TELECOMMUNICATION CABLES

In order to transmit energy between two points it is necessary to understand the existence of various mechanisms to transport electromagnetic energy. In general, there are three types of propagation media, characterized by:

1. Transmission lines, which generally, require two conductors
2. Waveguides, which generally require one hollow conductor
3. Antennas, which generally require nonphysical connections in the propagation medium

Each particular mode of transmission has its own advantages and disadvantages and is best used at a particular frequency range. At low frequencies, the most common example being power lines operating at 50 Hz or 60 Hz, transmission lines are the best choice. This is true even though attenuation, as a function of distance of transmission, is exponential. Transmission lines offer an advantage typically up to 1 GHz. At these frequencies, waveguides and antennas are too large to be practical.

A transmission line has cross-sectional dimensions that are electrically small, that is, small as compared with the wavelength of operation. However the longitudinal direction can be electrically large. Waveguides have the same exponential decay as transmission lines and usually have a lower energy loss from approximately 3 GHz to 30 GHz. In a waveguide, both the longitudinal and the transverse directions have di-

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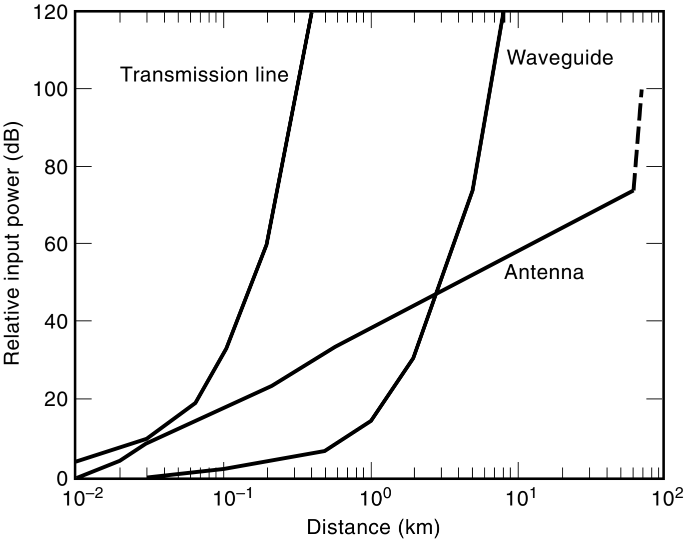

Figure 1. Relative input power required to maintain constant output power.

mensions comparable to the wavelength. Antennas are suitable for transmission of energy over longer distances, as they depict a loss which is inversely proportional to the square of the distance (1). Figure 1 shows the relative input power required for the three modes of transmission for a given fixed receiver power level. The plots are based on the assumption that representative values for energy loss have been used for each of the modes of transportation of energy. The coaxial transmission line with a solid dielectric has a loss of approximately 30 dB/100 m, whereas a waveguide has a loss of 1.5 dB/100 m. If the antenna has a gain of 30 dB along the desired direction of transmission, then it is seen from Fig. 1 that for short distances both transmission lines and waveguides are useful, whereas for longer distances, the antennas have a clear advantage.

TYPES OF TRANSMISSION LINES

Typically a transmission line contains at least two conductors which may be embedded or supported by a dielectric. In most of these transmission lines, the principal mode of energy propagation is by means of a transverse electromagnetic wave (TEM). This implies that the electric and the magnetic fields are transverse to the direction of propagation. If the operating frequency becomes high so that the transverse dimensions of the line become typically 0.1λ, then “higher-order” undesired modes can be set up. These lead to energy loss and hence are avoided in practice. Next, various types of transmission lines will be surveyed.

Two-Wire Open Line

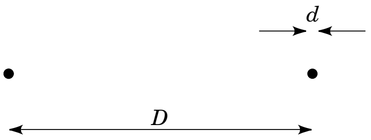

Figure 2. Cross-section of a two-wire line.

A two-wire open line, shown in Fig. 2, consists of two conductors embedded in a dielectric or located in free space. If the conductors have a diameter d, and are separated (center to center) by a distance D, then the characteristic impedance is given by

$$Z_0 = \frac{\eta}{\pi} \ln \frac{2D}{d} \tag{1}$$

where $\eta = 377\ \Omega$ is the characteristic impedance of free space.

If the lines are immersed in a material of relative permittivity ϵ_r, the characteristic impedance is reduced by a factor of $\sqrt{\epsilon_r}$. Typical impedance values for open wire lines vary from 200 Ω to 600 Ω. A two-wire line, encapsulated in a dielectric and with a characteristic impedance of 300 Ω, is commonly used to connect television receivers.

The two-wire line is symmetric and both lines have equal characteristics with respect to the ground. Hence, the two-wire line is called balanced. This is in contrast to the unbalanced coaxial cable (described below). The two-wire line is open (not shielded) and so is susceptible to external interference. Also, at frequencies beyond a few hundred MHz, the radiation losses become large.

Coaxial Cable

The coaxial cable, on the other hand, is an unbalanced line, that is, each conductor has different characteristics with respect to ground. The cross-section of a coaxial line is shown in Fig. 3. The outer conductor is grounded. The inner conductor is generally supported by a dielectric, either in the form of a solid dielectric core, by dielectric spacers, or a helix made of some dielectric material. The electromagnetic fields are confined to the space between the inner and outer conductor and hence the coaxial line is shielded, that is, a coaxial cable has no radiation losses. However, due to the finite conductivity of the inner and outer conductor, they do have a conductor loss. The loss tangent of the dielectric filling contributes a further dielectric loss. The characteristic impedance of an air-filled coaxial line is given by

$$Z_0 = \frac{\eta}{2\pi\sqrt{\epsilon_r}} \ln \frac{b}{a} \tag{2}$$

where a and b are the inside and the outside radius of the line, respectively, and ϵ_r is the relative permittivity of the dielectric material filling the coaxial cables.

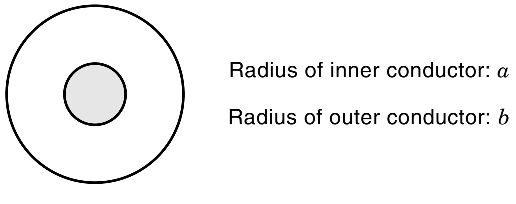

Figure 3. Cross-section of a coaxial cable.

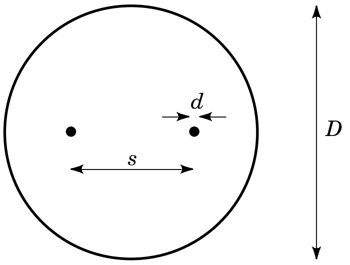

Figure 4. Cross-section of a shielded pair.

For high-power applications, the dielectric inside the cable is air and the line is often put under slight pressure with nitrogen gas to prevent entry of moisture and other contaminants. This increases the voltage breakdown level of the line. For low-power and receiver applications, a solid-dielectric is generally used. The RG58 A/U is a popular 50 Ω coaxial cable.

Shielded Pair Line

The shielded pair line provides a balanced line like the two-wire line, but eliminates radiation loss as in the coaxial cable. A cross-section of the shielded pair line is shown in Fig. 4. The characteristic impedance of the line is given by

$$Z_0 = \frac{\eta}{\pi\sqrt{\epsilon_r}} \ln\left[\frac{2S}{d}\frac{D^2 - s^2}{D^2 + s^2}\right] \tag{3}$$

for $D \gg d$ and $s \gg d$, where d is the diameter of each wire and S is the distance of separation between them. D is the diameter of the outside shield. The finite conductivity of the conductors and the loss tangent of the dielectric are the source of losses in shielded pair lines. Again, ϵ_r is the relative permittivity of the dielectric filling inside the cable.

Parallel-Plate Line

The parallel-plate line is often used in applications requiring low impedances, such as when high currents are required. A parallel-plate line is shown in Fig. 5 and its characteristic impedance is given by

$$Z_0 = \eta\frac{b}{w} \tag{4}$$

where b is the distance of separation between the plates and w is its width. The characteristic impedance of the line can be controlled by introducing a dielectric between the plates. A dielectric of relative permittivity ϵ_r reduces the characteristic impedance by a factor of $\sqrt{\epsilon_r}$.

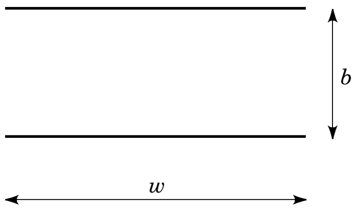

Figure 5. Cross-section of a parallel plate line.

Figure 6. Cross-section of a stripline.

Stripline

The stripline or triplate line consists of a signal conductor surrounded by a dielectric material and placed between two ground planes. A stripline is shown in Fig. 6. These lines are easy to manufacture using standard photo-etching techniques and are used to interconnect components up to a frequency range of 10 GHz. However, it is difficult to connect active devices or have access to the center conductor as the structure is assembled. The stripline has been used extensively in feed structures for microstrip and other kinds of antennas.

Microstrip Line

Microstrip line is the most widely used circuit topology applied in the design and fabrication of microwave devices. As shown in Fig. 7, it is essentially a stripline with the top conductor removed. Generally, one uses a high dielectric constant substrate so that most of the fields are confined in the dielectric region. Typically, the dielectric constant of the substrate is of the order of 10. Hence if the width w is approximately equal to h with t the thickness of the conductors very small, then the characteristic impedance is approximately 50 Ω. Also use of a high dielectric constant substrate leads to compact circuit components as the dimensions are scaled down by the square root of the dielectric constant.

The exact characteristic impedance of microstrip lines and striplines are complicated functions of the dielectric constant, the metal and dielectric thickness, and the width of the line. If two lines are close to each other it is usually difficult to analyze the lines theoretically and a numerical analysis is required.

CABLE PERFORMANCE

The performance of a cable is determined by the characteristic impedance, attenuation, power-handling capability, and velocity of propagation.

Figure 7. Cross-section of a microstrip line.

Characteristic Impedance

The characteristic impedance of the line is determined by the physical characteristics of the cable, which include physical dimensions and the electrical parameters of the structure. When a signal is transferred from one device to a cable, that is, the signal sees a discontinuity, the signal is partly transmitted and partly reflected. The reflected signal is wasted energy and may even interfere with the transimitting device. To eliminate the reflections, the impedance of the cable must match that of the device. A similar effect is seen when a transmission line transfers energy to another device. For maximum energy transfer, the transmission line must be matched at both ends.

To match a signal-launching device to the transmission line requires knowledge of the exact impedance characteristics of the line. In the case where multiple lines are in proximity to each other, the lines mutually interact and hence the impedance depends on the physical locations of the other lines as well. Unintended communication between transmission lines is called crosstalk. Crosstalk is especially important in the case of printed circuit boards, when many transmission lines, in the form of microstrip and stripline circuits, are densely packed in a small physical area. In modern-day digital applications, the signals being transmitted are discrete levels and need to be received at the same levels. If the signal level, on arrival, is different from that on transmit, a transmission error occurs. In building a system with many interconnections, it is extremely important to accurately predict the level of crosstalk and test for the conditions under which transmission errors can occur.

In the case of N transmission lines, due to cross talk, the characteristic impedance of a single line loses its meaning. In this case, all the lines are interrelated and the impedance of the overall system are matrices. The behavior of the transmission system depends on the resistance $[R]$, inductance $[L]$, capacitance $[C]$, and conductance $[G]$ matrices of the line. Each of these matrices is difficult to obtain theoretically and so must be obtained using numerical analysis.

In (2), the authors analyze the crosstalk and coupling between multiconductor transmission lines such as striplines, suspended striplines, and microstrip lines, based on modal analysis in the frequency domain. This approach is extended in the commercially available software packages LINPAR (3) and MATPAR (4). A time domain analysis of the multiconductor transmission problem (5) allows for the tracking of digital waveforms as they propagate along the stripline.

Attenuation

All cables reduce the strength of the signal as it passes through them. This is called attenuation. The attenuation is determined by the losses associated with the line. These losses can be radiation losses in a two-wire line, the conductor losses, and the losses due to the imperfections in the dielectrics. In a multitransmission line system, the attenuation is determined primarily by the operating frequency, which causes nonuniform current distribution on the conductors due to proximity effects and skin effects. The attenuation can be evaluated once the $[R]$, $[L]$, $[C]$, and $[G]$ parameters of the line are known. In addition, the losses in the dielectric material characterized by the loss tangent also attenuate the signal.

Power Handling

For cables designed to handle large amounts of power, like that at the output of a transmitter or an amplifier, the dimension of the conductors should be large enough so that no arcing or voltage breakdown occurs inside the cable.

All the three properties, namely, characteristic impedance, attenuation, and power-handling capability, discussed so far are interrelated and a cable can be optimized for delivering optimum performance, depending on the requirement. For example, if one takes a coaxial cable (Fig. 3) then one has the maximum power-handling capability for a cable of characteristic $Z_0 = 30\ \Omega$. The maximum break down voltage is achieved for cables with characteristic impedances of $Z_0 = 60\ \Omega$. Minimum attenuation is achieved for a cable with $Z_0 = 77\ \Omega$ (1).

Velocity of Propagation

Whenever a signal propagates through a cable there is a time delay between the instants when the signal enters one end of the cable and the time it arrives at the other end. The faster the signal travels, the less the time delay and usually the better the cable is. However, it is usually preferred that the signal arrive without distortion rather than with minimum delay. Time delay is directly related to the velocity of signal propagation in a transmission lime. The velocity of propagation of the signal in a lossless line is given by

$$\nu = \frac{c}{\sqrt{\mu_r \epsilon_r}} \tag{5}$$

where c is the velocity of light and ϵ_r and μ_r are the relative dielectric and permeability constants of the surrounding dielectric, respectively. Hence the velocity of propagation is lower in cables with a high dielectric constant.

Group Delay

In general, one transmits not a single frequency but a band of frequencies over a cable. In audio, music is such a signal consisting of many frequencies between 20 Hz and 20 kHz, simultaneously transmitted over a cable. In video, the picture is first decomposed into three component colors: red, green, and blue, and then transmitted along with a synchronizing signal.

If a cable has electrical properties, like attenuation and delay, that vary as a function of frequency, then the high-frequency signals will arrive later than the low-frequency signals. This is called group delay. This is more of a problem for wideband video than for audio.

TYPES OF CABLES

There are different types of cables for different types of applications. For example, there is audio cables for dealing with audio frequencies, and video cables for transmission of analog and digital video. Also there are cables for high-speed data transmission, and finally there is optical fiber.

Audio Cables (6)

The audio frequency bandwidth is typically from 20 Hz to 20 kHz. Because at these frequencies wavelengths are very long (e.g., the wavelength at 20 kHz is over 9 mi) the impedance of the cable is of no consequence. However, when telephone lines run for miles it is necessary to add equalizers to compensate for the frequency-dependent losses of the line; otherwise, the system would not function. For use in microphones the cables need to be shielded, as the signal level is typically 50 dB to 60 dB below the level of signal on the line and so prevention from external interference is critical.

Also the cables are stranded. The conductors are not a signal solid conductor but are composed of multiple wires. This is sometimes used to reduce the losses due to skin effect. Microphone cables are usually made for flexibility and low handling noise. The conductors are usually stranded and consist of either 19, 40, or 105 strands.

Another kind of audio cable is the speaker cable. Since the output impedance of an amplifier is high (kΩ), building a speaker to match the output impedance for maximum power transfer would require heavy coils. In order to avoid such a complex scenario a transformer is generally inserted between the amplifier and the speaker, to reduce the output impedance to 4 Ω, 8 Ω, or 16 Ω. With the advent of hi-fi and a great separation distance between the speakers and the amplifier it is necessary to use large-gauge cables to minimize transmission losses yet delivering power to the speakers. Large-gauge cables are cables with large diameters. They can be made of many small-gauge wires stranded together.

In digital audio, however, it is required to transmit data at a rate greater than 3 Mbits/s at an impedance level of 110 Ω with a ±20 % tolerance. This can be achieved in a number of ways. First one could use a twisted pair of cables and a dielectric to embed the wires in such a way that the separation distance between the cables does not change. The second is to use solid wires that can also be twisted; however, they lack flexibility. These problems can be avoided if a coaxial cable is used, however, it requires use of special devices to convert balanced lines into unbalanced lines and vice-versa. Such devices are called baluns. The use of coaxial cables can make the runs as long as 500 m. Typically they have 75 Ω characteristic impedance.

The problem with digital signals when propagating over cables is that, due to the attenuation of the cable and frequency dispresion, the signals no longer look like square waves. This is called jitter. Typically digital audio signals have jitter of the order of 300 ps to 500 ps. When jitter increases then the receivers fail. To check the quality of the digital audio cables one can perform the eye test and the bit error rate testing. The eye test deals with the response of a cable due to a pseudorandom bit sequence. The sequence is generated by creating an 8 bit word by taking all possible transitions between 0 and 1. By observing the response pattern to this so-called “eye” it is possible to characterize the time jitter and the noise margin.

The bit error rate (BER) is determined by comparing the output at the end of a long 75 Ω coaxial cable when compared to a short length. The interesting point is that the BER increases significantly over very short distances. Typically a BER of 10^{-12} (equivalent to one bad bit in almost two days at a transmission rate of 6 Mbits of digital audio) can be achieved over 5000 ft for a coaxial cable as opposed to 75 ft while using a standard audio cable. Also the crosstalk has to be less than 35 dB. Crosstalk can be reduced in flat cables by having signal ground configuration followed by twisting the signal cables.

Video Cables (6)

For analog video transmission, which generally covers from dc to 4.2 MHz, typically coaxial cable is used. The reason for using coaxial cables is that one can have tighter tolerances for the characteristic impedance. Precision video cables can be made with characteristic impedance tolerances of ±3 Ω or even ±1.5 Ω. For baseband video, it is necessary to use an all-copper-center conductor to obtain the best low-frequency performance followed by a braid or double-braid shield, as braid is most effective at low frequencies.

A video signal is generally decomposed into its blue, green, and red components for transmission. These components are followed by a synchronizing pulse at 3.58 MHz. Generally a bundled coaxial line containing three to five coax cables is used. The three component colors are sent separately over three cables and the synchronization signal over the fourth cable. The fifth cable may be used in addition for sending horizontal and vertical synchronizing signals separately. A timing error greater than 40 ns is considered to be problematical. Typically good-quality coax cables can run for several hundred feet before any problem with jitter occurs. A time domain reflectometer is often used to carry out fault diagnosis over these lines.

Sometimes triaxial lines are used in wiring cameras. Typically a high voltage, on the order of 160 V to 600 V, occurs between the two braids and the video signal is transmitted through the innermost conductor and the center braid.

For digital video, either one uses a parallel transmission mechanism, where a 270 Mbit signal is distributed using 10 pairs. An eleventh pair uses the clock signal. A typical length over which the signal is transmitted by a single run is about 30 m. For serial transmission of digital video one needs to transmit between 143 Mbit and 360 Mbit over a single coaxial line, which typically has a very low capacitance of 20 pF/ft and the impedance tolerance is around 50 ± 1.5 Ω. Also BNC connectors are used for these cables. Since a 270 Mbit data rate has a bandwidth of 35 MHz it is essential that few connectors are used between the source and the sink. Putting connectors on a line and thereby incorporating too many short segments of a line increases the level of mismatch. The cables in these cases have large skin effect losses at the higher frequencies (>50 MHz). The braids in these cable should be as close as possible, which leads to a foil-braid type of construction. Foil is very effective at high frequencies and has better performance than braids over 10 MHz.

Usually for the NTSC system (composite) the data rate is 143 Mbits. For the PAL system it is 177 Mbit and for HDTV it is 360 Mbit. The appropriate length of the cable over which the signal must be transmitted is determined by the BER when an attenuation of 6 dB is added to the line. If bit error appears with this extra 6 dB of attenuation then the cable is considered too long.

Multimedia Cables (6)

For multimedia applications the requirements for the cables are different. The world of multimedia generally encompasses publishing, broadcasting, and telephone, and implies that the signal from each component needs to be fused together. Once the fused data are obtained they will usually be digitized both for audio and video and transmitted over the respective cables. It is surprising that twisted pair cables and fiber optic cables are becoming popular while coaxial cable in this application is dying. The data are handled usually by a SCSI (small computer system interface), which generally deals with 8 bit words at a maximum of 5 Mbps. It is usually transmitted over 25-, 34- or 50-pair cable with an overall shield. For balanced lines they have a characteristic impedance of 120 Ω, and for unbalanced line it is 80 Ω. The maximum distance one can go with this system is 6 m for the unbalanced mode and 25 m in the balanced mode before the data become unreadable.

Even though fast SCSI deal with a 10 Mbps data rate whereas wide SCSI deals with 16 bit words, their combination will allow for maximum data rates of 40 Mbps, which is a far cry from 143 Mbps or 270 Mbps for digital video.

An alternate of SCSI is the RISC (reduced instruction set computing), which is a much newer approach than SCSI. They are often used in microprocessors which are a part of the desktop computers called workstations. The cables used to transmit the data are generally 100 Ω or 120 Ω shielded pairs for data transfers. The RISC standard uses three twisted pairs and uses the jacks which uses eight conductors (4-pairs) and is an outgrowth of the telephone jack. For paired cables, this type of connector is the simplest and cheapest. However, since the connector and the size of the cables that fits the jack are fixed, this is an inherent flaw of the RISC cables. This limitation is partially overcome by placing two layers of plastic over the wire leading to the low values of capacitance (12 pF/ft to 15 pF/ft), so this type of cable could be used for reasonable run lengths and data rates.

Finally, the Ethernet, which uses standard 50 Ω coaxial cables, has different versions. For a large-size, low-loss long run a quad-shield cable called thicknet may be used. A low-loss coaxial line with a solid center copper conductor having a braided shield, supported by a polystyrene dielectric, which has a loss of 14.5 dB per 100 ft at 900 MHz and 4.1 dB/ft at 100 MHz may be used. The difference in performance between various 50 Ω cables can be dramatic, as the attenuation changes dramatically depending on the quality of the cable.

At 155 Mbps, asynchronous transfer mode (ATM) is currently the fastest data-transfer system. Even though digital video at 143 Mbit can be transmitted through the ATM mode, this means it can only be used by a single user. This is still a far cry from data rates of 270 Mbits (NTSC) or 1.485 Gbits (HDTV). The ATM is carried by twisted pairs.

The next problem is how to check and test these cables for integrity. In addition, care must be taken during installation so that the electrical characteristics remain the same. The following items should be used as guidelines when dealing with telecommunication cables:

- Use proper connection hardware: This implies that proper connectors and jacks, which can transmit the desired bandwidth signals, must be used.
- Test the cable: After the cable is appropriately connected it is necessary to check its performance using a TDR and/or use the eye test to check for the bit error rate.
- Eliminate tension stress: The higher the data rate, the more careful one has to be with the cable. Strong pulling forces may change the physical cross-sectional dimensions of the cable and hence its characteristic impedance.
- Avoid tightly cinched bundle: Again, tying up the cables too tightly may change their physical dimensions, leading to the impedance mismatch.
- Keep kinks out: Kinks in a twisted pairs may lead to impedance mismatch and severe degradation in performance.
- Strip only as much as necessary: Stripping the cables changes its characteristic impedance. Typically no more than an inch of the cable should be stripped, which is determined by the types of connector to be used.
- Reduce untwisting of pairs: Since the twisted pair eliminate the common crosstalk, untwisting it will change its characteristics.
- Make no 180° bends: The cables should be bent, if necessary, gently, and the bent radii ideally should be less than 4 times the cable diameter for horizontal runs and never more than 10 times the diameter.
- Stagger the cables: Try to randomize the spacing between cables so as to reduce constructive interference such as crosstalk.

FIBER OPTIC CABLE

Fiber optic cable should be used whenever the device has an attachment to it and when fiber is connected to another fiber. It makes sense to use them for long runs, from hundreds of feet to hundreds of miles, depending on the type of fiber. Also, if the ambient radio frequency interference sources are high in number, it is good to use fiber optic cable, as it is immune from radio frequency interference including lightning. Also, when the sizes of the cables are a problem or if it is open to environment where oxidation can occur, fiber is a good solution. Finally, when wide bandwidths are desired, typically GHz, then fibers are desirable.

There are three kinds of fibers: (1) plastic, (2) single, and (3) multimode glass fibers. Plastic fibers are usually 900 μm (microns) in diameter; however, they are very lossy and cannot be practically used for distances greater than 20 ft to 30 ft.

Glass fiber, on the other hand, can run for long distances. They typically have a core with a cladding followed by a coating. Multimode fibers are generally used for short distances (1000 ft or less). They come in various sizes; however, the most common are 50 mm, 62.5 mm, and 100 mm. In addition, multimode connectors are cheap and easily available. The glass fibers operate at optical wavelengths of 850 nm or 1300 nm.

Because these two optical wavelengths are significantly different, various fibers have different operational bandwidths corresponding to these two windows. For example, in a 50 mm fiber, the operational bandwidth at the two windows are the same. However, at 100 mm, the operational bandwidths may differ by 50%. For 62.5 mm fiber the bandwidth is 660 MHz/km and could even carry 1.5 Gbits. The fiber can be step index or a graded index, which implies that the dielectric constant of the cladding and the core changes dramatically for a step index; whereas for a graded index, the change is gradual.

The single mode fiber is generally used for long-haul ultrawide bandwidth cables and is widely used by long-distance telephone companies. It can typically transmit 10 Gbps over hundreds of miles. The single mode fiber is generally 5 mm to 10 mm in diameter and hence very very small. Since the cross-sectional area of the cable is small a very powerful laser is required to transmit signals over long distances. The single mode fiber also has two operating windows, at 1300 nm and 1550 nm. Since fibers are affected by temperature fluctuations and water there are two types of packages to protect it from the environment. One is the loose tube and the other is the tight tube. The loose tube, as the terminology implies, fits loosely around the fiber and allows expansion and contraction of the fiber without affecting its performance.

A tight tube, on the other hand, would break the fiber if there were large temperature changes. So the "outdoor" tight-tube fibers are protected by conduits. Most tight-tube fibers are suitable for controlled environments like in an office or in connecting buildings. One can use either a single fiber per tube or a bunch of up to 240 fibers per tube.

It requires special care to put a connector on a fiber. The only way to check if the connector has been put on it properly is to test the assembly, either under a special microscope or use an optical reflectometer.

A cable is as good as the connectors that go with it. It is very important that, depending on the bandwidth and the frequency of operation, the proper connector be used. For example, at low frequencies, there are the RCA-type connectors (for up to a few MHz), used primarily in baseband video applications. BNC connectors operate up to a few hundred megahertz. The *N*-type connectors can be used up to 12 GHz, whereas the SMA connector can be used up to 26 GHz. Broadband *k*-type connectors can operate up to 40 GHz.

Two issues that are of particular relevance to the performance of the fiber are the connectors and the grounding. However, a thorough investigation of these two issues are beyond the scope of this article. A more thorough treatment can be found by Lampen (6).

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