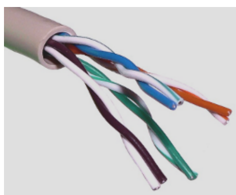
Common Transmission Media

This lecture describes the characteristics of the most common transmission media: twisted pair, co-ax and fiber-optic cables, and free space-propagation for wireless channels.
After this lecture you should be able to: identify the different types of transmission media described in this lecture, their component parts and their advantages and disadvantages; solve problems involving Z_0, velocity factor, ϵ_r, twisted pair and co-ax physical dimensions, and distributed L and C; solve problems involving signal levels and loss in logarithmic and linear units; convert between AWG and diameter; and solve problems involving free space propagation path loss.

Twisted Pair

Twisted pair cable consists of a pair of parallel insulated wires twisted around each other and covered with a plastic jacket. This is often called unshielded twisted pair (UTP):

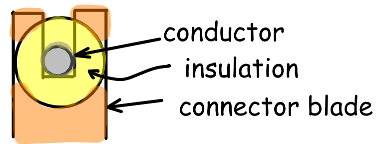


Twisted pair cables often contain several pairs in the same jacket. Each pair typically has a different twist rate.

The pairs can also be surrounded by a metallic, typically aluminum foil, shield. This is called "shielded twisted pair" (STP):

The shielding can be applied to the individual pairs to minimize interference between the pairs ("crosstalk"), or to other cables or systems. STP is more expensive and much less common than UTP.

The main advantages of twisted pair cables are low cost and ease of making connections. Connections are usually made by insulation-displacement connectors using small slotted blades that cut through the insulation to make contact with the conductors.



The main applications for twisted pair cables are telephone local "loops" that connect subscribers to the telephone switching office and local-area networks that connect computers and data networking equipment.

"Cat 5" (Cat 3, Cat 6, etc.) refer to specifications for four-pair (8 conductor) UTP cable typically used for LANs such as the various IEEE 802.3 standards that operate at rates from 10 Mb/s to 10 Gb/s.

Differential Signalling

Twisted pair cables typically use differential signaling. This means that opposite currents flow on each conductor of a pair.

This has the advantage that the electric and magnetic fields generated by the currents flowing in the wires cancel each other out at locations that are equally distant from the two conductors. This reduces radiation which might cause interference to other systems and reduces electro-magnetic interference (EMI) from fields generated by other systems.

To further reduce the coupling we can twist the two pairs so that each conductor is alternately closer to and then further away from a potential interference source or victim.

Wire Gauge

Twisted-pair wire diameters are often quoted in "American Wire Gauge," or AWG. 24-gauge wire, a very common gauge for communications applications, has a diameter of about 0.5mm. The wire diameter *decreases* as we increase the AWG. Increasing the wire gauge by 6 approximately halves the diameter. So, approximately, the diameter of n-gauge wire is:

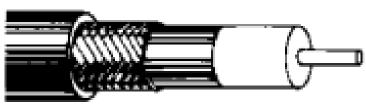
$$d \approx 0.5 \times 2^{-\frac{(n-24)}{6}} = 8 \times 2^{-\frac{n}{6}} \text{ mm}$$

For example 30-gauge wire has a diameter of about 0.25mm.

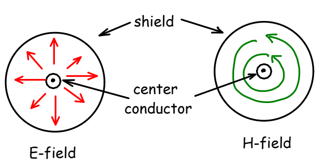
Exercise 1: How much does a cable's resistance increase when the gauge size increases by 6? By 3? Hint: a wire's resistance is proportional to its cross-sectional area.

Co-Axial Cable

Co-axial ("co-ax") cable is made from an inner conductor surrounded by a cylindrical shield. The separator can be air, various types of plastics or a combination. The shield can be thin-walled copper tubing, aluminum foil, braided wire or a combination.



Signals typically propagate in co-ax cables in transverse electro-magnetic mode (TEM). This means that both the electric and magnetic fields are perpendicular to the direction of propagation which is along the cable:



Co-ax cables tend to have lower loss and radiate less than twisted-pair cables because the electric and magnetic fields are confined to the inside of the shield. However, they tend to be larger and more expensive than twisted pair cables.

Co-axial cables are mainly used to transport radio frequency signals such as for the distribution of "cable TV."

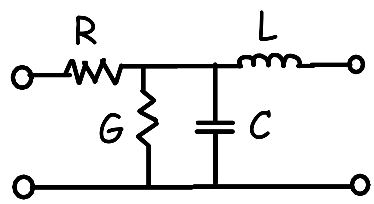
Co-ax cable names beginning with "RG" such as "RG-59" refer to an obsolete military specification for co-ax cables. These numbers specify the approximate dimensions and characteristic impedance of the cable but the actual specifications such as loss must be obtained from the manufacturer's datasheets for a specific cable.

Distributed Element Model for Transmission Lines

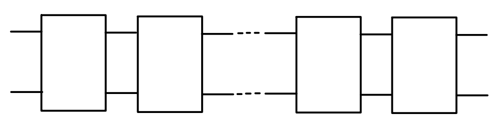
The conductors in a metallic cable (e.g. twisted pair or co-ax) have resistance. The cable also has a capacitance because of the charge stored in the electric field between the conductors. The cable also has inductance because of the magnetic field set up around the wires. AC and DC currents can also flow between the conductors particularly at higher frequencies.

These parameters are determined by the construction of the cable which is uniform along the cable. The resistance, capacitance, inductance and dielectric conductivity increase linearly as we increase the length of the transmission line.

We can thus model a short portion of the transmission line using the following circuit where R, C, L and G represent values per unit length of the line (e.g. pF per meter):



and the complete transmission line as a sequence of the above blocks:



A signal propagates along the transmission line as the capacitor voltages and inductor currents alternately increase and decrease.

Cable Specifications

Characteristic Impedance

The characteristic impedance of a transmission line is the ratio of the voltage across the transmission line to current flowing along it. Note that this ratio is only constant along the cable when the transmission line is terminated in its characteristic impedance. This ensures the signal propagating along the transmission line is completely absorbed at the load.

The characteristic impedance of the transmission line model above can be derived to be:

$$Z_O = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

ohms where the electrical quantities are specified in Henries, Farads and Ohms per unit length (per foot or per meter).

If $j\omega L >> R$ and $j\omega C >> G$ then the characteristic impedance becomes independent of frequency and is simply:

$$Z_O = \sqrt{\frac{L}{C}}$$

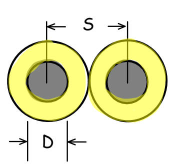
Exercise 2: What is the characteristic impedance of a lossless cable with an inductance of 94 nH per foot and capacitance of 17pF/ft?

The characteristic impedance of the transmission line is of interest because the impedances of the line driver (voltage/current source) and the receiver (termination) should match the characteristic impedance of the transmission line in order to:

- maximize power transfer for a given transmitter output impedance
- minimize reflections that can cause inter-symbol interference

Twisted Pair

The characteristic impedance of twisted pair transmission line as a function of the wire spacing S, the wire diameter D, and the dielectric constant (also called the relative permittivity[1]) of the insulation (ε_r):



[1] The relative increase in capacitance when this material is used as a dielectric in a capacitor instead of a vacuum.

is:

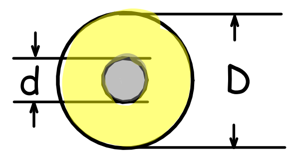
$$Z_0 \approx \frac{120}{\sqrt{\varepsilon_r}} \ln\left(\frac{2S}{D}\right) \quad \Omega$$

Exercise 3: What is the characteristic impedance of UTP made from 24-gauge wire with polyethylene insulation ($\varepsilon_r = 2.2$) of 0.25mm thickness?

Typical characteristic impedances of twisted pair are 100 and 150 ohms.

Co-Ax

The characteristic impedance of co-ax as a function of the inner conductor diameter d, the outer conductor diameter D and the separator dielectric constant ε_r:



is:

$$Z_0 \approx \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{D}{d}\right) \quad \Omega$$

Exercise 4: What is the characteristic impedance of a co-ax cable with a 0.8mm diameter center conductor, 3.5mm diameter shield and foamed polyethylene between them that has a dielectric constant of 1.5?

The most common co-ax impedance values are 50 ohm, mainly used for radio equipment and 75 ohm, mainly used for cable TV applications.

Loss

As the signal propagates through a transmission line, some of the signal's power is turned into heat in both the conductors (represented by the resistance R in the model) and the dielectric (represented by G). This is called "loss."

Loss measures how much the transmission line attenuates the signal. As with an amplifier, the loss is the ratio of voltage (or power) at the output of the transmission line to the power at the input. When measured in dB loss and gain have opposite signs (e.g. a loss of 3 dB is a gain of -3 dB and vice-versa).

Loss depends on the transmission line dimensions (conductor and dielectric diameters) and materials (e.g. copper vs aluminum conductors, air vs polyethylene dielectrics) used to construct the transmission line. It is a function of frequency and is typically specified in dB per unit length. For example, "3dB per 100m at 10 MHz". This makes it easy to calculate the loss of a given length of transmission line.

Exercise 5: An 800 MHz signal is output from a CATV amplifier at a power level of 10dBm. What power level would you expect at the other end of a 75m run of co-ax whose loss is specified as 24dB/100m at 800 MHz? Hint: gain $G_{dB} = 10\log_{10}(P_{out}/P_{in})$.

The loss is due to R and G in the transmission line models and is not a function of the characteristic impedance which only specifies the ratio of voltage to current and stays fixed along the length of the transmission line.

Exercise 6: Assuming the transmission line in the above example is properly terminated, what are the voltage and current at the input and output of the cable? Hint: $P = V^2/R$.

Velocity of Propagation

The speed at which an electrical signal propagates through a transmission line can be expressed in terms of the capacitance and inductance per unit length:

$$v = \frac{1}{\sqrt{LC}}$$

in m/s if L is in Henries and C is in Farads. Thus the velocity of propagation depends only on the inductance and capacitance per meter and decreases as L and C increase.

An intuitive explanation is that as the wavefront (change in voltage) propagates down the transmission line it must change the electrical charge stored in the distributed capacitance and the magnetic field created by the current flowing in the distributed inductance.

Velocity Factor

The velocity factor is the ratio of the velocity of propagation in the cable to the velocity of light in free space. For a transmission line where the energy propagates through a medium with a dielectric constant ε_r the velocity factor is:

$$VF = \frac{1}{\sqrt{\varepsilon_r}}$$

where ε_r is the dielectric constant of the medium relative to free space. For air $\varepsilon_r \approx 1$.

Exercise 7: What is the velocity factor for a cable with polyethylene insulation ($\varepsilon_r = 2.2$)? How long would it take for a signal to propagate 100m? For a cable with air dielectric?

Fiber-Optic Cables

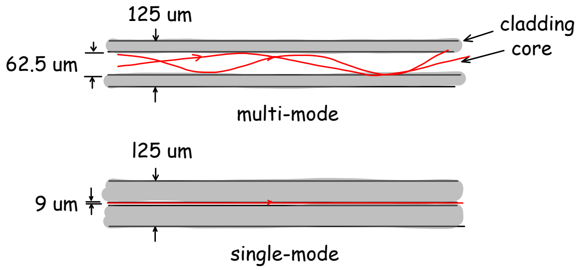
Optical fibers are fibers made from glass, with the central portion combined ("doped") with various materials so that it has has a higher index of diffraction, $n = \sqrt{\varepsilon_r}$ and lower velocity of propagation than the outer part ("cladding"). The difference in index of diffraction causes light to be reflected or refracted (bent) so it continues to travel down the fiber. As long as the fiber is not bent at too sharp an angle, almost all of the light will remain within the fiber. The fibers are also very thin which allows them to bend (again, within limits) without breaking.

Multi-mode fibers allow propagation along multiple paths inside the fiber. Since each path has a different propagation delay this causes dispersion of the signal in time due to the different propagation delays which in turn limits possible data rates. Multi-mode fiber is typically only used in local-area networks (distances <1 km).

Single-mode fibers only allow one propagation path, similar to TEM propagation mode in co-ax. This limits dispersion and allows very high data rates. The large majority of "outside plant" cable being installed today is single-mode optical fiber.

Standard fiber of either type are 125 micron[2] outside diameter. Most multi-mode fiber has an inner core of 62.5 microns and a loss of about 1dB/km at 1330nm (a common wavelength in the infrared region). Most single-mode fiber has a 9 micron inner core and a loss of about 0.25 dB/km at 1330nm. The glass fiber is coated with one more layers of plastic to protect the fiber and prevent crosstalk between multiple fibers in a cable.

[2] 1 micron = $1 \times 10^{-6} = 1\mu m$.



Exercise 8: If the optical signal wavelength is 1330nm what is the frequency? Note that the wavelength is specified in free space, not in the fiber.

The advantages of optical fiber include lower loss and higher bandwidth than the metallic cable alternatives (UTP and co-ax). Optical fibers are also immune from interference from electric and magnetic fields. However, connecting optical fibers is more complicated that for metallic cables and the interface electronics can be more expensive because of the need for optical–electrical conversions.

An optical fiber cable will typically include many colour-coded fibers as well as additional components to protect the fibers and strengthen the cable. This makes optical fiber cables more expensive than metallic cables on a cost-per-meter basis although, due to their much higher capacity, they are usually less expensive on a cost-per-Gb-meter basis.

"Breakout" cable has one strength member per fibre which allows individual fibers to be separated from the cable while "distribution" cable has a single strength member and is meant for point to point interconnection of all the fibers in the cable. In addition, optical fiber can also be rated as non-conductive which allows it to be safely run near high voltages.

Fiber optic cables will will often be marked according to various safety-related ratings. For example a cable marked as OFNP would be non-conductive (N) optical fiber (OF) rated for plenum (P) use (see below).

Optical fibers can be connected by fusion splicing (melting the two fibers together to fuse them) or mechanical splicing (butting the ends of two cleanly-cut fibers together with a connector that aligns them accurately).

There are many types of optical fiber connectors. Typical data networking connectors are square plastic connectors that support the end of the fiber in a ferrule. Data connectors are often used in duplex pairs (transmit and receive).

Fiber optic (FO) cables form the backbone of most modern communication system. Cable TV systems use a "hybrid fiber co-ax" (HFC) network architecture where fiber is run to optical nodes which convert to/from the RF signal which is distributed to homes over co-ax cable. Similarly, telephone companies use optical fiber links to connect remote DSLAMs (DSL access multiplexers) to the central office.

As costs drop and demand for bandwidth increases, the use of fiber is increasing. Optical "Fiber to the Home" (FTTH) is common in some areas.

The capacity of fiber optic links can be increased through wave division multiplex (WDM) where each fiber carries multiple optical signals, each at a different wavelength.

Plastic Optical Fiber

Plastic optical fiber is made from plastic rather than glass and has a much higher loss (about 1dB/m). It is used for consumer digital audio, automotive and some industrial applications where low costs and noise immunity are important but distances are short and data rates relatively low.

Practical Considerations

Stranded vs Solid Wire

Stranded wire is made from a number of uninsulated wires twisted together. Stranded wires are less likely to break after repeated flexing and are used to connect devices, such as computer peripherals, that are frequently moved. Solid wire should only be used where the cable will remain fixed after installation.

Plenum- and Riser-Rated Cables

Cables installed in certain locations need to be fire-resistant to minimize the spread of fire. "Riser" cables are made of self-extinguishing materials and are designed to limit the spread of fire between floors. "Plenum-rated" cables are meant to be run in air ducts and are made from materials less likely to produce toxic fumes in a fire. Plenum cable can be used as riser cable but not vice-versa.

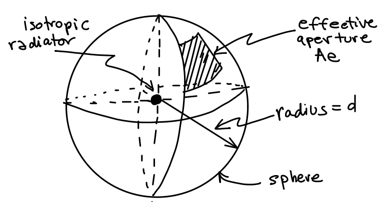
Free Space Propagation

Time-varying electromagnetic fields propagate through free space and can be used for wire-less communication. Frequencies between 3 kHz and 3 THz can be used.

The characteristic impedance of free space is defined as the ratio of the electric (E, in Volts/meter) to magnetic (H, in A/m) fields. In free space $E/H = 377\ \Omega$. For free space $\varepsilon_r = 1$ and the velocity of propagation is $\approx 3 \times 10^8$ m/s.

Although free space is lossless, the power density of the field transmitted from an antenna decreases as the square of the distance (for a line of sight or "LOS" link).

Consider an isotropic source (one that transmits equally in all directions) at the center of a sphere of radius d transmitting power P_T and a receiving antenna of area A_e that collects all of the power "shining" on it:



Since the transmit power is equally distributed over the whole surface of the sphere (area = $4\pi d^2$), the ratio of the received power to transmitted power is:

$$\frac{P_R}{P_T} = \frac{A_e}{4\pi d^2}$$

Rather than effective aperture, we typically measure another antenna parameter called gain which is the effective aperture normalized by the wavelength:

$$G = \frac{4\pi A_e}{\lambda^2}$$

Exercise 9: For some types of antennas, such as reflectors, the effective aperture is closely approximated by the physical area of the antenna. What are the approximate effective aperture and gain of a 1-m diameter Ku-band ($\approx$ 15 GHz) satellite dish?

Substituting for A_e and defining G_T get the Friis equation:

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2$$

where P_R and P_T are the received and transmitted powers, G_R is the gain of the receive antenna, λ is the wavelength and d is the distance from transmitter to receiver. The term G_T can be used to account for a non-isotropic transmit antenna that concentrates the transmit power by a factor (gain) G_T in the direction of the receiver.

This equation only applies at distances that are in the "far field" which means there must be many wavelengths and antenna dimensions between the antennas.

Exercise 10: A point-to-point link uses a transmit power of 1 Watt, transmit and receive antennas with gains of 20dB and operates at 3 GHz. How much power is received by a receiver 300m away?

Governments allocate frequency ranges ("spectrum") to specific users (broadcasters, radar, cell phone carriers, etc). Some frequencies are allocated for unlicensed devices such as wireless LANs.

Wired vs Wireless Channels

A signal can propagate between the transmitter and receiver over free space ("wireless transmission") and this has one important advantage: it allows the transmitter and/or receiver to communicate without using cables ("mobility").

However, there are significant advantages to having the electromagnetic wave carrying the signal propagate along a cable or waveguide instead:

- the signal strength decays linearly with distance rather than the square (or more) of the distance
- because of this the receiver and transmitter can be less complex, less expensive and use less power
- the signal is less likely to be intercepted or interfered with
- there is no need to license spectrum or share it between different users
- we can increase the capacity of the system as necessary by by adding more cables/waveguides

Exercise 11: Rank each of twisted-pair, co-ax, optical fiber and free space media according to cost of the medium, cost of the interface, media size and immunity to interference.