Chapter 1 Principles of Transmission

Chapter 1 focuses on the main concepts related to signal transmission through metallic and optical fiber transmission media. Among those concepts, this chapter discusses types of signals and their properties, types of transmission, and performance of different types of transmission media. The appendix provides additional information about signals provided in North America and Europe.

This chapter has been updated to reflect current best practices, codes, standards, and technology.

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Metallic Media

IMPORTANT: It is assumed that the reader has an elementary knowledge of physics, electronics, and electrical concepts.

Overview

Section 1 of this chapter provides basic information about how signals are transmitted and received over metallic media. Section 1 also presents information specific to balanced twisted-pair transmission topics, including:

- Transmission fundamentals.
- Standards.
- Applications support.
- Performance and equipment compatibility.

Section 2 of this chapter addresses optical fiber transmission topics, including:

- Transmission fundamentals.
- Standards.
- Applications support.
- Performance and equipment compatibility.

NOTE: Approximate metric measurements with corresponding imperial conversions within this chapter are denoted with the approximate symbol (≈) at the beginning of the metric measurements. Exact metric measurements with corresponding imperial conversions will not have this approximate symbol.

Electrical Conductors

Overview

An electrical conductor is any material that can carry an electric charge from one point to another. Copper's properties and cost make it a suitable conductor for processing into information technology systems (ITS) wire and cable.

The most common electrical conductors that ITS wire and cable are made of are:

- Copper.
- Copper-covered steel.
- High-strength copper alloys.
- Aluminum.

Silver and gold also are good electrical conductors, but they are not generally used because of their high cost.

Description of Conductors

Table 1.1 gives a brief description of the most common conductors.

Table 1.1
Conductor descriptions

Conductor	Description
Copper	Sets the standard for comparing the conductivity of other metals. Annealed copper is used as the reference value (e.g., 100% conductivity). Other common conductors have less than 100% of annealed copper's electrical conductivity.
Copper-covered steel	Also known as copper-clad steel, it combines the conductivity of copper with the strength of steel. It is typically used as a conductor for aerial, self-supporting drop wire. In the production of this type of conductor, a copper layer is bonded to a steel core.
High-strength alloy	A mixture of copper and other metals to improve certain copper properties and characteristics of copper. Alloys such as cadmium–chromium copper and zirconium copper offer important weight reductions or greater strength. These factors are especially important in aerospace and computer applications. However, the alloying of pure copper always has an adverse effect on its conductivity. The alloys mentioned above have 85% conductivity ratings.
Aluminum	A bluish silver-white malleable ductile light trivalent metallic element that has good electrical and thermal conductivity, high reflectivity, and resistance to oxidation. It has about 60% conductivity compared with copper and is lighter in weight than copper. Aluminum is most commonly used in electrical utility distribution lines.

Comparison of Solid Conductors

The properties of solid conductors made of different metals or alloys are shown in Table 1.2.

Table 1.2
Solid conductor properties

Property	Copper	Copper/Steel	High-Strength Alloys	Aluminum
Electrical conductivity	Sets the Standard	Less than Copper	85% typical	61% typical
Ductility	Good	Good	Best	Good
Solderability	Good	Good	Good	Special techniques
Corrosion resistance	Good	Good	Poor	Good
Oxidation resistance	Good	Good	Good	Poor
Weight	≈14.25 kg (31.4 lb)	≈13.06 kg (28.8 lb)	—	≈4.32 kg (9.5 lb)
Tensile strength	250,000 kPa (36,250 psi)	380,000 kPa (55,114 psi)	To 550,000 kPa (79,771 psi)	69,000 kPa (10,000 psi)

kg = Kilogram
kPa = Kilopascal
lb = Pound
psi = Pound per square inch

NOTE: Weight and strength are approximate and based upon ≈305 meters (m [1000 feet (ft)]) of 10 American wire gauge (AWG) [2.6 millimeters (mm [0.10 inch (in)])] solid conductor at 20 degrees Celsius (°C [68 degrees Fahrenheit (°F)]).

Solid Conductors versus Stranded Conductors

Solid conductors consist of a single piece of metal wire. Stranded conductors bundle together a number of small-gauge solid conductors to create a single, larger conductor.

Advantages of solid conductors include the following:

- Less costly
- Less complex termination systems
- Better transmission performance at high frequencies
- Less resistance

Advantages of stranded conductors include the following:

- More flexible
- Longer flex life
- Less susceptible to damage during crimp termination processes

Composite Conductor

Composite conductor is a term used to describe conductors constructed from nontraditional materials (e.g., metallic resins, graphite). This conducting substance is impregnated into, coated over, or between layers of polymer tape or other similar material. These types of conductors are often used in telephone receiver and mounting cords, inexpensive headsets, and other low-end audio devices. They also are used to embed audio devices into plastic shells such as helmets.

Advantages of composite conductors include the following:

- Flexible
- Lightweight
- Inexpensive and easy to produce
- Easily embedded into other materials
- Low coefficient of expansion

Disadvantages of composite conductors include the following:

- Poor analog transmission characteristics, including high attenuation, especially above 4000 hertz (Hz)
- Poor digital transmission characteristics
- Easily damaged unless encased in a rigid material
- Inconsistent quality

Cables with these types of conductors are not recommended for use with modern telecommunications networks. If equipment is shipped with this type of cable, discard and replace the cable with the proper structured cabling patch cord for the project.

American Wire Gauge (AWG)

Overview

Through usage and industrial standardization, the AWG sizing system has become generally accepted in North America. The AWG system is important because it provides a standard reference for comparing various conductor materials.

NOTE: For further information on AWG and conductor size, see Chapter 9: Power Distribution.

Insulation

Overview

Insulation (also called a dielectric) is used to isolate the flow of current by preventing direct contact between:

- Conductors.
- A conductor and its environment.

The insulation on most modern wire and cables consists of one or more plastic materials applied by a variety of methods. Extruded polymers are generally used as insulation because they have proven to be the most functional, dependable, and cost effective insulation materials.

The electrical performance of balanced twisted-pair cables is inversely related to the insulation's dielectric constant and dissipation factor. Cables with a lower dielectric constant and dissipation factor have better transmission performance, including lower attenuation characteristics and lower capacitance.

Dielectrics also reduce the electromagnetic (EM) coupling between conductors by increasing conductor separation.

Historically, telecommunications cable conductors were insulated with polyvinyl chloride (PVC) and polyethylene (PE). PVC-insulated conductors were commonly used for inside plant cables, and PE-insulated conductors were commonly used for outside plant (OSP) cables. PE-insulated conductors display better transmission performance. However, they are unsuitable for indoor use unless they are encased in a suitable fire-retardant jacket material.

Overview, continued

Transmission performance has been improved. Several materials have been introduced to the indoor cabling market.

These materials, which provide lower smoke and flame spread characteristics as well as improved transmission performance, include:

- Fluorinated ethylene propylene (FEP [e.g., Teflon®, NEOFLON FEP™]).
- Ethylene chlorotrifluoroethylene (ECTFE [e.g., Halar®]).

NOTE: Teflon is a trademark of E.I. du Pont de Nemours & Company, Inc.; NEOFLON FEP is a trademark of Daikin America, Inc.; and Halar is a trademark of Solvay Solexis.

Electrical Characteristics of Insulation Materials

Table 1.3 compares the electrical characteristics of various insulation types.

Table 1.3
Electrical characteristics of common insulation types

Insulation Type	Dielectric Constant	Dissipation Factor
FEP	2.1	0.0005
PE	2.3	—
ECTFE	2.5	0.01
PVC (nonplenum rated)	3.4	—
PVC (plenum rated)	3.6	0.04
XL polyolefin	3.8	—

ECTFE = Ethylene chlorotrifluoroethylene
FEP = Fluorinated ethylene propylene
PE = Polyethylene
PVC = Polyvinyl chloride
XL = Cross-linked

The electrical characteristics listed in Table 1.3 do not account for the increase in dielectric properties that occur in all cables as temperatures rise. ECTFE and FEP insulations perform better than PVC as temperatures increase. The dielectric properties of insulation materials can have a significant effect on cable attenuation at high frequencies.

Electrical Characteristics of Insulation Materials, continued

Table 1.4 explains the electrical characteristics used to compare and evaluate types of insulation.

Table 1.4
Explanations of insulation electrical characteristics

Electrical Characteristic	Explanation
Dielectric constant	The ratio of the capacitance of an insulated conductor to the capacitance of the same conductor uninsulated in the air. Air is the reference with a dielectric constant of 1.0. Generally, a low dielectric constant is desirable. The dielectric constant changes with temperature, frequency, and other factors.
Dielectric strength	Measures the maximum voltage that an insulation can withstand without breakdown. Dielectric strength is recorded in breakdown tests in which the voltage is increased at a controlled rate until the insulation fails. The voltage at that time, divided by the thickness of the insulation, equals the dielectric strength. Dielectric strength is expressed in volts (V) per millimeter (or V per mil, where 1 mil equals 0.001 inch). A high value is preferred (to withstand voltage stress). Insulated conductors in telecommunications applications have a typical dielectric strength of between 7500 and 30,000 V per millimeter (300 and 1200 V per mil).
Dissipation factor	The relative power loss in the insulation is due to molecular excitement and subsequent kinetic and thermal energy losses. This is of primary concern in the high-frequency megahertz ranges where signal loss increases because of the structure of the insulating material. For example, polar molecules, such as water, absorb energy in an EM field. This effect is best understood in terms of microwave heating. A low dissipation factor is preferable.
Insulation resistance (IR)	The insulation's ability to resist the flow of current through it. For inside conductors, IR is typically expressed in megohm•kilometer or megohm•1000 feet. NOTE: There is an inverse relationship between insulation resistance and cable length (i.e., as the cable length increases, the insulation resistance becomes smaller).

Balanced Twisted-Pair Cables

Overview

Metallic conductor cables commonly use balanced twisted-pair construction. Production of small cables of this type involves twisting individual pairs and grouping those twisted pairs to form either a cable or a unit for larger cable.

The main reason for twisting pairs of conductors is to minimize crosstalk and noise by decreasing capacitance unbalance and mutual inductance coupling between pairs. Twisting conductors also improves the balance (physical symmetry) between conductors of a pair and reduces noise coupling from external noise sources.

Pair-to-pair capacitance unbalance is a measure of the electric field coupling between two pairs if a differential voltage is applied on one pair and a differential noise voltage is measured on another pair in close proximity.

Mutual inductance is a measure of the magnetic field coupling between two pairs if a differential current is applied on one pair and a differential noise current is measured on another pair in close proximity.

NOTE: The conditions under which crosstalk is measured include both capacitance unbalance and mutual inductance coupling effects.

Pair Twists

Both mutual inductance and capacitance unbalance are affected by the relative length and uniformity of pair twists. To minimize crosstalk within a multipair cable, each pair is given a different twist length within a standard range.

Generally, a counterclockwise twist length between ≈50 mm and ≈150 mm (2 in and 6 in) is used for voice and low-frequency data cables. Adjacent pairs are generally designed to have twist length differences of at least ≈12.7 mm (0.50 in). These specifications vary according to the manufacturer.

Tight Twisting

The option of tight twisting, where pair twist lengths are less than ≈12.7 mm (0.50 in), is used particularly within and between computers and other data processing equipment.

Category 5e, category 6, category $6_{A,}$ and higher category cables employ tight twisting for optimum transmission performance.

Tight twists tend to preserve their shape better in a cable. Longer twists tend to nest together as they are packed in a cable, whereas shorter, tighter twists are less likely to deform.

Environmental Considerations

Electromagnetic Interference (EMI)

Electromagnetic interference (EMI) is stray electrical energy radiated from electronic equipment and electronic systems (including cables). EMI can cause distortion or interference to signals in other nearby cables or systems.

NOTE: See Chapter 2: Electromagnetic Compatibility for a detailed discussion of EMI.

Temperature Effects

Balanced twisted-pair cables used in premises applications are expected to operate under a variety of environmental conditions. One concern is the attenuation increase at higher cable temperatures (above 20 °C [68 °F]).

High temperatures can be routinely encountered in:

- Exterior building walls.
- Ceiling spaces, including plenums.
- Mechanical rooms.

Intermittent failures have been reported in LANs as a result of solar heating of walls and the cabling inside them. To avoid such problems, the attenuation at the highest expected temperature must be used in the premises cabling design process.

Attenuation increases with temperature because of increased:

- Conductor resistance.
- Insulation dielectric constant.
- Dissipation factor.

The attenuation of some cables may exhibit significant variations because of temperature dependence of the material.

All twisted-pair cables are referenced in the cabling standards at 20 °C +/- 3 °C (68 °F +/- 5.4 °F). For adjustment purposes, the attenuation increase is 0.2 percent per degree Celsius for temperatures above 20 °C (68 °F) for screened cables, 0.4 percent per degree Celsius for all frequencies and for all temperatures up to 40 °C (104 °F), and 0.6 percent per degree Celsius for all frequencies and for all temperatures from 40 °C to 60 °C (104 °F to 140 °F) for all unscreened cables.

A temperature coefficient of 1.5 percent per degree Celsius is not uncommon for some category 3 cables.

NOTE: Consult the manufacturer's specifications on the cable insertion loss margin compared with the maximum insertion loss that is specified in the standard.

Temperature Effects, continued

Reference should be made to the relevant cabling component standard for the authority having jurisdiction (AHJ) because the attenuation requirements for each cable type and category or class vary.

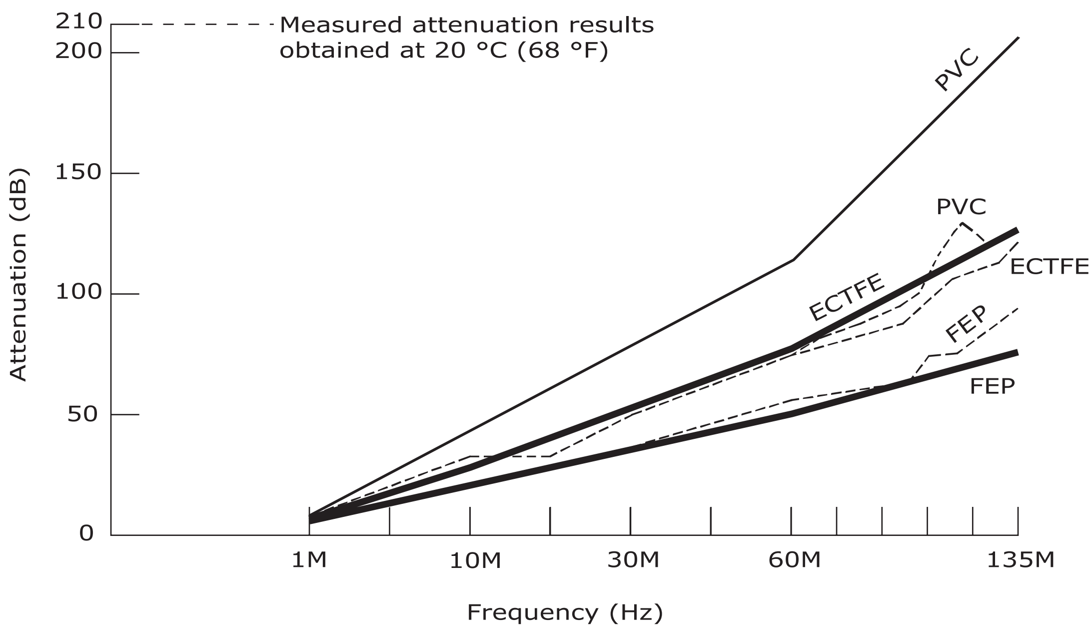
Some insulation performs better than others under high temperature conditions. Figures 1.1, 1.2, and 1.3 show a comparison of attenuation and frequency at various temperatures for:

- FEP (e.g., Teflon®, NEOFLON™ FEP).
- ECTFE (e.g., Halar®).
- PVC.

NOTE: Teflon is a trademark of E.I. du Pont de Nemours & Company, Inc.; NEOFLON FEP is a trademark of Daikin America, Inc.; and Halar is a trademark of Solvay Solexis.

For more information on Figures 1.1, 1.2, and 1.3, refer to "Temperature-Related Changes in Dielectric Constant and Dissipation Factor of Insulations Increase Attenuation in Data Cables Used in Building Plenums," by C.Y.O. Lin and J.P. Curilla, which is available from IEEE®.

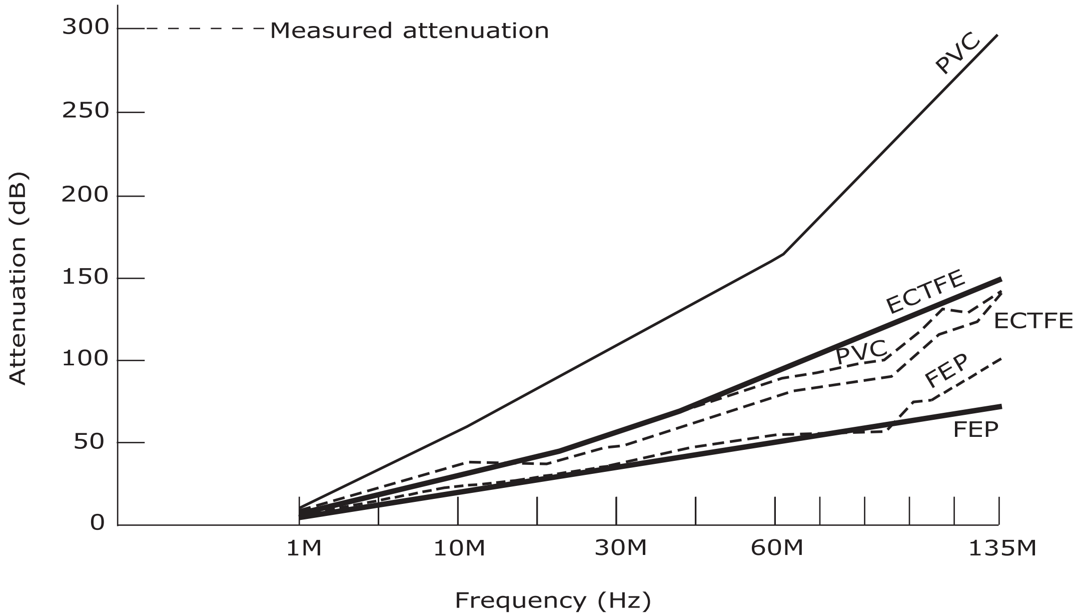
Figure 1.1
Calculated attenuation values for cables insulated with FEP, ECTFE, and PVC from 1 MHz to 135 MHz at 22 °C (72 °F)



°C = Degree Celsius
dB = Decibel
ECTFE = Ethylene chlorotrifluoroethylene
°F = Degree Fahrenheit
FEP = Fluorinated ethylene propylene
Hz = Hertz
m = Meter
MHz = Megahertz
PVC = Polyvinyl chloride

Temperature Effects, continued

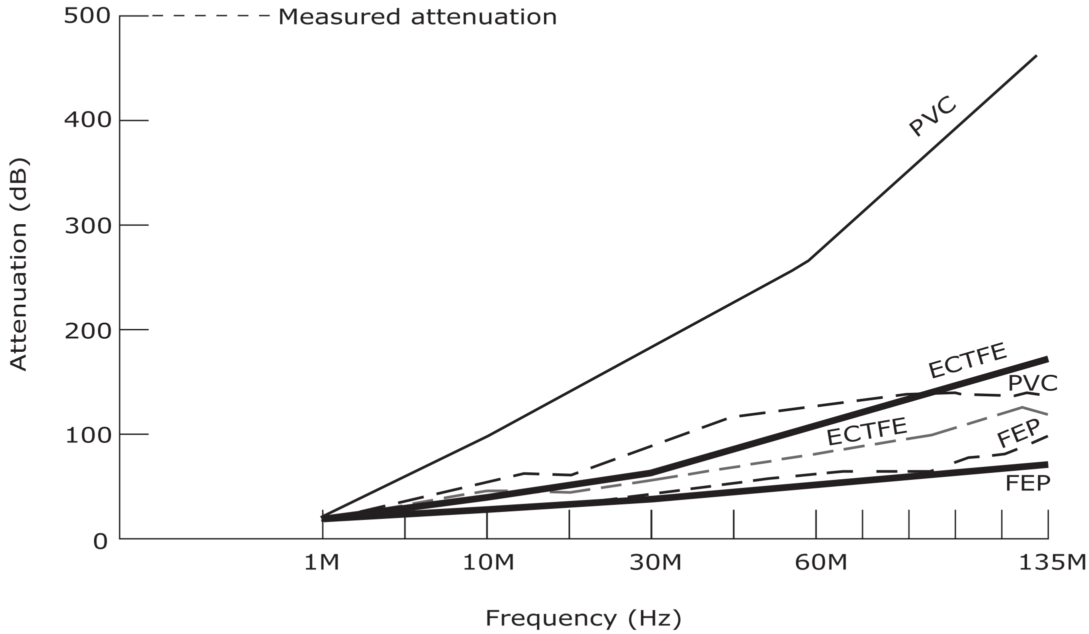
Figure 1.2
Calculated and measured attenuation values for cables insulated with FEP, ECTFE, and PVC from 1 MHz to 135 MHz at 40 °C (104 °F)



dB = Decibel
ECTFE = Ethylene chlorotrifluoroethylene
FEP = Fluorinated ethylene propylene
Hz = Hertz
m = Meter
MHz = Megahertz
PVC = Polyvinyl chloride

Temperature Effects, continued

Figure 1.3
Calculated and measured attenuation values for cables insulated with FEP, ECTFE, and PVC from 1 MHz to 135 MHz at 60 °C (140 °F)



dB = Decibel
ECTFE = Ethylene chlorotrifluoroethylene
FEP = Fluorinated ethylene propylene
Hz = Hertz
m = Meter
MHz = Megahertz
PVC = Polyvinyl chloride

Cable Shielding

Description

A shield is a metallic covering or envelope enclosing the:

- Insulated conductor.
- Individual group of conductors within a core.
- Cable core.

Shields are made of foil or braided metal strands. They are usually tinned copper, bare copper, aluminum, or another electrically conductive material.

When properly terminated, bonded, and grounded (earthed) cable shields can:

- Reduce the radiated signal from the cable.
- Reduce the effects of electrical hazards.
- Minimize the effect of external EMI on the conductors within the shielded cable.

Shielding Effectiveness

EM waves are attenuated and reflected by a shield. Consequently, the effectiveness of a shield depends on such factors as the:

- Type and thickness of the shield material.
- Number and size of openings in the shield.
- Effectiveness of the bonding connection to ground.

The shielding effectiveness of a cable shield is determined by measuring the surface transfer impedance. The surface transfer impedance is the ratio of the conductor-to-shield voltage per unit length to the shield current. Surface transfer impedance is usually measured in milliohms per meter or ohms per foot.

Cable shields are usually connected in such a way that they may be called upon to carry relatively large currents that are induced from an external field. The current flowing in the shield results in a voltage drop along the shield because of the shield resistance. As a result, there is a voltage gradient between the conductors inside the shielded cable and the shield itself.

Types of Shields

There are many types of shields, including:

- Braided wire.
- Spiral-wrapped wire.
- Reverse spiral-wrapped wire.
- Metal foils, either helically or longitudinally wrapped.
- Hybrids, combining other types.
- Metal tubes.
- Conductive nonmetallic materials.

Solid Wall Metal Tubes

A low-resistance solid wall metal tube (conduit) is the best possible shield, displaying superior shielding properties at all frequencies. While solid metal tubes are used as shields in some specialized applications, their rigid nature makes them inappropriate for most normal cable applications.

Conductive Nonmetallic Materials

Conductive nonmetallic materials (e.g., semi-conductive tapes made with high carbon content) are sometimes used at power and some low audio frequencies. These semiconductive shields are not normally used for applications at frequencies above 500 kilohertz (kHz).

Selecting a Cable Shield

Consider the following primary criteria when selecting a cable shield for a given application:

- Nature of the signal to be transmitted—Frequency range affects the performance of most shields.
- Magnitude of the EM fields through which the cable will run—EM fields are usually expressed in volts per meter (V/m) at a given frequency.
- Electromagnetic compatibility (EMC) regulations—Any cable operating within a given system must be designed to conform to the EMC radiation limits of that system.

  NOTE: See Chapter 2: Electromagnetic Compatibility, Class A and Class B limits.

- Physical environment and specific mechanical requirements—The shield may need to add support to the cable.

  NOTE: Overall cable size limitations also may affect this decision.

Comparison of Cable Shields

Types of cable shields are compared in Table 1.5.

Table 1.5
Types of cable shields

Characteristic	Single-Layer Braid	Multiple-Layer Braid	Foil Foil + Braid	Solid Conduit	Flexible Conduit
Shield effectiveness audio frequency	Good	Good	Fair to excellent NOTE: Depending on the thickness of foil and the shield resistance of the foil/ foil + braid	Excellent	Good
Shield effectiveness radio frequency	Good	Excellent	Excellent	Excellent	Poor
Normal coverage	60–95%	95–97%	100%	100%	90–97%
Fatigue life	Good	Good	Fair	Poor	Fair
Tensile strength	Excellent	Excellent	Poor	Excellent	Fair

NOTE: In the shield effectiveness ratings:

- Poor means less than 20 decibels (dB).
- Fair means 20 to 40 dB.
- Good means 40 to 60 dB.
- Excellent means more than 60 dB.

The effectiveness of single-layer and multiple-layer braids against magnetic fields is poor. For foil and conduit to effectively shield against magnetizable fields, a high-permeability material must be used. Permeability is the property of a magnetic substance that determines the degree in which it modifies the magnetic flux in the region occupied by it in a magnetic field.

Drain Wires

Overview

If a shield is not properly grounded, its effectiveness is reduced. Drain wires are sometimes applied in addition to a shield to provide an easier means for grounding (earthing) the shield and to ensure shield continuity for metallic foil shields. A drain wire running the length of the cable next to the shield provides ample grounding (earthing).

NOTE: Shield coverage over exposed conductors shall be maintained at a connector termination and not only through a drain wire.

Drain wires are used:

- With foil, nonmetallic, and hybrid shields.
- Occasionally with braided shields to make it easier to terminate the shield ground.

Applications

Drain wires are usually:

- Applied longitudinally next to the metallic part of the shield for the length of the cable.
- Made of solid or stranded copper conductors, which may be bare or tinned.

Specifying Drain Wire Type

The type of drain wire must be specified when selecting the type of cable. The termination requirements of the application determine whether the drain wire should be made of bare or tinned copper in stranded or solid construction.

Analog Signals

Overview

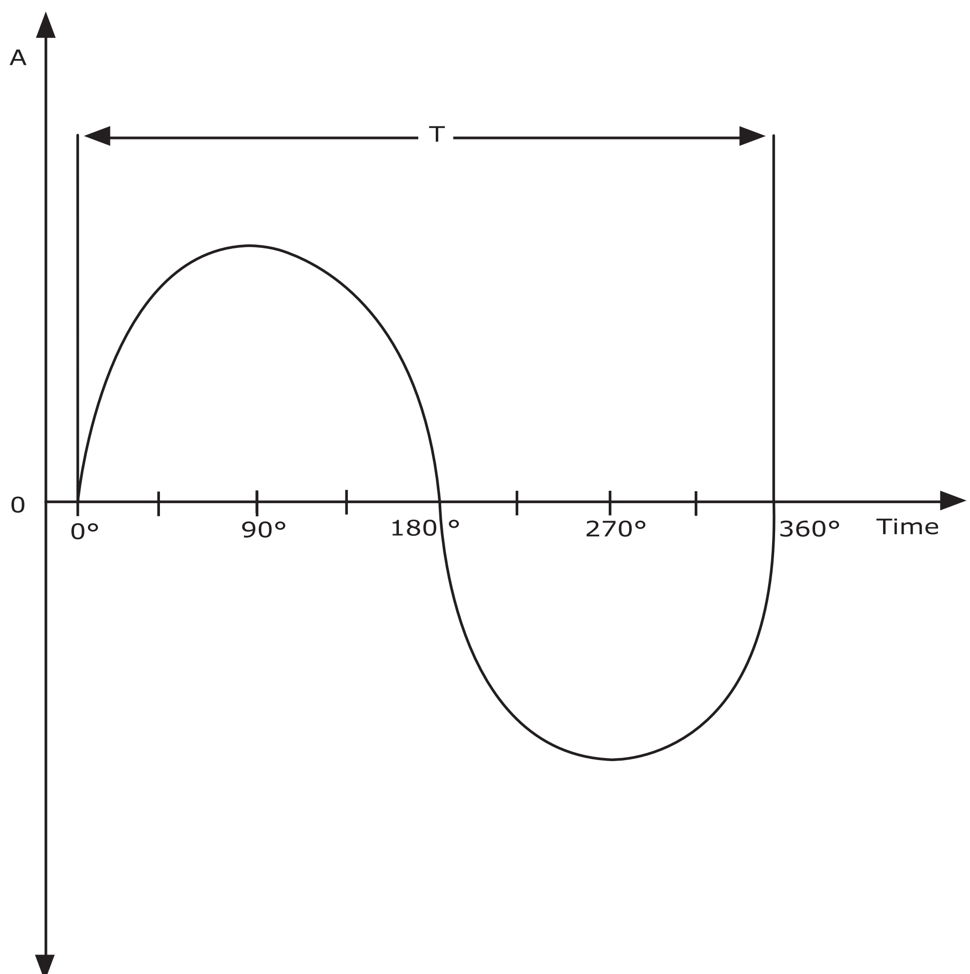
A review of some of the fundamental concepts of voice telephony is covered in this section. It serves as an introduction to the subject of analog signals. Subsequent sections provide a concise and in-depth treatment of both analog and digital transmission.

An analog signal is in the form of a wave that uses continuous variations in time (e.g., voltage amplitude or frequency variations) to transmit information.

Sinusoidal Signals

The most fundamental example of an analog signal is a sinusoid. (see Figure 1.4).

Figure 1.4
Example 1 of a sinusoidal signal



A = Amplitude
0 = Zero
T = Time for one cycle

Sinusoidal Signals, continued

A sinusoid is an oscillating, periodic signal that is completely described by three parameters:

- Amplitude
- Frequency
- Phase

In Figure 1.4, the amplitude of the sinusoid is A. The sinusoid oscillates with a period indicated by the interval T, called the cycle time. The number of these periods that occurs in a second defines the frequency (f) of the sinusoid in cycles per second (Hz). Cycle time and frequency are related by the relationship $f = 1/T$. For example, a sinusoid with a cycle time of .001 seconds (s) has a frequency of 1000 Hz.

Hertz is the standard unit of frequency measurement. The range of frequencies that human beings can hear is approximately 20 Hz to 20,000 Hz. Voice telephone circuits are generally limited to the range of 300 to 3400 Hz, which provides adequate quality for normal conversation.

Standard notations for frequencies often encountered in communications systems are shown in Table 1.6.

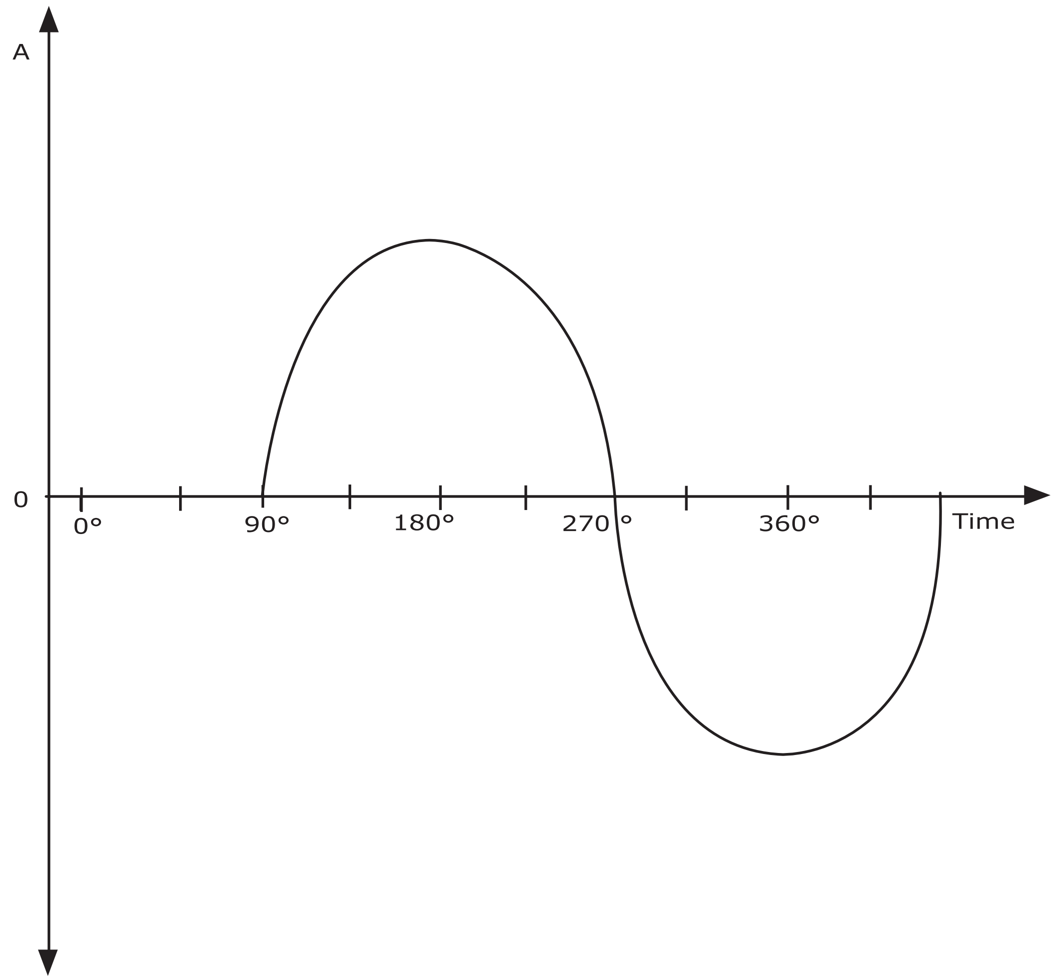
Table 1.6
Common units of frequency measurement

Unit	Abbreviation	Value
Kilohertz	kHz	1000 Hz
Megahertz	MHz	1,000,000 Hz (1000 kHz)
Gigahertz	GHz	1,000,000,000 Hz (1000 MHz)

Sinusoidal Signals, continued

Phase is a description of the reference time, t = 0. For example, the sinusoid shown in Figure 1.5 has the same amplitude and frequency as the sinusoid in Figure 1.4; these two sinusoids differ only in phase (by 90 degrees in this case). One cycle is equal to 360 degrees.

Figure 1.5
Example 2 of a sinusoidal signal



A = Amplitude
0 = Zero
T = Time for one cycle

Sinusoidal Signals, continued

Mathematically, any sinusoid can be expressed as:

$$v(t) = A \sin(2\pi ft + \varphi)$$

Where:

A = Amplitude
f = Frequency
φ = Phase
t = Time

Sinusoidal signals are of fundamental importance in understanding signal transmission. This is largely the result of a mathematical theory developed by Joseph Fourier (1768-1830). Fourier was able to show that any analog signal can be mathematically described as a sum of sinusoidal signals that differ in amplitude, frequency, and phase. This description of a signal in terms of its sinusoidal components is called the signal's spectrum.

A consequence of Fourier's theorem is that the transmission of an analog signal can be viewed as the transmission of its individual sinusoidal components. It follows that if the received signal is to be an exact duplicate of the transmitted signal, the transmission system must not change the frequency of any components. Furthermore, the relative amplitudes and phases of all components must be maintained. The frequency range of the sinusoidal signals needed to describe an analog signal defines the signal's bandwidth.

Standard Frequency Bands

The bandwidths, which are also called spectrums, of several standard frequency bands are shown in Table 1.7.

Table 1.7
Spectrums of standard frequency bands

Band	Symbol	Description	Range
Audio	VLF	Very low frequency	3–30 kHz
Audio	LF	Low frequency	30–300 kHz
Radio (RF)	MF	Medium frequency	300–3000 kHz
Radio (RF)	HF	High frequency	3–30 MHz
Video (TV) and Radio (RF)	VHF	Very high frequency	30–300 MHz
Video (TV) and Radio (RF)	UHF	Ultra high frequency	300–3000 MHz
Video (TV)	CATV	Community antenna TV	54–1002 MHz
Radar	SHF	Super high frequency	3–30 GHz
Radar	EHF	Extremely high frequency	30–300 GHz

GHz = Gigahertz
KHz = Kilohertz
MHz = Megahertz

Decibel (dB)

An important property of a signal is its strength (power), which is often expressed in decibels. The decibel is a measure that compares two power levels. The decibel is defined as:

$$dB = 10 \log (P_1/P_2)$$

It is critical to observe that the dB is a relative power measurement. The power of a signal (P_1) stated in decibels indicates the power of that signal relative to some reference power (P_2).

Table 1.8 shows a range of 0 to 60 dB and the power ratios that they express.

Table 1.8
Power ratios from 0 to 60 decibels

Decibels	Power Ratio	Decibels	Power Ratio
0	1.0	16	39.8
1	1.3	17	50.1
2	1.6	18	63.1
3	2.0	19	79.4
4	2.5	20	100.0
5	3.2	30	1000
6	4.0	40	10,000
7	5.0	50	100,000
8	6.3	60	1,000,000
9	7.9		
10	10.0		
11	12.6		
12	15.8		
13	20.0		
14	25.1		
15	31.6		

Table 1.8 indicates that if P_1 has 100 times the power of P_2, then P_1 has a power of 20 dB relative to P. A doubling of power also results in a change of +3 dB. If the power in a signal is reduced by one-half, the power change is –3dB. (This observation follows from the fact that log (x) = -log (1/x), which implies that log(x) is negative for all x<1.)

Decibel (dB), continued

It is often convenient to define a signal power to be used as a reference. For instance, 1 milliwatt (mW) is frequently used as a reference power in telephony. The power of a 50.1 mW signal would be expressed as 17 decibel milliwatt (dBm). Notice that m is added to dB to indicate that the reference power is 1 mW. If a reference power of 1 W is used, the signal power is expressed as dBW.

Decibel levels are used to express power ratios of all types of analog and digital signals, regardless of the medium.

Echo and Delay

Another phenomenon that occurs in signal transmission is echo. When a signal encounters a discontinuity in the impedance of the medium carrying the signal, some of the signal power is reflected back to the transmitter. The reflected signal appears as a delayed version (e.g., echo) of the original signal. A familiar, but extreme, example of this phenomenon is when a sound wave encounters a rock wall.

Echoes of voice are occurring at all times, but they usually return so fast that they cannot be distinguished from the original sound. For an echo to be experienced, there must be enough delay for it to be distinguishable from the original source of the sound. In telephony, delays greater than 50 milliseconds (ms) are perceptible if they are of sufficient strength.

Phase and Delay

As previously mentioned, one of the three defining parameters of a sinusoidal signal is phase. The two sinusoids shown in Figures 1.4 and 1.5 differ only in phase. Note that the signal in Figure 1.4 is simply a delayed (in time) version of the signal in Figure 1.5. Thus, the delay of a sinusoidal signal can be equally well expressed as either a phase shift or a time delay.

It should be observed that the result of adding the two sinusoids of the same frequency would depend on their phase difference. For example, if the phase difference is zero, the sum will be a single sinusoid with amplitude 2A. However, if the phase difference is exactly one-half of the period, the sum will be zero. Two sinusoids whose sum is zero are considered 180 degrees “out of phase.”

For more complex signals that are composed of many sinusoidal components, a delay is expressed only in time (seconds), not in phase.

Telephony

Overview

A telecommunications transmission system consists of three basic components:

- Source of energy
- Medium to carry the energy
- Receiving device

In telephony, the three basic components of the transmission system are:

- Source of energy—The acoustic energy of speech is converted to an equivalent electrical signal at the transmitting handset by a microphone.
- Medium to carry the energy—A balanced twisted-pair cable is commonly used as the transmission medium.
- Receiving device—The transducer in the receiving handset acts like a small loudspeaker and converts the electrical energy back to sound energy for the ear.

Analog telephones convert voice information (sound waves) into electrical analog signals that can be transmitted over longer distances than the sound waves can travel.

Although speech may contain frequencies from 50 Hz to 12 kHz, early studies found that good quality speech intelligibility could be obtained if only the frequency range of about 300 Hz to 3400 Hz was actually transmitted. Consequently, this is the frequency band that early telephone circuits were designed to support.

The electrical signal corresponding to the voice waves is transmitted over a pair of conductors with some loss of energy, but under proper conditions, without substantial distortion. To work as a circuit, two conductors are required to carry the electrical signal. Current sent on one conductor must eventually return to the source. In the early days of telecommunications, earth was used as one of the conductors. This was found to be noisy, and eventually two conductors were used. This marked the beginning of the telecommunications cabling industry.

Devices that convert electrical energy back into sound energy are typically called receivers. The receiver is an EM device, much like a miniature loudspeaker that converts the electrical waveform back into an acceptable reproduction of the original sound.

The handset is the part of the telephone that is held close to the mouth and ear. The transmitter and receiver are mounted in the handset. A typical analog telephone includes a handset and a dialing mechanism.

Overview, continued

Telephone Line Impedance

The telephone from which the voice signal originates can be considered a signal generator that is connected to a load, which is a combination of the connecting cables and the other telephone. The connecting cables make up a transmission line.

The maximum transmission of electrical power occurs when a transmitting device and a receiving device have the same load resistance or, more specifically, the same impedance. Impedance is a parameter that applies to alternating current (ac) signals. Like resistance, impedance is expressed in ohms, but it has both a magnitude and a phase component.

It is important to ensure that the source or load impedance connected to a line is matched in the best way possible for maximum efficiency. Telephone cables have a characteristic impedance that depends on frequency. In voice-band applications, a typical impedance of either 600 or 900 ohms is used to match the cable pairs. The 600 ohms impedance is preferred for private line circuits and trunks while 900 ohms is used in CO switching system line circuits.

NOTE: The characteristic impedance of telephone cable pairs is approximately 600 ohms for 22 AWG [0.64 mm (0.025 in)] cables and 900 ohms for 26 AWG [0.041 mm (0.016 in)] cables.

Telephony Echo

Occasionally, users might encounter echoes on long-distance calls. For an echo to be perceived, part of the transmitted signal must be sent or reflected back to the originating end.

Part of a transmitted signal is sent back to the transmitter (reflected) when the impedances of the transmission line and the receiver are not matched. In this case, the maximum power is not transmitted. Matching these impedances improves transmission efficiency and minimizes the echo.

Many of us have been given the impression that electricity always travels at the speed of light (≈300,000 km/s [186,000 mi/s]). Since light is an EM wave, this speed applies to all EM radiation in free space. The speed of light in free space is usually represented by the symbol c. EM radiation travels slower than c in any physical medium. For example, signals travel slower in cables—about .56 c to 74 c. Longer circuits will have proportionately longer delays. The signal propagation speed in twisted-pairs will depend on the type of insulation used and its thickness, among other factors.

Although satellite signals travel at velocity c, geostationary satellites are such a great distance away (≈35,786 km [22,236 mi]) that the round-trip delay is close to 1/4 s and is quite perceptible when holding a telephone conversation.

Overview, continued

Telephony Distortion

The transmission characteristics of conductor pairs vary with frequency. Consequently, the various sinusoidal frequency components of a signal that are sent over a transmission line will emerge in a somewhat different form—each signal component will experience a signal loss and a phase shift that is frequency dependent. At voice frequencies, the principal elements contributing to loss and phase distortion are the conductor resistance and the mutual capacitance of the cable pair.

Increasing the frequency increases the speed of transmission through cable pairs. Using the example of 19 AWG [0.91 mm (0.036 in)] balanced twisted-pair cable, the velocity of transmission is 37,000 kilometers per second (km/s [23,000 miles per second (mi/s)]) at 300 Hz. At 3400 Hz, the velocity of transmission is ≈125,529 km/s (78,000 mi/s). This frequency-dependent transmission speed variation does not noticeably affect speech intelligibility, but it can have a great effect on data transmission.

The application of inductors, called loading coils, placed at intervals along a cable improves speech transmission quality. Loading coils:

- Compensate for the capacitance of a cable pair.
- Reduce the capacitive current loading in the range of audio frequencies.

The most common distances between loading points are ≈1.37 km (4495 ft) for D loading and ≈1.83 km (6004 ft) for H loading.

NOTE: Load coils, by their design, will cut off frequencies above the voice range. Because of this, load coils will block analog high fidelity and digital signals.

Although loading coils improve speech, they adversely affect data transmission. While loading improves the loss versus frequency characteristics, it causes severe delay problems. The delay of the higher frequencies is far greater on loaded facilities than nonloaded facilities. Loading coils also limit the frequency at which information can be transmitted. The loading coil spacing determines the upper cutoff frequency. The shorter the spacing is between loading points, the higher the cutoff frequency.

Trends

The tremendous capital investments in the existing analog transmission network indicate that analog transmission will continue to be a fundamental part of telecommunications for many years. However, it is apparent that the ITS industry is moving increasingly toward digital transmission. Analog-to-digital (A/D) conversion is already occurring within telephone sets used in digital private branch exchanges (PBXs). This trend is expected to expand to include the local loop.

Internet Protocol (IP) Telephony

Overview

A current development in telecommunications is the movement of voice communications from circuit switched networks to Internet protocol (IP) packet-based systems known as IP telephony or voice over Internet protocol (VoIP). Traditional voice systems utilize a local premises telephone switch or central exchange (CENTREX) lines. Calls are then routed through the public switched telephone network (PSTN). IP telephony systems use the packet-switched data networks for voice communications. Internal calls are established through Ethernet switches using IP to the desktop. A processor or server controls call traffic.

External calls can be routed over an existing data network to the Internet or over the public telephone network. Data networks must have quality of service (QoS) capabilities to support IP telephony. Although speech does not use much bandwidth, it cannot tolerate delays or traffic bottlenecks.

Internet Protocol (IP) Telephony Devices

Three common interface options are available for use with IP telephony:

- An IP telephone—looks like a telephone but has features of a computer
- A computer with IP telephony software and a microphone/speaker or universal serial bus (USB) handset
- Multifunctional devices with a wireless receiver (e.g., handheld wireless device, media devices, other mobile media device)

IP telephones allow access to more advanced services (e.g., online voice mail, call forwarding, cloud services). They also can be used as switches to connect a computer directly to the telephone.

A computer with IP telephony software is limited to the reliability and capabilities of the computer and is only operational when the computer is running.

Multifunction handheld mobile devices allow for the downloading of music, videos, and other files from the Internet using wireless technology.

Internet Protocol (IP) Telephony Architecture

There are three common implementation options for IP telephony architecture (see Figure 1.6):

- Separate lines—one for the IP telephone and one for the computer
- One line for everything using a dual-port IP telephone or softphone
- Wireless connection using access points (APs) to connect the IP telephone

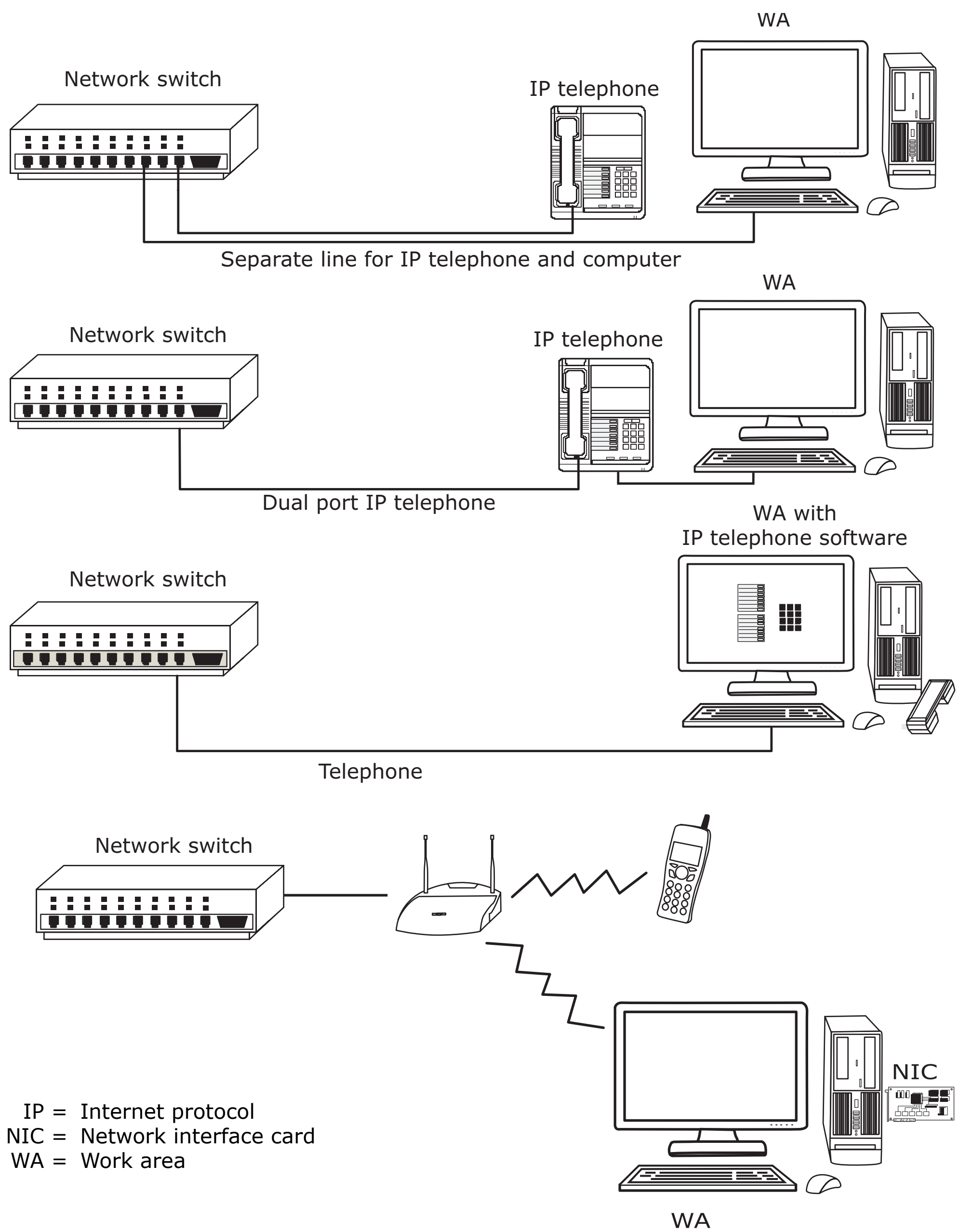
Deciding to install a dual-port IP telephone or softphone, using one line for everything, may seem an attractive option since it requires just one data cable for two devices—the IP telephone and computer. However attractive that option sounds at first, a single cable carrying all information reduces flexibility and redundancy. For example, the need for additional or upgraded services (e.g., 1000BASE-T) may require pulling new cables, which means disrupting services and additional costs.

Internet Protocol (IP) Telephony, continued

Two telecommunications outlets or connectors are recommended for each individual work area—one may be associated with voice and the other with data. Since IP telephony is now being added to the data network, both horizontal cables at the work area location should be considered cables that support data applications.

NOTE: Throughput to the computer may be limited by the telephone throughput when one cable is provided.

Figure 1.6
Internet protocol telephony architecture



Internet Protocol (IP) Telephony, continued

Power Over Balanced Twisted-Pair

A critical need for any telephone system is the ability to function at any time, especially during a power outage. In traditional telephone systems, uninterrupted power is provided to the telephone set by either the central office (CO) or the PBX system. In IP telephony, this is done using power over Ethernet (PoE).

NOTE: See Chapter 15: Data Networks for further information.

In June 2003, the Institute of Electrical and Electronics Engineers® (IEEE®) approved IEEE Standard 802.3af, *Data Terminal Equipment (DTE) Power via Media Dependent Interface (MDI)*, which defines the power sources to be used with Ethernet standard-based products. This standard is informally referred to as PoE. The standard allows DTE (e.g., IP telephones, video cameras, wireless APs) to draw power from the same generic cabling used for data transmission.

Power source equipment may deliver direct current (dc) power over the two unused pairs in 10BASE-T or 100BASE-TX (pair 4-5 and pair 7-8). Alternatively, the standard allows for delivering power over the signal pairs (pair 1-2 and pair 3-6) directly through switch ports. Powered devices are designed to accept power over both options, whichever is being used by the power source. The maximum source power output level is 15.4 watts (W) at 44 to 57 V (nominally 48 V).

Three practical power source options for VoIP are available:

- VoIP switches with integrated power supplies—Installed in the telecommunications room (TR), these switches can be used to provide power to IP telephones via the cabling system.
- Midspan units—These devices are installed between the active switch and the patch panels to add a dc signal to the data signal, allowing the existing network to power up the IP telephones. The advantage of midspan units is that they offer power to IP telephone units using legacy switches.
- Local power sources, consisting of a simple power source plugged into a regular electrical outlet.

Mission-Critical Data Network

IP telephony is an emerging technology that is rapidly evolving. The last major effect that IP telephony will have on the data network is to make it critical to ensure an uninterrupted transmission and high QoS. Structured cabling systems must be carefully controlled to ensure a minimum category 5e/class D and preferably category 6/class E, category 6A/EA, or higher for optimum performance. The implementation of structured cabling for IP telephony also must consider both present and future application requirements.

NOTE: Where IP telephone communications is vital for life safety or emergency communications, PoE power sources should have emergency power or an uninterruptible power supply (UPS).

Digital Signals

Definition

A digital signal changes from one state to another in discrete steps. Figures 1.9 through 1.13 show examples of digital signals. The most significant property of digital signals is that at any time they can take on only a value from a discrete set of values. For example, the digital signal in Figure 1.12 can have only one of four possible values. Analog signals can be converted to digital data using a process called A/D conversion, as explained below.

Transmission Data Rates

Typical rates encountered in the transmission of digital data are shown in Table 1.9.

Table 1.9
Transmission data rates

Transmission Rate Unit	Definition
Bit per second (b/s)	1 b/s
Kilobits per second (kb/s)	1000 b/s
Megabits per second (Mb/s)	1,000,000 b/s
Gigabits per second (Gb/s)	1,000,000,000 b/s
Terabits per second (Tb/s)	1,000,000,000,000 b/s

Converting an Analog Signal to a Digital Signal

Analog signals (e.g., speech, video) can be converted into a digital signal by a multistep process:

1. Filtering
2. Sampling
3. Quantizing/companding

Filtering

Since the sampling rate is determined by the analog signal's frequency content, the analog signal is filtered before being sampled to limit its frequency content.

Converting an Analog Signal to a Digital Signal, continued

Sampling

Sampling involves observing the exact value of the analog signal at regular time intervals. The sampling rate must be at least twice the highest frequency component of the analog signal to faithfully reproduce the analog signal when it is converted from analog to digital data and then back to analog. In 1928, Harry Nyquist (1889-1976) discovered this result (often called the sampling theorem).

For example, a sampling rate of 8000 samples/s is required to digitize a speech signal containing frequencies up to 4 kHz. For high-fidelity speech or music signals containing frequency components up to 16 kHz, the sampling rate needs to be increased to 32,000 samples/s.

Quantizing/Companding

The final step in the process involves quantizing the sampled values. Each sampled value is assigned a discrete level, which approximates the analog signal at the sampling instant. For example, if the source signal varies in amplitude between 0 and 1 V, each sample value could be assigned one of 256 discrete levels within this range. The increments between levels can be uniform or follow a nonuniform relationship.

In the case of speech signals, it is desirable to assign a greater number of levels when the speech signal is weak (close to zero) than when the speech signal is strong (close to one). This nonuniform mapping between the analog sampled value to an assigned digital level is called companding. It is used to increase the signal-to-noise ratio (SNR) of low-level signals, which improves the intelligibility of speech as perceived by the human ear.

There are two types of companding in current use called A-Law and Mu-Law. Mu-Law is used in the United States, Canada, and Japan. A-Law is used in Europe. Although performing similar functions, the algorithms used are different, and the two are not compatible.

The final result of these three operations is to convert an analog signal to an equivalent sequence of digital data. The entire process is called pulse code modulation (PCM).

Pulse Code Modulation (PCM)

As an illustration of PCM, each sampled value of an analog signal is assigned one of 256 levels, which can be represented by an 8-bit binary number. For example, a sample value of 137 can be represented as the binary number 10001001. It follows that an analog speech signal with a 4 kHz bandwidth can be represented by a binary data sequence having a bit rate of:

8000 samples/s x 8 bits/sample = 64,000 b/s, assuming 8-bit quantization for each sampled value.

Pulse Code Modulation (PCM), continued

Digital signal processing is used to encode speech signals at data rates lower than 64 kb/s. Adaptive differential pulse code modulation (ADPCM) can use 40, 32, 24, or 16 kb/s. PCM and ADPCM attempt to reproduce the input speech signal waveform as accurately as possible. Devices called codecs do the conversion of speech to digital data and its subsequent decoding to speech.

Other, more complex, techniques process the speech signal in frames (e.g., 20 ms in length) and extract basic descriptive parameters from each frame. These techniques use devices called vocoders (rather than codecs). Using vocoders, speech can be transmitted at rates from 8 to 2.4 kb/s.

Lower bit rates typically imply a degraded signal quality.

Time Division Multiplexing (TDM)

Telecommunications systems typically combine binary data from several different sources (e.g., voice channels) into a single composite bit stream. This process is called time division multiplexing (TDM). TDM is one means of increasing the information-carrying capacity of a digital telecommunications channel. TDM is accomplished by predetermined (deterministic) interleaving of samples from different voice channels along with one or more bits for control purposes to make up a frame. The most popular form of TDM is a statistical TDM that allows more effective, nondeterministic interleaving.

Most TDMs assign time slots to data by user addresses or codes. If the data fills the users assigned time slots, the remaining data must wait for the same slots in the next rotation. If the user does not have data, the slot remains empty until the user transmits again. Both of these cases are inefficient.

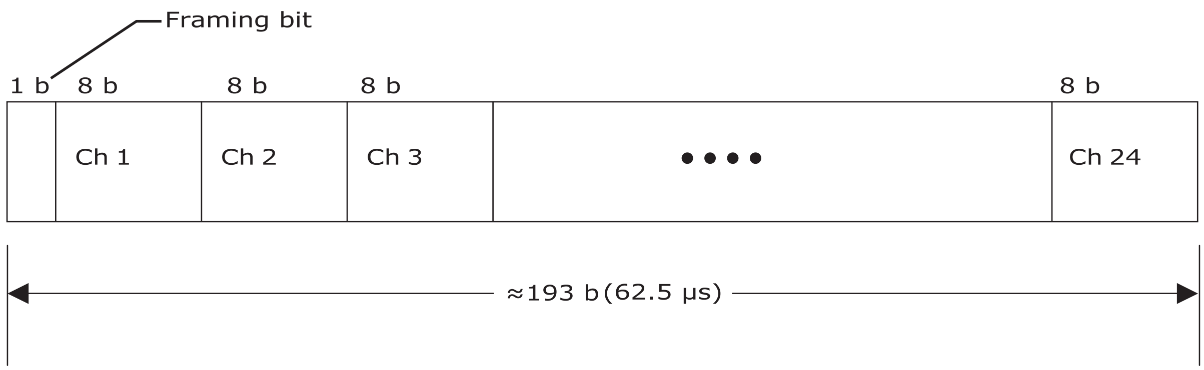
Statistical TDM corrects this problem by statistically sampling and segmenting the data into multiple frames. These frames are then loaded into available empty time slots as they appear. This process greatly improves the multiplexer's efficiency, but it does not deal with the issue of partial time slot usage.

Two classic examples of TDM are the digital signal level one (DS1) format and European Conference of Postal and Telecommunications Administrations (CEPT) PCM-30 format. These are both subject to International Telecommunication Union-Telecommunication Standardization Sector (ITU-T) Recommendation G.704.

Time Division Multiplexing (TDM), continued

In the DS1 format, the digital data from 24 speech channels is combined for transmission over a single transmission channel. The data from the 24 voice channels is arranged in a frame, as shown in Figure 1.7.

Figure 1.7
Digital signal level one frame format



b = Bit
Ch = Channel
µs = Microsecond

For telephone quality, speech is sampled at a rate of 8000 samples/s. Thus, an 8-bit speech sample is generated every 1/8000 = 62.5 microsecond (µs) for each speech channel. Consequently, transmission of the digital speech data requires sending one 8-bit sample every 62.5 µs for each channel, as shown in Figure 1.7. One bit is added to each frame for control purposes.

The data rate for this format is:

$$(8 \text{ b/s channel} \times 24 \text{ channels} + 1 \text{ framing bit}) \times 8000 \text{ frames/s} = 1.544 \text{ kb/s}$$

T1 lines are designed to carry DS1 frames.

The classic European example of TDM is the CEPT PCM-30 format. In the CEPT PCM-30 format, the digital data from 30 speech channels is combined for transmission over a single transmission channel.

Time Division Multiplexing (TDM), continued

The data from the 30 voice channels is arranged in a frame together with alignment, alarms, and signaling, as shown in Figure 1.8.

Figure 1.8
E1 frame format

8 b	8 b	8 b		8 b	8 b	8 b	8 b		8 b	8 b
TS0 Slot 0 Alarms, etc.	TS1 Channel 1	TS2 Channel 2	......	TS15 Channel 15	TS16 Signaling	TS17 Channel 16	TS18 Channel 17	......	TS30 Channel 29	TS31 Channel 30

b = Bit
TS = Timeslot

For telephone quality, speech is sampled at a rate of 8000 samples/s. An 8-bit speech sample is generated every 1/8000 = 62.5 µs for each speech channel. Consequently, transmission of the digital speech data requires sending one 8-bit sample every 62.5 µs for each channel, as shown in Figure 1.8. Eight bits are added to each frame for service purposes and 8 bits for signaling.

The data rate for this format is:

$$(8 \text{ b/s channel} \times 32 \text{ channels}) \times 8000 \text{ frames/s} = 2.048 \text{ Mb/s}$$

TDM also is used to multiplex signals from a lower level in the digital hierarchy to a higher-level signal. For example, four T1 (DS1) signals can be combined to form a T2 (DS2), or 28 T1 can be combined to form a T3 (DS3) signal. In Europe, four E1 signals can be combined to form an E2 (8 Mb/s), four E2 can be combined to form an E3 (34 Mb/s), or four E3 can be combined to form an E4 (140 Mb/s) signal.

The process of reconstituting the individual channels from the composite signal is called demultiplexing. The multiplexing and demultiplexing equipment is commonly called a channel bank. Modern units also are called intelligent multiplex terminals.

It is important to remember that only the first order multiplexing stage (T1 or E1) contains any A/D conversion. From the second order upward, the system only deals with digital frames. It is not possible to extract a single channel from the digital stream without demultiplexing back to the first order stage.

Converting Digital Data to Digital Signals

In both the T and E formats, frames are combined into multiframes. In the United States, multiframes are often referred to as superframes (12 T1 frames = 1 superframe) or extended superframes (24 T2 frames = 1 ESF)—in Europe 16 E1 frames = 1 multiframe.

Digital signals are used to encode digital data (e.g., sequences of ones and zeros). Each one or zero is called a bit (e.g., short for binary digit). The bit is the basic unit of digital data.

Digital data is represented (encoded) using digital signals that represent (encode) the original sequence of data bits. There are many ways to do the encoding; Figures 1.9 through 1.13 show some of the common options. Having several encoding options allows an ITS distribution designer to select a digital signal that best matches the telecommunications channel being used.

Encoding Techniques

A sequence of binary pulses consisting of ones and zeros is not the optimum format for transmitting digital data over balanced twisted-pair cables. The final step in the encoding process is the modification of the shape and pattern of pulses to achieve more efficient transmission.

Various techniques are used to shape the pulses to limit the bandwidth (frequency content) of the transmitted signal. This improves the signal relative to the noise induced from adjacent systems that are operating in the same cable.

Line-encoding techniques are designed to:

- Eliminate the dc component, which can have an adverse effect on signal detection.
- Improve timing recovery.

Two common methods of encoding are:

- Inverting alternate pulses for ones and using a zero level for zeros. Many consecutive zeros are replaced with a unique pattern (B8ZS). This technique is used for T1 carriers and is commonly referred to as bipolar alternate mark inversion (AMI [see Figure 1.10]).
- Using Manchester (or differential Manchester) coding where each bit within a unit data bit interval is represented by a positive pulse over one half the interval and a negative pulse over the remaining half interval. Thus, a signal transition occurs in the middle of every bit interval. These regularly occurring signal transitions provide time information for the receiver (see Figure 1.11).

As previously discussed, a digital signal can assume one of a finite number of states (e.g., signal levels) in each encoding interval. The digital signal is typically restricted to change states only at regularly spaced time intervals. For example, in Figure 1.9, the number of possible levels is two, and each time interval (designated as T in the figure) encodes a single bit.

Converting Digital Data to Digital Signals, continued

Figure 1.12 shows a digital signal that has four possible states (levels) that can be selected in each encoding interval. Each possible level can be associated with a different two-bit pattern. In this figure, the rate of state change is one-half the data rate. If a digital signal was allowed to choose between eight states in each encoding interval, three bits per encoding interval could be encoded and transmitted.

In Figure 1.11 the bits are encoded by changes in signal level. In the middle of each encoding interval, if the transition is positive, a one is encoded; if the transition is negative, a zero is encoded. These transitions occur at a regular rate and determine the bit rate. The rate at which signal level changes occur may be twice the bit rate (e.g., consider the Manchester digital signal that encodes a continuous string of ones or zeros).

NOTE: The rate at which the digital signal state changes and the bit transmission rate are not necessarily the same.

The term baud is often encountered when discussing modems. It describes the rate at which a signal can change state. One baud is equal to one state change per second. As noted above, the rate at which a digital signal can change state may or may not be the rate that the signal transmits binary data (b/s). For example, in Figure 1.9, the signaling rate in bits per second and the signaling rate in baud are the same; however, in Figure 1.11, the signaling rate in bits per second is half the signaling rate in baud.

With the proper encoding method, higher data speeds are achieved by using encoded symbols at lower line rates. This increases the distance that the signal can be transmitted over balanced twisted-pair. It also reduces radio frequency interference (RFI) emissions.

Converting Digital Data to Digital Signals, continued

Table 1.10 and Figures 1.9 through 1.13 show several coding methods.

Table 1.10
Coding methods

Line Application	Encoding Rate	Transmission Method	Bandwidth
ISDN (basic rate)	160 kb/s	2B1Q	40 kHz
ISDN (primary rate)	1.544 Mb/s	Bipolar	772 kHz
HDSL	2 x 784 kb/s	2B1Q	196 kHz
ADSL	up to 7 Mb/s	DMT or CAP	1.04 MHz
IBM System 3X	1.0 Mb/s	Manchester	750 kHz
IBM System 3270	2.35 Mb/s	Manchester	1.76 MHz
IEEE 802.3			
10BASE-T	10 Mb/s	Manchester	7.5 MHz
100BASE-TX	100 Mb/s	4B5B/MLT-3	62.5 MHz
1000BASE-T	1000 Mb/s	8B/1Q4 PAM5	62.5 MHz
IEEE 802.5 token ring	16 Mb/s	Differential Manchester	12.0 MHz
ATM	12.96 Mb/s	CAP-2	12.96 MHz
ATM	25.6 Mb/s	4B5B	32 MHz
ATM (STS-1)	51.8 Mb/s	CAP-16	29 MHz
ATM (STS-3)	155 Mb/s	NRZ	77 MHz
TP-PMD	125 Mb/s	MLT-3	62.5 MHz

2B1Q = Two binary bits encoded into one quaternary
ADSL = Asymmetric digital subscriber line
ATM = Asynchronous transfer mode
CAP = Carrierless amplitude and phase
DMT = Discrete multitone
HDSL = High bit rate digital subscriber line
IBM® = International Business Machines
IEEE® = Institute of Electrical and Electronics Engineers, Inc.®
ISDN = Integrated services digital network
kb/s = Kilobit per second
kHz = Kilohertz
Mb/s = Megabit per second
MHz = Megahertz
MLT = Multilevel transition
NRZ = Non-return-to-zero
STS = Synchronous transport signal
TP-PMD = Twisted-pair physical media dependent

NOTE: Although frequencies are transmitted above the transmission bandwidth indicated, most of the energy will not exceed this bandwidth.

Converting Digital Data to Digital Signals, continued

Figure 1.9
Polar non-return-to-zero level

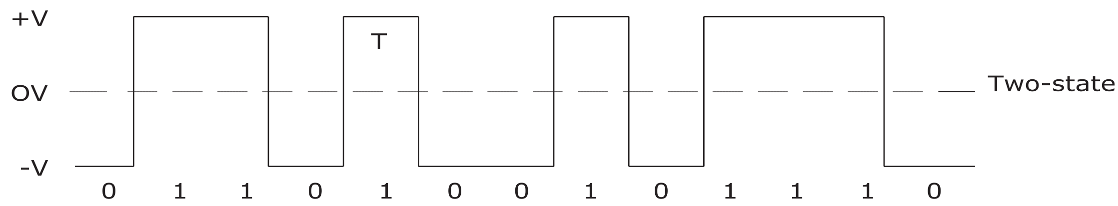


Figure 1.10
Bipolar alternate mark inversion

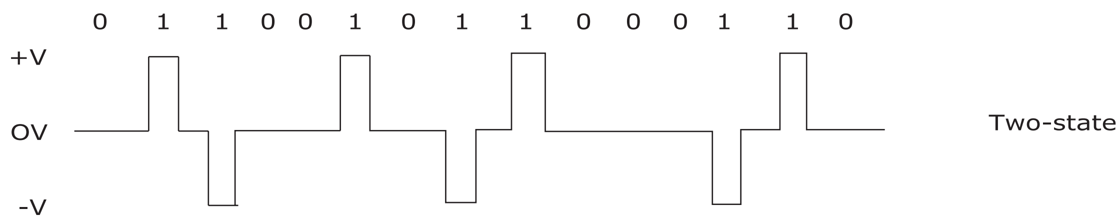
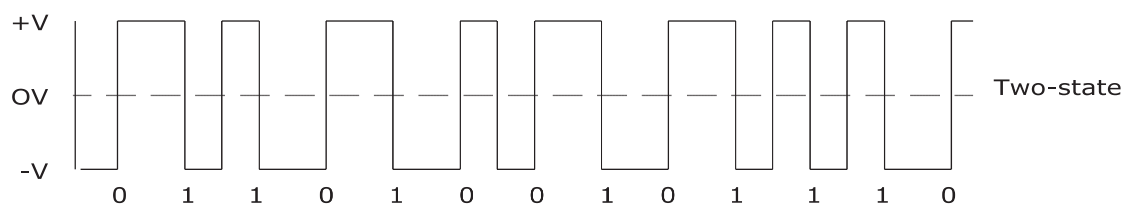


Figure 1.11
Biphase Manchester



Converting Digital Data to Digital Signals, continued

Figure 1.12
Two binary bits encoded into one quaternary (2B1Q)

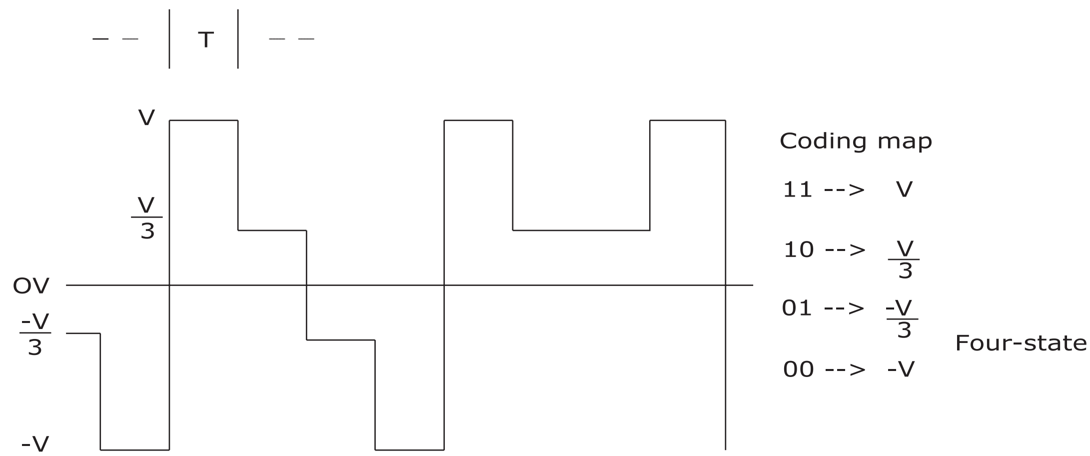
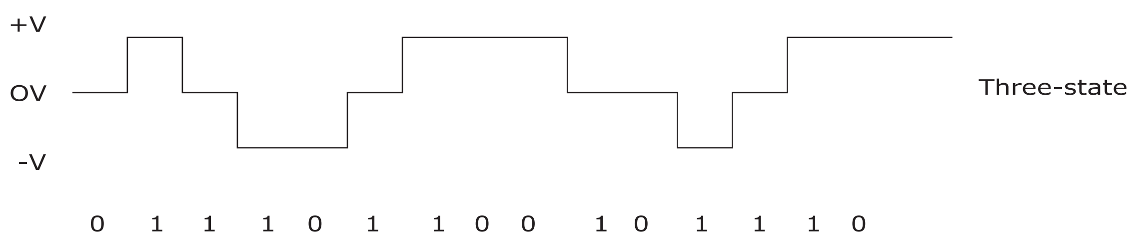


Figure 1.13
Multilevel transition-3 (MLT-3, also referred to as non-return-to-zero inverted [NRZI-3])



Quadrature Amplitude Modulation (QAM)

Quadrature amplitude modulation (QAM) is a widely used modulation technique for sending digital data. QAM and its derivatives are used in both mobile radio and satellite telecommunication systems. It is the basis for discrete multitone (DMT) and similar schemes used in x digital subscriber line (xDSL) systems.

A QAM signal is composed of two sinusoidal carriers, each having the same frequency but differing in phase by one quarter of a cycle (hence the term quadrature). One sinusoid is called the I signal, and the other is called the Q signal.

Mathematically, these two signals are equivalent to a sine wave and a cosine wave. At the transmitter, the I and Q carriers are amplitude modulated by bits selected from the data. The two amplitude modulated carriers are then combined for transmission. The combined signal is both amplitude and phase modulated by the data bits (e.g., data bits determine both the amplitude and the phase of the transmitted signal). At the destination, the carriers are separated; the data is extracted from each; and the data is converted into the original modulating digital data.

Discrete Multitone (DMT)

DMT uses multicarrier modulation. A frequency band is sliced into several hundred (typically 256) sub-bands, each of which carries a signal modulated with part of the data stream. Data rates can be adjusted with DMT by increasing the number of sub-bands and by varying the number of bits carried in each sub-band.

8B/1Q4 PAM5 Encoding

The 8B/1Q4 PAM5 encoding scheme is specified in IEEE 802.3ab for use with 1000BASE-T, which uses all four cable pairs for simultaneous transmission in both directions. This is accomplished through the use of echo cancellation and 8B/1Q4 PAM5 encoding. Each group of eight bits (8B) is converted to one transmission of four quinary symbols (1Q4) across four balanced twisted-pairs. Each symbol represents two binary bits using PAM5 modulation.

Digital versus Analog

The information transmitted by a telecommunications system can originate in two fundamental forms—digital and analog. Digital data is represented by a string of bits, whereas analog data (e.g., speech waveform) is represented by the continuous variation of the data.

As previously discussed, an analog signal can be converted to an equivalent string of data bits before transmission, the data bits can be transmitted, and the original analog signal can be reconstructed from the data bits at the receiver. Alternately, the analog signal can be used to directly modulate a carrier (e.g., amplitude modulation [AM], frequency modulation [FM]) without the conversion to and from digital data.

Generally, a larger bandwidth is required to transmit the analog information if it is represented as digital data bits. However, using sophisticated digital encoding schemes and complex signal processing techniques can offset this effect.

Sending digital data does offer one major advantage over sending analog data. If the digital data stream is recovered before the effects of attenuation and added channel noise become so large that bit errors occur, then the digital data can be recovered exactly. Thus, digital data can be transmitted (noise free) over essentially unlimited distances if the digital data is received and regenerated at intervals before it is degraded by added noise.

The situation is different for analog data. Added noise within the spectrum of an analog data signal transmission cannot be removed. To send analog data over long distances, the transmission signal must be amplified at intervals to overcome the effects of attenuation. However, the amplifier will amplify the in-band added noise as well as the analog data signal. Thus, over a long distance, the effects of added noise will be cumulative.

An additional advantage of digital is that digital transmission systems can transmit analog data—by first converting it to equivalent digital data—but a transmission system that is designed to transmit analog data cannot efficiently handle high-speed digital data.

Types of Transmission Circuits

Overview

Transmission circuits are generally classified as:

- Simplex.
- Half-duplex.
- Full-duplex.

These terms apply to any transmission media. Similar terms are used differently in radio and microcomputer communications. The following definitions clarify the use of these terms in telecommunications.

Simplex

Simplex is a term used to describe the transmission of signals in one direction only. A simple, but familiar, example of simplex transmission is a public address system without two-way speakers. The signal, which represents the speaker's voice, is carried to a number of loudspeakers. There is no path for listeners to respond.

Half-Duplex

Half-duplex is a term used to describe the transmission of signals in either direction, but only in one direction at a time.

This requires agreement between stations and typically employs a:

- Push-to-talk switch arrangement on voice circuits.
- Signaling protocol.

A home intercom is a familiar example of a half-duplex operation.

Full-Duplex

Full-duplex is a term used to describe the transmission of signals in both directions at the same time. All telephone lines are full-duplex, allowing both parties to talk simultaneously.

Asynchronous and Synchronous Transmission

Overview

For the purposes of this section, the terms asynchronous and synchronous refer to different methods of timing digital signals for transmission. The equipment involved generally dictates the method used.

Asynchronous Transmission

Asynchronous transmission occurs without a precise time relationship in the signal characters or the bits that represent them.

Each character of the information:

- Is sent without a precise time relationship between it and any other character of information.
- Carries with it start and stop signals.

Asynchronous transmission is a popular method of telecommunications among microcomputer users because of a common standardized interface and protocol between machines.

Asynchronous transmission is less efficient than synchronous transmission because it requires the addition of some combination of start and stop bits to the data stream, but it is not difficult to implement in systems at speeds less than 20 kb/s.

Synchronous Transmission

Synchronous transmission is performed by synchronizing the data bits in phase or in unison with equally spaced clock signals or pulses. Both the sender and the receiver must have timing and synchronizing capabilities. The clocking pulses prevent confusion of the characters in the data stream.

Synchronous transmission is more efficient than asynchronous transmission because no start and stop bits are required. It is used with digital baseband transmission systems.

Digital Hierarchy

Overview

Several techniques can be taken in transmission to maximize the number of communications channels available. One of the most common is to combine multiple digital data streams into one data stream using TDM.

NOTE: Refer to the previous discussion of TDM in this chapter.

Integrated Services Digital Network (ISDN)

Integrated services digital network (ISDN) uses digital transmission at a basic or primary rate, depending upon the application.

Basic rate ISDN:

- Is intended for residential and small business users.
- Uses a digital signal consisting of two 64 kb/s B channels (assigned for voice and data) and one 16 kb/s D channel (assigned for signaling and packet data).
- Has a total information capacity of 144 kb/s (line rate = 160 kb/s).

Primary rate ISDN North America:

- Is intended for large business users.
- Has a total information capacity of 1.536 Mb/s (line rate = 1.544 Mb/s).
- Uses a digital signal consisting of 23 B channels and one D channel, each operating at 64 kb/s.

Primary rate ISDN can be implemented over repeated T1 carrier or high bit-rate digital subscriber line (HDSL) facilities. It also may be embedded in the higher rate transmission systems.

Primary rate ISDN Europe:

- Is intended for large business users.
- Has a total information capacity of 1.92 Mb/s (line rate = 2.048 Mb/s).
- Uses a digital signal consisting of 30 B channels and one D channel, each operating at 64 kb/s.

Primary rate ISDN can be implemented over repeated E1 carrier or HDSL facilities. It also may be embedded in the higher rate transmission systems.

Digital Subscriber Line (DSL)

Several related telecommunications technologies fall under the broad category of digital subscriber line (DSL) solutions (also referred to as xDSL).

Variants of DSL technology include:

- HDSL.
- Symmetrical digital subscriber line (SDSL).
- Asymmetric digital subscriber line (ADSL, ADSL2, ADSL2+).
- Rate-adaptive digital subscriber line (RADSL).
- Very high bit-rate digital subscriber line (VDSL).

In general terms, all of these solutions are oriented toward providing high-speed, high-quality transmission of data, voice, and video over existing balanced twisted-pair telephone lines.

High Bit-Rate Digital Subscriber Line (HDSL)

HDSL is a way of transmitting DS1 rate signals over balanced twisted-pair cable. HDSL requires no repeaters on lines less than ≈3600 m (11,811 ft) for 24 AWG [0.51 mm (0.020 in)].

Using advanced modulation techniques, HDSL transmits 1.544 Mb/s (DS1) or 2.048 Mb/s (E1) in bandwidths of less than 500 kHz, both upstream and downstream. Depending upon the specific technique, HDSL requires two twisted-pairs for DS1 and three twisted-pairs for E1, each operating at half or third speed.

HDSL has effectively been replaced by SDSL and other xDSL technologies.

Symmetrical Digital Subscriber Line (SDSL)

SDSL is a single-pair version of HDSL, transmitting up to DS1 rate signals over a single balanced twisted-pair. SDSL has an important advantage compared with HDSL. SDSL suits the market for individual subscriber premises that are often equipped with only a single telephone line.

SDSL is desired for any application needing symmetrical access (e.g., servers, power remote LAN users) and therefore complements ADSL (see the following section on ADSL Technologies). It should be noted, however, that SDSL would not reach much beyond ≈3000 m (9850 ft), a distance over which ADSL achieves rates up to 6 Mb/s.

Asymmetric Digital Subscriber Line (ADSL) Technologies

ADSL technology is asymmetric—it allows more bandwidth downstream (server to client) than upstream (client to server).

An ADSL circuit connects an ADSL modem on each end of a single balanced twisted-pair telephone line, creating three information channels—a high-speed downstream channel, a medium-speed duplex channel, and a plain old telephone service (POTS) channel.

The POTS channel is split off from the digital modem by filters, thus guaranteeing uninterrupted POTS, even if ADSL fails. The high-speed downstream channel ranges from 1.5 to 8 Mb/s, while the upstream rate for ADSL varies from about 128 kb/s to just over 1 Mb/s.

Good Internet performance requires a down-to-upstream ratio of at least 10:1. ADSL is ideal for Internet connections, video on demand, and remote LAN access—typical applications that are found in the home.

Several ADSL technologies have been defined in standards (see Table 1.11).

Table 1.11
Asymmetric digital subscriber line standards

Standard Name	Standard Type	Downstream	Upstream
ITU G.992.1	ADSL (G.DMT)	8 Mb/s	1.0 Mb/s
ITU G.992.2	ADSL Lite	1.5 Mb/s	0.5 Mb/s
ITU G.992.3/4	ADSL2	12 Mb/s	1.0 Mb/s
ITU G.992.3/4 Annex J	ADSL2	12 Mb/s	3.5 Mb/s
ITU G.992.5	ADSL2+	24 Mb/s	1.0 Mb/s
ITU G.992.5 Annex L	ADSL2+	24 Mb/s	3.5 Mb/s

ADSL = Asymmetric digital subscriber line
DMT = Discrete multitone modulation
ITU = International Telecommunication Union
Mb/s = Megabit per second

ADSL modems provide data rates consistent with North American and European digital hierarchies and can be purchased with various speed ranges and capabilities. ADSL modems will accommodate ATM transport with variable rates and compensation for ATM overhead as well as IP protocols.

Asymmetric Digital Subscriber Line (ADSL) Technologies, continued

Downstream data rates depend on a number of factors, including the length of the balanced twisted-pair cable, its wire gauge, the presence of bridged taps, and crosstalk interference. Ignoring bridged taps, ADSL will perform as shown in Table 1.12.

Table 1.12
Asymmetric digital subscriber line performance

Data Rate	American Wire Gauge (AWG)	Distance
1.5 or 2 Mb/s	24 AWG [0.51 mm (0.020 in)]	≈5.5 km (18,000 ft)
1.5 or 2 Mb/s	26 AWG [0.41 mm (0.016 in)]	≈4.6 km (15,000 ft)
6.1 Mb/s	24 AWG [0.51 mm (0.020 in)]	≈3.7 km (12,000 ft)
6.1 Mb/s	26 AWG [0.41 mm (0.016 in)]	≈2.7 km (9000 ft)
8 Mb/s	24 AWG [0.51 mm (0.020 in)]	≈2.0 km (6500 ft)

ft = Foot
in = Inch
km = Kilometer
Mb/s = Megabit per second
mm = Millimeter

Many applications envisioned for ADSL involve digital compressed video. MPEG movies require 1.5 to 3.0 Mb/s. As a real-time signal, digital video cannot use link or network level error control procedures commonly found in data telecommunications systems. Therefore, ADSL modems incorporate forward error correction (FEC) that dramatically reduces errors caused by impulse noise.

Rate-Adaptive Digital Subscriber Line (RADSL)

RADSL is the rate-adaptive variation of ADSL. Transmission speed is rate adaptive based on the length and signal quality of the line. RADSL products have the option to select the highest practical operating speed automatically or as specified by the access provider (AP).

RADSL allows the AP to adjust the bandwidth of the DSL link to fit the need of the application and to account for the length and quality of the line. Additionally, RADSL extends the possible distance from the subscriber to the AP facility, thus increasing the percentage of users served by DSL services.

Very High Bit-Rate Digital Subscriber Line (VDSL)

While VDSL has not achieved the same degree of definition as ADSL, it has advanced enough to discuss realizable goals, beginning with data rate and range.

Downstream rates derive from submultiples of the synchronous optical network (SONET) and synchronous digital hierarchy (SDH) canonical speed of 155.52 Mb/s, namely 51.84 Mb/s, 25.92 Mb/s, and 12.96 Mb/s. Each rate has a corresponding target range over existing outside plant (OSP [see Table 1.13]).

Table 1.13
Very high bit-rate digital subscriber line data rate and target range

Data Rate	Target Range
12.96 to 13.8 Mb/s	≈1500 m (4925 ft)
25.92 to 27.6 Mb/s	≈1000 m (3281 ft)
51.84 to 55.2 Mb/s	≈300 m (984 ft)

ft = Foot
m = Meter
Mb/s = Megabit per second

It is possible to achieve greater distance using a broadband plastic insulated conductor (PIC) cable. For example, 52 Mb/s can be achieved over ≈1000 m (3281 ft) using broadband PIC 22 AWG [0.64 mm (0.025 in)] cabling.

Upstream rates under discussion fall into three general ranges:

- 1.6 to 2.3 Mb/s
- 19.2 Mb/s
- Equal to downstream

Early versions of VDSL will typically incorporate the slower asymmetric rate. Higher up-stream and symmetrical configurations may only be possible for short lines.

Like ADSL, VDSL may transmit compressed video, which is a real-time signal unsuited to error retransmission schemes used in data communications. To achieve error rates compatible with compressed video, VDSL will need to incorporate FEC with sufficient interleaving to correct all errors created by impulsive noise events of some specified duration. Interleaving introduces delay in the order of 40 times the maximum length correctable impulse.

In many ways, VDSL is simpler than ADSL. Shorter lines impose far fewer transmission constraints, so the basic transceiver technology can be less complex, even though it is 10 times faster.

Very High Bit-Rate Digital Subscriber Line (VDSL), continued

Currently, VDSL targets only ATM network architectures, obviating channelization, and packet-handling requirements imposed on ADSL. VDSL is planned to use passive network terminations, enabling more than one VDSL modem to be connected to the same line at customer premises in much the same way as extension telephones connect to home cabling for POTS.

VDSL was called VASDL or BDSL or even ADSL prior to June 1995 when VDSL was chosen as the official title. The other terms still linger in technical documents created before that time and in media presentations unaware of the convergence.

The European counterpart to VDSL has temporarily appended a lowercase “e” to indicate that the European version of VDSL may be slightly different from the U.S. version. This is the case with both HDSL and ADSL although there is no convention for reflecting the differences in the name. The differences are sufficiently small (mostly concerning data rates) that silicon technology accommodates both.

Video Transmission

Baseband Analog

A baseband analog video signal is a continuous varying signal whose magnitude and frequency represent the video content (e.g., luminance, chrominance, synchronization). A baseband video signal contains all the necessary information to reproduce a picture, but it does not modulate a radio frequency (RF) carrier.

Two terms commonly used to describe different types of baseband signaling are:

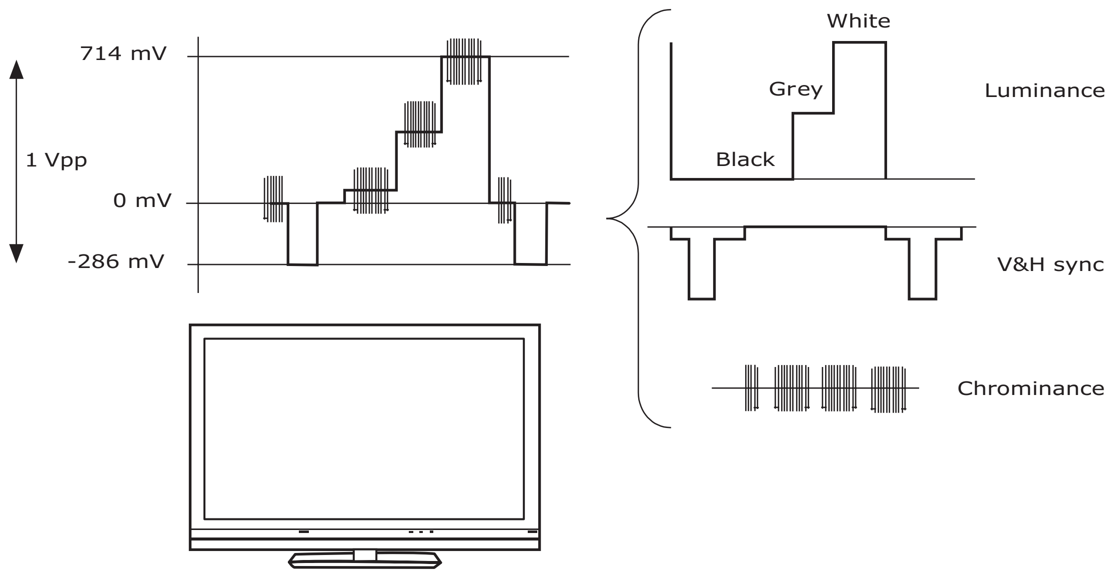
- Composite.
- Component.

Baseband Analog, continued

Composite Format

In the composite format, the analog signal contains all the components necessary to construct a monochrome or color picture, but it contains no audio information. This type of signal is typically found as the output from a digital recording device, TV monitor, camera, or camcorder. Figure 1.14 illustrates the composition of the signal.

Figure 1.14
Composite video



mV = Millivolt
V&H sync = Vertical and horizontal synchronization
Vpp = Volts peak-to-peak

Component Format

A color video picture is made up of three colors (red, green, and blue [RGB]), which are mixed in varying intensities to create a complex image. Component video, also called RGB video, keeps separate the three-color components of the image using three cables to carry the video signal.

RGB signals separate the primary color information from the luminance signal, which minimizes crosstalk and permits higher resolutions. RGB signaling is typically used for high-end graphic workstations where the need for higher-quality imaging is required.

Broadband Video

The term broadband video refers to composite baseband video and audio signals that are amplitude and frequency modulated, respectively, with an RF carrier in accordance with the video and audio information that need to be conveyed (e.g., CATV). Each RF carrier represents a TV channel. RF carriers are separated by 6 to 8 MHz.

NOTE: See Chapter 13: Audiovisual Systems for more information.

Balanced Twisted-Pair Media Implementation

Video signals traditionally have been transported using coaxial and optical fiber cables. Because of increased requirements for the transmission of video signals in commercial applications, support for analog video transmission, along with the associated audio component, using structured balanced twisted-pair cabling systems has been developed.

Baseband composite signaling can be supported over category 3/class C or higher cabling in excess of ≈100 m (328 ft). RGB component signals are supported with category 3/class C or higher cabling for a minimum of ≈100 m (328 ft) using passive media adapters.

Broadband analog CATV signaling can be implemented on category 5e/class D or higher balanced twisted-pair cabling. For example, category 5e/class D cabling can support CATV downstream delivery between 55 MHz and 550 MHz over limited distances.

Category 6/class E cabling provides better performance because of lower signal loss, higher SNR, and higher noise immunity. It can support more broadband channels or longer distances than category 5e/class D.

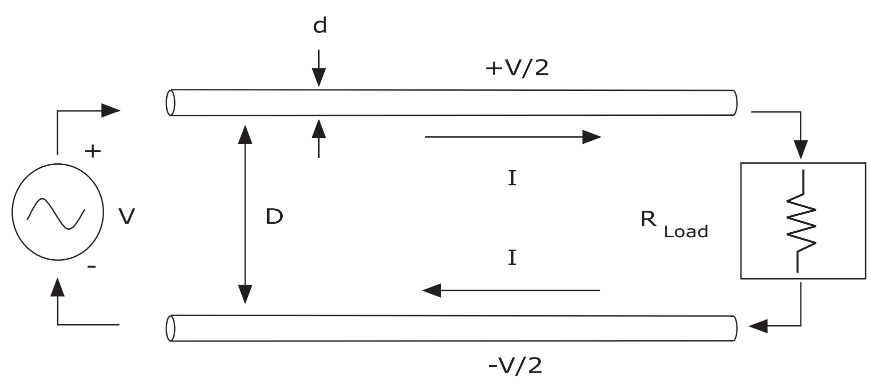
Transmission Line Concepts

Overview

An idealized transmission line consists of two conductors that are separated by a dielectric material uniformly spaced over its length.

Figure 1.15 illustrates a transmission line consisting of two conductors of a diameter (d) that are physically separated by a distance (D). A balanced voltage (V) is applied between the two conductors. Equal and opposite currents (I) flow in each conductor.

Figure 1.15
Two-conductor transmission line



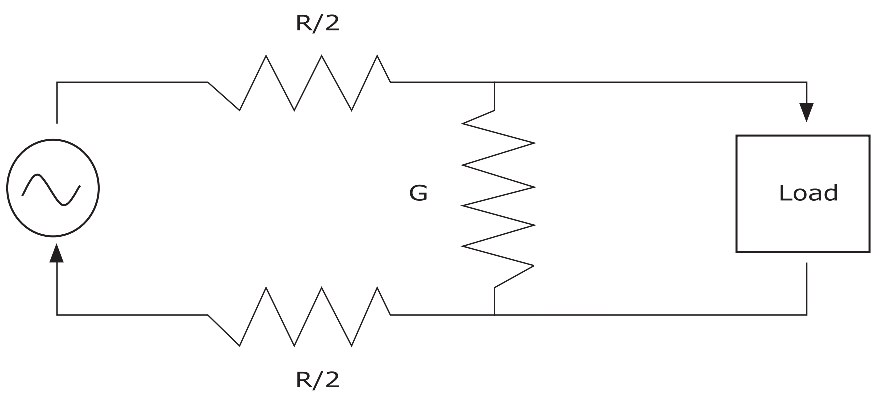
d = Diameter (in meters, m)
D = Distance (in meters, m)
I = Equal and opposite currents (in amperes, A)
R = Resistance of the line (in ohms, Ω)
V = Voltage (in volts, V)

Overview, continued

The earliest functional model of a transmission line was based on resistive loss (see Figure 1.16). The voltage drop in each conductor is directly proportional to the current flow and the resistance of the line (R) in ohms. The larger the conductor diameter, the lower the resistance. The higher the conductivity of the conductor material, the lower the resistance.

An additional factor, conductance (G), represents leakage current through a nonideal dielectric. G is the reciprocal of the resistance between the two-line conductors and is always expressed this way for calculation purposes.

Figure 1.16
Resistive model



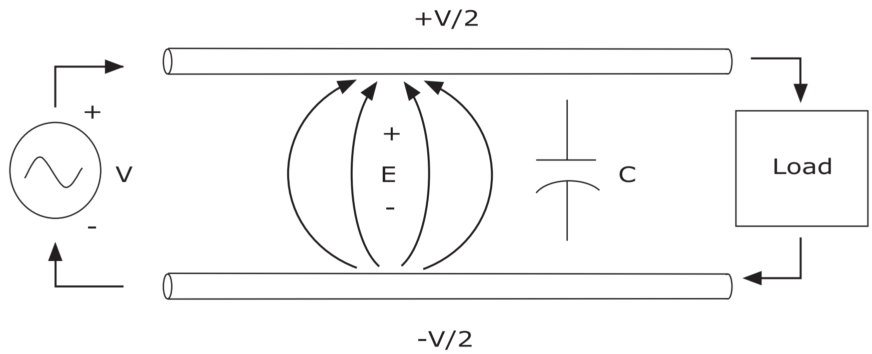
G = Conductance (in siemens, S)
R = Resistance of the line (in ohms, Ω)

Overview, continued

As longer transmission distances and higher frequencies were attempted, it became clear that the simple resistive model was not adequate. An additional factor helped in explaining observed limitations in distance and bandwidth.

The applied voltage between conductors causes a movement of electric charge such that equal and opposite charges are deposited on the surface of each conductor (see Figure 1.17). The distribution of electric charge sets up an electric field (E) in the dielectric space surrounding each conductor. This electric field is typically modeled as capacitance (C). Units of capacitance are measured in farads (F).

Figure 1.17
Capacitance model



C = Capacitance (in farads, F)
E = Electric field (in volts per meter, V/m)
V = Voltage (in volts, V)

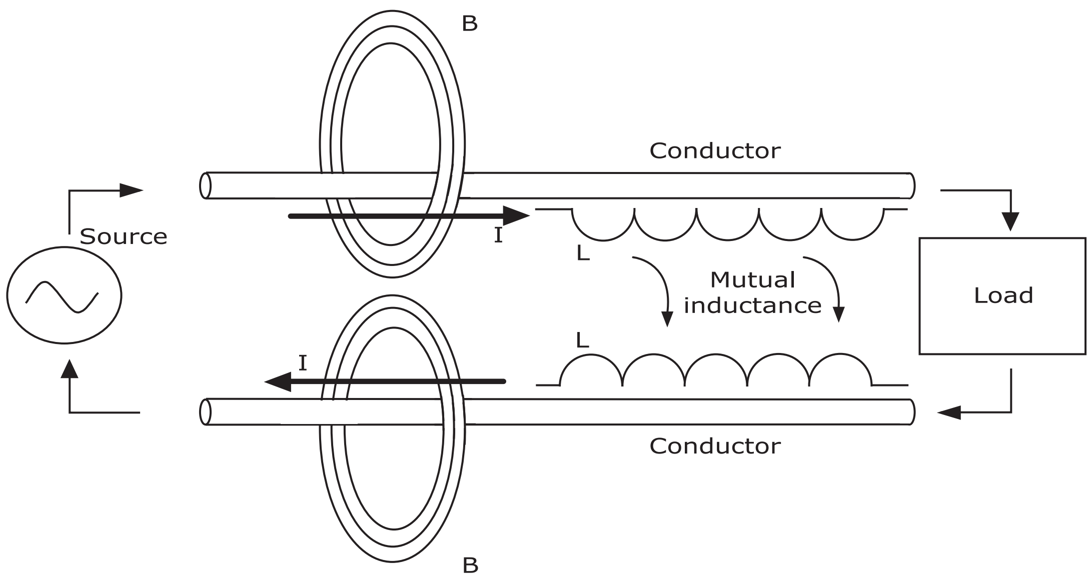
Overview, continued

As further progress was made in transmission technology, it became apparent that even the combined resistive and capacitive models were not adequate. Another factor needed to be considered.

The flow of current sets up a concentric magnetic field (B) that surrounds each conductor (see Figure 1.18). The magnetic field is reinforced in the space between the conductors and is diminished in the region outside both conductors. A larger separation between conductors results in a larger magnetic field and hence a higher inductance. The magnitude of the inductance also depends on the magnetic permeability of the dielectric material or any magnetic coating surrounding the conductors.

A material of high permeability results in a higher magnetic field intensity for a given current and, therefore, a higher inductance. The magnetic field effects can be modeled as an inductance. Units of inductance are measured in henries (H).

Figure 1.18
Inductive model



B = Concentric magnetic field (in tesla, T)
I = Equal and opposite currents (in amperes, A)
L = Inductance (in henries, H)

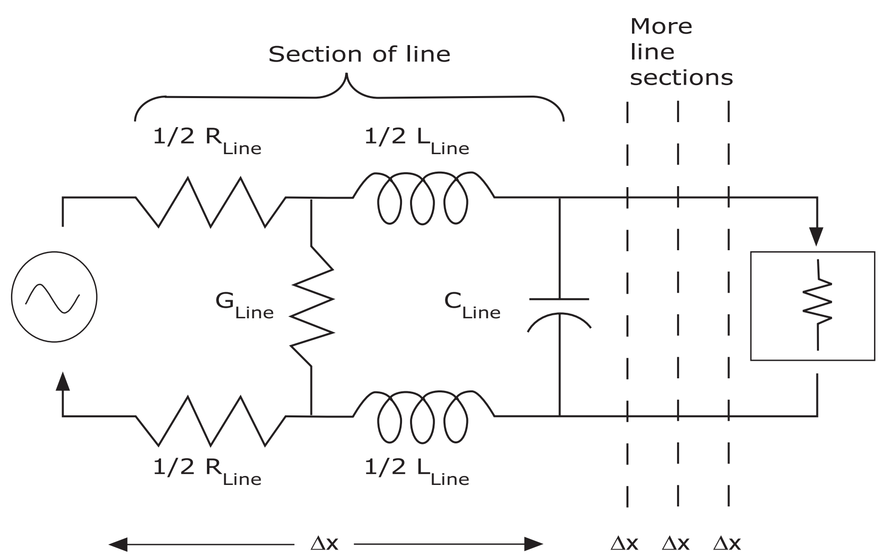
Overview, continued

A transmission line can be represented by an electrical circuit containing only passive components that are arranged in a ladder network. The ladder network is built up of cascaded sections, each with a very small length (Δ×), consisting of a series resistance and a series inductance in parallel with a mutual capacitance and a mutual conductance (see Figure 1.19). These distributed components are called the primary transmission parameters.

The primary transmission parameters are defined as follows:

- The series resistance R, expressed in ohms, is the loop resistance of a pair of conductors for an incremental length (Δ×). Series resistance is related to the dimensions and separation of conductors.
- The series inductance L, expressed in H, is the loop inductance of a pair of conductors for an incremental length (Δ×). Series inductance is related to the dimensions and separation of conductors.
- The mutual capacitance C, expressed in F, is capacitance between a pair of conductors for an incremental length (Δ×). Mutual capacitance is related to the dimensions and separation of conductors and to the dielectric constant of the insulation and jacket materials.
- The mutual conductance G, expressed in siemens (S), is the conductance between a pair of conductors for an incremental length (Δ×). Mutual conductance is related to the dielectric loss of the insulation and jacket materials.

Figure 1.19
Primary transmission line parameters



Overview, continued

The electric and magnetic fields, along with the circuit currents and voltages, are not independent but are intrinsically related through Maxwell's equations.

NOTE: A discussion of Maxwell's equations is outside the scope of this chapter. It is sufficient to know that it forms the foundation of all EM wave theory.

These primary parameters (R, L, G, and C) can be calculated from the knowledge of the physical design of the cable.

These design relationships tend to be complex and will depend on the:

- Cable geometry.
- Properties of the cable materials.
- Frequency of the applied signal.

It is not essential to know these relationships to appreciate transmission line concepts.

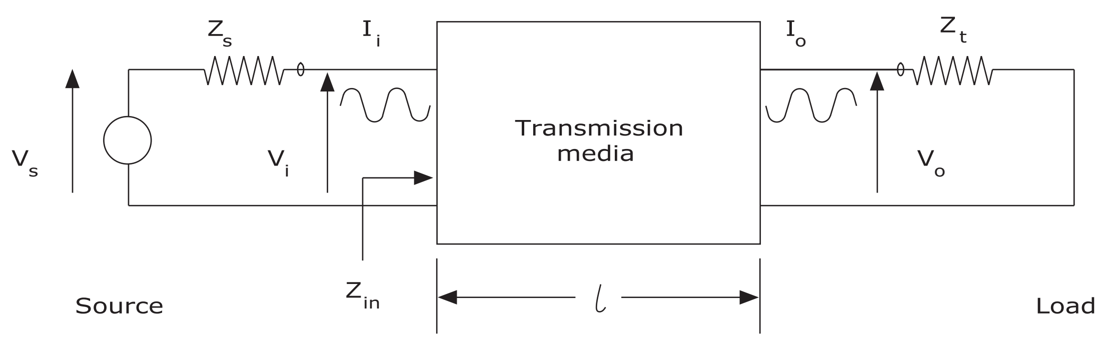
NOTE: For more information about cable design and transmission, see the Bibliography at the end of this manual.

The secondary parameters of a transmission line are:

- Calculated from the primary parameters.
- Obtained by direct measurement.

The secondary parameters can be used to model the behavior of an electrical signal as it passes through the cable. For this purpose, the cable can be considered as a black box. The output response can be measured as a function of the applied signal for different terminating conditions. Figure 1.20 illustrates the general transmission model.

Figure 1.20
General transmission model



Characteristic Impedance

Characteristic impedance corresponds to the input impedance of a uniform transmission line of infinite length:

$$Z_{in} = V_i/I_i = Z_o, t \rightarrow \infty$$

It also corresponds to the input impedance of a transmission line of finite length that is terminated in its own characteristic impedance. In general, the characteristic impedance has both a resistive and reactive component. Characteristic impedance is a function of the frequency of the applied signal, but it is unrelated to the cable length.

Maximum power is transferred from the source to the load when the source impedance (Z_s) and the terminating impedance (Z_t) are equal to the complex conjugate of the transmission line characteristic impedance (Z_o).

NOTE: Two impedances are complex conjugates if they have the same resistive component and their reactive components have opposite signs.

Under these conditions, all the energy is transmitted and none of the energy is reflected back at the cable termination. At very high frequencies, the characteristic impedance asymptote leads to a fixed value that is resistive. For example, coaxial cables have an impedance of 50 or 75 ohms at high frequency. Typically, balanced twisted-pair telephone cables have an impedance of 100 ohms above 1 MHz.

Attenuation

Attenuation corresponds to the ratio in decibels of the output power (or voltage) to the input power (or voltage) when the load and source impedance are matched to the characteristic impedance of the cable.

Where the terminations are perfectly matched, the ratio of output to input power (or voltage) is called attenuation. Practical attenuation measurements yield values that are higher than the attenuation, depending on the degree of mismatch. When evaluated in terms of voltage ratio, attenuation can be determined according the expression below.

$$Attenuation\ (dB) = -20 \log\left(\frac{V_{out}}{V_{in}}\right)$$

Where:

V_{in} = Input voltage (in volts, V)

V_{out} = Output voltage (in volts, V)

Crosstalk

Crosstalk is signal interference between cable pairs, which may be caused by a pair picking up unwanted signals from either:

- Adjacent pairs of conductors.
- Nearby cables.

For example, this interference can result from the magnetic field that surrounds any current-carrying conductor. The crosstalk interference can be intelligible or unintelligible, depending on the coupling modes. Refer to the Glossary at the end of this manual for specific types of crosstalk, including near-end crosstalk (NEXT), far-end crosstalk (FEXT), equal level far-end crosstalk (ELFEXT), power sum near-end crosstalk (PSNEXT), and power sum equal level far-end crosstalk (PSELFEXT).

Nominal Velocity of Propagation (NVP)

A signal traveling from the input to the output is delayed in time by an amount equal to the length of cable divided by the velocity of propagation (υ) for the transmission medium. In the case of an ideal transmission line consisting of two conductors in free space, the velocity of propagation is equal to the velocity of light in a vacuum (c).

For practical cables, the velocity of propagation depends on the properties of the dielectric materials surrounding the conductors. At very high frequencies, υ asymptote tends toward a constant value.

$$\upsilon = \frac{c}{\sqrt{\mu\varepsilon}}$$

Where:

c = Velocity of light in a vacuum
μ = Relative permeability of dielectric
ε = Relative permittivity of dielectric

NOTE: For balanced twisted-pair cables, a nominal velocity of propagation (NVP) for a specific cable design is provided by the cable manufacturer and is expressed as a percentage of the speed of light. For example, NVP = 62 percent or .62c. Typical values range from .56c to .74c for 100-ohm balanced twisted-pair cables range.

Propagation Delay

The development of new high-speed applications using multiple pairs for parallel transmission has shown the need for additional transmission specifications (e.g., propagation delay, delay skew) for 100 ohm, 4-pair cabling systems.

The following equation is used to compute the maximum allowable propagation delay between 1 MHz to the highest referenced frequency for a given category of cable.

$$\text{Delay (ns/100 m)} = 534 + 36/\sqrt{\text{freq}}\ \text{MHz}$$

Delay Skew

Delay skew is the difference in propagation delay between any pairs within the same cable sheath. The delay skew between the fastest and slowest pairs in category 6/class E and category 5e/class D cabling shall not exceed 45 nanoseconds (ns) at ≈100 m (328 ft [see Table 1.14]).

Table 1.14
Propagation delay/delay skew

Frequency MHz	Maximum Delay ns/≈100 m (328 ft)	Minimum Velocity of Propagation	Maximum Delay Skew ns/≈100 m (328 ft)
1	570	58.5%	45
10	545	61.1%	45
100	538	62.0%	45

ft = Foot
m = Meter
MHz = Megahertz
ns = Nanosecond

Reflection Coefficient

Consider the case where the terminating impedance is not the same as the characteristic impedance of a cable (e.g., $Z_t \neq Z_o$). In this case, a signal will be partly reflected at the cable/load junction.

The magnitude of the reflection is given by the reflection coefficient (ρ). If $Z_t < Z_o$, then the polarity of the reflected wave is inverted; if $Z_t > Z_o$, then the polarity of the reflected wave is not inverted.

$$\text{Reflection coefficient}\,(\rho) = (Z_t - Z_o)/(Z_t + Z_o)$$

Return Loss

The power of the reflected signal is called the return loss (RL) in. The better the impedance matching, the lower the reflected energy and the higher the return loss. Return loss can be determined as follows:

$$\textit{Return loss}\ (dB) = -10 \log\left(\frac{P_{\text{reflected}}}{P_{\text{in}}}\right)$$

Where,

P reflected = Signal power of the reflected signal (in watts, W)

P in = Signal power of the injected signal (in watts, W)

Return loss is an important parameter for gigabit networks that employ parallel, full-duplex transmission over all four pairs because each pair will carry information in both directions, the same as an analog telephone line. Any impedance mismatch between components will result in signal reflections (echoes) that appear as noise at the receiver. Although this noise is partially canceled in the equipment, it can be a significant contributor to the overall noise budget.

Signal-to-Noise Ratio (SNR)

Signal-to-noise ratio (SNR) is the ratio of the level of the received signal at the receiver-end and the level of the transmitted signal. The level of the received signal must significantly exceed the level of the received noise for a feasible communication condition. SNR can be determined by the following expression.

$$SNR\ (dB) = -20 \log\left(\frac{V_{\text{noise}}}{V_{\text{signal}}}\right)$$

Where,

V_{noise} = Level of the noise voltage at the receiver-end (in volts, V)

V_{signal} = Level of the transmitted signal (in volts, V)

Attenuation-to-Crosstalk Ratio (ACR)

The attenuation-to-crosstalk ratio (ACR) is a ratio obtained by subtracting the attenuation (dB) from NEXT (dB). ACR is normally stated at a given frequency.

It can be calculated as follows:

ACR = Minimum NEXT loss – maximum attenuation

Power Sum Attenuation-to-Crosstalk Ratio (PSACR)

The power sum attenuation-to-crosstalk ratio (PSACR) is a ratio in decibels determined by subtracting the attenuation from PSNEXT loss.

It can be calculated as follows:

PSACR = Minimum PSNEXT loss – maximum attenuation

Power Sum Attenuation-to-Alien-Crosstalk Ratio at the Near End (PSAACRN)

The power sum attenuation-to-alien-crosstalk ratio at the near end (PSAACRN) is a ratio in decibels determined by subtracting the attenuation from the power sum alien near-end crosstalk (PSANEXT) loss between cables or channels in close proximity.

It can be calculated as follows:

PSAACRN = Minimum PSANEXT loss – maximum attenuation

Power Sum Attenuation-to-Alien-Crosstalk Ratio at the Far End (PSAACRF)

The power sum attenuation-to-alien-crosstalk ratio at the far end (PSAACRF) is a ratio in decibels determined by subtracting the attenuation from the power sum alien far-end crosstalk (PSAFEXT) loss between cables or channels in close proximity.

It can be calculated as follows:

PSAACRF = Minimum PSAFEXT loss – maximum attenuation

Balanced Twisted-Pair Performance

Balanced twisted-pair cables are commonly used for data telecommunications in buildings. Successful implementation of the balanced twisted-pair approach for LAN installations requires proper design, installation, and testing to ensure that channel performance requirements are met. A channel, as defined in the cabling standards, includes all cables, cords, and connectors from an equipment connection at one end to the equipment connection at the other end.

The transmission characteristics of telecommunications cables, cords, and connectors depend on the frequency of the applied signal. These differences are most apparent at frequencies above one MHz. It is important for the ITS distribution designer to be able to assess the capabilities of different transmission media for a given application.

The transmission parameters of greatest importance include the:

- Signal attenuation as a function of frequency.
- Signal reflections at terminations.
- Amount of noise relative to the received signal.

The noise can be coupled into the cable from adjacent circuits sharing the same sheath (crosstalk coupling) or from external influences.

Balanced twisted-pair cables have a nominal characteristic impedance of 100 ohms at 100 MHz. The improvement in attenuation for high-performance cables is realized through improved design and materials. Likewise, an improvement of upward of 10 dB in crosstalk performance is attained through better balance and pair-twist optimization. These balanced twisted-pair cables provide increased signal-to-noise margins, which equate to higher data throughput (fewer bit errors), a longer reach, or higher transmission rate capability.

NOTE: Refer to Appendix A: Codes, Standards, Regulations, and Organizations at the end of this manual for the relevant cable and component standards for a specific country or region.

Balanced Twisted-Pair Channel Performance

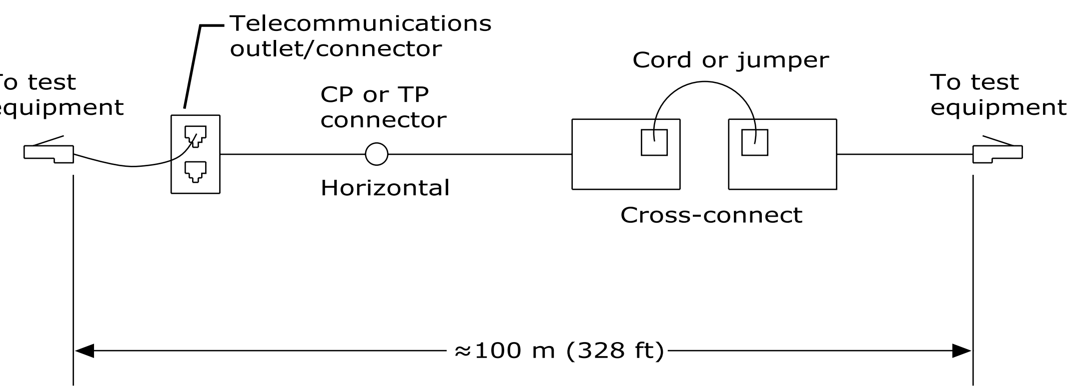
Channel Model

Figure 1.21 shows a channel and the cabling components that determine the channel performance.

The components that may make up the channel consist of a:

- Telecommunications outlet/connector.
- Balanced twisted-pair cable of ≈90 m (295 ft).
- Cross-connect system.
- Equipment and patch cords.
- Consolidation point (CP).
- Horizontal connection point (HCP).
- Transition point (TP).
- Multiuser telecommunications outlet assembly (MUTOA).

Figure 1.21
Example of a channel test configuration



CP = Consolidation point
ft = Foot
m = Meter
TP = Transition point

Performance Parameters

The most important parameters that affect performance are insertion loss, PSNEXT loss, and return loss in the case of bidirectional transmission. Other parameters (e.g., velocity of propagation, delay skew, longitudinal conversion loss, attenuation deviation, PSELFEXT [also called PSACRF]) are also important for certain higher speed applications where more complex encoding schemes and duplex balanced twisted-pair transmissions are implemented.

For 10GBASE-T applications (IEEE 802.3an standard), alien crosstalk parameters, including PSANEXT loss and PSAACRF, are specified.

Insertion Loss Performance Limits

Channel insertion loss is equal to the sum of the attenuation of the various components in the test channel, plus all the mismatch losses at cable and connector interfaces, and the increase in attenuation adjusted for temperature. In the worst case, the channel shown in Figure 1.21 consists of ≈90 m (295 ft) of horizontal cable and up to a total of ≈10 m (33 ft) of equipment and patch cords combined. Generally, patch cords are of flexible stranded construction, thereby presenting higher losses per meter or foot than horizontal cables.

All components must meet the minimum attenuation requirements of the appropriate standard for balanced twisted-pair category or class.

NOTE: In many documents, the terms attenuation and insertion loss are used interchangeably. Strictly speaking, attenuation is a measure of the signal loss under ideal termination conditions where the load and source impedance matches the cable characteristic impedance and all components are exactly matched in impedance.

Near-End Crosstalk (NEXT) Loss Limits

The NEXT loss in the channel is the vector sum of crosstalk induced in the cable, connectors, and patch cords.

NEXT loss is dominated by components in the near zone (less than ≈20 m [66 ft]).

To verify performance, measure NEXT loss from both the TR and the telecommunications outlet/connector. All components must meet the minimum NEXT requirements for the appropriate standard for balanced twisted-pair category or class.

Power Sum Equal Level Far-End Crosstalk (PSELFEXT) Loss Limits

PSELFEXT is a computation of the unwanted signal coupling from multiple transmitters at the near end into a pair measured at the far end. PSELFEXT is calculated in accordance with the power sum algorithm. All components must meet the minimum PSELFEXT requirements for the appropriate standard for balanced twisted-pair category or class.

Return Loss Limits

Return loss is a measure of the reflected energy caused by impedance mismatches in the cabling system. All components must meet the minimum return loss requirements for the appropriate standard for balanced twisted-pair category or class.

Power Sum Attenuation-to-Crosstalk Ratio (PSACR)

The balanced twisted-pair channel performance specified previously is determined from transmission measurements on cables and termination hardware. These measurements are performed in the frequency domain. The range of frequencies that can be successfully transmitted for a given distance determines the available channel bandwidth in MHz for a specified channel.

Different criteria can be used to determine the available bandwidth. One such criterion is the minimum signal level at the output of a channel relative to the peak NEXT noise level. This criterion is defined as PSACR.

To ensure an acceptable bit error rate (BER), the signal should be a reasonable replica of the transmitted signal. Attenuation is a decrease in signal magnitude. Higher frequency components of the digital signal incur more attenuation over a given balanced twisted-pair channel. The net effect is not only a reduction in amplitude, but also a change in the shape of the transmitted signal as it appears at the receiver. Additionally, NEXT noise adds abrupt variations in the signal magnitude. The reliability of the receiver to detect changes in the signal waveform is affected by these signal impairments.

Concept of Bandwidth

There is a fundamental relationship between the bandwidth of a channel expressed in Hz and the data rate expressed in b/s. The traffic flow on a major highway provides a good analogy to illustrate the concept of bandwidth versus data rate. The bandwidth is similar to the width of the highway and the number of lanes of traffic. The data rate is similar to the traffic flow or the number of vehicle crossings per hour. One way to increase the traffic flow is to widen the highway. Another way is to improve the road surface and eliminate bottlenecks.

Similarly, it is possible to support a higher data rate for any channel by using a more elaborate line-encoding scheme to pack more bits of information per Hz of available bandwidth. More elaborate line encoding requires a higher SNR, which is like a smoother road surface in this analogy.

The available bandwidth is commonly determined as the frequency range where the SNR is positive. For most LAN systems today, the dominant noise source is NEXT interference between all transmit pairs and a receive pair. If all four pairs are employed for parallel transmission, then the total NEXT noise is PSNEXT.

In this case:

- SNR is the PSACR when other noise sources are negligible and where $\text{PSACR} = \text{PSNEXT} - \text{attenuation}$.
- Bandwidth is the frequency range where $\text{PSACR} > 0$.

Summary

The key performance drivers of balanced twisted-pair channels are:

- Insertion loss.
- PSNEXT loss.
- PSELFEXT loss.
- Return loss for bidirectional applications.

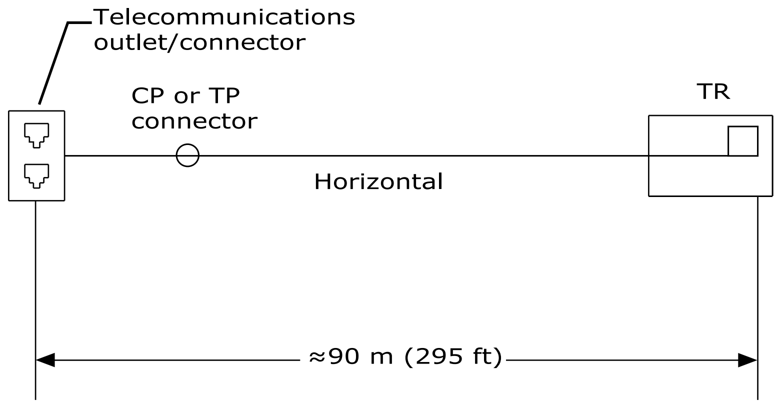
NEXT and PSNEXT are of particular concern in network configurations of balanced twisted-pair cables. When measuring insertion loss, the ITS distribution designer needs to know that the cable length and signal frequency affect the amount of loss. However, NEXT and PSNEXT occur at the beginning of the channel and do not change appreciably as the cable gets longer.

Balanced Twisted-Pair Permanent Link Performance

Permanent Link Model

Figure 1.22 depicts a permanent link model.

Figure 1.22
Permanent link test configuration



CP = Consolidation point
ft = Foot
m = Meter
TP = Transition point
TR = Telecommunications room

Permanent link consists of up to ≈90 m (295 ft) horizontal cabling, including a connector at each end.

Balanced Twisted-Pair Patch Cords and Cross-Connect Jumpers

Cross-connect jumpers and cables used for patch cords shall meet the same transmission performance requirements as those specified for 100-ohm horizontal cabling with the following exceptions:

- Stranded conductor cable has more attenuation than solid conductor cable.
- A requirement in the category 5e, category 6, category 7, and higher standard is a patch cord return loss test. The patch cord is often a weak link in a cabling system. The patch cord return loss test requires that the patch cord be tested before and after mechanical handling to ensure that the impedance remains stable and within tight limits.

A deviation of greater than ± 5 ohms above a nominal impedance of 100 ohms can result in a failure. It had been observed in practice that many category 5 stranded patch cords tended to exhibit large swings in impedance when flexed or handled. Category 5e and category 6 patch cord designs are optimized to ensure stable return loss performance.

Balanced Twisted-Pair Applications

Design Considerations

As transmission speeds increase and users migrate to higher performance cabling, it is important for the industry to provide guidance on the cabling available for data applications.

The transmission categories of all components used in the same cabling system must be matched to provide a consistently high level of reliability and transmission performance.

The development of new high-speed applications using multiple pairs for parallel transmission has shown a need for additional transmission requirements (e.g., propagation delay, delay skew).

Exercise caution when using cables with mixed insulation since the velocity of propagation can vary with the insulation used, and the skew between pairs may be excessive for some high-speed applications.

To determine the overall suitability of the cabling described for specific applications, the ITS distribution designer should also consult with the:

- Cabling systems suppliers.
- Equipment manufacturers.
- Systems integrators.

100-Ohm Balanced Twisted-Pair Performance Category

Balanced twisted-pair cabling performance is described using a scale based on installed systems (International Organization for Standardization [ISO] classes) or individual components (ISO categories). The Telecommunications Industry Association (TIA) defines installed systems and individual components by categories.

Table 1.15 provides both ISO and TIA designations for cabling system and individual component performance. While category 3/class C is the minimum acceptable performance for network cabling, category 5e/class D is the minimum recommended by most standards. Category 6/class E or higher cabling represents BICSI best practices.

Table 1.15
Balanced twisted-pair cabling channel performance

ISO Categories/Classes	TIA Categories	Frequency Characterization
Category 3/class C	Category 3	16 MHz
Category 5/class D	Category 5e	100 MHz
Category 6/class E	Category 6	250 MHz
Category 6_A/class E_A	Category 6A	500 MHz
Category 7/class F	N/A	600 MHz
Category 7_A/class F_A	N/A	1000 MHz

ISO = International Organization for Standardization
MHz = Megahertz
N/A = Not applicable
TIA = Telecommunications Industry Association

100-Ohm Balanced Twisted-Pair Performance Category, continued

Table 1.16 lists applications supported using 100-ohm balanced twisted-pair cabling.

Table 1.16
Applications supported using 100-ohm balanced twisted-pair cabling

Application	Specification Reference	Date	Additional Name
	Class A (defined up to 100 kHz)		
PBX	National requirements		
X.21	ITU-T Recommendation X.21	1994	
V.11	ITU-T Recommendation X.21	1994	
	Class B (defined up to 1 MHz)		
S0-Bus (extended)	ITU-T Recommendation I.430	1993	ISDN Basic Access (Physical Layer)
S0 Point-to-Point	ITU-T Recommendation I.430	1993	ISDN Basic Access (Physical Layer)
S1/S2	ITU-T Recommendation I.431	1993	ISDN Primary Access (Physical Layer)
CSMA/CD 1BASE5	ISO/IEC 8802-3	2000	Starlan
	Class C (defined up to 16 MHz)		
CSMA/CD 10BASE-T	ISO/IEC 8802-3	2000	
CSMA/CD 100BASE-T2	ISO/IEC 8802-3	2000	Fast Ethernet
CSMA/CD 100BASE-T4	ISO/IEC 8802-3	2000	Fast Ethernet
ISLAN	ISO/IEC 8802-9	1996	Integrated Services LAN
Demand priority	ISO/IEC 8802-12	1998	VGAnyLANTM
ATM LAN 25,60 Mb/s	ATM Forum af-phy-0040.000	1995	ATM-25/Category 3
ATM LAN 51,84 Mb/s	ATM Forum af-phy-0018.000	1994	ATM-52/Category 3
ATM LAN 155,52 Mb/s	ATM Forum af-phy-0047.000	1995	ATM-155/Category 3

100-Ohm Balanced Twisted-Pair Performance Category, continued

Table 1.16, continued
Applications supported using 100-ohm balanced twisted-pair cabling

Application	Specification Reference	Date	Additional Name
	Class D (defined up to 100 MHz)		
CSMA/CD 100BASE-TX	ISO/IEC 8802-3	2000	Fast Ethernet
CSMA/CD 1000BASE-T	ISO/IEC 8802-3	2000	Gigabit Ethernet
TP-PMD	ISO/IEC FCD 9314-10	2000	Twisted-Pair Physical Medium Dependent
ATM LAN 155.52 Mb/s	ATM Forum af-phy-0015.000	1994	ATM-155/Category 5
	Class E (defined up to 250 MHz)		
ATM LAN 1.2 Gb/s	ATM Forum af-phy-0162.000	2001	ATM-1200/Category 6
CSMA/CD 1000BASE-TX	ANSI/TIA/EIA-854	2001	Gigabit Ethernet/ Category 6
	Class E (defined up to 500 MHz)		
CSMA/CD 10GBASE-T	ISO/IEC 8802-3	2006	10 Gigabit Ethernet
	Class F (defined up to 600 MHz)		
Fibre Channel 1000BASE-T	ISO/IEC 14165-114	2005	Gigabit Ethernet/ Category 7

af-phy = ATM Forum, physical layer specification
ANSI = American National Standards Institute
ATM = Asynchronous transfer mode
CSMA/CD = Carrier sense multiple access with collision detection
EIA = Electronic Industries Alliance
FCD = Final committee draft
IEC = International Electrotechnical Commission
ISDN = Integrated services digital network
ISLAN = Integrated services-LAN
ISO = International Organization for Standardization
ITU-T = International Telecommunications Union-Telecommunications Standardization Sector
MHz = Megahertz
PBX = Private branch exchange
TIA = Telecommunications Industry Association
TP-PMD = Twisted-pair physical medium dependent

Media Selection

Table 1.17 shows various applications and the suggested media choice or choices.

Table 1.17
Media selection

Application or Interface	Balanced Twisted-Pair Category 3	Balanced Twisted-Pair Category 5e	Balanced Twisted-Pair Category 6/6_A
Analog telephone set	X	X	X
Digital telephone set	X	X	X
ANSI/TIA/EIA-232-F	X	X	X
ANSI/TIA/EIA-422-B	X	X	X
ISDN	X	X	X
IEEE 802.3 10BASE-T	X	X	X
IEEE 802.5 Token ring 16 Mb/s	See Note 1	X	X
ANSI X3.263 (TP-PMD)		X	X
IEEE 802.3 100BASE-TX		X	X
IEEE 802.3ab 1000BASE-T		X	X
IEEE 802.3an 10GBASE-T	See Note 3		
ATM 25.6 Mb/s	X	X	X
ATM 12.96 Mb/s	X	X	X
ATM 51.8 Mb/s	X	X	X
ATM 155 Mb/s		X	X
ATM 1 Gb/s			X
ANSI/TIA/EIA-854 1 Gb/s			X

Media Selection, continued

Table 1.17, continued
Media selection

Application or Interface	Balanced Twisted-Pair Category 3	Balanced Twisted-Pair Category 5e	Balanced Twisted-Pair Category $6/6_A$
Video baseband composite	X	X	X
Video baseband component	X	X	X
Video broadband		See Note 2	X

ANSI = American National Standards Institute
ATM = Asynchronous transfer mode
EIA = Electronic Industries Alliance
Gb/s = Gigabit per second
IEEE = Industry of Electrical and Electronics Engineers, Inc.®
ISDN = Integrated services digital network
Mb/s = Megabit per second
TIA = Telecommunications Industry Association
X = Media supported

NOTES:

1. This application is not normally recommended, but it may be used if the installed cable meets qualification guidelines.
2. This application has a limited distance (e.g., less than ≈100 m [328 ft]) or a limited number of broadband channels. Check the manufacturer's recommendations.
3. This application has limited support over balanced UTP category 6. Screened category 6 solutions will also support between ≈55 m (180 ft) and ≈100 m (328 ft). Augmented category 6 (category 6) will support the application for ≈100 m (328 ft).

Distances and Pair Requirements

Table 1.18 shows typical transmission distances and the number of balanced twisted-pairs required for various data applications.

Table 1.18
Transmission, speed, distance, and pair requirements

		Typical Distances Achieved on 24 AWG [0.51 mm (0.020 in)] Balanced Twisted-Pair		
Application	**Line Rate**	**m**	**ft**	**Balanced Twisted-Pairs**
Integrated voice/data	64 kb/s	1220	4000	1 to 2
ANSI/TIA/EIA-232-F	19.2 kb/s	45	150	2 to 4
ANSI/TIA/EIA-422-B	Up to 10 Mb/s	15 to 1220*	50 to 4000*	2
ISDN-BRI (2B+D)	160 kb/s	1000	3280	2 to 4
ISDN-PRI (23B+D)	1.544 Mb/s	1500	4920	2
DS1 rate	1.544 Mb/s	1500	4920	2
Token ring (IEEE 802.5)	16 Mb/s	100	328	2
Ethernet (IEEE 802.3)				
10BASE-T	10 Mb/s	100	328	2
100BASE-TX	100 Mb/s	100	328	2
100BASE-T4	100 Mb/s	100	328	4
1000BASE-T	1000 Mb/s	100	328	4
10GBASE-T	10 Gb/s	55-100	180-328	4

Distances and Pair Requirements, continued

Table 1.18, continued
Transmission, speed, distance, and pair requirements

Application	Line Rate	Typical Distances Achieved on 24 AWG [0.51 mm (0.020 in)] Balanced Twisted-Pair m	ft	Balanced Twisted-Pairs
ATM				
Category 3	12.96 Mb/s	200	656	2
Category 5		320	1050	2
Category 5e		320	1050	2
Category 6		365	1200	2
ATM				
Category 3	25.6 Mb/s	100	328	2
ATM				
Category 3	25.92 Mb/s	170	550	2
Category 5		275	900	2
Category 5e		275	900	2
Category 6		300	1000	2
ATM				
Category 3	51.84 Mb/s	100	328	2
Category 5		165	520	2
Category 5e		165	520	2
Category 6		180	600	2
ATM				
Category 5/5e	155.52 Mb/s	100	328	2
Category 6		110	361	2
ATM				
Category 6	1 Gb/s	100	328	4

Distances and Pair Requirements, continued

Table 1.18, continued
Transmission, speed, distance, and pair requirements

Application	Line Rate	Typical Distances Achieved on 24 AWG [0.51 mm (0.020 in)] Balanced Twisted-Pair: m	ft	Balanced Twisted-Pairs
ATM				
Category 3	12.96 Mb/s	200	656	2
Video baseband composite				
Category 3	0–6 MHz	365	1200	1 (+2 stereo)
Category 5/5e/6		455	1500	1 (+2 stereo)
Video baseband component				
Category 3	0–30 MHz	100	328	3
Category 5/5e/6		150	492	3
Video broadband				
Category 5e	550 MHz	60	200	1
	250 MHz	100	328	1
Category 6	550 MHz	70	230	1
	300 MHz	100	328	1

*The typical distance achieved depends on data rate—from ≈15.2 m (50 ft) at 10 Mb/s to ≈1220 m (4003 ft) for data rates of 90 kb/s or less.

ATM = Asynchronous transfer mode
ANSI = American National Standards Institute
AWG = American wire gauge
BRI = Basic rate interface
DS1 = Digital signal level 1
EIA = Electronic Industries Alliance
ft = Foot
Gb/s = Gigabit per second
IEEE = Industry of Electrical and Electronics Engineers, Inc.®
ISDN = Integrated services digital network
kb/s = Kilobit per second
m = Meter
Mb/s = Megabit per second
MHz = Megahertz
PRI = Primary rate interface
TIA = Telecommunications Industry Association

Shared Sheath Applications and Compatibility

Installing additional cables is labor intensive and, therefore, costly. To make maximum use of the cabling resources, multipair cable may be utilized to serve a number of different applications.

Whenever possible, it is recommended to segregate different applications in separate binder groups. Although PBX or key systems may coexist within the same cable, this is not recommended for some systems because of crosstalk and impulse noise.

With regard to horizontal balanced twisted-pair cabling, it is generally recommended that only one application be supported in a single cable sheath.

Examples of the restrictions on shared sheaths for specific applications using binder groups in multipair cables having category 3 transmission characteristics include the following:

- No more than twelve 10BASE-T systems can share a common binder group.
- ANSI/TIA/EIA-232-F, *Interface Between Data Terminal Equipment and Data Circuit-Terminating Equipment Employing Serial Binary Data Interchange,* and ISDN applications should be on separate binder groups.
- Signals from hosts with multiple controllers should not share the same binder group (e.g., signals from the same controller can share the same binder group).
- Signals with significantly different power levels should not share the same binder group.

Generally, data transmission interfaces that are unbalanced with respect to ground cannot be mixed with other systems. For example, the ANSI/TIA/EIA-232-F interface, when it is extended using balanced twisted-pair cables, is incompatible with almost everything else. However, the ANSI/TIA/EIA-232-F interface can be extended using limited distance modems (ANSI/TIA/EIA-422-B, *Electrical Characteristics of Balanced Voltage Digital Interface Circuits),* voice band modems, or optical fibers, which ease the compatibility constraints. Although the ANSI/TIA/EIA-232-F standard limits the transmission distance to ≈45.8 m (150 ft) on metallic cable based on the 2500 picofarad (pF) limit, ITS distribution designers or installers frequently attempt to extend this distance.

Backbone cabling systems may be called upon to carry both analog and digital signals from more than one type of LAN, PBX, key system, and alarm system. Generally, all baseband digital data transmission systems that operate at speeds of 64 kb/s or less are compatible with analog and digital PBX and key system station circuits as long as they use balanced transmission schemes.

Media Conversion

Terminal equipment that is equipped with a media interface other than balanced twisted-pair can be easily adapted to balanced twisted-pair for signal transmission and can operate with equivalent performance to that of coaxial, twinaxial, and dual coaxial.

In most cases, stricter distance limitations apply when media conversion is used. The advantages of media conversion to balanced twisted-pair include the following:

- It can be a cost-effective solution.
- Moves can be simpler to implement.
- Less space in risers or conduits is required.

The three main categories of terminal interfaces are:

- Impedance-matching devices.
- Signal converters.
- Media filters.

Impedance-Matching Devices (Baluns)

Impedance-matching devices are commonly known as baluns. The term balun is taken from the words balanced to unbalanced. Baluns are used to adapt the balanced impedance of twisted-pairs to the unbalanced impedance of coaxial cables. Each media type requires a specific type of balun to properly match its respective impedance. Baluns are required wherever a transition is made from twisted-pair to coaxial or from coaxial to twisted-pair.

Baluns are additionally used to convert UTP cabling to coaxial cabling to support the transmission of video over UTP. These baluns are normally located in the wall outlet for the video service.

Signal Converters

Signal converters are electronic devices that receive one type of signal and output another type of signal.

Some of the features of signal converters include:

- Filtering.
- Amplification.

The various types of signal converters include:

- Analog-to-digital converters (ADCs).
- Digital-to-analog converters (DACs).
- Voltage converters.
- Frequency converters or translators that convert an input frequency to a different output frequency.

Signal Converters, continued

Some of the advantages of signal converters are that they:

- Decrease the risk of transmission and EMI problems.
- Extend the unbalanced signal reach of a DTE.

Media Filters

Media filters may be required for the transmission of higher frequencies on balanced twisted-pair. The filters eliminate unwanted frequencies affecting link performance that could radiate from the balanced twisted-pair cable.

Transceivers

Transceivers are radio frequency devices capable of sending and receiving radio frequencies. These devices can be wired or wireless and are used in many two-way telecommunications devices. Transceiver devices are also used in optical devices.

Conclusion

Knowledge of the design and performance of transmission systems is important to an ITS distribution designer, even though the ITS distribution designer may never become involved in any project requiring an in-depth knowledge of these parameters. Such familiarity will be especially useful when determining the type of media to employ for a particular job.

Although the cabling transmission parameters are complex, the final result is that a transmission circuit should be cost-effective, meet applicable standards, and have:

- A uniform characteristic impedance that is matched to the equipment.
- Low insertion loss/attenuation.
- High SNR and available bandwidth.
- Velocity of propagation that is relatively constant with frequency.
- High NEXT and FEXT loss between pairs.
- High NEXT and FEXT loss between pairs in adjacent cables and connectors.
- High noise immunity.

Optical Fiber

Overview

The two transmission media most often encountered in structured cabling systems are balanced twisted-pair and optical fiber. Section 1 has discussed in detail the properties of balanced twisted-pair cabling. In Section 2, the properties of optical fiber cabling are addressed.

A simple model of a telecommunications system has three parts:

- Transmitter
- Receiver
- Medium

In an optical fiber system the medium is, of course, optical fiber. The transmitter and receiver are designed to match with the properties of the medium. For an optical fiber system, this means that the transmitter and receiver operate at optical frequencies. In this section, the properties and performance of optical fiber transmitters, optical fiber receivers, and optical fiber medium are addressed, in that order. At the end of the section, several system applications are presented.

The optical fiber transmitter and receiver convert one type of energy to another type of energy. An optical transmitter converts electrical signals to optical signals for transmission over an optical fiber cable. At the receiver, the optical signals are converted back into electrical signals. The use of optical transceivers, which combine the functions of an optical transmitter and receiver, is common in the industry.

Optical Fiber Transmitters

Overview

Almost all available optical fiber electronics contain an optical transmitter. This optical transmitter consists of one of the following:

- Light-emitting diode (LED)
- Short wavelength laser
- VCSEL
- Laser diode (LD)

The transmitter is an electronic device that:

- Receives a modulated electrical signal.
- Converts the modulated electrical signal into a modulated optical signal (usually digital).
- Launches the modulated optical signal into an optical fiber.

Light-Source Characteristics that Influence Optical Fiber Selection

Some common characteristics of the light pulses emitted by an optical transmitter influence optical fiber selection are the:

- Center wavelength.
- Spectral width.
- Emission pattern.
- Average power.
- Modulation frequency.

Center Wavelength

Any light source emits light within some range of wavelengths. Optical fiber transmitters used with glass optical fibers normally emit light at or near one of the following four nominal wavelengths, measured in nanometers (nm):

- 850 nm
- 1300 nm
- 1310 nm
- 1550 nm

This nominal value is called the center wavelength.

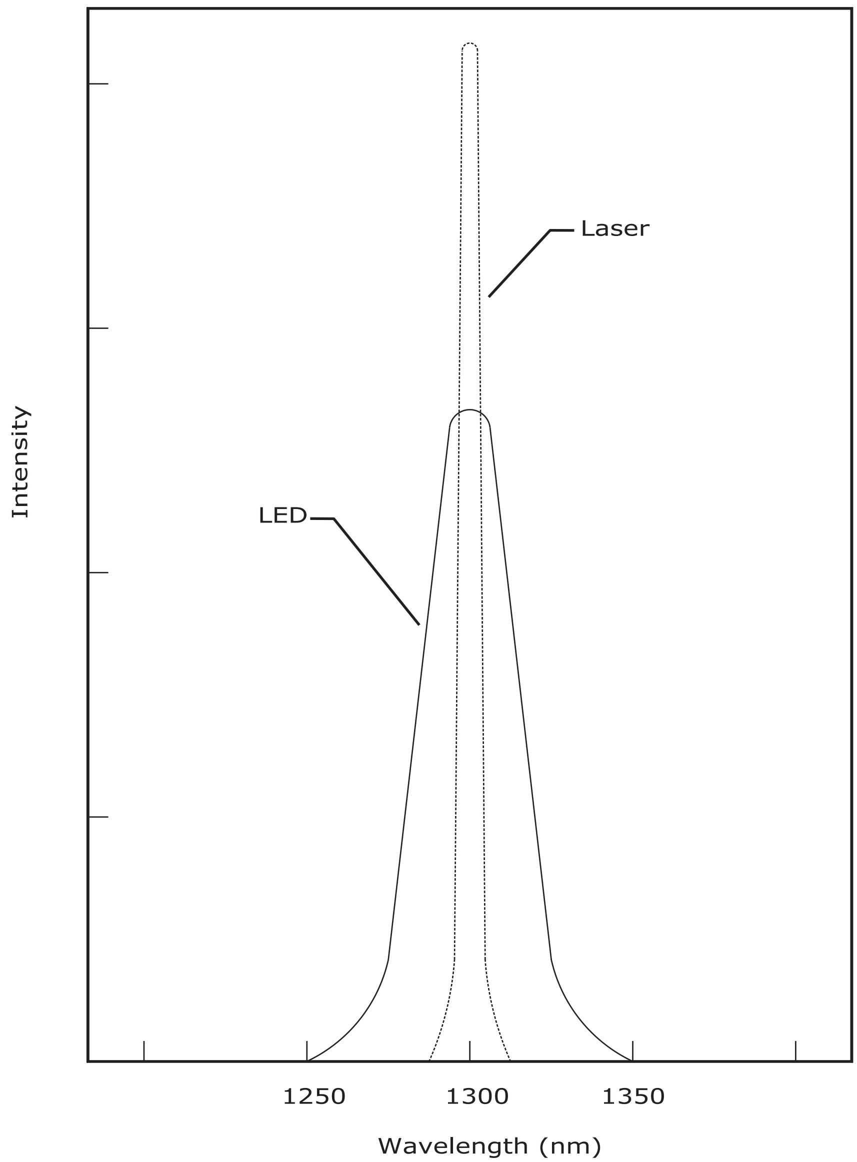
Although the periodicity of the EM radiation emitted by optical transmitters could be specified using either frequency (f) or wavelength (λ), it is traditionally specified by wavelength. Recall that frequency and wavelength are related by the formula $v = f\lambda$, where v is the velocity of propagation in the transmission medium.

Light-Source Characteristics that Influence Optical Fiber Selection, continued

Spectral Width

The total power emitted by a transmitter is distributed over a range of wavelengths spread around a center wavelength. This range is the spectral width, typically specified in nanometers. Spectral widths vary from narrow for lasers (several nanometers) to wide for LEDs (from tens to hundreds of nanometers [see Figure 1.23]).

Figure 1.23
Spectral profile comparison of laser and light-emitting diode

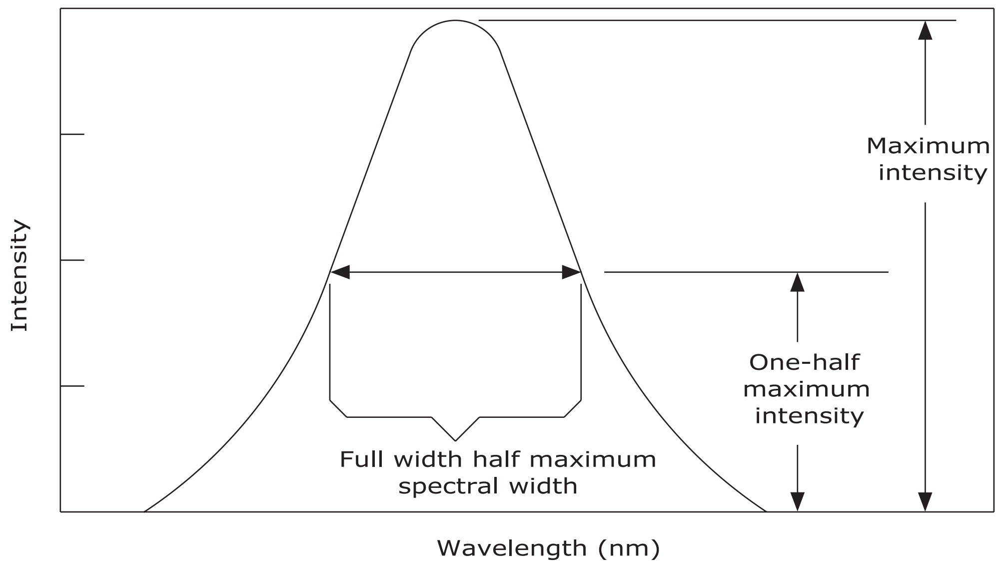


LED = Light-emitting diode
nm = Nanometer

Light-Source Characteristics that Influence Optical Fiber Selection, continued

Spectral width is usually given as the range of wavelengths emitted with an intensity level greater than or equal to one half of the peak intensity level, referred to as the full width half maximum (FWHM) spectral width. See Figure 1.24.

Figure 1.24
Spectral width of a light-emitting diode source showing full width half maximum



nm = Nanometer

Wide spectral widths lead to increased dispersion of light pulses as the light pulses propagate through an optical fiber.

Average Power

The average power of the transmitter is the mean level of power output of a given light source during modulation.

Measured in dBm or mW, the average coupled power is usually specified for a particular:

- Optical fiber core size.
- Numerical aperture (NA).

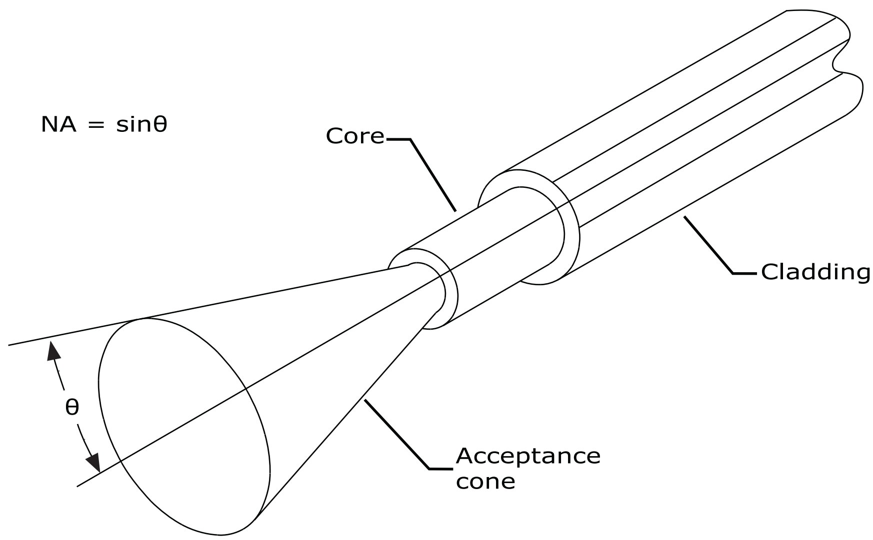
The more power a transmitter launches into an optical fiber, the more optical power is available for the loss budget.

A mismatch of the NA and core size may cause a different level of power launched into the optical fiber than the expected average power. This is because an LED launches a large "spot" size of light. Short wavelength lasers and VCSELs launch a smaller spot size of light, typically 25 µm. Therefore, the average power launched into a 62.5/125 µm or 50/125 µm by these sources is the same as the expected average power.

Light-Source Characteristics that Influence Optical Fiber Selection, continued

Figure 1.25 shows a comparison of the core size, NA, and LED.

Figure 1.25
Numerical aperture



Comparison of Core Size, NA, and LED—Coupled Power		
Fiber Size (μm)	Numerical Aperture (NA)*	Relative Coupled Power to 62.5/125 μm
50/125	0.20	-2.2 dB
62.5/125	0.275	0 dB

* Variations of 1% to 5% in NA specifications among different optical fiber and suppliers can result in different measurement results.

dB = Decibel
LED = Light-emitting diode
NA = Numerical aperture
μm = Micrometer

Light-Source Characteristics that Influence Optical Fiber Selection, continued

Modulation Frequency

The modulation frequency of a transmitter is the rate at which the transmission changes in intensity. Typically, the transmitter is modulated by a string of bits that turns the transmitter's light source on and off. LEDs have a relatively low modulation frequency and are limited to data rates of 622 megabits per second (Mb/s) and below. Lasers have a higher modulation frequency and can support data rates in excess of 10 gigabits per second (Gb/s).

Transmitter Light Sources

The four major types of transmitter light sources are:

- LEDs.
- Short wavelength lasers.
- VCSELs.
- LDs.

Light-Emitting Diode (LED)

The LED is a common and relatively inexpensive transmitter light source. Table 1.19 describes the characteristics of typical LED sources.

Table 1.19
Characteristics of typical light-emitting diode sources

Item	Characteristics
Cost	Relatively inexpensive
Use	Primarily used with multimode optical fiber telecommunications systems
Center wavelength	• 800 to 900 nm • 1250 to 1350 nm
Spectral width	Usually: • 30 to 60 nm FWHM in the lower region (near 850 nm) • Up to 150 nm FWHM in the higher region (near 1300 nm) because lower material dispersion LED sources operating near 850 nm are typically more economical. Data rates up to 100 Mb/s typically use short wavelength LEDs; long wave length LEDs are for data rates of 100 to 622 Mb/s.
Modulation frequency	• Most are under 200 MHz • Can be as high as 600 MHz
Average launched	–10 to –30 dBm into multimode optical power level fiber

FWHM = Full width half maximum
LED = Light-emitting diode
Mb/s = Megabit per second
MHz = Megahertz
nm = Nanometer

Transmitter Light Sources, continued

Short Wavelength Lasers

Table 1.20 describes the characteristics of typical short wavelength laser.

Table 1.20
Characteristics of typical short wavelength laser

Item	Characteristic
Cost	Relatively inexpensive
Use	Primarily used with multimode optical fiber information technology systems at the higher data rates from 200 megabits per second to 1 gigabit per second
Center wavelength	Principal application is Fibre Channel
Spectral width	780 nm Narrow compared with LEDs (4 nm)
Modulation frequency	Higher than LEDs (can exceed 1 gigahertz), allowing them to operate at higher data rates
Average launched optical power level	+1 to –5 decibels per milliwatt

LED = Light-emitting diode
nm = Nanometer

Transmitter Light Sources, continued

Vertical Cavity Surface Emitting Laser (VCSEL)

VCSELs were introduced as a cost-effective multimode transmitter for Gigabit Ethernet and Fibre Channel. They are also used for 10 Gigabit Ethernet and Fibre Channel and will be considered for future data rates such as 40 Gigabit.

Although VCSELs have laser performance characteristics, they are easy to manufacture and are priced less than LEDs by many manufacturers. Table 1.21 describes the characteristics of typical VCSEL sources.

Table 1.21
Characteristics of typical vertical cavity surface emitting laser sources

Item	Characteristics
Cost	Relatively inexpensive
Use	Used with multimode optical fiber information technology systems at high data rates of gigabit and greater
Center wavelength	850 nm and 1300 nm
Spectral width	Very narrow (1 to 6 nm) root mean square
Modulation frequency	Much higher than LEDs, allowing data rates up to 10 gigahertz
Average launched	+1 to –3 decibels per milliwatt into optical power level multimode fiber

LED = light-emitting diode
nm = nanometer

NOTE: Unlike LEDs, VCSELs launch their full power into multimode optical fiber cabling.

Transmitter Light Sources, continued

Laser Diodes (LDs)

LDs (or simply lasers) are typically more expensive than LED and short wavelength laser sources. Table 1.22 describes the characteristics of typical LD sources.

Table 1.22
Characteristics of typical laser diode sources

Item	Characteristics
Cost	More expensive than LED and short wavelength laser sources
Use	Used almost exclusively in singlemode optical fiber links Some available systems use lasers with multimode optical fiber to maximize the achievable system length.
Center wavelength	Center wavelengths of about: 1300 nm are the most predominant. 1550 nm are becoming more popular for long-distance communications in singlemode systems.
Spectral width	Narrow (usually 1 to 6 nm full width half maximum) compared with LEDs
Modulation frequency	Faster than LEDs. Modulation frequencies exceeding 5 gigahertz are achievable.
Average launched power level	Higher than LEDs, with common values of +1 to –3 decibels per milliwatt into singlemode optical fibers **WARNING:** These power levels may present a safety hazard if viewed directly.

LED = light-emitting diode
nm = nanometer

Comparison of transmitters

Table 1.23 provides a summarized comparison of LED, short wavelength laser, VCSEL, and LD.

Table 1.23
Comparison of transmitters

	LED	Short Wavelength Laser	VCSEL	Laser (LD)
Cost	Less expensive	Less expensive	Less expensive	More expensive
Primary optical fiber type	Multimode	Multimode	Multimode	Singlemode
Center wavelength	850 nm and 1300 nm	780 nm	850 nm	1310 nm and 1550 nm
Spectral width	For 850, 30 to 60 nm FWHM For 1300, up to 150 nm FWHM	4 nm	1 to 6 nm FWHM	1 to 6 nm FWHM
Modulation frequency	Usually under 200 MHz	Can exceed 1 GHz	Up to 10 GHz	Can exceed 10 GHz
Average launched power level	–10 to –30 dBm	+1.0 to –5 dBm	+1 to –3 dBm	+1 to –3 dBm

dBm = Decibel milliwatt
FWHM = Full width half maximum
GHz = Gigahertz
LED = Light-emitting diode
MHz = Megahertz
nm = Nanometer
VCSEL = Vertical cavity surface emitting laser

Optical Fiber Receivers

Overview

Almost all types of optical fiber receivers incorporate a photodetector to convert the incoming optical signal to an electrical signal.

The receiver is selected to match the transmitter and the optical fiber.

Characteristic Parameters

The characteristic parameters of optical fiber receivers are the:

- Sensitivity.
- BER.
- Dynamic range.

Sensitivity and Bit Error Rate (BER)

Receiver sensitivity and BER are related:

- The sensitivity of a receiver specifies the minimum power level an incoming signal must have to achieve an acceptable level of performance, which is usually specified as a BER.
- BER is the fractional number of errors allowed to occur between the transmitter and receiver. For example, a BER of 10^{-9} means one bit error for each one billion bits sent. (This error rate is readily available in current systems.)

If the power of the incoming signal falls below the receiver sensitivity, the number of bit errors increases beyond the maximum BER specified for that receiver.

If too little power is received at the detector, the results can be:

- A detected signal with high bit errors.
- No signal detection.

Dynamic Range

Too much received signal power can also compromise the receiver's operation.

If too much power is received at the detector, the results can be:

- Higher than acceptable BER.
- Possible physical damage to the receiver.

The dynamic range is the range of power that a receiver can process at a specified BER. This is determined by the difference between the maximum power and the minimum power that the receiver can process at a specified BER.

Optical Fiber Medium

Optical Fiber Core Size Selection Parameters

The key factors in determining which optical fiber to use in a given application are:

- Active equipment.
- Distance.
- Bandwidth (data rate).

Active Equipment

Before determining the core size of the optical fiber, certain considerations should be evaluated that determine how cable and components are selected for an ITS link, segment, or system.

While the order may occur differently, the elements that need to be considered are the same. At the heart of the design is the application to be serviced. This determines what electronics and passive equipment are available to support the application. This may be a new service or an addition to existing equipment.

Existing equipment limits the choices because some of the system parameters and specifications are already established. If there is no existing equipment, the system design is more flexible. An important factor is the distance between the two end points of the system. The characteristics of the optical fiber and the capability of the active equipment determine how far apart the end points can be.

Optical fiber ITS links range from short links between mainframe computers to long telephone trunk lines. The end-to-end length of the longest link in the system is a major consideration in the selection of an optical fiber type or size based on the active components. In some networks, there may be more than one acceptable type of optical fiber because of the range of link lengths involved and the available active equipment.

For example, a bank in Philadelphia may use a:

- Multimode optical fiber network for telecommunications between its local branches.
- Singlemode optical fiber for a link to its main office in Baltimore.

Increasing the length of a link results in:

- An increase in the total attenuation of the signal from one end to another.
- Reduced system bandwidth because of dispersion.
- Signal distortion caused by the differential mode delay (DMD) phenomenon in multimode fiber.

Active Equipment, continued

Active equipment has either LEDs, VCSELs, or lasers. If the equipment has LEDs or VCSELs, multimode optical fiber of either 50/125 or 62.5/125 µm must be used. If the active equipment has standard laser technology, then singlemode optical fiber 8/125 µm must be used nominally.

After determining which optical fiber to use based on the loss budget available and the type of active equipment, the correct optical fiber cable can be assembled so that the system functions correctly within the required parameters of all the components that make up the channel.

Transmission Media

There are four classes of multimode optical fiber cabling—optical multimode 1 (OM1), optical multimode 2 (OM2), optical multimode 3 (OM3), and optical multimode 4 (OM4). There are two classes of optical singlemode (OS1 and OS2).

Table 1.24 shows the performance of optical fiber cable by type.

Table 1.24
Optical fiber cable performance by type

Classification	Optical Fiber Type	Performance
OM1	62.5/125 µm multimode	Minimum bandwidth of 200 and 500 megahertz over 1 kilometer (MHz•km) at 850 and 1300 nm, respectively.
OM2	50/125 µm multimode	Minimum bandwidth of 500 and 500 MHz•km at 850 and 1300 nm, respectively.
OM3	50/125 µm 850 nm laser optimized multimode	Minimum bandwidth of 2000 and 500 MHz•km at 850 and 1300 nm, respectively.
OM4	50/125 µm 850 nm laser optimized multimode	Minimum bandwidth of 4700 and 500 MHz•km at 850 and 1300 nm, respectively.
OS1	Singlemode	Specified for 1310 and 1550 nm.
OS2	Singlemode	Low water-peak, suitable for coarse wavelength division multiplexing specified for 1310, 1383 and 1550 nm.

µm = Micrometer
nm = Nanometer

Bandwidth

Overview

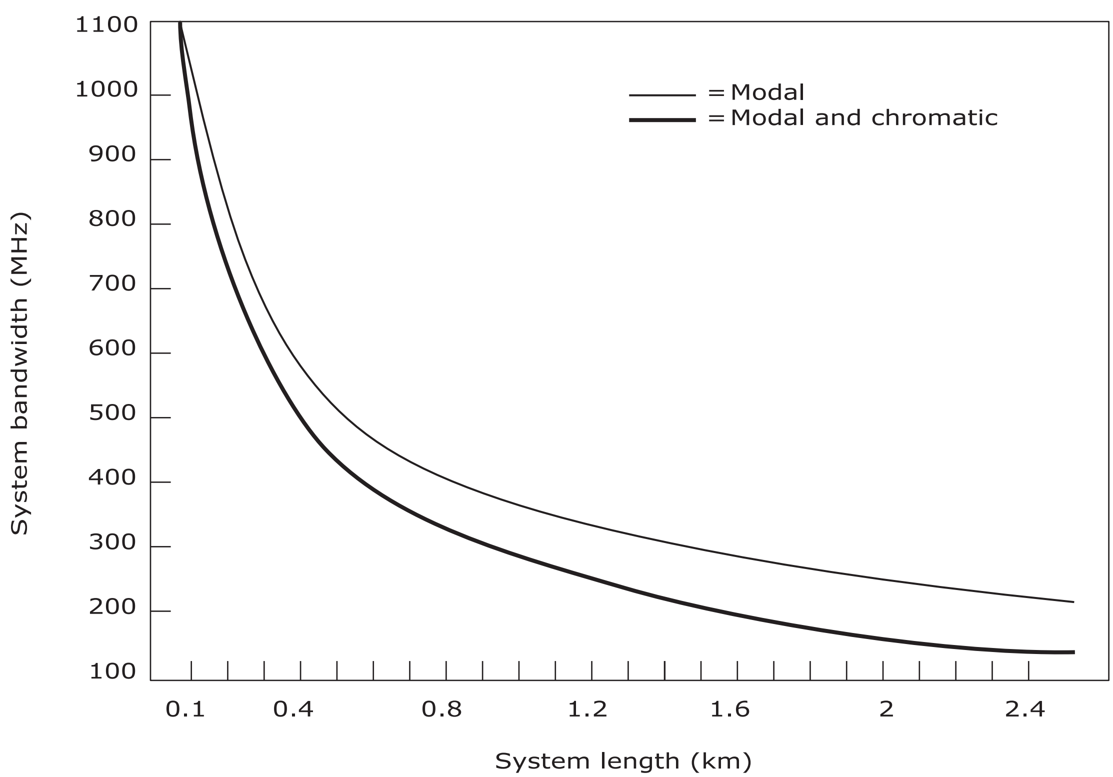
Bandwidth is the information-carrying capacity of a system. The end-to-end bandwidth of a system is related to the respective bandwidths of its component parts. Figure 1.26 represents an example of system bandwidth versus distance.

For an optical fiber system, the essential determinants of the end-to-end bandwidth are the:

- Transmitter.
- Optical fiber.

Installation techniques cannot adversely affect optical fiber bandwidth (multimode) and dispersion (singlemode). Therefore, field measurements are not required.

Figure 1.26
System bandwidth versus distance example



km = Kilometer
MHz = Megahertz

Transmitters and Rise Time

Transmitters have bandwidth limitations because they take time to change from a low-power state (logical 0) to a high-power state (logical 1). This period is called the rise time.

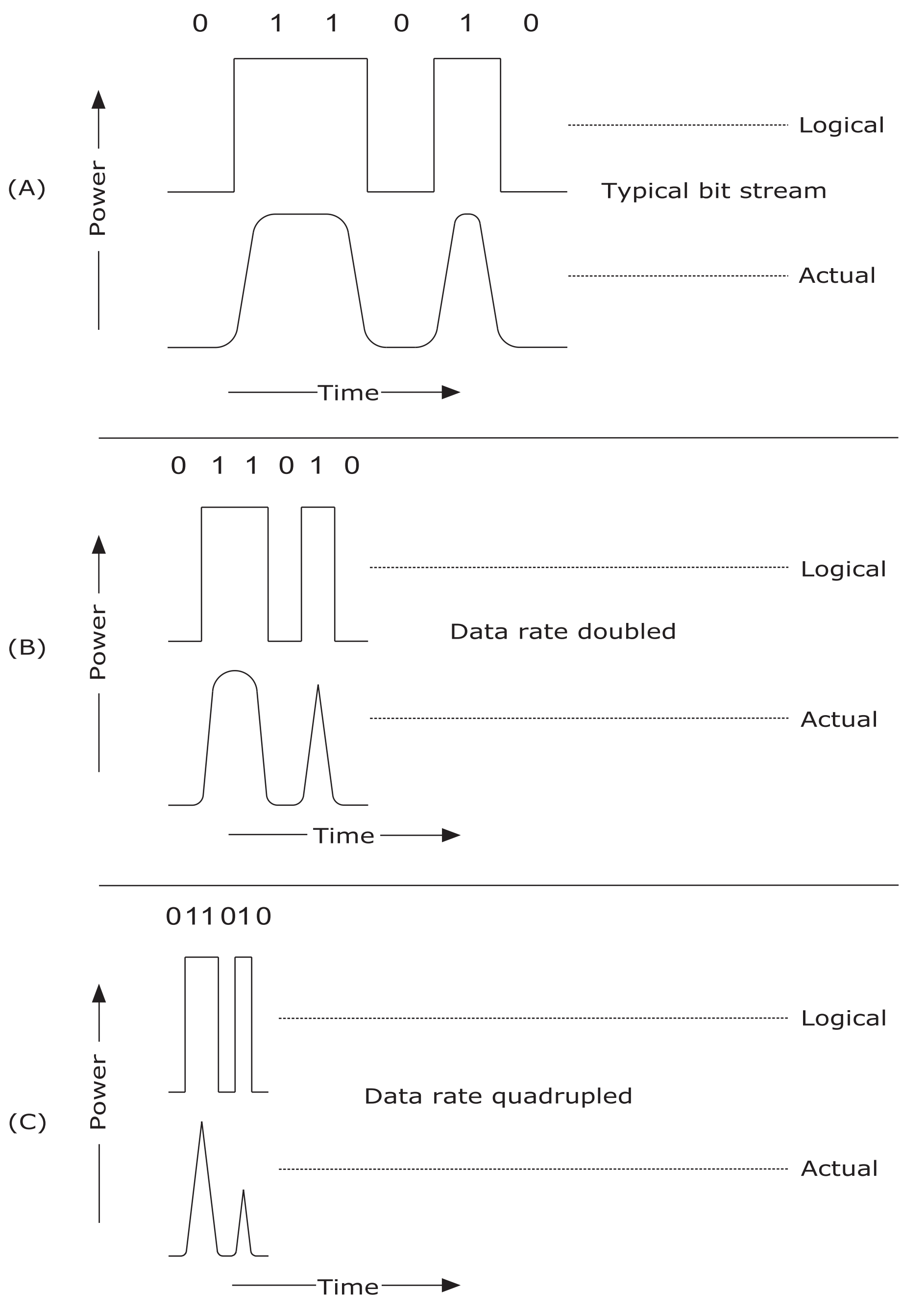
Rise time is usually measured from 10 percent to 90 percent power level. In simplified discussions, the rise time is assumed to be zero. At high data rates, the rise time becomes significant.

Figure 1.27 illustrates how transmitter rise time limits the maximum data rate of a system. The illustration shows the difference between the simplified logical depiction of a bit stream and actual performance of an optical transmitter.

- In Area A, the transmitter has a real rise time that has no impact on the signal.
- Areas B and C show how the signal becomes distorted as the data rate is doubled and then doubled again.

Transmitters and Rise Time, continued

Figure 1.27
Pulse distortion because of rise time and data rate



NOTE: As the data rate is doubled and then doubled again, the effect of a nonperfect actual pulse results in more and more distortion.

Optical Fibers

Optical fibers have bandwidth limitations because of dispersion. Dispersion causes a light pulse to broaden in duration as it travels through the optical fiber.

Singlemode System

Instead of bandwidth, the maximum pulse distortion is frequently used to define system capacity in singlemode systems. Pulse distortion is a function of transmitter spectral width and the optical fiber construction and length.

NOTE: Singlemode dispersion is seldom a concern in premises applications.

The maximum optical fiber dispersion is usually expressed in picoseconds (psec) of pulse broadening per the product of nanometers of transmitter spectral width and system length (psec/nm-km).

NOTE: To calculate link dispersion, multiply the specified optical fiber dispersion value at the center wavelength of the light source by the source spectral width and the length of the optical fiber link. Compare this figure with the maximum allowable dispersion stated by the manufacturer for the receiver in question.

Dispersion in singlemode systems is a function of wavelength. It is important that the optical fiber dispersion specification coincides with the operating wavelength range of the transmitter.

Multimode System

Calculating and predicting the bandwidth requirements of a multimode system is more complex than determining the dispersion of a singlemode system. It consists of combining the effects of all three of the following:

- Transmitter rise time
- Optical fiber modal dispersion
- Chromatic dispersion

NOTE: This involves complex assumptions and calculations that are beyond the scope of this publication. The application standards or original equipment manufacturer (OEM) typically determine the minimum optical fiber bandwidth necessary to support a given system.

Chromatic and Modal Dispersion in Multimode Systems

The bandwidth of a multimode system is a function of chromatic dispersion and modal dispersion as well as length.

Chromatic Dispersion

The LED sources frequently used with multimode systems have broader spectral widths than singlemode laser sources. This results in chromatic dispersion. Chromatic dispersion occurs when the wider range of wavelengths in each pulse travels at a wider range of individual speeds. This causes the duration of a pulse to increase with distance.

The amount of chromatic dispersion that occurs depends partly on the center wavelength of the link. Most glass optical fibers have minimal chromatic dispersion characteristics near 1300 nm.

Modal Dispersion

The various modes of light propagation in a multimode optical fiber follow different paths through the core of the optical fiber. These individual paths have different lengths. The light that travels along the shortest path (lowest order mode) arrives at the end of the optical fiber before the light that travels along the longer paths (higher order modes). A pulse of light, which consists of hundreds of modes in a multimode optical fiber, broadens in time as it travels through the optical fiber. This type of dispersion is called modal dispersion.

Measurement and Specification of Multimode Systems

Optical fiber suppliers usually measure bandwidth using a narrow laser source on a fixed length of optical fiber because of the variation of chromatic dispersion with source characteristics (e.g., center wavelength, spectral width) and optical fiber length. The bandwidth value stated by the supplier only represents the effect of modal dispersion because the spectral width of a typical laser source is usually so small it makes chromatic dispersion negligible.

Measurement and Specification of Multimode Systems, continued

Because the bandwidth reported by the optical fiber and cable supplier is the result of a measurement made with an LD source, this measurement is not readily applied to LED system design.

The modal bandwidth (e.g., usually called the optical fiber bandwidth by manufacturers and suppliers) is commonly expressed as a frequency-distance product (e.g., MHz/km). This means a given optical fiber can support higher transmission rates over a shorter distance than it can over a long distance.

For example, a system requiring 90 MHz of end-to-end bandwidth requires a higher grade of optical fiber for a ≈2 km (1.2 mi) link than for a ≈1 km (0.6 mi) link. For links of several hundred meters/feet or less, optical fiber bandwidth often is not a consideration.

Calculation

Much experimentation has been conducted to characterize the relationship between the:

- Modal component of multimode optical fiber bandwidth.
- System bandwidth of a complete optical fiber channel.

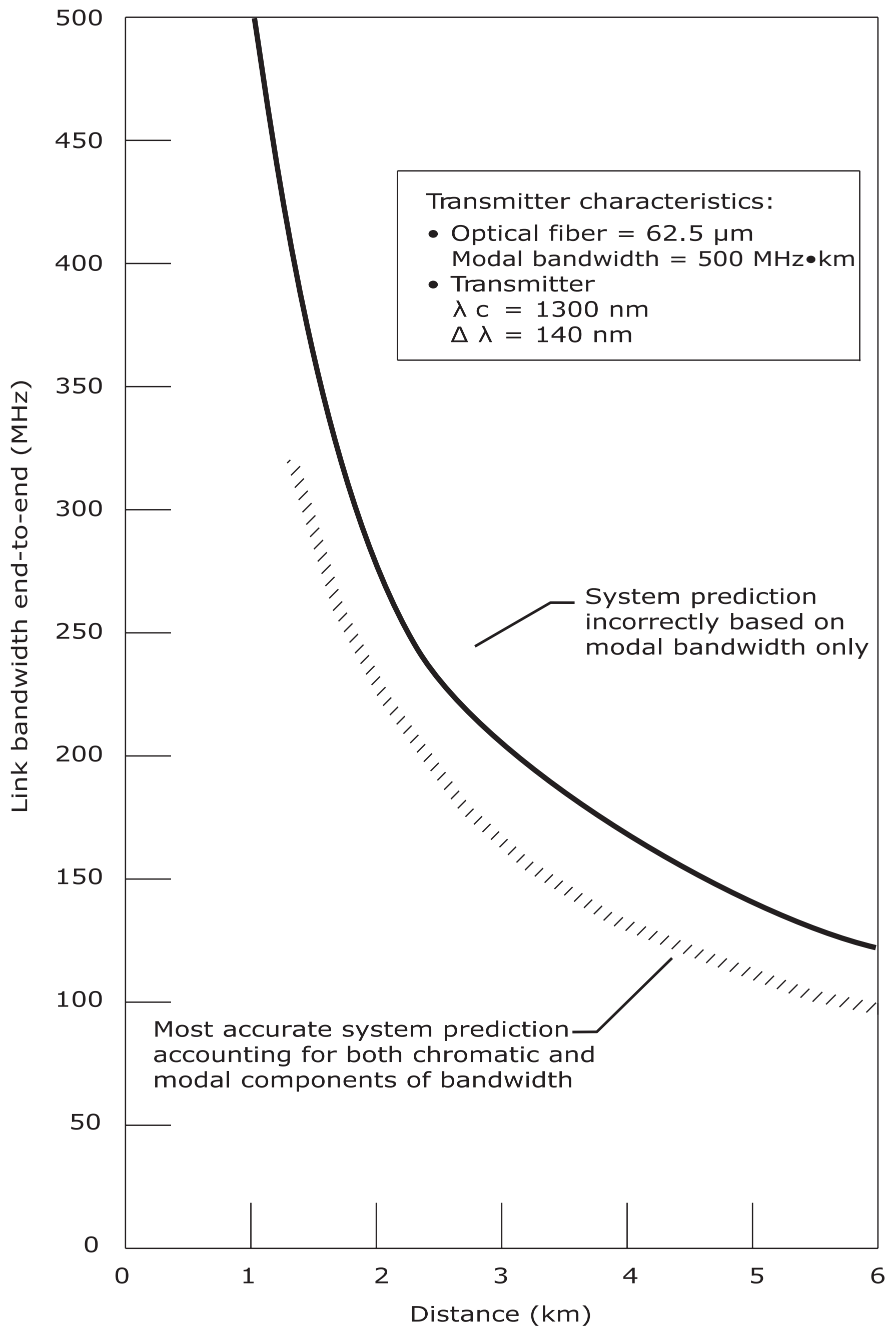
Several methods are proposed for approximating this relationship—all are mathematically cumbersome. They take into account the:

- Dispersion behavior of the optical fiber.
- Spectral characteristics of the transmitter.

Figure 1.28 shows one of the conservative algorithms used to generate a curve of system length versus system bandwidth for a typical 62.5/125 µm multimode optical fiber and a specific LED transmitter. If only the bandwidth-distance product from the manufacturer's specification were used, the curve would predict a longer achievable system length. This demonstrates the dangerous errors that result from oversimplification of a bandwidth calculation.

Measurement and Specification of Multimode Systems, continued

Figure 1.28
Link bandwidth at 1300 nanometers using 62.5/125 micrometer multimode optical fiber



km = Kilometer
µm = Micrometer
MHz = Megahertz
nm = Nanometer

Determining the required optical fiber bandwidth is best left to the electronics, cable, or optical fiber manufacturer.

Classification of Optical Fiber

The two major classifications of optical fiber are multimode and singlemode.

Multimode optical fiber is best suited for premises applications where links are less than:

- ≈2000 m (6562 ft) for data rates of 155 Mb/s or less.
- ≈550 m (1800 ft) for data rates of 1 Gb/s or less.
- ≈300 m (984 ft) for data rates of 10 Gb/s or less.
- ≈100 m (328 ft) for data rates of 100 Gb/s or 40 Gb/s or less.

Multimode optical fiber's higher NA allows the use of relatively inexpensive LED, VCSEL, and short wavelength laser transmitters. These are more than adequate for short-distance applications.

NOTE: See Multimode Optical Fiber in this chapter for typical characteristics of multimode optical fiber.

Singlemode optical fiber is best suited for:

- Bandwidth requirements exceeding multimode's capability.
- Distances exceeding multimode's capability.
- When the application requires singlemode.

NOTE: See Singlemode Optical Fiber in this chapter for typical characteristics of singlemode optical fiber.

Table 1.25 summarizes the comparisons between the two multimode types and singlemode optical fibers.

Table 1.25
Summarized comparison of core sizes of multimode and singlemode optical fiber cable

	Multimode		Singlemode
Item	**62.5/125 µm**	**50/125 µm**	**Dispersion-Unshifted**
Attenuation	Low	Low	Lowest
Bandwidth	Moderate	Higher	Very high
Numerical aperture	Midrange	Smaller	Very small
Optical fiber outside diameter	125 µm	125 µm	125 µm
Wavelength	850 nm and 1300 nm	850 nm and 1300 nm	1310 nm and 1550 nm

µm = Micrometer
nm = Nanometer

Multimode Optical Fiber

The typical characteristics of multimode optical fiber are shown in Table 1.26.

Table 1.26
Typical characteristics of multimode optical fiber

Item	Characteristic
Optical fiber size	The two popular sizes of multimode optical fibers are: • 62.5/125 µm. • 50/125 µm. See Table 1.28 for more information. NOTE: Multimode optical fibers are frequently referred to by the core and cladding diameter in micrometers (see Figure 1.29). For example, a multimode optical fiber with a core diameter of 62.5 µm and a cladding diameter of 125 µm is typically designated as a 62.5/125 µm optical fiber.
Cost	While the multimode optical fiber cable is more expensive than singlemode, the installed system is less expensive than singlemode systems because of the more cost-effective electronics and connectors.
Distance	Used mostly for information technology systems links less than ≈2.0 km (1.2 mi) long.
Capacity	• Data rates of 155 Mb/s are common for campus links of less than ≈2.0 km (1.2 mi). • Data rates of 1 Gb/s are common for building or campus backbones of less than ≈550 m (1800 ft). • Data rates of 10 Gb/s are for building backbones less than ≈300 m (984 ft).
Operating wavelength	Operates at: • 850 nm (first window—LED or vertical cavity surface emitting laser). • 1300 nm (second window—LED or laser diode).
System type	Used for voice, data, security, and closed-circuit video systems.

ft = Foot
Gb/s = Gigabit per second
km = Kilometer
LED = Light-emitting diode
µm = Micrometer
m = Meters
Mb/s = Megabit per second
mi = Mile
nm = Nanometer

Multimode Optical Fiber, continued

Figure 1.29
Core and coating

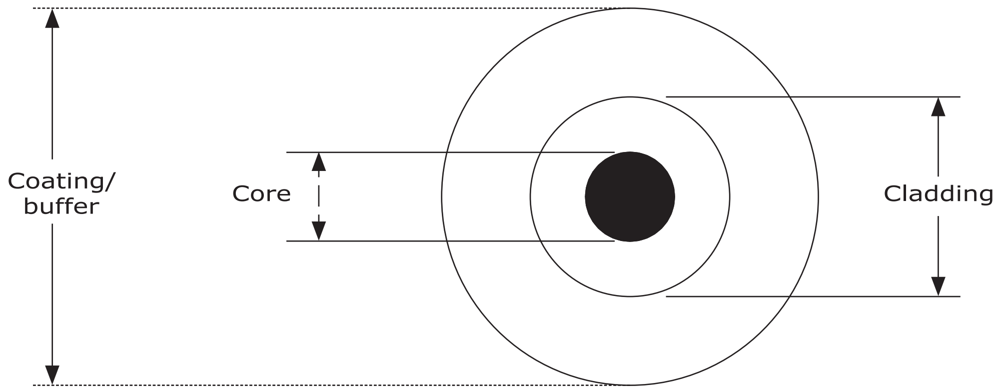


Table 1.27 shows the characteristics of 50/125 µm multimode optical fiber.

Table 1.27
Characteristics of 50/125 µm multimode optical fiber

Item	Characteristic
Attenuation	Low attenuation at 850 nm and 1300 nm wavelength regions.
Bandwidth	Higher than that of 62.5/125 µm multimode fiber.
Numerical	Lower NA and smaller core size results in less coupling power compared with that of 62.5/125 fiber for LED systems aperture (NA). Laser systems (VCSELs) are not affected.
Mechanical	Compatible with all 62.5/125 µm multimode and compatibility singlemode optical fiber connector parts because of the common cladding diameter.

LED = Light-emitting diode
µm = Micrometer
NA = Numerical aperture
nm = Nanometer
VCSEL = Vertical cavity surface emitting laser

As more strict tolerance is required for ferrules used with SM fiber, termination of multimode connector onto singlemode fiber is not recommended. The opposite combination does not adversely affect the performance.

Multimode Optical Fiber, continued

Table 1.28 shows the characteristics of 62.5/125 µm multimode optical fiber.

Table 1.28
Characteristics of 62.5/125 µm multimode optical fiber

Item	Characteristic
Attenuation	Slightly higher attenuation than 50/125 µm optical fiber.
Bandwidth	Moderate bandwidth that accommodates most data applications. Numerical Higher NA than 50/125 µm optical fiber, allowing more power aperture (NA) coupled from an LED into the optical fiber.
Compatibility	Compatible with all 50/125 µm multimode and singlemode optical fiber connector parts because of the common cladding diameter.

LED = Light-emitting diode
µm = Micrometer
NA = Numerical aperture

As more strict tolerance is required for ferrules used with SM fiber, termination of multimode connector onto singlemode fiber is not recommended. The opposite combination does not adversely affect the performance.

Wavelength Windows

Optical fibers do not transmit all wavelengths of light with the same efficiency. The attenuation of light signals is higher for visible light (wavelengths of 400 nm to 700 nm) than for light in the near infrared region (wavelengths of 700 nm to 1600 nm).

Within this near infrared region, there are wavelength bands of decreased transmission efficiency. This leaves only several wavelengths that optical fibers can operate with low loss. These wavelength areas that are most suitable for optical communications are called windows. The most commonly used windows are found near 850 nm, 1300 nm, and 1550 nm.

Singlemode Optical Fiber

Singlemode optical fiber is similar to multimode optical fiber in physical appearance and composition, but it has performance characteristics that differ by orders of magnitude from those of multimode optical fibers (see Table 1.29).

Table 1.29
Typical characteristics of singlemode optical fiber

Item	Characteristic
Distance	Used by service providers (e.g., telephone, CATV). Unrepeated spans in excess of ≈80 km (50 mi) are achievable with state-of-the-art equipment.
Capacity	Data rate transmission in excess of 10 Gb/s range is common.
System performance	• Very high bandwidth • Very low attenuation • Good for telephony and CATV applications • Ideal for local applications having links over ≈2 km (1.2 mi) long • Satisfies high bandwidth needs in backbone applications up to ≈80 km (50 mi)
Optical fiber	• Core diameter: between 8 and 9 µm characteristic • Diameter: 125 µm • Attenuation: 0.3 to 1.0 dB/km at 1310 nm and 1550 nm • Bandwidth: greater than 20 GHz • Numerical aperture: Because the NA is very small, the optical fibers are used almost exclusively with laser sources that can concentrate more power into a smaller launch area.
Cost	Less expensive than multimode optical fiber, but the higher cost of singlemode transmission equipment usually means a higher system cost in short length (premises) systems.
Operating wavelength	1310 nm and 1550 nm

CATV = Community antenna television
dB/km = Decibels per kilometer
Gb/s = Gigabits per second
GHz = Gigahertz
km = Kilometers
µm = Micrometers
mi = Miles
NA = Numerical aperture
nm = Nanometers

NOTE: For singlemode optical fiber cable, the following maximum attenuation values are generally specified:

- Outside cable—0.5 dB/km at 1310 nm and 1550 nm
- Inside cable—1.0 dB/km at 1310 nm and 1550 nm

Optical Fiber Applications Support Information

Overview

This section provides an overview regarding applications support for many of the available optical fiber LAN applications across the optical fiber media types. This information allows the user to easily access enough basic information to make informed decisions about optical media choices and system design.

With a predetermined knowledge of the required distances, an idea of the applications support required and the cabling system design, the ITS distribution designer can determine the media most appropriate for the situation.

Three primary factors must be considered in optical fiber selection and system design:

- Maximum supportable distance
- Maximum channel attenuation
- Application requirements

The first factor is maximum supportable distance based on bandwidth, transmitter and receiver specifications, propagation delay, jitter, and numerous other factors. Maximum supportable distance is established by the application standards.

The second factor is maximum channel attenuation, which is established by the difference between the minimum transmitter output power coupled into the optical fiber and the receiver sensitivity, less any power penalties established. The channel attenuation can be affected by the system design (e.g., number of connections and/or splices, length, wavelength of operation, loss values of components).

The third factor is application requirements, which is that end devices may require a specific type of interface (e.g., singlemode).

Supportable Distances and Channel Attenuation

For existing systems, measure the channel attenuation. For new installations, use the equations below, which are based on the minimum component specifications, to verify the system design:

- Channel attenuation < Maximum channel attenuation
- Channel attenuation = Cable attenuation + connector attenuation + splice attenuation
- Channel attenuation = [Cable attenuation coefficient (dB/km) x length (km)] + [# connector pairs x 0.75 dB] + [# of splices x 0.3 dB]

Therefore, to determine maximum length for a particular system design, the resulting equation is:

$$\text{Maximum length} = \frac{(\text{Maximum channel attenuation} - [\#\ \text{connector pairs x } 0.75\ \text{dB}] - [\#\ \text{splices x } 0.3\ \text{dB}])}{\text{Cable attenuation coefficient}}$$

The maximum cable attenuation coefficients are listed in Table 1.30.

NOTE: Chapter 11: Field Testing of Structured Cabling contains information on the maximum supportable distances and maximum channel attenuation for optical fiber applications by type. The maximum supportable distances and maximum channel attenuation listed apply to the specific assumptions and constraints provided in the notes. Different assumptions or constraints may change the maximum supportable distance and maximum channel attenuation.

Table 1.30
Maximum cable attenuation coefficient

Optical Fiber Cable Type	Wavelength (nm)	Maximum Attenuation
50/125 µm multimode	850 1300	3.5 dB/km 1.5 dB/km
62.5/125 µm multimode	850 1300	3.5 dB/km 1.5 dB/km
Singlemode inside plant cable	1310 1550	1.0 dB/km 1.0 dB/km
Singlemode outside plant cable	1310 1550	0.5 dB/km 0.5 dB/km

dB = Decibel
km = Kilometer
µm = Micrometer
nm = Nanometer

Verifying Optical Fiber Performance and Electronics Compatibility

Overview

This section is designed to provide an understanding of the relationship of the link to the requirements of the electronics (transmitter and receiver). However, it is more critical to ensure that the installed link meets the requirements of a generic cabling system, independent of a specific application or electronic product.

Standards have been developed for generic cabling systems, both for multimode and single mode systems, and for horizontal and backbone cabling. These requirements are based on long-standing and field-proven test procedures, allowing both the end user and contractor to certify the installation.

It is necessary to verify that the overall system will work properly whenever new components are installed to reconfigure an existing system.

This is true whether the changes involve a new:

- Optical fiber cabling system for active components that have already been chosen.
- Active component system retrofitted to previously installed optical fiber cabling.

This verification is a repetitious process. Decisions regarding route, electronics, wavelength, and system configuration are all interrelated. Often a trade-off analysis—varying one or more of these parameters—is necessary.

Industry standardization is making verification easier. More manufacturers have developed multimode LAN systems, which operate over multimode optical fiber. However, it is still important that the ITS distribution designer or end user understand some of the fundamental concepts and calculations necessary to verify that a system will work properly.

For short or basic systems, performance requirements have often already been considered by the manufacturer and translated into system specifications for the:

- Optical cable lengths.
- Number of splices and connectors.
- Optical cable performance.

For longer or complex applications, it is generally recommended that the ITS distribution designer analyze the proposed system.

Key Parameters

The two key parameters in optical fiber cabling performance that must be verified for compatibility with the proposed electronics are:

- Attenuation.
- Bandwidth.

It is important to consider how specific grades of optical fiber affect system performance.

Verification Theory and Methodology

The theory and methodology used to verify appropriate optical fiber performance are the same for both singlemode and multimode optical fibers at any wavelength.

IMPORTANT: The specifications used for each of the components (e.g., transmitter, receiver, optical fiber, connectors) must correspond to the optical fiber type and wavelength.

For example, if designing a 62.5/125 μm multimode system to operate at 1300 nm, the attenuation specified for a 50/125 μm multimode connector cannot be used, nor can the transmitter average power from an 850 nm LED source specified for 50/125 μm optical fiber. Only the 62.5/125 μm optical fiber specifications for 1300 nm and connector loss specification for 62.5/125 μm optical fiber can be used.

Additionally, any transition from 50/125 μm optical fiber (or a transmitter source specified for 50/125 μm optical fiber) into 62.5 μm fiber for LED systems will have to take into account the attenuation at that junction (see Table 1.31).

To increase testing accuracy for optical fiber link and channel loss measurements, it is recommended to use an LED light source with an encircled flux (EF) mode conditioner to control the near field at the output of the launching test cord. The encircled flux test method is specified in ANSI/TIA-526-14-B and IEC 61280-4-1.

Verification Theory and Methodology, continued

Table 1.31
Mismatch of core size and power loss

Receiving Fiber \ Transmitting Fiber	50 µm (NA = 0.20)	62.5 µm (NA = 0.275)
50 µm (NA = 0.20)	0.00	-5.7 dB
62.5 µm (NA = 0.275)	0.00	0.00

dB = Decibel
µm = Micrometer
NA = Numerical aperture

NOTE: Total loss = Total loss using OFL launch = Loss (NA) + Loss (dia)
Loss (NA) = $10\log_{10}(0.20/0.275)^2 = -2.8$ dB
Loss (dia) = $10\log_{10}(50/62.5)^2 = -2.9$ dB

For telecommunications networks that have more than one optical fiber link, the ITS distribution designer may:

- Choose the longest, most complex link to verify system performance and select that optical fiber grade for the entire network.
- Select a specific optical fiber grade for each individual link. This is generally unnecessary and is not recommended.

Bandwidth

The bandwidth for an optical fiber cannot be tested or validated in the field. Validation of the bandwidth can only be through manufacturer's specification and quality checking of the product specification sheets with the installed components. Specifically, for laser-enhanced 50/125 µm, OM3, and OM4 optical fiber, the bandwidth performance for each glass element of the end-to-end optical fiber channel, cable, cords, and pigtails should always be of the same specification and preferably from the same manufacturing source and type.

When choosing the fiber type, it is important to know the applications that are to be supported by the optical fiber channels and the applications bandwidth requirements for each of the optical fiber types being considered. High-speed LAN applications (e.g., 1Gb Ethernet, 10Gb Ethernet) require the use of a VCSEL to deliver the light source. Because a VCSEL illuminates a smaller number of modes in the optical fiber than an LED, the bandwidth statement for these laser-enhanced optical fiber are higher than for the LED.

Most optical fibers that are suitable for medium distance delivery of high-speed applications have two bandwidth statements in the 850 nm window—one for an LED source over fill launch (OFL) and one for the VCSEL restricted modal launch (RML).

Attenuation

The maximum permissible end-to-end system attenuation in a given link is determined by the average transmitter power and the receiver sensitivity. To analyze a system's attenuation and determine whether the proposed electronics will operate over the cable plant, follow the nine steps shown in Table 1.32 and then check the minimum system loss (see Checking Minimum System Loss in this chapter). The nine steps are explained in detail on the pages following Table 1.32.

NOTE: Be sure the test setup simulates the actual system. (Use the jumpers or at least include their losses in final calculations.)

Table 1.32
Calculating optical fiber performance

Objective	Step	Calculation
A. Calculate the link loss budget	1	Calculate the system gain.
	2	Determine the power penalties.
	3	Calculate the link loss budget by subtracting the power penalties from the system gain.
B. Calculate the passive cable system attenuation loss	4	Calculate the optical fiber loss.
	5	Calculate the connector loss.
	6	Calculate the splice loss.
	7	Calculate other component losses (e.g., bypass, switches, couplers, splitters).
	8	Calculate the total passive cable system attenuation by adding the results of Steps 4-7.
C. Verify performance	9	Subtract the passive cable system attenuation (result of Step 8) from the link loss budget (result of Step 3). The result is the system performance margin. If this result is a negative number, the system will not operate.

Attenuation, continued

Example 1.1 illustrates how to calculate the system performance margin to verify adequate power. Detailed information is provided on the following pages.

Example 1.1
Optical fiber performance calculations example

A. Calculating the Link Loss Budget

Example manufacturer's electronic specifications	System Wavelength	1300 nm
	Optical fiber type	62.5/125 µm multimode
	Average transmitter output	-18.0 dBm
	Receiver sensitivity (10^{-9} BER)	-31.0 dBm
	Receiver dynamic range	11.0 dB

1. Calculate system gain		Average transmitter power	−	18.0 dBm
	−	Receiver sensitivity	−	(−31.0 dBm)
	=	System gain		13.0 dB
2. Determine power penalties		Operating margin (none stated)		2.0 dB
	+	Receiver power penalties (none stated)	+	0.0 dB
	+	Repair margin (2 fusion splices) at 0.3 dB each)	+	0.6 dB
	=	Total power penalties		2.6 dB
3. Calculate link loss budget		System gain		13.0 dB
	−	Power penalties	−	2.6 dB
	=	Total link loss budget		10.4 dB

B. Calculating the Passive Cable System Attenuation

4. Calculate optical fiber loss at operating wavelength		Cable distance		1.5 km
	x	Individual optical fiber loss	x	1.5 dB/km
	=	Total optical fiber loss		2.25 dB
5. Calculate connector loss (exclude transmitter and receiver connectors)		Connector pair loss		0.75 dB
	x	Number of connector pairs	x	4
	=	Total connector loss		3.0 dB
6. Calculate optical splice loss		Individual splice loss		0.3 dB
	x	Number of splices	x	3
	=	Total splice loss		0.9 dB
7. Calculate other component losses		Total components (none)		0.0 dB
8. Calculate total passive cable system attenuation		Total optical fiber loss		2.3 dB
	+	Total connector loss	+	3.0 dB
	+	Total splice loss	+	0.9 dB
	+	Total components	+	0.0 dB
	=	Total system attenuation		6.2 dB

C. Verifying Performance

9. Calculate system performance margin to verify adequate power		Link loss budget		10.4 dB
	−	Passive cable system attenuation	−	6.2 dB
	=	System performance margin		4.2 dB

Attenuation, continued

A. Calculating the Link Loss Budget

The link loss budget is the maximum allowable loss for the end-to-end cable system. To calculate the link loss budget, calculate the system gain and power penalties:

- System gain is the difference between the transmitter average power and the receiver sensitivity.
- Power penalties are factors that adjust the system gain, including the operating margin, receiver power penalty, and repair margin.

Table 1.33 explains how to calculate the system gain, power penalties, and link loss budget.

NOTE: For information on link loss budget calculations by the manufacturer, see the foot note at the end of Table 1.33.

Attenuation, continued

Table 1.33
System gain, power penalties, and link loss budget calculations

<table>
<tr><th>To Calculate the…</th><th>You Must…</th></tr>
<tr><td>System gain</td><td>Subtract the receiver sensitivity (in dBm) from the transmitter average power (in dBm). This gives the maximum allowable loss (in dB) between the transmitter and receiver for the BER specified for the receiver.
NOTE: If the transmitter power is not based on the optical fiber type of the system, it can be adjusted using the information in Table 1.31.</td></tr>
<tr><td>Power penalties</td><td>Add the loss values for the:
• Operating margin*—This loss accounts for:
– Variations in the transmitter center wavelength.
– Changes in the transmitter average power and receiver sensitivity that result from age.
– Variations in the component temperature within the operating range of the system. If the system manufacturer does not specify the operating margin, use value of:
• 2 dB for LEDs.
• 3 dB for lasers.
• Receiver power penalty*—Some manufacturers may specify other power penalties (dispersion, jitter, bandwidth, or clock recovery) that must be subtracted from the system gain. If these are provided, they must be subtracted from the available system gain.
• Repair margin*—If the cable is located where it could be cut or damaged by accident, allow sufficient loss margin in the design to accommodate at least two repair splices. If the cable is in a high-risk area or reroutings are anticipated, the ITS distribution designer may decide to allow for more than two splices.</td></tr>
<tr><td>Link loss budget*</td><td>Subtract the total value (in dB) for all of the power penalties from the system gain. The result is the link loss budget.</td></tr>
</table>

* In some cases, the electronics manufacturer will have already calculated the link loss budget. In these cases, it is usually safe to assume the operating margin (e.g., transmitter aging) and receiver power penalties have been included in the manufacturer's calculations. However, the repair margin is usually not included in a manufacturer's link loss budget calculations, unless the product documentation specifically states a repair margin. When a repair margin is not stated by the manufacturer, the ITS distribution designer must subtract it from the system gain to determine the link loss budget.

BER = Bit error rate
dB = Decibel
dBm = Decibel milliwatt
LED = Light emitting diode
ITS = Information technology systems

Attenuation, continued

B. Calculating the Passive Cable System Attenuation

To calculate the passive cable system attenuation, total the values for the:

- Optical fiber loss.
- Connector loss.
- Splice loss.
- Other component losses.

NOTE: When working with existing cable plant, passive cable system attenuation can be measured directly. Table 1.34 explains how to calculate each of these losses.

Table 1.34
Calculating losses

To Calculate the…	You Must…
Optical fiber loss	Multiply the length of the proposed link by the normalized cable attenuation (dB/km) for the optical fiber at the operating system wavelength. NOTE: Temperature may affect the loss of the optical fiber cable. See Effects of Temperature on Optical Fiber Loss.
Connector loss	Add the individual attenuation values (in dB) for every connector pair along the optical fiber route, from transmitter to receiver, excluding the transmitter and receiver connectors (see Connector Loss Values). NOTE: A connector as described here refers to a mated connector pair in a channel where all the connectors are the same type. The channel may have two, three, or four connectors. For channels with more than two connectors, a lower loss connector is required to meet the loss budget.
Splice loss	Add the individual local attenuation values (in dB) for every splice along the optical fiber route, from transmitter to receiver (see Splice Loss Values).
Other component	Add the attenuation values of any other components that contribute to losses in the optical fiber route, from transmitter to receiver.
Total loss	Add the values for each of these losses to get the total passive cable system attenuation.

NOTE: Example calculations for the passive cable system attenuation and its four components are shown in Example 1.1.

dB = Decibel
km = Kilometer

Attenuation, continued

Effects of Temperature on Optical Fiber Loss

Temperature changes may affect the loss of optical fiber cable. Loss variations because of temperature changes can sometimes be as high as 0.2 dB/km. Some manufacturers' specifications indicate the cable's loss only at room temperature rather than throughout the operating temperature range.

Add an additional margin (in dB/km) to the normalized optical fiber attenuation value when calculating the optical fiber link loss, as explained earlier in this section, if the cable's specifications are:

- For room temperature only.
- Based on an average of several optical fibers.

Connector Loss Values

When designing links with:

- Zero to four connector pairs, use the maximum value.
- Five or more connector pairs, use the typical value.

NOTE: The maximum connection loss of 0.75 dB is recommended. The new small form factor (SFF) connectors should meet or exceed these attenuation requirements. Consult the connector manufacturer to provide the average and maximum loss values for the connector type selected.

Splice Loss Values

General splice loss values for system planning and link loss analysis are given in Table 1.35. Specific suppliers or contractors may use other values.

NOTE: A maximum splice loss of 0.3 dB is recommended.

Table 1.35
Splice loss values in decibels

	Multimode		Singlemode	
Splice Type	**Average**	**Maximum**	**Average**	**Maximum**
Fusion	0.05	0.3	0.05	0.3
Mechanical	0.10	0.3	0.10	0.3

Attenuation, continued

C. Verifying Performance

To verify performance, subtract the passive cable system attenuation from the link loss budget. If the result is:

- Above zero (i.e., the passive cable system attenuation is less than the link loss budget), the system has enough power to operate over the passive portion of the link.
- Below zero (i.e., the passive cable system attenuation is more than the link loss budget), the system does not have enough power to operate.

NOTE: For this purpose, maximum transmitting average power should be considered.

If the result is below zero and the system has not been installed, make design changes (e.g., use lower loss connectors, splices, or optical fibers; reroute the design) to reduce passive system losses. In rare cases, it may be necessary to add active components with greater system gains.

When working with an existing cable plant, passive cable system attenuation can be measured directly. Remember that the test setup should simulate the actual system (e.g., use the jumpers or at least include their losses in the final calculations).

Example link loss calculations are shown in Example 1.1.

Checking Minimum System Loss

After verifying that the electronics have enough power to operate, one more attenuation check of the system design remains. Compare the link attenuation with the receiver's dynamic range to ensure there is not too little loss in the link (see Table 1.36).

Insufficient minimum system loss (e.g., too little loss in the link) is sometimes a problem when a laser source is used in premises environments (where lengths are short).

To calculate the minimum required system loss, subtract the receiver's dynamic range from the system gain (both in dB, see Example 1.1):

	System gain		13 dB
–	Receiver's dynamic range	–	11 dB
=	Minimum required system loss	=	2 dB

Attenuation, continued

Table 1.36
Minimum system loss

If the Result Is…	Then…
Less than zero	No further checking is necessary as it is impossible to overdrive that transmitter/receiver combination.
Greater than zero	The resulting number represents the minimum loss that must be introduced into the link between the transmitter and receiver to maintain the specified BER. The total optical fiber, connector, and splice loss must exceed this value. Using Example 1.1: Optical fiber loss 2.25 dB Connector loss + 3.00 dB Splice loss + 0.90 dB Total = 6.15 dB Because 6.15 > 2, the system will operate as installed.

BER = Bit error rate
dB = Decibel

If additional loss is required in a given link, it is easy to add an appropriate link attenuator to the system. Attenuators are devices that can be inserted into optical fiber transmission systems, usually at a point where there is a connector, to introduce additional loss. There are two types of attenuators:

- Fixed attenuators cause a specific level of additional loss.
- Variable attenuators can be tuned to a given link.

Determine if the minimum loss criteria are met by measuring the attenuation of each link after it is installed.

Selecting an Optical Fiber Core Size to Application or Original Equipment Manufacturer (OEM) Specifications

Applications standards (e.g., IEEE) specify the maximum supportable distance of each optical fiber type for specific applications.

OEMs of optical transmission equipment also determine the maximum distance over which their systems can operate. They recommend a specific core size and optical fiber performance for given lengths and data rates.

Deviations from the OEM recommendations may be justified in the following circumstances:

- Optical fiber selection is made during the cabling design process and before the selection of active components.
- Cabling systems are designed for potential upgrades for which the active elements are not yet available.
- Existing installed optical fibers are used whether or not they are the type recommended for the particular end equipment.

Therefore, it is important for the ITS distribution designer to understand:

- The characteristics of the application and the active equipment.
- How the characteristics of the application and the active equipment affect optical fiber selection.

Synchronous Optical Network (SONET) and Synchronous Digital Hierarchy (SDH) Concepts

Similar in nature to digital hierarchy for balanced twisted-pair transmissions, standards have been established for optical fiber carrier transmissions.

SONET is the standard for North America, and synchronous digital hierarchy (SDH) is the international standard. These two standards are basically identical. These standards organize transmission into 810-byte frames that include bits related to signal routing and destination as well as the data being transported.

The term synchronous means that all network nodes ideally derive their timing signals from a single master clock; however, because this is not always practical, SONET and SDH can accommodate nodes with different master clocks.

Table 1.37 shows the common SONET and SDH transmission rates.

Table 1.37
Common synchronous optical network and synchronous digital hierarchy transmission rates

Rate Name	Data Rate (Mb/s)	Voice Channels
STS-1/OC-1	51.84	672
STS-3/OC-3	155.52	2016
STS-12/OC-12	622.08	8064
STS-48/OC-48	2488.32	32,256
STS-96/OC-96	4976.64	64,512
STS-192/OC-192	9953.28	129,024
OC-768	39,813.12	
OC-1536	79,626.12	
OC-3072	159,252.24	

Mb/s = Megabit per second
OC = Optical carrier
STS = Synchronous transport signal

Unlike the T and E multiplex formats covered previously, SDH allows single channels to be extracted from the signal at any of the data rates. This makes it far more flexible and cost effective.

Other key advantages of SDH are that the line-side transmission format and alarm format are identical between all vendors, which allows for greater equipment choice. Previously, the transmit and receive terminals had to be from the same vendor to ensure compatibility.

The SDH concept is based around the ability that any signal from a lower order multiplex stage can be inserted directly into a higher order signal.

System Example

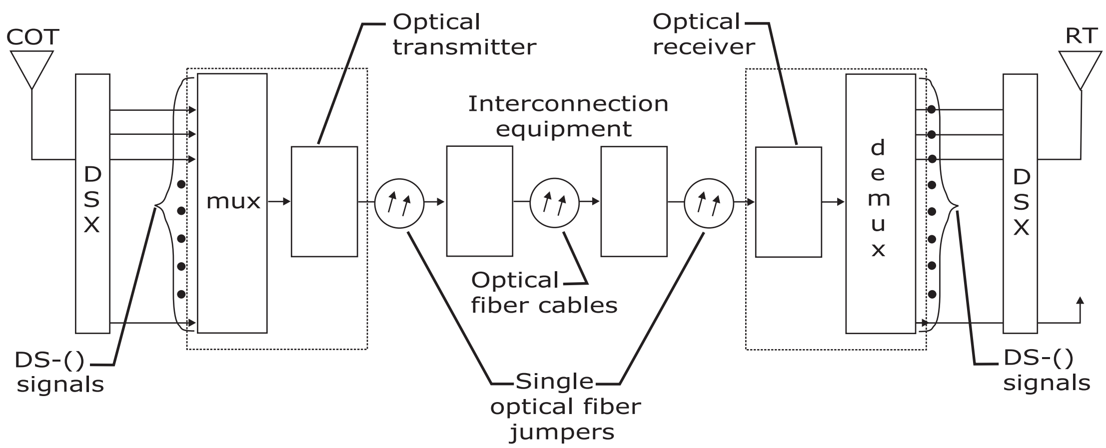
Prior to the optical transmitter receiving the electrical signal, there may be some conditioning or multiplexing of the electrical signal for use on the optical network. For typical LAN applications, either no changes are made to the electrical signal, or the signal is slightly modified to be placed in the proper optical format.

NOTE: See Chapter 15: Data Networks for more information.

For channel transmissions, specifically synchronous transmissions such as digital signal cross-connect (DSX) and SONET, often the individual channels are multiplexed prior to being sent to an optical receiver.

Figure 1.30 illustrates a configuration that multiplexes like-DSX signals onto one or more optical fibers.

Figure 1.30
Digital signal cross-connect optical multiplexing design

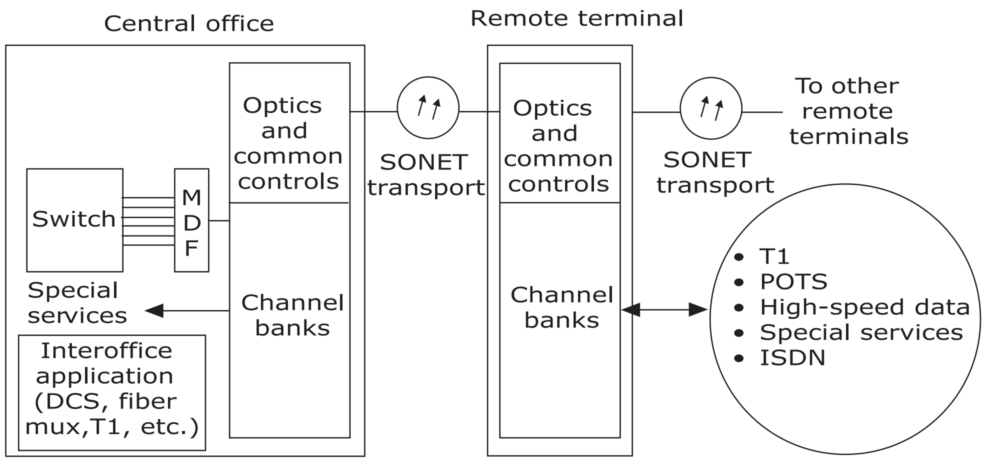


COT = Central office terminal
demux = Demultiplexer
DS = Digital signal
DSX = Digital signal cross-connect
mux = Multiplexer
RT = Remote terminal

System Example, continued

Figure 1.31 illustrates a configuration that multiplexes different types of signals onto SONET.

Figure 1.31
Synchronous optical network multiplexing design



DCS = Digital cellular system
ISDN = Integrated services digital network
MDF = Main distribution frame
mux = Multiplexer
POTS = Plain old telephone service
SONET = Synchronous optical network

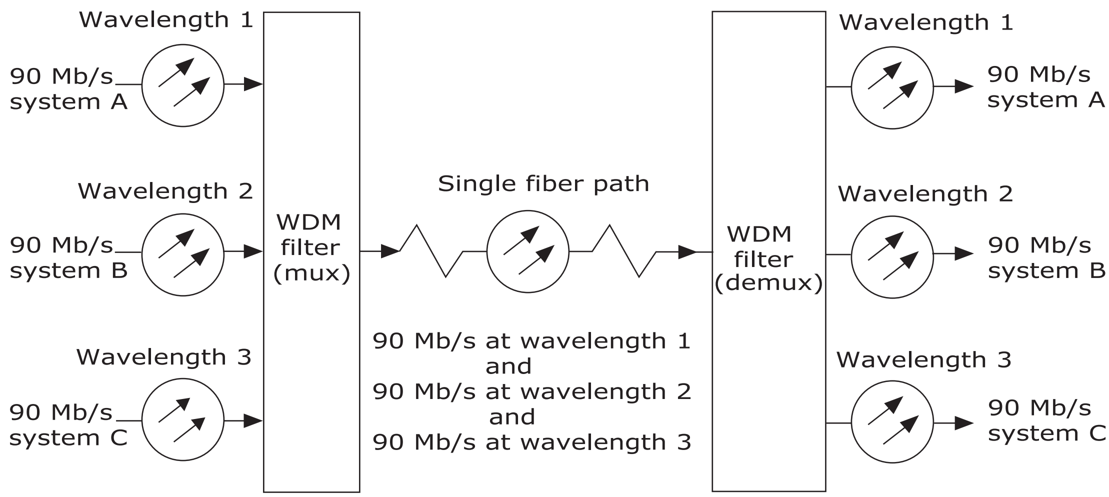
Wavelength division multiplexing (WDM) is an alternative means of multiplexing signals onto an optical fiber system. WDM multiplexes multiple electrical signals to separate optical wavelengths at the source that are sent along one optical fiber to its receiver at the opposite end. To accomplish this, WDM uses a series of lenses to refract and direct light pulses into a single optical fiber that carries the combined wavelengths.

At the other end of the optical fiber cable, a WDM receiver separates the wavelengths and converts them to separate electrical signals. WDM may also be used to enable a single optical fiber to both transmit and receive. WDM is most commonly used in long-haul, high-bandwidth data transmissions.

System Example, continued

Figure 1.32 illustrates WDM being used to transmit three separate 90 Mb/s signals over a single optical fiber.

Figure 1.32
Wavelength division multiplexing



demux = Demultiplexer
Mb/s = Megabit per second
mux = Multiplexer
WDM = Wavelength division multiplexer

Appendix

North American Digital Signal (DS)

The levels of multiplexing used in North America are DS0, DS1, DS1C, DS2, and DS3.

Digital Signal Level Zero (DS0)

The lowest level of digital carrier is known as DS0. In PCM systems, a DS0 channel contains 64 kb/s of information.

Digital Signal Level One (DS1)

The first level of TDM is DS1, which:

- Uses a transmission rate of 1.544 Mb/s.
- Can transmit up to 64 kb/s data over any one of 24 channels if the transmission system has clear channel capability.

  NOTE: Many systems can transmit only up to 56 kb/s per channel because of pulse density requirements of clock recovery.
- Is capable of handling 24 standard (3100 Hz bandwidth) analog voice channels when standard 64,000 b/s PCM is used. Forty-eight voice channels are available if 32,000 b/s ADPCM encoding is used.
- Can operate over standard balanced twisted-pair cables within specific distance limits and design conditions.

  NOTE: The transmit and receive pairs are normally separated in nonadjacent binder groups or screened compartments.
- Is widely used for short-haul carrier transmission (up to ≈322 km [200 mi]).

A DS1 rate system without clear channel capability is capable of handling approximately 1344 kb/s of data (24 x 56 kb/s); 1536 kb/s of data (24 x 64 kb/s) can be handled if clear channel capability is available. Therefore, these systems can be used with wideband data terminals.

Repeater T1 carrier operated at the DS1 rate is coded bipolar AMI with a 50 percent duty cycle.

North American Digital Signal (DS), continued

Digital Signal Level One C (DS1C)

The special requirements for T2 carrier led to the development of an intermediate level, known as DS1C (T1C), which:

- Uses a process called pulse stuffing to synchronize the two DS1 signals.
- Makes more use of existing cable plant for short and medium distances.
- Has not been designated for use with higher level multiplexing.
- Can transmit two DS1 signals (48 voice channels total) at a 3.152 Mb/s transmission rate (DS1C rate).

NOTE: This system is no longer being deployed.

Digital Signal Level Two (DS2)

The second full level of multiplexing is DS2, which:

- Typically handles four DS1 channels, for a total of 96 voice channels.
- Employs a 6.312 Mb/s pulse stream.

NOTE: This is slightly more than four times the DS1 rate because of bit stuffing.

For distances beyond ≈300 m (984 ft), T2 carrier requires special balanced twisted-pair cable (e.g., low-capacitance [locap cable]) that has special crosstalk and attenuation characteristics. Balanced twisted-pair systems using T2 carrier are obsolete; however, low-speed optical fiber systems carry DS2 signals.

Digital Signal Level Three (DS3)

The DS3 level is seeing increased use between customer locations and between customer and main entrance facility locations.

The DS3 level:

- Is used to multiplex 28 DS1 or 7 DS2 signals at 44.736 Mb/s.
- Is a common speed for optical fiber and digital radio systems.
- Uses bit stuffing to synchronize the incoming DS1 or DS2 streams to the multiplex terminal.

North American Digital Signal (DS), continued

Higher Levels

Higher levels of multiplexing and carrier transmission are summarized in Table 1.38.

Table 1.38
Levels of multiplexing and carrier transmission in North America

Digital Signal	Rate (Mb/s)	Channels	Facility	Notes
DS1	1.544	24	Paired cable	Basic North American system
DS1C	3.152	48	Paired cable	Expansion system for existing DS-1
DS2	6.312	96	Special locap paired cable or optical fiber	
DS3	44.736	672	Optical fiber, digital radio, or coaxial cable	
DS4	274.176	4032	Optical fiber, microwave radio, or coaxial cable	High-density long-haul system

DS1 = Digital signal level 1
DS1C = Digital signal level 1C
DS2 = Digital signal level 2
DS3 = Digital signal level 3
DS4 = Digital signal level 4
mb/s = Megabit per second

European E

The levels of multiplexing used in Europe are E1, E2, E3, and E4.

B Channel

A single 64 kb/s channel is sometimes referred to as a B channel.

E1 Level

The first level of TDM is E1, which:

- Uses a transmission rate of 2.048 Mb/s.
- Can transmit up to 64 kb/s data over any one of 30 channels if the transmission system has clear channel capability.

  NOTE: Two additional 64 kb/s channels perform alignment and carry signaling.
- Is capable of handling 30 standard (3100 Hz bandwidth) analog voice channels when standard 64 kb/s PCM is used. 60 voice channels are available if 32 kb/s ADPCM encoding is used.
- Can operate over standard balanced twisted-pair cables within specific distance limits and design conditions.

  NOTE: The transmit and receive pairs are normally separated in nonadjacent binder groups or screened compartments.
- Is widely used for short-haul carrier transmission (up to ≈322 km [200 mi]). A repeated carrier operated at the E1 rate is coded bipolar HDB3.

E2 Level

The second full level of multiplexing is E2, which:

- Typically handles four E1 channels for a total of 120 voice channels.
- Employs an 8.192 Mb/s pulse stream.

For distances beyond ≈300 m (984 ft), E2 carrier requires special balanced twisted-pair cable (e.g., locap cable) that has special crosstalk and attenuation characteristics. Balanced twisted-pair systems using E2 carrier are obsolete; however, low-speed optical fiber systems carry E2 signals.

E3 Level

The E3 level is seeing increased use between customer locations and between customer and main entrance facility locations. The E3 level:

- Is used to multiplex four E2 signals at 34.816 Mb/s.
- Is a common speed for optical fiber and digital radio systems.
- Uses bit stuffing to synchronize the incoming E2 streams to the multiplex terminal.

European E, continued

Higher Levels

Higher levels of multiplexing and carrier transmission are summarized in Table 1.39.

Table 1.39
Levels of multiplexing and carrier transmission in Europe

Digital Signal	Rate (Mb/s)	Channels	Facility	Notes
E1	2.048	30	Paired cable	Basic system
E2	8.192	120	Special locap paired or coaxial cable or optical fiber	
E3	34.816	480	Optical fiber, digital radio, or coaxial cable	
E4	139.264	1920	Optical fiber, microwave radio, or coaxial cable	High-density long-haul system

E1 = European 1
E2 = European 2
E3 = European 3
E4 = European 4
mb/s = Megabit per second

