias may refer to the circuitry used to achieve the dc operating point. Such circuitry may be passive (consisting primarily of resistors) or active (using a device with gain, such as a transistor or MOSFET).

Binary Coded Decimal (BCD)
A number system in which each nibble (group of four bits) represents a coded decimal character. The decimal number 69 becomes 0110 1001 in BCD. Also known as the 8421 Code.

Bi-Phase Code
A transmission code in which each bit interval be-gins with either a low-to-high or a high-to-low level transition. If the data bit to be encoded is a logical "1" then another transition must occur before the end of the bit interval. If the data bit is a "0" there is no transition until the beginning of the next bit interval.

Either of these biphase codes can be inverted without inverting the data. They are also self-clocking because each bit cell has a transition at the beginning, called a

clocking edge. The duty factor is 50 percent because the offset from a bit without a mid-cell transition is cancelled by the next bit without a mid-cell transition. Because the code requires two transitions per bit, the data rate in bits per second is half the signaling rate in baud.

Bit
An abbreviation for binary digit. A bit is the smallest unit of information that a computer uses. A bit can have one of two values, generally represented as 0 or 1 or, in electrical terms, "on" or "off". Computers calculate by using binary (base 2) arithmetic, which involves rapidly manipulating strings of bits according to certain fixed rules.

Bit Error Rate (BER)
In an actual transmission system, various electronic noise sources can change or corrupt the stream of data bits. The number of these corrupted bits divided by the total number of received bits within an arbitrary time period is the bit error rate (BER). The lower the BER value, the fewer the number of errors in the transmission.

Breakdown Voltage
The voltage measured at a specified current in the breakdown region of a semiconductor diode at which there is substantial change in characteristics from those at lower voltages.

Byte
Eight consecutive bits treated as an entity. See also Bit.

Cable, Optical
A cable containing plastic or glass fiber(s) used as a waveguide to carry light waves. Each fiber has three well-defined regions: the core, which is surrounded by the cladding, which in turn is surrounded by tensile strength members and an outer scuff-resistant jacket or sheath. The cable may contain a single fiber or many fibers. See also Fiber Bundles.

Cathode
The part of the diode that, when negative with respect to the anode, causes forward current flow. (see Anode)

Central Processing Unit (CPU)
The brain of any computer system. The CPU consists of storage elements called registers, computation circuits in the ALU, the Control Block, and I/O. As soon as LSI technology was able to build a CPU on an IC chip, the microprocessor became a reality. The one-chip microprocessors have limited storage space, so memory is added in modular fashion. Most current microproces-

sors consist of a set of chips, one or two of which form the CPU.

Cladding
Silica (glass) or plastic that surrounds the core of an optical fiber to minimize surface scattering loss-es and establish the NA (Numerical Aperture) for Total Internal Reflection to occur.

Clock
A device that provides a continuous series of alternating 1's and 0's to control the timing of bits sent in a data stream and controls the timing of the sampling of bits received in a data stream.

Computer System
A computer and software plus one or more pieces of peripheral equipment.

Continuous Wave (CW)
An electromagnetic signal consisting of waves having successive oscillations that are identical under steady state conditions, as opposed to a pulsed signal, consisting of waves that vary
with time.

Control Bus
A device that conveys a mixture of signals, which regulate system operation. These "traffic" signals are commands that may also originate in peripherals for transfer to the CPU or in the CPU for transfer to the peripherals.

Core
The center of the optical fiber through which the transmitted light is propagated. It has the highest refractive index of the fiber.

Critical Angle
The incident angle within a high-index medium that causes the exit angle of a light ray into the second medium to equal ninety degrees.

At incidence angles less than the critical angle, only partial reflection occurs. Incidence and re-fraction angles are measured from a line perpendicular to the boundary. See also TIR, and Snell's Law.

Curvature
A smooth change in the direction taken by a fiber cable. The minimum curvature radius is limited by the actual fiber strength. Curvature causes optical radiation losses.

Daisy Chain
A bus line that connects devices in series by means of active repeaters.

Data Format

 (see Transmission Code)

Data Rate

Bits of information (data) transmitted per second depending on the transmission code used, for ex-ample, RZ (Return-to-Zero), NRZ (Non-Return-to-Zero). The data rate is affected by the data for-mat. RZ delivers a lower data rate than NRZ. If a system's signaling rate is limited to a high of 10 Bd, a higher data rate may be achieved by dividing the data stream among additional channels.

Data Rate (Mb/s) = Signaling Rate (Mbaud) x Efficiency of Transmission Code

See also Baud.

dBc

Decibels referenced to the signal carrier level.

dBm

Decibels referenced to 1 mW.

The standard unit of power level used in microwave work.

dBm	mW
0	1
10	10
20	100

See also dB.

DC (Direct Current)

A unidirectional current in which the changes in value are either zero or so small that they may be neglected.

Debugging

The process of removing errors from a computer program so that it executes instructions properly.

Decibel (dB)

A unit of gain equal to ten times the common (base 10) logarithm of the ratio of two power levels or 20 times the common logarithm of the ratio of two voltage or current levels, as shown in the following table.

dB	Gain	dB	Gain	dB	Gain
0	x1.00	4	x2.50	8	x6.40
1	x1.25	5	x3.20	9	x8.00
2	x1.58	6	x4.00	10	x10.00
3	x2.00	7	x5.00		

Decoder

A circuit or device that automatically converts a signal to the appropriate switching action

Detectivity

A parameter of a photodiode. Detectivity characterizes the normalized area of a photodiode surface by normalizing the signal-to-noise ratio with respect to the square root of the area and the incidence (optical power per unit area).

Detector, Photo

A device that reacts to light by producing or modulating an electrical signal. See also Photodiode, Pin Diode and Avalanche Photodiode.

Dispersion

The increase in rise/fall time of the optical signal at the far end of long fiber-optic cables. It is ex-pressed in nanoseconds per kilometer. Dispersion is linearly related to the inverse of the bandwidth-times-length constant. It results from either modal or material effects. See also Modal Dispersion and Material Dispersion.

Digital

Pertaining to data in the form of discrete quantities or digits. See also Analog.

Diode

An electronic device composed of two different mixtures of semiconductor materials that allows large currents to pass in only one direction.

Directional Sensitivity

The off-axis response of a detector.

Doping

Adding impurities to a substance to change its electrical properties.

Dual In-line Package (DIP)

A housing for integrated circuits with two rows of pins.

Duty Cycle

The ratio of on time to off time in repetitive opera-tion, generally expressed as the on percentage of total cycle time.

Duty Factor

When an LED is rapidly pulsed On and Off, the duty factor is the ratio of On time to total On plus Off time.

$$DF = \frac{On}{On + Off}$$

Electro-Magnetic Capability (EMC)

The ability of electronic equipment to be operated in the intended electromagnetic environment at designed levels of efficiency. Fiber Optics helps solve EMC problems.

Electro-Magnetic Interference (EMI)
An electromagnetic disturbance generated within or external to electronic equipment that impairs the reception of a desired electromagnetic signal.

Typical sources could be power-line transients, noise from switching-type power supplies or spurious radiation from oscillators or both. EMI is suppressed by power-line filtering or shielding.

Electro-Static Discharge (ESD)
The instantaneous release of stored electricity from one body to another. Fiber optic transmission is immune to ESD.

Emitter, Optical
A device that generates optical power. See also ILD, LED, and Light Source.

Extinction Ratio
The ratio of the output power of a digital transmitter for a logic 1 state compared to a logic 0 state. This ratio is important in system design because it affects the recovered signal level at the receive end. Laser transmitters are usually designed with a compromise between switching speed and extinction ratio performance.

Fall Time
On the trailing edge of a pulse, the time it takes for the instantaneous power to decrease from 90 per-cent of the peak pulse power level to 10 percent of the peak pulse power level.

Fiber Optics
The technique of conveying light through a particular configuration of glass or plastic fibers.

Fiber Strength
(See Tensile Strength)

Filter
A device that rejects signals of certain frequencies while passing others.

Flux Budget
(See Optical Power Budget)

Forward Current
Current through a diode in the direction of its maximum conduction.

Forward Voltage (VF)
Voltage across a diode for a given forward current.

Frequency (f)
The repetition rate of a periodic signal, expressed in cycles per second. The units of frequency are Hertz (Hz). Common multipliers include:

kHz (kilohertz): 10^3 Hz
MHz (megahertz) : 10^6 Hz
GHz (gigahertz): 10^9 Hz

Most Agilent FCD products are designed to operate in the MHz to GHz frequency range.

Frequency Range
The minimum and maximum frequencies between which a particular component will meet all guaranteed specifications. Alternatively, the minimum and maximum frequencies between which a particular component will have "useful" performance.

Full-Width Half-Minimum (FWHM)
(see Spectral Width)

Gain
The amplification available from a component expressed as the ratio of the output power to the input power. Gain is usually measured in decibels (dB).

Graded-Index Fiber
An optical fiber whose index of refraction decreases as a function of the distance from the center of the core, until it reaches the cladding index of refraction at the core radius. Graded-index fibers offer multi-mode (large NA) characteristics along with low dispersion and are used in all fiber applications. It is one of the two most popular fibers, the other being Step-Index Fibers. See also Index Profile.

Hertz (Hz)
A unit of frequency equal to one cycle per second.

High-Order Mode
(see Modes of Propagation)

Hole
A vacant, electron energy state apparent as a charge defect in a crystal. This defect behaves as a positive charge carrier, equal to the charge strength of an electron.

Index Grading Coefficient (g)
Describes the variation of refractive index within the fiber core as a function of radial distance, r, from the center of the core, relative to the core radius, a.

Index Profile
The index of refraction through the fiber core as a function of the distance from the center of the core. A sharp

reduction of the index at the boundary between core and cladding results in a step-index fiber. A gradual lowering of the index in the core areas approaching the cladding results in a graded-index fiber. (See also Index Grading Coefficient)

Index of Refraction (n)
The ratio of the velocity of light in a vacuum (such as the fiber core, n, or cladding, n) to the velocity of light in a given medium. (See also Snell's Law)

Infrared (IR)
Wavelengths that extend beyond 770 nanometers.

Injection-Laser Diode (ILD)
A p-n junction semiconductor that converts direct forward bias electric input directly into coherent optical output power. The ILD provides a light source suitable for optical fibers. It can supply much higher optical power output in a smaller NA and smaller spectral width than LEDs, but is costly and temperature dependent.

Input/Output (I/O) Data Lines
Package pins which are tied directly to the internal bus network to enable an I/O to interface the microprocessor with other components of the system and the outside world.

Insertion Loss
A loss resulting from the insertion of a component in a system, the ratio of the power delivered to that part of the system following the component to the power delivered to that same part before insertion. Insertion loss is typically measured in dB.

Integrated Circuit
A circuit with many elements fabricated on one piece of semiconductor substrate material. Abbreviated IC

Intensity (Iv)
Number of flux lines per unit solid angle.

Interface
1. A surface forming a common boundary between adjacent regions.
2. A common boundary between adjacent components, or systems enabling the devices to yield and/or acquire information from one another.

International Electrotechnical Committee Regulation No. 825 (IEC 825)
The standards body in Europe that sets general standards and safety regulations for various electrical products. IEC 825 sets the eye safety optical output power limits for laser- and LED-based devices. Similar in concept to

the CHRH in the USA, the IEC has specific regulations that may cause different eye safety classification.

Ionization
The process of giving net charge to a neutral atom by adding or subtracting an electron. Can be accomplished by radiation, or by creation of a strong electric field.

Junction
The region between semiconductor layers of opposite polarities.

Lambertian Emitter
An emitting area whose luminous intensity varies directly as cos θ varies (constant sterance).

Lambertian Source or Reflector
A source or reflector whose numerical aperature (N.A.) is unity.

Light-Emitting Diode (LED)
A p-n junction that emits light when biased in the forward direction.

A semiconductor device that provides a spontaneous (non-coherent) light source through the process of electroluminescence. LEDs emit visible or invisible (infrared) radiation. LEDs are suitable for optical fibers when adapted to match the fiber's core area. This interface may be in the form of a pigtail fiber lead attached to the light-emitting slide.

Light Sources
Injection Laser Diodes (ILDs) and Light Emitting Diodes (LEDs). ILDs are capable of coupling a few mW of light power into an optical cable; LEDs can couple only a few hundred μW. (See also ILD and LED)

Linear
A device whose output is directly proportional to its input.

Linear Dynamic Range
The linear dynamic range is determined by three parameters:

  - noise floor,
  - gain of the amplifier; and
  - linear output power

of the amplifier. The range between the noise floor and the 1 dB gain compression point is the linear dynamic range.

The lowest input signal level that produces a detectable output is determined by the thermal noise generated within the amplifier itself. Any signal below this "noise floor" causes an amplifier output with a signal-to-noise

ratio of less than one, which requires special techniques to recover useful information. The noise floor may be calculated from:

$$Pni (dBm) = -114 \text{ dBm} + 10 \log B + NF$$

Pni = effective input noise power in dBm
  B = noise bandwidth of amplifier or system in MHz
 NF = amplifier or system noise figure in dB

Note: Noise bandwidth can be approximated by the 3-dB bandwidth of the amplifier gain response. The published bandwidth of most Agilent amplifiers is not the 3-dB bandwidth, but is the flat gain response region. It is suggested that bandwidth be limited by external filtering or system selectivity.

When performing sensitivity calculations, it is usually assumed that the actual minimum detectable signal (MDS) is some level above the noise floor (typical value is 3 dB).

Linearity
Any deviation from a best-fit straight-line approximation under specified conditions. Common measurements of linearity include intermodulation distortion level (IM level), spurious content, compression, and intercept point.

Lumen
A basic unit of measure used for the total amount of light flux in any particular situation; for example, from a source, in a beam, through an aperture, and so forth.

Luminous
Relating to how the human eye sees the light.

Luminous Efficiency
The ratio of light output to power input.

Luminous Intensity
A measure of the visibility of a light source generally expressed in millicandelas. It is defined as lumens per unit solid angle (steradian) .

Manchester Code
A modulation code that has a transition in the center of each bit cell. The transition is low-to-high for a "0", high-to-low for a "1". Successive "ones" or "zeros" require additional transitions at the ends of the bit cells.

This code is self-clocking because each bit has a mid-cell transition called a clocking edge. The duty factor is 50 percent because the second half of each bit cell has a polarity opposite that of the first half. The code is not invertible because the mid-cell transition is polarized. It must be low-to-high for a "0" so that inverting the signal also inverts the data.

Because the code requires two transitions per bit, the data rate in bits per second is half the signaling rate in baud.

Material Dispersion
The separation of the light wave into its component frequencies over a specified time period as it travels through the fiber. This phenomenon limits bandwidth in fiber-optic cores. It is caused by two conditions:

1. The velocity of optical transmission in the core varies inversely as the index of refraction.
2. The index of refraction varies according to the wavelength spectrum.

This means that although all portions of the optical signal may be launched simultaneously, they will not all arrive simultaneously. Due to differences in travel time, some portions of the spectrum will arrive at a different time (that is, be dispersed).

Mean Time Between Failures (MTBF)
A calculated figure representing the estimated average lifetime of a repairable device before it fails.

Mean Time To Failure (MTTF, MTF)
A calculated figure representing the time at which 50% of a population of devices will have failed. MTTF is used to predict the reliability of non-repairable devices such as individual semiconductors.

Microprocessor
A Central Processing Unit fabricated on one or two chips. While no standard design is visible in existing units, a number of well-defined, separate areas are present in all of them: Arithmetic and Logic Unit, Control Block, and Register Array. When joined to a memory storage system, the resulting combination is referred to in today's usage as a Microprocessor.

Miller Code
A modulation code in which each logic "1" has a transition at the center of the bit cell, and a logic "0" has a transition at the beginning of the bit cell, unless the "0" follows a "1" (compare with Manchester Code) Note that the Miller code has a transition (either rising or falling) corresponding to each rising edge in the Manchester code.

The Miller code has a duty factor that ranges from 33 to 67 percent, but is typically about 50 percent. It can be self-clocking with a phase-locked oscillator. Its main advantage is that it requires only one transition per bit, making the data rate in bits per second equal to the signaling rate in baud. Also, inverting the signal does not invert the data.

Modal Dispersion
The expansion of the rise and fall times of the signal as it travels along the fiber, expressed in ns/km. The time of arrival of simultaneously transmitted flux (optical radiation) depends on the path length traveled. Since reflections of the flux rays occur at different angles, path lengths will vary, causing dispersion. Also referred to as spreading. Modal dispersion is greatly reduced by use of fully graded fiber and reduced to zero in single-mode fiber. See also Material Dispersion.

Modem
Abbreviation for modulator-demodulator, a device that couples a computer or terminal to a telephone line. In general, any device that modulates an out-going signal for transmission and demodulates an incoming signal to proper format. Used for long-distance data transmission.

Modes of Propagation
Optical rays may propagate at various angles with respect to the fiber axis. The smaller angles are called low-order modes and the larger angles are called high-order modes. Both classes of modes are totally reflected within the core.

Mode Mixing
Conversion of low-order modes to high-order modes due to bends in the fiber.

Modulation
Adding information to a carrier frequency by varying some combination of signal amplitude, signal phase, and or signal frequency.

Modulation may be either analog (continuous) or digital (transmission of a finite number of discrete states).

Common Fiber-Related Modulations

Type	Description
AM	Amplitude Modulation - information is passed by varying the signal amplitude
FM	Frequency Modulation - information is passed by varying the signal frequency
PM	Phase Modulation - information is passed by varying the phase of the signal

Modulator, Optical
Light sources such as LEDs and ILDs can be modu-lated directly by varying the drive current (100 to 300 mA) at a data rate from dc to 150 Mb/s NRZ (for LEDs) and beyond (for ILDs).

Monomode Fibers
(see Single-Mode Fibers)

Multi-mode Fibers
Single fibers that can accommodate both high-order and low-order propagation modes. Such fibers have large NA.

Multiplexer
A device that accepts a number of parallel inputs and serializes them for transmission to a remote demulti-plexer where they are converted back to parallel signals.

Multi Quantum Well (MQW)
The MQW structure is a change to basic laser physics that improves a laser's operation. The practical advantage to the MQW is that it typically has more stable operating characteristics over its temperature range.

Multiplexing
The process of combining two or more channels of information for transmission on a single channel.

Noise Equivalent
An input signal that produces an output signal level that is equal in value to the noise level present when no signal is applied.

Noise Equivalent Power (NEP)
The input signal power that produces an output signal level equal in value to the noise level present when no signal is applied. This noise equivalent in watts is called the Noise Equivalent Power.

$$NEP = \frac{\text{Noise Current (amps per square root Hz)}}{\text{Optical Power Responsivity (amps per Watt)}}$$

Devices for photon detection can be compared on the basis of NEP.

Non-Return-to-Zero (NRZ)
A transmission code or data format in which the signal level does not periodically return to zero between a succession of high or "1" bits. A clock signal at the receiving end is required to define the point at which each bit of data is valid. A separate channel is required to transmit the clock signal.

Numerical Aperture (NA)
A number that expresses the angular light-gathering characteristic of an optical fiber. It is ex-pressed by the sine of the acceptance angle, the maximum angle with respect to the fiber axis at which an entering ray will experience total internal reflection (TIR).

Optical Power Responsivity
At any particular wavelength and for the flux in a small spot falling entirely within the active area of the photo-

diode, responsivity is the ratio of the incremental photodiode current to the incremental optical flux producing it.

Optics
The scientific study of light and vision, chiefly the generation, propagation, and detection of electromagnetic radiation having wavelengths greater than X-rays and shorter than microwaves.

Optical Power Responsivity
The ratio of incremental photodiode current to the incremental optical power producing it. Usually expressed in amperes per watt (A/W).

Optoelectronics
Technology dealing with the coupling of functional electronic blocks by light beams. Circuitry in which solid-state emitters and detectors of light are involved.

Packing Fraction
The ratio of the active areas of a fiber-optic bundle to the total bundle area. Only the core areas are considered active; other areas of a cable bundle, including the cladding, do not contribute to coupling efficiency.

Parallel Operation
Processing all the digits of a word or byte simultaneously by transmitting each digit on a separate channel or bus line.

Peak Wavelength
The wavelength at which the output spectrum of an LED is at a maximum.

Peripheral Equipment
Input-output and data storage devices: printers, keyboards, cathode ray tubes (CRTs), remote terminals, and tape and disk drivers.

Phonon
A quantum of heat energy.

Photometry
A branch of science which deals with the measurement of light intensity.

Photodetector
(see PIN Photodiode, Photodiode and Avalanche Photodiode)

Photoconductor
A resistor whose conductance (reciprocal of resistance) increases with exposure to optical radiation.

Photodiode
A solid-state device similar to an ordinary diode with the exception that the light incident on the pn- junction causes the device to produce a current in the direction from cathode, n, to anode, p, rather than in the other direction.

Photon
An elementary particle of light (quantum) with energy hf, where h is Plank's constant, and f the light frequency.

$$h = 0.004133 \text{ electron-volts per terahertz}$$
$$f(THz) = 300,000/\text{wavelength (nm)}$$

PIN Photodiode
In this semiconductor type, the p-doped and n-doped regions are separated by a lightly doped "intrinsic" region in which the absorbed photons generate an electric current. Hence the acronym PIN. PINs have the advantage of broad spectral response, wide dynamic range, high speed and low noise, but no internal gain.

Point Source
A source of light which emits light in all directions as if from one point. Sometimes used to refer to very tiny light sources.

Polarized Light
Light in which the electric field points in a known direction

Port
Device terminals which provide electrical access to a system or circuit. The point at which the I/O is in contact with the outside world.

Power Budget
The ratio (usually given in dB) by which the power provided by a transmitter exceeds the power required at a receiver. Power Budget describes the transmission loss ratio that is tolerable to the transmitter-receiver system.

Power Budget, Optical
Optical power (light rays) that radiates in a flux of energy packets called photons. These photons have no electrical charge and no magnetic field.

Printed Circuit Board (PCB or PC Board)
A circuit in which the interconnecting wires have been replaced by conductive strips printed or etched onto an insulating board.

Propagation Delay

The time difference between a logic transition at the output of a circuit (or device) and the input transition that caused it.

Pulse Dispersion
 (see Modal Dispersion, Material Dispersion and Dispersion)

Quantum Efficiency
A measure of photodetector efficiency. It is the ratio of primary photoelectrons to photons incident on the detector, expressed as the ratio: "electrons per photon" at a specific wavelength and temperature.

Radiant Energy
Relating to the actual energy emitted.

Radiometry
A branch of science dealing with the intensity of radiant energy.

Random Access Memory (RAM)
Immediate access to any storage location point in the memory by means of vertical and horizontal coordinates. Information may be "written" in (stored) or "read" out (retrieved) in the same rapid way.

Receiver (Fiber Optic)
A device that reacts to light signals, and converts them to electrical signals. See also Detector.

Reflection
When an optical ray encounters a change of refractive index, there is a reflection. If the ray is incident on the low-index side, the reflection is always partial. If it is incident on the high-index side, the reflection is partial only for incidence angles less than the critical angle. At incidence angles greater than critical, the reflection is total. The partial reflection is given by:

$$R = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2}$$

For $n_1 < n_2$, the critical angle $= \arcsin \frac{(n_2)}{(n_1)}$

Refraction
The bending of an optical ray incident at a boundary where there is a change of refractive index of the optical material. A fraction of the ray will pass through if the angle of incidence is less than the critical angle. The fraction passing through emerges at an angle (called refraction angle or exit angle) that is related to the incidence angle by Snell's Law.

Refractive Index

 (see Index of Refraction)

Refresh
To restore information; in displays, to strobe over and over again with the same data.

Register
Computer memory on a smaller scale. The words stored therein may involve arithmetical, logical, or transferral operations. Storage in registers may be temporary, but even more important is their accessibility by the CPU. The number of registers in a microprocessor is considered one of the most important features of its architecture

Repeater, Optical
A device that amplifies and reshapes the parameters of an optical signal to agree with the original information and transmits the new signals through a fiber optic line to another repeater or to a receiving terminal.

Resistance (R)
The real (frequency invariant) portion of the Impedance (Z). The basic unit of resistance is the ohm (Ω).

Responsivity
The measure of a photodetector's performance. The unit of measure is signal current divided by optical power, A/W. See also Optical Power Responsivity.

Return-to-Zero (RZ)
A pulse-type transmission code in which the signal level remains at zero for logic "zeroes," and momentarily deviates from zero for each logic "one," returning to zero between successive "ones," hence the name.

Reverse Breakdown
Phenomenon where large reverse currents flow in a diode due to mechanisms other than normal diode characteristics. Occurs when reverse break-down voltage is exceeded.

Reverse Current
Current flowing through a diode in the direction opposite to the direction of maximum conduction.

Reverse Voltage (VR)
Voltage across the diode for a given reverse current.

Rolloff
A gradual decrease in signal strength.

RS-232

Standard wire interface defined for a short-distance connection to a modem data communications equipment (DCE). It is specified at 19.2 kBd for distance up to 15 metres (50 feet).

SDH
Synchronous Digital Hierarchy, the European equivalent of ANSI SONET. (See also SONET)

Secondary Optics
Any reflector control or lens or both employed to redirect light emitted from an LED package

Semiconductor
A solid crystalline substance with electrical conductivity greater than an insulator but less than a good conductor.

Single In-Line Package (SIP)
A housing for integrated circuits with one row of pins.

Single-Mode Fibers
Fibers with core areas and numerical apertures so small that only one mode can be propagated through them. See also Modes of Propagation.

Snell's Law
At a boundary where there is a change of index of refraction light bends toward the normal when it enters an optically denser medium, and it bends away from the normal as it enters an optically less dense medium.

$$n_A sin\theta_A = n_B sin\theta_B$$

SONET (Synchronous Optical Network)
A set of standards that allow telecommunications equipment from various manufacturers to inter-operate. SONET specifies standard data rates of OC-1 (51 Mb/s), OC-3 (155 Mb/s), OC-12 (622 Mb/s), and OC-48 (2.488 Gb/s). The data format, signaling and monitoring functions are also specified. In Europe SONET is known as SDH (Synchronous Digital Hierarchy), with STM-1 (OC-3) at 155 Mb/s, STM-4 (OC-12) at 622 Mb/s, and STM-16 (OC-48) at 2.488 Gb/s.

Spectral Width
1. The incremental energy emitted by a light source as a function of wavelength. Because the Index of Refraction varies over the wavelength spectrum for a fiber, the travel time of different parts of a spectrum will vary, causing Dispersion.

2. The wavelength range over which the performance of emitters, detectors and other optical materials is regarded as being high enough to be useful. In most cases this is the wavelength difference between the half-peak levels, and is called FWHM (Full-Width Half-Maximum).

Spectrum
A continuous range of electromagnetic radiation (power from a source is not the same at all wavelengths, and the response of a detector varies with wavelength).

Spreading
(See Modal Dispersion)

Step-Index Fibers
Fibers whose index of refraction is reduced sharply at the boundary between the core and the cladding. They are useful for multi-mode operation over short distances up to one kilometer.

Steradian
A unit of solid angle.

Sterance
Intensity per area, usually in millicandellas per square meter.

Strobe/Multiplex
To rapidly pulse an LED On and Off or to rapidly pulse a set of LEDs On and Off in sequence (only one on at any one time), so as to share circuitry and wires.

Substrate
A material that supports other (usually thinner) material.

Tensile Strength
The total mechanical strength of a fiber, and the force in newtons or pounds at which breakage occurs. It is determined by the condition of its surface. Coating the glass fiber with a thin plastic film increases mechanical strength compared to the naked fiber.

Thermal Resistance
Resistance to heat flow.

$$\text{Conducted Heat} = \frac{\text{Temperature Difference}}{\text{Thermal Resistance}}$$

Three-Five (III-V) Compounds
Compounds manufactured from elements in groups III and V of the periodic table. These compounds have semiconductor properties.

Total Internal Reflection (TIR)
Reflections from rays incident on the high-index side of a boundary between materials of different refractive index, in which the incidence angle exceeds the critical angle. Optical fibers have a core surrounded by cladding with an index lower than that of the core.

Optical rays that approach the wall of the core at incidence angles greater than the critical angle are totally

reflected back into the core until they reach the far end of the fiber. See also Reflection.

Transistor-Transistor Logic (TTL)
A logic circuit design with the diode inputs re-placed by a multiple-emitter transistor. TTL gates using npn transistors are positive-level NAND gates or negative-level NOR gates.

Transmission, Optical
A method of transmitting information by means of modulated light waves through an optical system. The system may be composed of any combination of lens optics, mirror optics, or fiber optics.

Transmission Code
A code used to efficiently transmit data along a link. The speed of the stream of data bits in bits per second depends on the transmission code. The most common codes are known as NRZ, RZ, Manchester, BiPhase, and Miller. See also Non-Return to Zero (NRZ), Return to Zero (RZ), Manchester and Bi-Phase.

Transmission Loss
(See Attenuation)

Transmitter, Optical
A device that takes electrical signals and converts them to light signals. See also Light Source and Emitters.

Valence Band

The range of energy states containing the valence electrons that bind crystals together. In a semiconductive material, it is directly below the conduction band.

Viewing Angle
The off-axis angle where the display may be satisfactorily viewed (limited by lenses, obstructions, or intensity decrease).

Wafer
A thin slice cut from a cylinder of III-V compounds. These slices are cut into smaller sections to form chips.

Waveguide, Optical
A transmission line consisting of a plastic, liquid, or glass fiber or bundle of fibers through which light is propagated both axially and by internal reflections.

Wavelength
Length (usually in nanometers) of one cycle of a light wave.

Word
A group of numeric and/or alphabetic characters and symbols, treated as a unit and given a single location in computer memory. See also Byte.

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