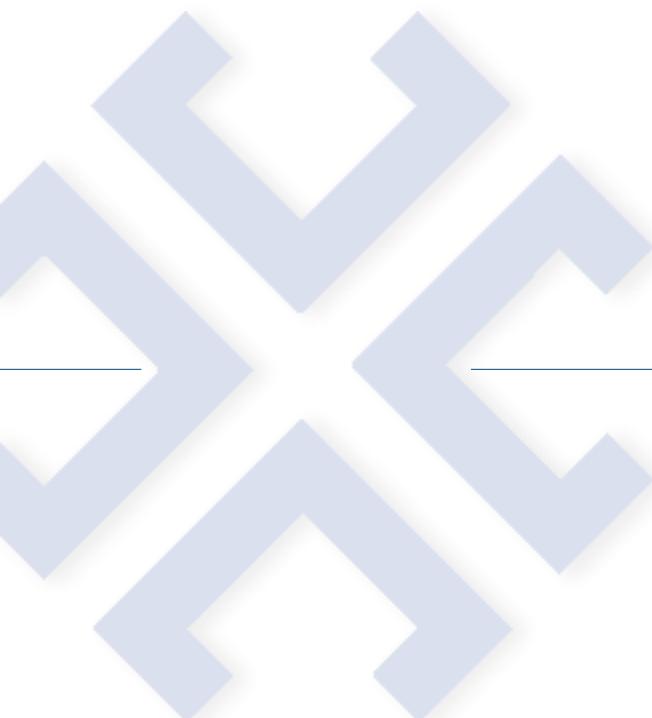


Guide to Industrial Fiber Optics



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Guide to Industrial Fiber Optics

The purpose of this Guide is to provide the industrial user enough information about fiber optics to install and successfully use the Carrier-band Fiber Optic Repeater.

Fiber optic technology has caught the imagination of many people. The ability to shine a light through a small glass fiber over considerable distances has been utilized for diverse applications.

- Long distance telephone lines use fiber optics. Signals for many conversations can be carried over a single fiber without amplifiers.
- An anti-tank missile uses fiber optic cable for flight control. Signals on fiber optic cables cannot be jammed.
- Medical equipment uses fiber optics to illuminate and observe inside the body and in some cases to send high-energy laser pulses through the fiber to perform internal surgery.
- An intrusion alarm system uses fiber optic cable as the sensing element.

The largest volume of fiber optics cable has been used for telephony. As most of the long distance telephone trunks were completed, an over-capacity of fiber optic cable manufacturing resulted. This sent fiber optic cable sales people out in search of new applications. Every so often, proposals are made to bring fiber optic cables to the home for both telephony and cable television use. Technically this is feasible, but economically it makes little sense. Current copper cable technology is adequate and is already in place. This is but one area where fiber optic technology has been oversold. A relatively new area where fiber optics is being touted is Local Area Networks, LANs. Fiber optics is said to have a very high data carrying capacity and low cost. Both parts of this statement are true. High quality glass fiber optic cable can carry a large amount of data and plastic fiber optic cable is inexpensive. Unfortunately, this is not one and the same cable. Many other aspects of fiber optic technology have been similarly oversold for LANs.

This Guide provides information so that facts and fiction about fiber optics can be separated and that the true benefits of fiber optic communications can be utilized effectively for industrial applications.

The Repeater is used as the example in this Guide and examples about fiber optics are general. At this writing, fiber optic technology is advancing rapidly. There may be fiber optic products or laboratory test results that are different than the examples given. This Guide does not address the many other aspects of fiber optics that may be interesting to design engineers or researchers.

For further reading, an excellent book, *Technician's Guide to Fiber Optics*, #82118, is available from:

AMP
Harrisburg, PA 17105
USA
Tel: 717-564-0100

Benefits and Drawbacks of Fiber Optics

Fiber optic technology has a number of benefits for industrial communications:

- **Long Distance** Signals can be sent over fiber optic cable for long distances—for example 9 km—without the need for intermediate amplifiers.
- **Ground Isolation** Since electrical currents do not flow on fiber optic cables, differences in ground potentials between end points do not affect signal transmission. Ground isolation is useful in power plants and switching yards where the differences in ground potentials are high. Grounding systems are not needed for fiber optics.
- **Lightning Protection** Because fiber optic cables do not conduct electricity, signals are not affected by lightning.
- **Cable Routing** Since fiber optic cables do not conduct electricity, they can be placed on the same cable trays as power carrying cables.
- **Noise Immunity** Fiber optic cables are immune to electromagnetic noise from radio stations, motor turn-on surges, welding discharges, electrostatic discharges, florescent lights, typewriters, and other Radio Frequency Interference, RFI.

NOTE: Although fiber optic cable is not susceptible to RFI, that does not mean that fiber optic data communications are error free. As will be explained later, a fiber optic communications system as a whole has error rates comparable to quality copper cable-based communications systems.

- **Intrinsic safety** In places such as chemical plants and grain silos, the atmosphere is often potentially explosive. Great care has to be taken with electrical wiring and data communications wiring to insure that sparks will not ignite the atmosphere. Signals on fiber optic cable will not cause sparking and are intrinsically safe.

- **Small size** Fiber optic cables are relatively small. Where cable has to be added to conduits that are already partially filled with existing cables, the small size cable can be advantageous.

There are other benefits to using fiber optics, but generally these are not relevant for industrial applications:

- **High data carrying capacity** Fiber optics cables are able to carry high data rates; for example, 300 Mbits/second. In most industrial applications, however, data is transmitted at 1 to 10 Mbits/second. For these moderate data rates, there is no need for the high data rate capability.
- **Security** Unlike copper cables, fiber optic cables are difficult to tap and to extract part of the signal without disrupting the operation of the fiber optic communications system. Also, fiber optic cables do not radiate electromagnetic signals that can be picked up with sensitive antennas. For these reasons, it is difficult for unauthorized parties to eavesdrop on fiber optic networks. Generally, security from eavesdropping is not a requirement of industrial communications.

If there were only advantages to fiber optics, it would be used universally. Fiber optics is not used everywhere because it also has disadvantages:

- **Costly** The fiber optic cable and the electronics in the equipment attached to fiber optic cables are more expensive than comparable copper cable-based communications systems. Moreover, two fibers are needed rather than just one to have two-way communications. The connectors and the equipment needed to install them is more costly than for copper cable.
- **Signal Distribution** In copper communications systems, many devices can share the same cable and communicate with each other. In fiber optics this is not practical. Signal transmissions and reception are point-to-point. A central signal distribution device is necessary to interconnect more than two stations.
- **More Training** Technicians working with fiber optic equipment need more training than copper cable installers.
- **More Care** Fiber optics is very susceptible to mishandling and dirt. Workers dealing with fiber optics have to use extreme care not to damage or degrade the performance of the fiber optic communications system.

Fiber Optic Technology and Terminology

A fiber optic communications system is composed of three types of parts: the **Transmitter**, the fiber **Medium** (cable) and the **Receiver**. The transmitters and receivers are located inside the computers, robots, controllers, or other devices that need to send or receive data. These end devices are called **Stations**. The Repeater is a station. Signals are transmitted over a fiber optic cable in only one direction. This is called **Simplex** communication. Generally, two-way communication is needed between stations so that two of each of the basic components are needed. The two-way communication is called **Duplex**. The Repeater requires duplex communications.

The transmitter is made up of a light emitter and the electronics that modulate the light to send information. The emitter is generally a **Light Emitting Diode, LED**.

The medium is the fiber optic cable and the associated connectors, splices. etc. that carry the light from the transmitter to the receiver.

The receiver is a light detector, that turns the received light signals back to electrical signals and an amplifier that conditions the signal for use in the station. The detector is a light detecting diode.

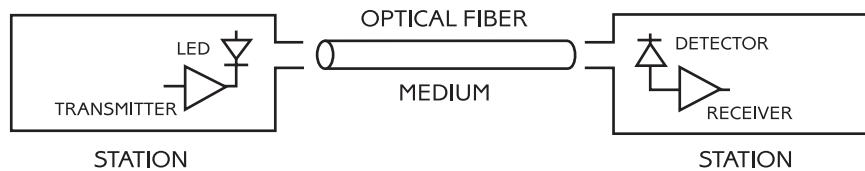


Figure 1 | Fiber optic system components

Signal Measurement

The strength of the optical signal is measured in two types of units: **micro-Watts**, μW ; and **dBm**. These two measurements are related by the equation:

$$\text{dBm} = 10 \log \frac{\text{signal } \mu\text{W}}{1000}$$

For the signal levels applicable to fiber optics, the relationship is shown in the table below:

dBm	μW
+3	2000
0	1000
-3	500
-6	250
-9	125
-12	62
-15	32
-18	16
-21	8
-24	4
-27	2
-30	1
-33	0.5
-36	0.25
-39	0.125
-42	0.062

The above values are absolute signal levels. Relative signal strengths, used to compare two signals, are described in **dB** (deci-Bell). If the power of signal A in μW is twice that of another signal B, then signal A is 3 dB more than signal B. As the table shows, when a signal in μW is twice as large as another it is 3 dBm more; when a signal in μW is half as much as another signal, it is 3 dBm less.

Fiber Optic Cable Characteristics

As light travels through fiber, it is **Attenuated**; it gets smaller. Attenuation is stated in dB per unit length. For example, if a 2 km long fiber cable has an attenuation of 4 dB/km and light entered the cable at -17 dBm, the light leaves the cable at:

$$-17 \text{ dBm} -(2 \text{ km} \times 4 \text{ dB/km}) = -25 \text{ dBm}$$

Another property of the fiber optic cable is that light signals traveling in the fiber become distorted. The longer the cable, the more distorted the signal gets. A way to quantify this distortion is by stating a **bandwidth-distance product**. For example, if the cable has a bandwidth-distance product then the fiber can transmit a 300 MHz signal over 1 km or a 150 MHz signal over 2 km, etc. ($150 \text{ MHz} \times 2 \text{ km} = 300 \text{ MHz km}$).

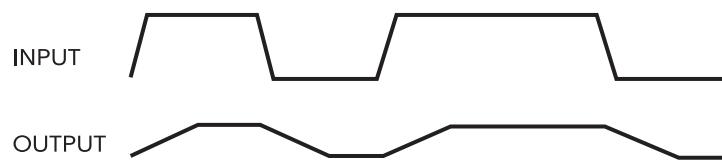


Figure 2 | Distortion

The bandwidth required depends on the rate at which the data is sent, how the data is encoded for transmission, and on the rise and fall times of the optical signal. Suppose that data is sent at 5 Mbits/second and that the transmitted data is encoded so that there are as many as four signal periods for each bit of data. The signal rise and fall times generally must be no more than 20% of the width of the shortest period. In this example, the signal periods are 50 ns wide so that the rise and fall times should be about 10 ns.

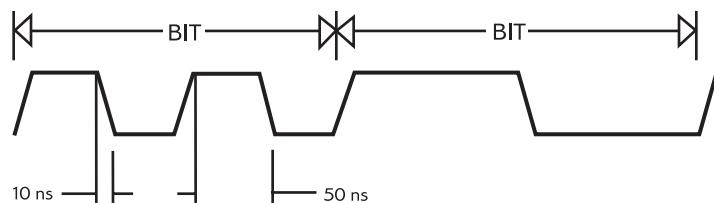


Figure 3 | Signal rise and fall times

The needed bandwidth of the transmission system that will carry such signals is given by

$$BW = \frac{0.35}{\text{risetime or falltime}}$$

In this 5 Mbit/second example, the required bandwidth is at least

$$BW = \frac{0.35}{10 \text{ ns}} = \frac{0.35}{10 \times 10^{-9}} = 35 \text{ MHz}$$

If a fiber optic cable is to carry this signal for 2 km, then the cable's bandwidth-distance rating should be at least

$$2 \text{ km} \times 35 \text{ MHz} = 70 \text{ MHz km}$$

There are many different types of fiber optics cables available that have different attenuation and bandwidth characteristics. A cable with two fibers in it is shown below.

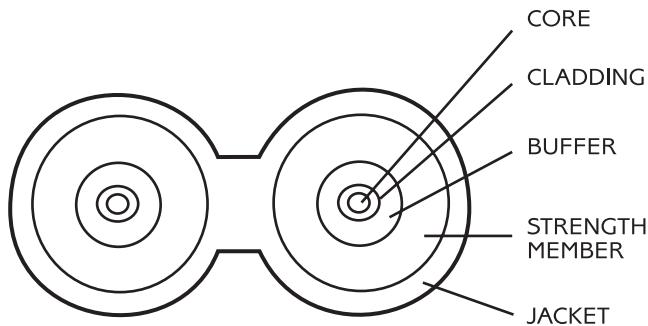


Figure 4 | Two-fiber cable with tight buffer

The major classification of cable is its light carrying fiber physical size. **Core** diameter is the center part of the cable that carries the light ; the **Cladding** diameter is the part that confines the light to the core. Both are made of high purity glass. The measurement of the diameter of the fiber is in **microns**, millionths of a meter, also called **micro-meters**, or abbreviated as **μm** . A representative listing of popular fiber sizes is given below. The size of the fiber is often written as the core size/cladding size. The 62.5/125 fiber is pervasive in North America. the 50/125 fiber is popular in Japan and Europe and the 100/140 fiber is frequently used by IBM.

Core	Cladding	Attn. (dB/km) (850 nm)	BW-dist. (MHz-km)	Relative Light Launched (dBm)
50	125	4	400	-17.3
62.5	125	4	160	-13.5
100	140	5	100	-8.0

The fiber sizes listed above are ***multi-mode*** fibers. The light traveling in multi-mode fiber can take multiple paths through the fiber. There are also ***single-mode*** fibers where the light takes one path through the fiber. Single mode fibers are used for very high data rate applications because the signal distortion is low. The core diameter in single mode fibers is about $6 \mu\text{m}$. Single mode fibers are more expensive, require a laser as an emitter, and require a great deal more care and expertise than multi-mode fibers. For these reasons, single mode fibers are less common in industrial applications.

The amount of optical signal put into the fiber depends on the amount of signal put out by the emitter and the reception characteristics of the fiber. One of the main factors in the amount of power launched into the fiber is the size of the fiber core. The larger the core, the more signal power is launched. As shown in the table above, for a given emitter, the difference between a $50 \mu\text{m}$ core and a $100 \mu\text{m}$ core cable is 9.3 dB. This suggests that a large core fiber should be used. The extra light, however, should be considered against the greater attenuation and the lower bandwidth-distance rating of the larger fiber.

The amount of attenuation of the signal in the fiber depends on the **wavelength** (color) of the light of the emitter. Wavelength is given in **nanometers (nm)** (10^{-9} meter). Visible light, such as that emitted by a red LED is highly attenuated when it travels through a fiber. Infra-red light, which has a longer wavelength, is less attenuated. One common low-loss wavelength is at about 850 nm and another is at 1300 nm. As an example, the attenuation of a 62.5/125 micron fiber at 850 nm is 4 dB/km and the attenuation at 1300 nm is 1.5 dB/km.

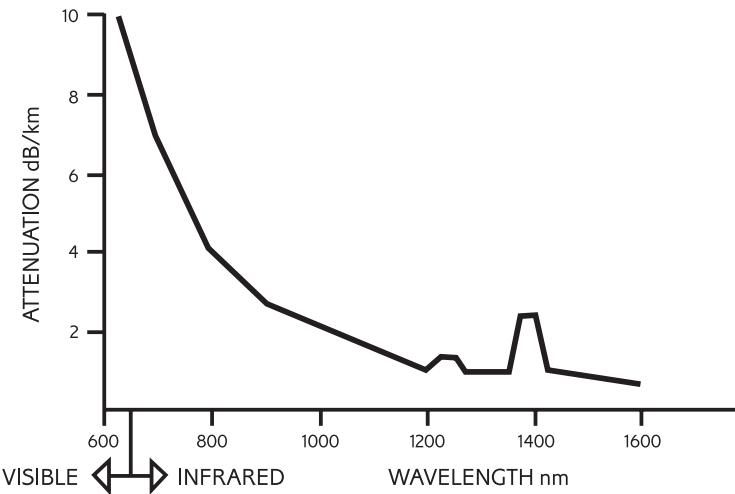


Figure 5 | Wavelength and Attenuation

The 850 nm emitters and detectors are about 4 to 10 times less expensive than the 1300 nm ones. For this reason, 850 nm wavelength light is used the most. The 1300 nm wavelength is used primarily in high data rate or long distance applications.

Another important characteristic to consider is the construction of the fiber optic cable. The glass portion of the cable is enclosed in a **buffer** that protects it. There are two types of buffers, tight and loose.

A tight buffer is applied directly over the fiber. This protects the fiber well but introduces a potential problem if the temperature drops below freezing. At low temperatures, the buffer material shrinks more than the glass fiber. This puts stress on the fiber and causes the glass to develop "**micro-bends**" or spots where light escapes from the fiber. Micro-bends increase the attenuation of the fiber.

In contrast, loose buffers hold the glass strand in a tube. At low temperatures, the buffer can shrink without the fiber developing micro-bends. Generally, loose buffers do not protect the glass fiber as well as tight buffers. The loose buffer tube can be filled with a compound to keep moisture from getting onto the fiber.

Multiple buffered fibers can be in a single cable assembly. A **strength member** is added to the buffered fibers to provide mechanical strength to the cable assembly. The strength member is often made of Kevlar but can also be fiberglass or steel. The cable assembly is covered by a jacket made of plastic material to protect the cable from abrasion, solvents, oils and other environmental hazards.

When selecting a fiber cable, it is important to scrutinize the cable specifications for temperature ratings and cable construction details. If fiber optic cable is to be buried directly into the ground, a metal jacket is used on the outside of the cable. The metal provides extra strength and protects the cable from rodents. If fiber optic cable is suspended from poles, a steel messenger wire is used to relieve the tension. In either case, the metal portions of the cable have to be well grounded before entering buildings so that lightning strikes are not brought inside.

Detector Characteristics

When the light signal emerges from the end of the fiber cable, it shines on the detector. The more the light shines on the detector the more electrical output the detector produces. There are limits to the detectors performance, however.

Even when there is no light shining on the detector, it produces some unwanted electrical signal-noise. The equivalent amount of this nonexistent light is about -41 dBm. This is called the **noise floor**. The real light signal needs to be greater than this noise in order to receive meaningful data. The amount that the signal needs to be greater depends on the desired error rate—how many data bits can be received in error out of the ones sent.

For the error rate performance of a fiber optic communications system to be comparable to its quality copper cable counterparts, the **Bit Error Rate (BER)** should be less than one error per one billion bits sent or 10^{-9} . In order to achieve a BER of 10^{-9} , the minimum light signal should be 12 dB higher than the noise floor. If the noise floor is -41 dBm, then the minimum optical signal should be -29 dBm.

Too much signal at the detector, on the other hand, makes the detector and amplifier distort the received signal and makes the BER worse. For example, -8 dBm may be the maximum detector signal level for a given detector.

Given these receiver characteristics, the fiber medium needs to deliver signal to the receiver that is less than -8 dBm but more than -29 dBm.

Emitter Characteristics

Emitters can be LEDs or laser diodes. Laser diodes emit a much narrower spectrum of light and are able to couple the light better into the fiber. Laser diodes, however, are much more expensive and not as reliable as LEDs. For these reasons LEDs are used in most applications.

The amount of light produced by the emitter versus the amount coupled into the fiber depends on a number of factors. The only relevant figure is the amount of light coupled from a given emitter into a given size fiber. The manufacturer of the equipment containing the emitter should provide a specification listing fiber types and the amount of optical signal power at the end of a one meter length of a given fiber. For example, a given emitter will launch -7 dBm maximum to -15 dBm minimum into a 62.5/125 fiber. These maximums and minimums should take into consideration all factors including the station's internal voltage variations, temperature, aging of the transmitter, etc.

In order to get more light out of an LED emitter, it can be driven with more signal current. Very large currents, however, cannot be used. The light output of an LED decreases with time. The higher the drive current and temperature, the faster the LED deteriorates and decreases in light output. When an LED degrades to where it emits only half of its initial light power, -3 dB, then the LED is said to have "failed." Depending on how hard the LED has been driven and the temperature under which it has been operating, the ***Mean Time To Failure (MTTF)*** can be as large as several million hours or as little as a few thousand. For this reason it is important to know not only the minimum and maximum output of an emitter but to also know if the minimum includes the LED's aging and the hours of MTTF.

Signal Budget

Once the transmitter and receiver characteristics are known, the overall system signal budget can be determined. For example, if the emitter launches a minimum of -17 dBm into a $62.5 \mu\text{m}$ fiber and the detector requires at least -29 dBm, then the fiber optic medium has to deliver signals with attenuation of less than

$$29 - 17 = 12 \text{ dB}$$

The signal budget is 12 dB. The fiber optic transmission medium includes more than just the fiber cable. It also includes the connectors and splices. Connectors and splices also attenuate the light signal. These will be discussed later. The transmitter power specification already includes one connector so at a minimum only one other connector has to be considered. Assuming that there are two splices in the fiber optic medium with attenuation of 0.5 dB each and one connector with 1 dB maximum attenuation, the amount of signal that can be attenuated by the fiber optic cable is

$$12 - (2 \times 0.5) - 1 = 10 \text{ dB}$$

If the attenuation of the fiber is 4 dB/km, then the fiber can be up to

$$10 \text{ dB} / 4 \text{ km} = 2.5 \text{ km}$$

long. Good practice dictates that all the available signal power should not be used up. A signal margin should be left. In this example, a safe distance might be 2 km. This example illustrates a very conservative approach to signal budgeting. The calculations include the minimum emitter specification at the end-of-life degradation and the maximum losses in the connectors and splices.

Connectors

The fiber optic cable needs to be connected to the station's transmitter and receiver by connectors. There are a number of different types of fiber optic connectors. The type most popular at this writing is a connector called "ST".

All connectors cause some attenuation. For quality connectors, the attenuation should be less than 1 dB maximum. Manufacturers' claims about average connector attenuation should be ignored unless very many connectors are used in a single cable and statistics about averages are meaningful. Generally, only two connectors are used and therefore statistical averaging is not useful. The connector attenuation figure should also include allowances for temperature and other environmental conditions of the industrial environment.

Fiber optic connector ends are highly polished so that the connector can have low attenuation. Some means should be provided to protect the polished connector ends from damage during routine handling.

The connectors should have means to secure them to the station so that they do not come loose with vibration. In fiber optics, even an extremely small separation of optical components can cause major signal losses.

Compared to connectors for copper cables, fiber optic connectors are relatively difficult to install on the cable. The installer has to work with hair-thin fiber (hair thickness is about 40 μm), mix and apply epoxy, polish the end of the connector to a mirror finish, etc. Installation takes a great deal more care, requires specialized tools, and trained technicians. Fiber cable connectorization can be performed by the end user but it is risky. There are several ways to avoid the risk.

One way for the end-user to avoid installing fiber optic connectors is to buy pre-connectorized cables. The cables are made and tested by the manufacturer and are known to be good. The drawbacks are that the exact length of the cables needs to be known and extreme care needs to be taken to protect the connectors while the cables are installed. Lead times for getting cables for initial installation and possible subsequent reconfiguration should also be considered.

Another approach is to contract a fiber optic installer. Because an installer works with fiber optic cables and connectors professionally, there is some hope that the job will be done right. The professional installers are supposedly trained and have the right equipment to do the job. As with other types of contractors, a good contract and references are a must. Even with excellent contractors, there is a risk. In industrial situations where downtime is critical, reliance on outside contractors for making repairs or modifications in a timely fashion may not be practical.

Another approach that avoids fiber optic connector risks, is to use fiber optic splices. As the name implies, splices are devices that connect two pieces of fiber optic cable to each other. A short piece of fiber optic cable with connectors on both ends can be purchased. These short cables and connectors are known to be good because the vendor has tested the cable assembly. The short cable is then cut in half and each half spliced to the end of the long fiber optic cable. Splices are relatively easy to install and do not require the ends of the fiber to be polished.

There are connectors which combine a connector and splice. The connector part contains a short piece of fiber which is pre-polished at the factory. The part also has an integral splice that is relatively easy to attach to the fiber cable. The drawback of the connector/splice combination is that it is about five times more expensive than an ordinary fiber optic connector.

Recently, low-cost connectors have been developed that do not require the fiber to be glued into the connector with epoxy. The fiber is simply crimped into the connector. This greatly simplifies the assembly procedure. However, the connector end still has to be polished.

Splices

There are many different types of splices. One major type is a fusion splice. With this technique, two of the glass fibers are melted and permanently fused together. This produces an excellent splice with very low signal loss. The equipment used for this technique is very expensive, however, and requires highly trained personnel to operate.

The other splice methods provide a cavity where two of the fibers are held together end-to-end. The ends of the fibers do not have to be polished. A simple tool is used to cleave the end of a fiber such that it breaks cleanly. The splice contains an **index matching fluid** which has the same optical properties as the fiber so that the light can leave one fiber and get into the other without light reflections occurring at the splice.

Once a splice is made, it needs to be protected so that the fiber cables do not pull apart. Often the splices are put into a box made specifically to hold splices.

Usually splices are used to connect together different types of fiber optic cables. For example, an armored type of cable is used between the building and is buried. Inside the building, a lighter duty cable is used. Although the construction of the cables is different, the glass fibers themselves should be the same size. If the fiber sizes are different, the splice losses are high.

Testing

Once the fiber optic cables have been installed, they need to be tested to see if they can transmit signals within the calculated power budget requirements. An optical signal source and an optical power meter are needed for this. The Repeater's emitter puts out an optical signal, even if it is not transmitting data. The signal source is measured with the optical power meter, the medium is connected to the source, and the optical signal is measured at the other end of the medium. If everything has been installed properly, the signal attenuation should be within the levels required by the power budget.

If the signal measured at the end is below the power level required, then the task becomes one of finding the cause or location of the signal loss. For this purpose, an optical time domain reflectometer, OTDR, can be used. This device will show graphically the locations of signal loss in the medium. OTDRs, however, are relatively expensive.

Network Topologies

Generally, fiber optics are used in only point-to-point communications. Multi-point communication, common for copper based networks where a number of stations share the same cable bus, are not practical for fiber optics.

A way to make fiber optic communications multi-point is to use a ***passive star coupler***. A passive star is a device which can receive optical signals from a number of stations at each of its ports, divide the signal more-or-less equally and send the signal to all the other attached stations. The signals leaving the passive star are attenuated considerably. The table below shows representative attenuation of some couplers. These numbers include the attenuation of the connectors on the coupler.

Number of ports	Attenuation
4	-9 dB
8	-11 dB
12	-13 dB

With this attenuation, the distances between the stations and the passive star are considerably less. Given the example of a 12 dB signal budget, a 4-port passive star, two splices and one connector, the amount of usable signal is only

$$12 - 9 - (2 \times 0.5) - 1 = 1 \text{ dB}$$

Assuming a fiber optic cable attenuation of 4 dB/km and a connector attenuation of 1 dB, the maximum distance between the stations and the passive star can only be

$$1/4 = 250 \text{ meters}$$

This example shows that given a 12 dB signal budget, a 4-port passive star is the maximum that can be used.

Carrier-band Repeaters can be used with a passive star coupler, as shown below. In this configuration, the best attributes of both fiber optics and copper cable-based technologies are employed. The carrier-band network segments provide local signal distribution on a bus and the fiber optic segments provide the electrical isolation and noise immunity.

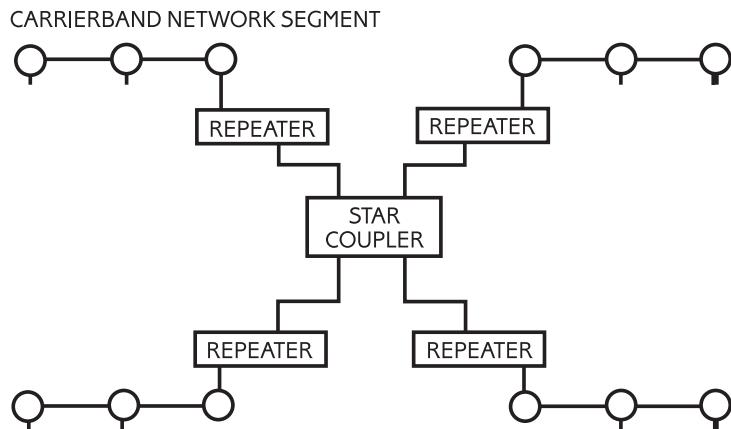


Figure 6 | Carrier-band and fiber optics



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