Cables and Transmission Lines

Cables

A cable is two or more insulated wires bundled or grouped together in a common sheath. Two wire cables are probably the most common. AC power cords and speaker cables are some examples. However, cables may contain many wires. Cables, such as telephone cables with hundreds of wires, are commonly used. Cables are usually classified by the kinds of voltages they handle. The most common categories of cables are:

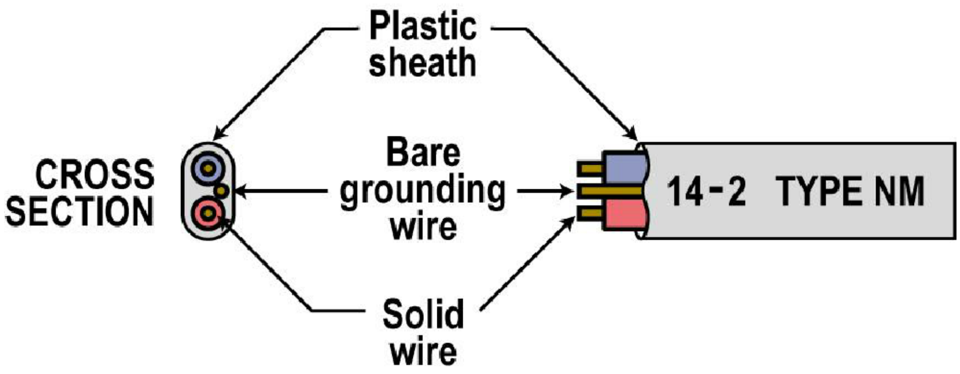
- AC power
- DC power
- Audio
- Telephone
- Video
- Radio frequency (RF)
- Optical

AC Power Cables

The most common AC cable is the line cord used on lamps, appliances, and other electrical and electronic equipment. Most lamps use a simple two wire cable called zip cord or lamp cord. The wire is usually #18 stranded.

3-wire AC cords that include a ground wire are also common. Most AC cords are from 5 to 10 feet long. Longer cords and extension cords up to 100 feet use larger wire such as #16 or #14 stranded.

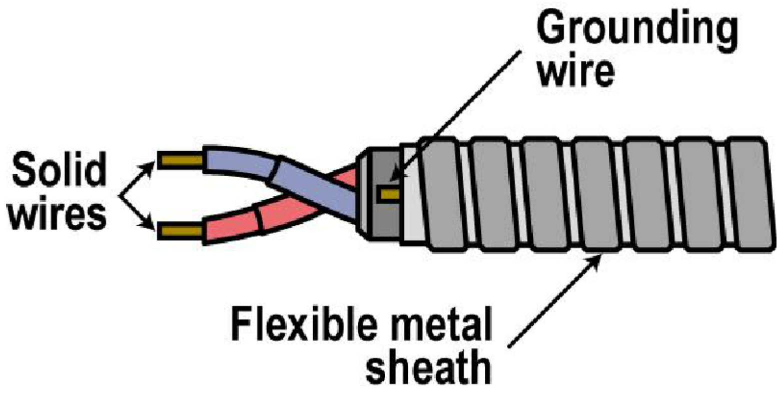
AC Power Cables



AC power line wiring inside the walls and ceilings is another example. Two solid #14 insulated wires are bundled with a bare copper ground wire and the combination is contained in a plastic insulation. This is called non-metallic sheathed cable (NM). You will also hear this kind of cable called Romex. Romex is a brand name but it is so common that it is used generically to describe this widely used AC power cabling.

In the figure shown, the designation 14-2 is a common way to express a cable composition. In this case, it is two #14 wires.

AC Power Cables: Sheathing



Cables can also be insulated with an armoured sheath. The insulated wires are protected from the metal sheath by a paper wrap. The metal outer sheath is flexible. The tough armour sheath protects the wires from physical damage in environments where wiring is exposed to possible physical abuse.

The shield is usually connected to earth ground.

DC Power Wiring

There is essentially no standard DC wiring cable as the needs vary so widely. Cables with two to dozens of wires are used.

Wire for DC power is typically stranded with sizes varying from #22 up to #12.

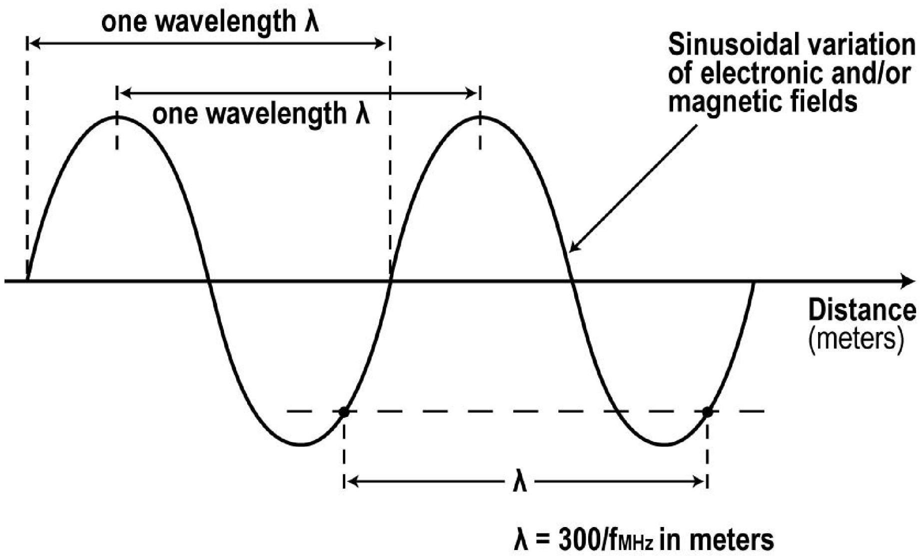
Cables vs. Transmission Lines

Cables carrying DC, AC power, or audio/telephone signals are just wires. The primary consideration is wire size and resistance. The objective is to use a wire size with minimum resistance so that most of the applied voltage reaches the load. Furthermore, it is essential that the wire size is great enough to carry the current without causing heat build up.

When the frequency of the signals carried by the cable get high enough, the cable begins to act more like a complex circuit than just some wires with resistance. At frequencies above several hundred kiloHertz (kHz), the cable become a transmission line.

A two-wire cable becomes a transmission line when its length is greater than one tenth wavelength (0.1λ). The Greek letter lambda (λ) is used to represent wavelength.

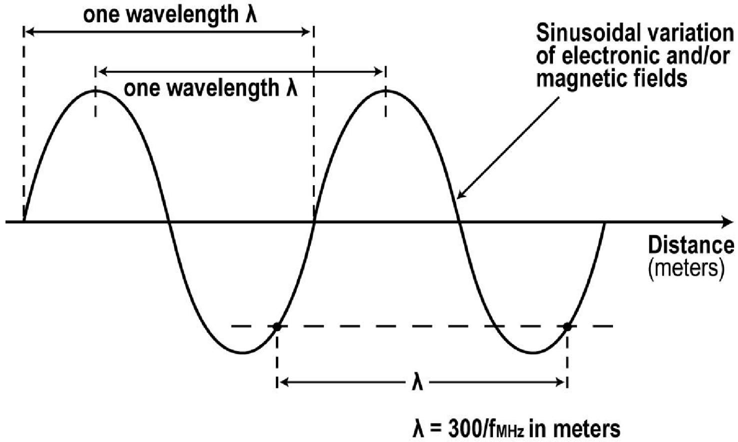
Wavelength



Wavelength is the distance between two points of the same phase on a wave of two consecutive cycles. The wave is usually a sine wave representing voltage, current, power, or even electric of magnetic field intensities.

Wavelength is also the time travelled by an electromagnetic wave (radio signal) in the time of one cycle.

Wavelength and Speed



Wavelength (λ) is related to the speed of light or radio signals and the frequency of the wave (f).

The speed of light is 300,000,000 meters per second or about 186,400 miles per second.

λ (in meters) = 3000,000,000/f (in Hz) or $300/f_{MHz}$

For example, the wavelength of a 150 MHz signal is

300/150 = 2 meters.

A Cable is a Transmission Line If....

If a cable is one tenth of a wavelength long or more at the operating frequency, it is considered to be a transmission line. A cable carrying a 150 MHz signal is a transmission line if it is longer than one tenth of 2 meters or 0.2 meters (about 8 inches).

Is a cable 50 feet long at 14 MHz a transmission line?

$\lambda = 300/14 = 21.4$ meters

There are 3.28 feet per meter.

21.4 meters = 21.4 x 3.28 = 70.2 feet

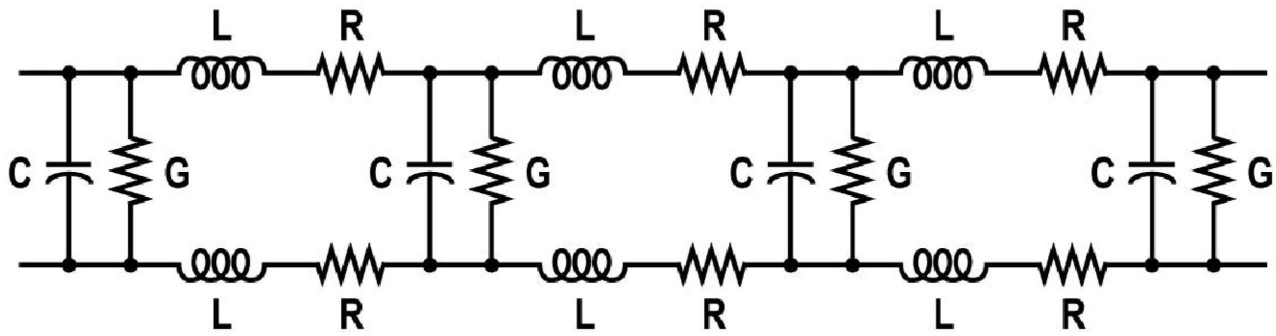
One tenth of 70.2 is 7.02 feet. Anything longer is a transmission line.

A 50 foot cable is a transmission line.

Characteristics of a Transmission Line

At high frequencies, you have to take into consideration the inductance and capacitance of the two wires making up the cable. All wire, coiled or not, has inductance. Capacitance exists between any two conductors separated by insulation. Such inductance and capacitance is called stray or distributed inductance and capacitance. Usually we measure or express it in terms of inductance or capacitance per foot of cable.

Transmission Line

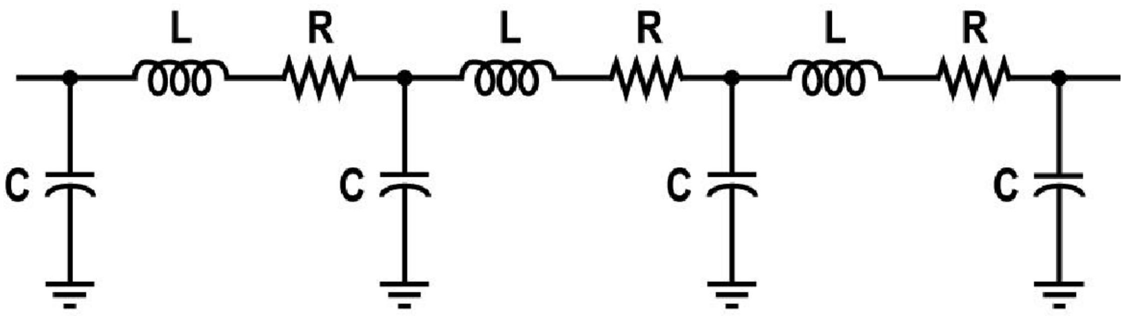


Considering this inductance and capacitance, the cable becomes a circuit that appears like the circuit in the figure above.

Each foot of wire is represented by an inductance L and resistance in series and a capacitor C in parallel.

The G represents conductance between the wires which in most cases is a very high resistance due to any leakage. We normally neglect it.

Equivalent Circuit

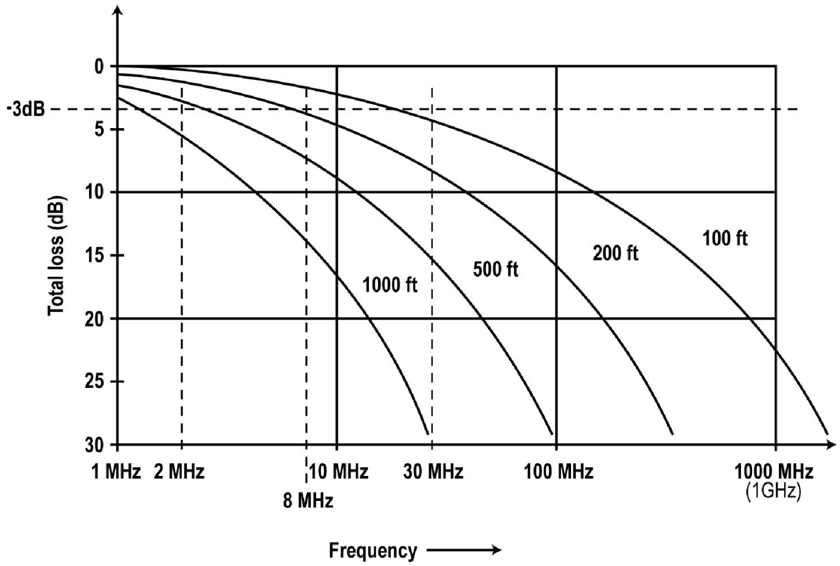


Equivalent Circuit

This equivalent circuit is simplified by lumping the inductance per foot into one symbol so it now appears as in this figure.

As you can see by the equivalent circuit of a transmission line, it is a low pass filter. The actual characteristics of the filter are dependent upon the nature of the transmission line and its length. The upper cut-off frequency varies with length: the longer the line, the lower the cut-off frequency.

Frequency Response



This figure shows a frequency response curve of a transmission line of different lengths. Like a low pass filter, the cable attenuates the higher frequencies more than the lower frequencies. Therefore, a cable can distort complex signals like pulses since the cable can attenuate the higher harmonics in a pulse according to Fourier theory thereby distorting the signal.

Characteristic Impedance

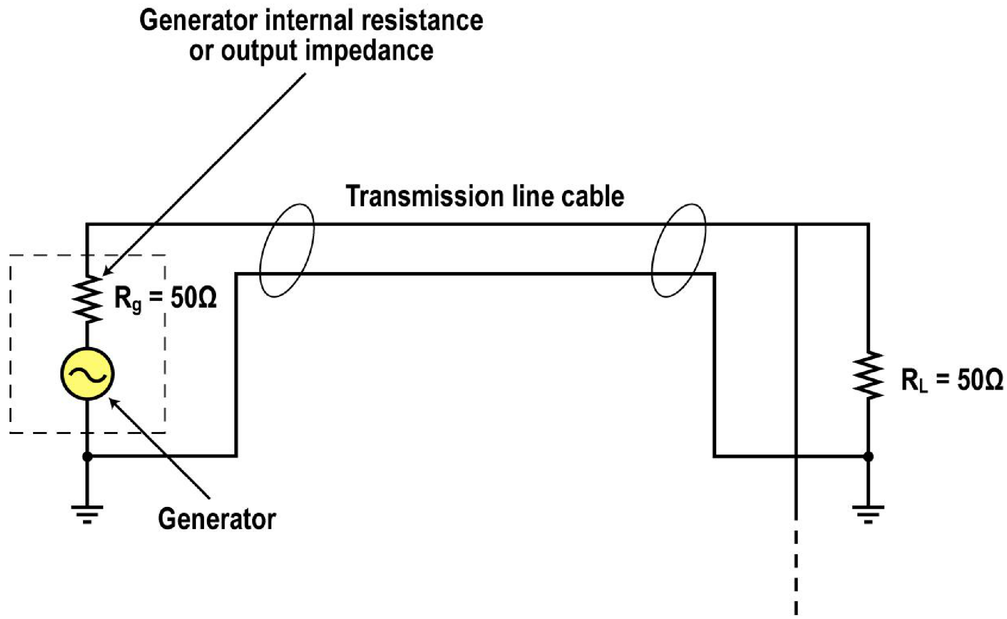
A key specification of a transmission line is its characteristics impedance (Z_o). Also called the surge impedance, this is the resistive impedance value that a generator would see if it were connected to an infinite length of that line.

The characteristic impedance is calculated by knowing the inductance and capacitance per foot.

$Z_o = \sqrt{L/C}$ where L and C are the inductance and capacitance per foot.

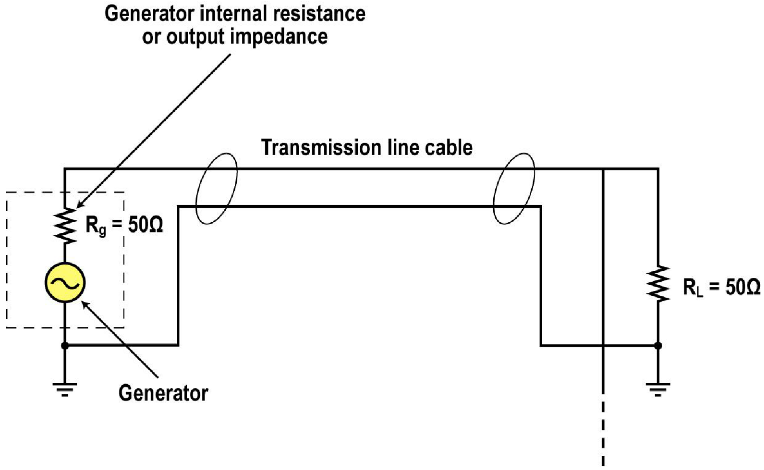
It is not necessary to calculate the characteristic impedance as it is fixed and known for any given transmission line. The most common values are 50, 75, and 100 ohms.

Using a Transmission Line



To use a transmission line correctly, it must be terminated in a load equal to its characteristic impedance. The generator driving impedance should also be equal to the characteristic impedance.

Examples of a Transmission Line



With the generator and load resistance being equal, maximum power transfer will take place between the generator and the load.

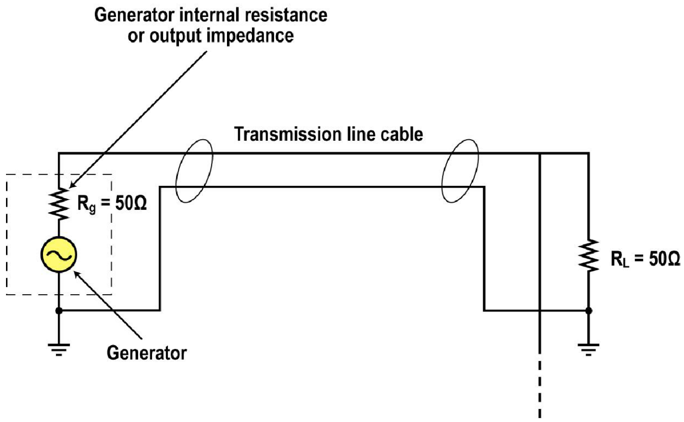
Some examples are:

The generator is a radio transmitter and the load is an antenna.

The generator is a frequency synthesizer and the load is a circuit under test.

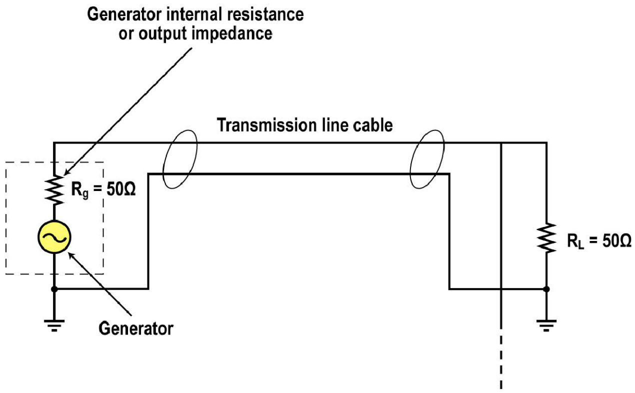
The generator is serial binary data source and the load is a network card in a PC.

Incorrect Termination



If a transmission line is not terminated in its characteristic impedance, the signal applied to the line will not all be absorbed by the load. Instead, the signal will travel down the line charging the inductance and capacitance until it comes to the load. If the load equals the characteristic impedance, all of the signal will be absorbed by the load. If not, some if not all of the signal will actually be sent back the line toward the generator. We say that the signal is “reflected” back to the generator.

Complex Impedance



The worst case of this is when the load end of the line is either open or shorted. In this case, all of the applied signal will be reflected back to the load.

If the line is terminated but not in its characteristic impedance, only a part of the signal will be reflected back.

Under these conditions, the combined line and load will appear to the generator to be some complex impedance depending upon line length. $Z = R \pm jX$. Z = impedance, R = resistance, X = reactance (-X = Xc, +X = XL). The j is the imaginary operator which is the square root of -1.

Effect of an Improperly Terminated Line

If a transmission line is not terminated in its characteristic impedance, signal reflections occur. The reflected signal adds to the forward signal from the generator forming a composite signal that sets up electric and magnetic fields around the line. These are called standing waves and are not desirable.

The effect of an improper termination is that some, if not all, of the signal will not reach the load as desired. Some of the signal will be reflected back to the source.

The reflected signal can also add to the generator signal creating a larger signal that could damage the generator.

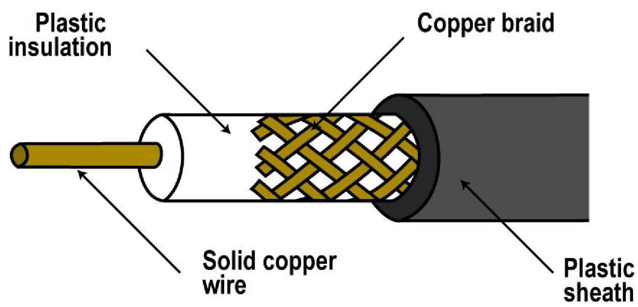
Finally, excessive power will be lost in the line itself.

Types of Transmission Lines

There are two basic types of transmission lines in wide usage, coaxial cable and twisted pair. Other forms do exist but these are the ones you will most likely to encounter.

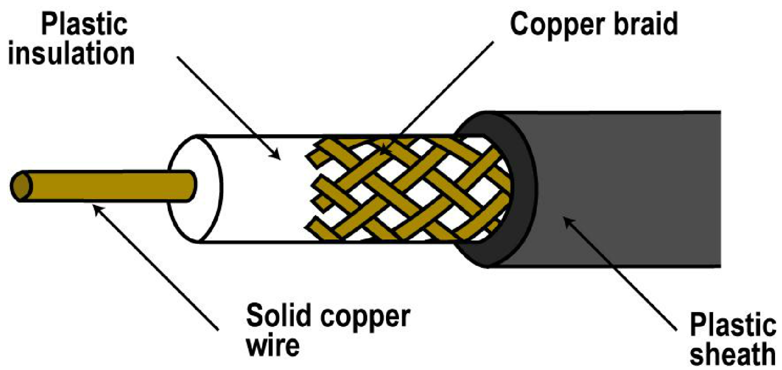
Coax cable, shown here, is available in a wide range of sizes and characteristics. The most commonly used characteristic impedances are 50 and 75 ohms.

Coax cable consists of a solid wire center conductor covered by an insulator.



Shield

A wire braid is used around the insulator as a shield. The braid is made up of a cross hatch of very fine copper wires that together act as one of the cable conductors. The braid shields the inner conductor from noise pickup and prevents electromagnetic radiation from the inner wire. Both the wire and braid carry the signal. The braid is usually connected to ground.



Common Coaxial Cables

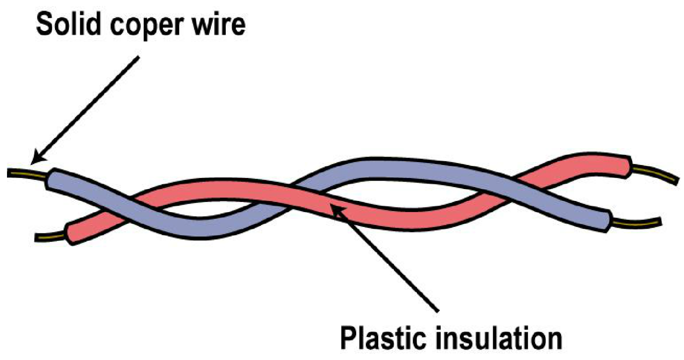
Here are some of the most common types of coax cable.

Designation	Impedance	Common Application
RG-6/U	75 ohms	Cable TV connections
RG-8/U	52 ohms	RF, antenna connections
RG-11/U	75 ohms	Radio use, video connections
RG-58/U	53.5 ohms	RF, antenna connections
RG-59/U	75 ohms	RF, test equipment, video
RG-62/U	93 ohms	Older computer networks
RG-213/U	50 ohms	Satellite TV and microwave

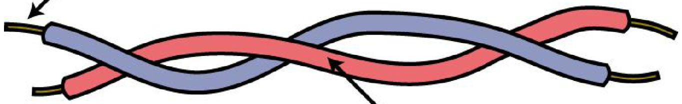
Twisted Pair

Twisted pair, shown in this figure, consists of two solid insulated wires loosely twisted together. This is called unshielded twisted pair (UTP).

A shield twisted pair (STP) is available where the two twisted wires are enclosed in a metal shield such as the braid like that in coax or aluminium foil.



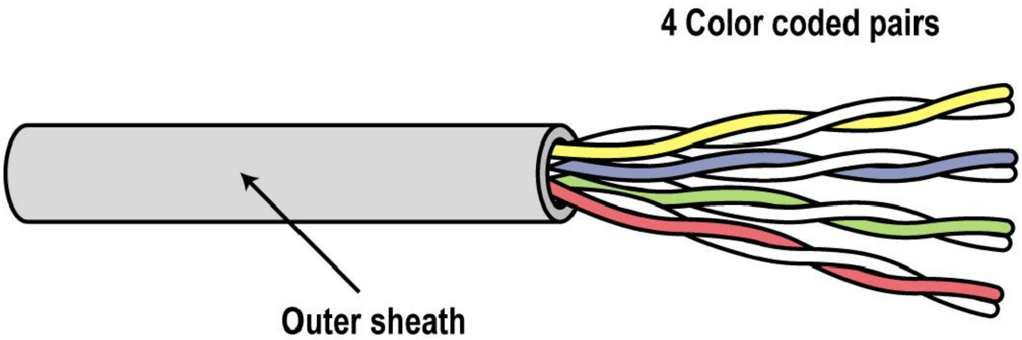
Twisted Pair Usage



The characteristic impedance of twisted pair varies with wire size and tightness of twist (twists per inch). It varies from about 90 ohms to 150 ohms with 100 ohms being the most common.

UTP is widely used in low voltage (e.g. 12 to 24 volts) power wiring, telephone wiring, and in computer network wiring. Wire sizes range from #24 to #28.

Twisted Pair Categories



There are different grades of twisted pair for different applications. These are designated by a category number such as CAT 5.

The most widely used UTP cables are CAT 5, CAT 5e, or CAT6. Millions of miles of CAT5 run inside walls and ceilings to connect PCs in local area networks (LANs). It is commonly available with four twisted pairs per cable as shown in the figure above. A version with a foil shield around all four pairs is known as shielded twisted pair (STP).

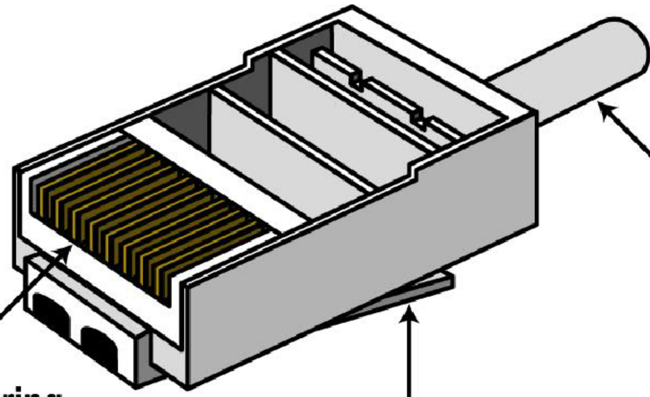
Common Twisted Pair Categories

The most common categories of UTP are:

Category	Max. Data Rate	Applications
CAT1	I Mbps	Telephone and low voltage
CAT2	4 Mbps	IBM Token Ring LAN
CAT3	16 Mbps	Telephone, 10 Mbps Ethernet
CAT4	20 Mbps	IBM Token Ring
CAT5	100 Mbps	100 Mbps Ethernet, 155 Mbps ATM
CAT5e	1000 Mbps	1 Gbps Ethernet
CAT6	10 Gbps (4 pairs) 400 MHz BW	10 Gbps Ethernet, video
CAT7	0.6 – 1.2 GHz	Requires special connector

For details on these cables, look at the TIA/EIA-568 standard.

Twisted Pair Connector



The most common connector is the RJ-45 with 8-pins as shown here. It is similar to telephone modular connectors called RJ-11.

Cable Characteristics and Specifications

Cable characteristics and specifications include impedance, capacitance per foot, attenuation, velocity, time delay, and cross talk.

Characteristic impedance is 50 or 75 ohms for coax, 90 to 150 ohms for twisted pair.

Capacitance per foot is the amount of capacitance between the conductors usually in pF/ft. The range is about 10 to 40 pF/ft.

Attenuation, how much the cable attenuates the signal, is given in decibels (dB) per 1000 feet.

The velocity factor is a percentage that indicates the speed of the signal in the cable compared to the speed of light in free space.

Time delay is the amount of time delay introduced as the signal is propagated down the cable.

Cross talk, near end cross talk (NEXT), and far end cross talk (FEXT) are mainly a twisted pair specification.

Cable Attenuation

Cables cause a signal applied to them to be attenuated. The cable introduces a loss.

The loss in a cable is expressed in decibels of power per 1000 feet. Depending upon the type of cable, the loss can be less than 1 dB/1000 ft or up to 10 dB/1000 ft.

Coax has the greatest amount of loss per foot with the smaller coax cables introducing the most attenuation.

Assume a cable has a loss of 0.2 dB per foot. What is the output power (P_o) of a 40 foot cable if the input power (Pi) is 1 watt?

Total loss 40 x 0.2 dB = 8 dB. This is expressed as – 8 dB where a negative sign means loss.

dB = 10 log (P_o/P_i) therefore $P_o = P_i \log^{-1}(dB/10)$

$P_o = \log^{-1}(80/10)$ x 1 watt = 0.1585 watt (158.5 mW)

Velocity Factor

Velocity factor (VF) is a number that tells how much slower a signal travels in the cable than in free space. The speed of a radio signal in free space is the speed of light or 300,000,000 meters per second.

The velocity factor varies from about 0.6 to 0.95 in most cables. Common VF in coax varies from 0.66 to 0.8.

Velocity factor mainly affects the length of cable when computing wavelengths. For example, if a cable must be made a specific length in wavelengths, the velocity factor must be taken into consideration.

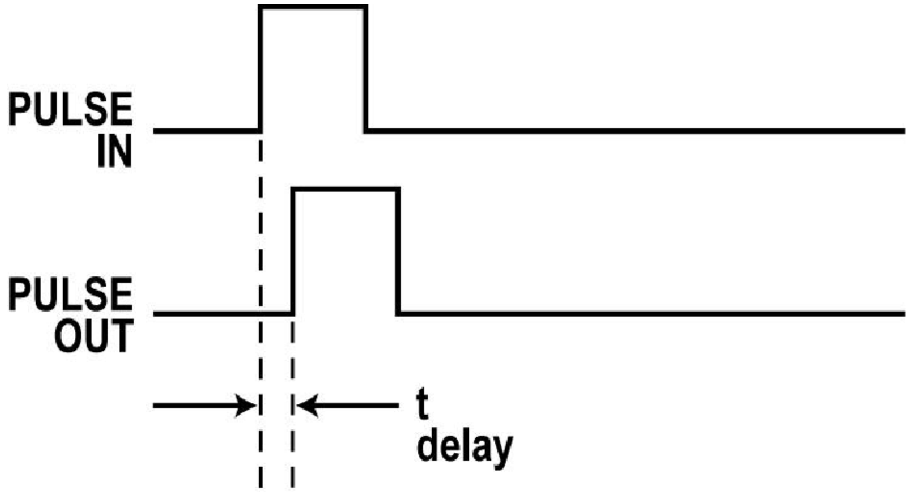
What is the correct length of one quarter wavelength of a cable with a 0.66 VF? The frequency is 800 MHz.

Wavelength (λ) = $984/f_{MHz}$ = 984/800 = 1.23 feet

One quarter wavelength = 1.23/4 = 0.3075 feet

Considering VF, one quarter wavelength = 0.66 x 0.3075 = 0.203 feet.

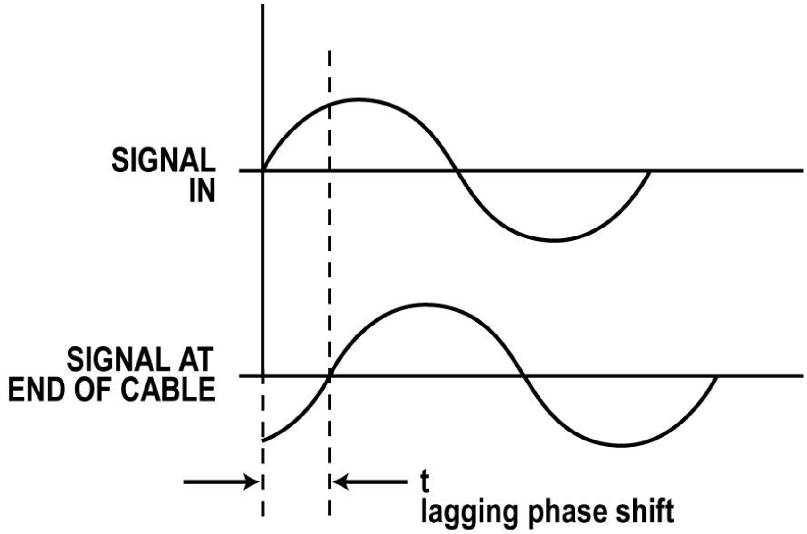
Time Delay: Pulse and Digital



Cables also introduce a time delay. The signal applied to the cable comes out of the cable some time later due to the inductance and capacitance of the cable.

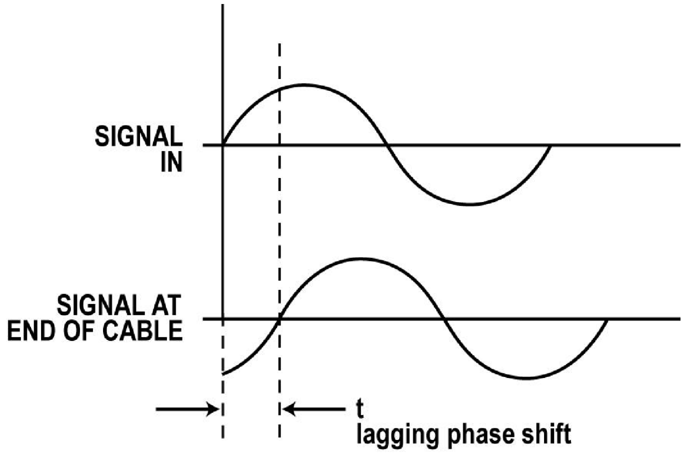
Pulse or digital signals are delayed in time as shown in the figure above.

Time Delay and Phase Shift



Sine wave and analog signals experience a phase shift (lag). The time delay (t) is computed with the expression: $t = \sqrt{LC}$ where L and C are the inductance and capacitance per foot.

Time Delay and Phase Shift Example



To determine the phase shift, let's look at an example.

Assume L = 75 mH and C = 30 pF per foot.

$t = \sqrt{LC} = \sqrt{(75 \times 10^{-9})(30 \times 10^{-12})} = 1.5$ nS per foot

A 30 foot cable would cause an input pulse to appear 30 x 1.5 = 45 nS later.

For a sine wave of 5 MHz with a period of $T = 1/f = 1/\ 5 \times 10^{6} =$ 200 nS.

The phase shift (θ) = 360t/T = 360 (45)/200 = 81°

Cross Talk

Cross talk is the effect caused by some signal leaking from one twisted pair to another inside a cable. The leakage is caused by both magnetic and capacitive coupling. Cross talk is undesirable since the signal on one pair can interfere with the signals on the other pair.

Cross talk is expressed in decibels (dB) of power. It is measured at the near end of the cable and the far end of the cable.

Near end cross talk (NEXT) is the amount of signal transferred from the signal input of one pair to the adjacent pair.

Far end cross talk (FEXT) is measured from the signal input end of one cable and the far end of the adjacent cable.

The greater the dB value, the better the cable. FEXT and NEXT vary widely with cable type and length as well as input power level. The range is from about -30 to over -100 dB.

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Cables and Transmission Lines

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