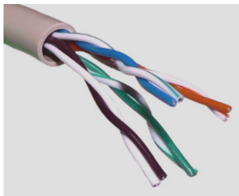
ELEX 4340 : Data Communications
2013 Fall Session

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.
You should be able to: identify the different types of transmission lines described in this lecture, their component parts and their advantages and disadvantages; compute common-mode and differential voltages; solve problems involving Z_0*, velocity factor,* ϵ_r*,TP and co-ax physical dimensions, and distributed L and C; compute signal levels and velocity factor; 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.*

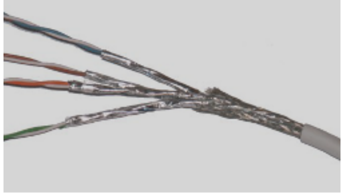
Twisted Pair

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.

The pairs can 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"), to the cable as a whole to minimize interference with other cables, or to both. STP is more expensive and less common than UTP.

The main applications for twisted pair cables are telephone "loops" and local-area networks.

"Cat 5" (Cat 3, Cat 6, etc.) refer to EIA specifications for four-pair 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.

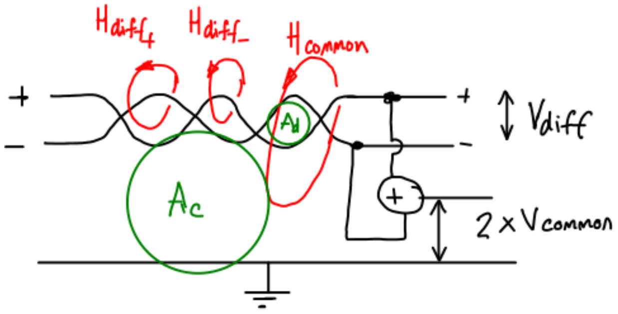
Differential Signalling

Twisted pair cables use differential signaling: opposite currents flow on each of the two wires. This has two advantages:

- the electric and magnetic fields generated by the currents flowing in the wires cancel each other out. This reduces radiation which might cause interference to other systems. Twisting is not required for this to happen.
- the voltages induced by external electric or magnetic fields on adjacent twists are opposite and thus cancel out. This reduces interference from fields generated by other systems. This only happens if the wire is twisted.

The voltage between the two wires is the differential voltage. The voltage between the average of the voltages on the two wires and ground is called the common-mode voltage.

The following diagram shows the differential and common-mode voltages and the two loops through which magnetic fields could flow to cause differential and common-mode noise:



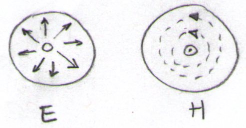
The area between the wires (Ad) is typically much smaller than the area between the wires and ground

(Ac). In addition, the voltages induced on the twisted pair by the magnetic field (the parts of the field Hdiff+ and Hdiff-) will cancel out due to the twisting. Thus the noise induced on the differential voltage will be much less than the noise induced on the common-mode voltage. The receiver can ignore the common-mode voltage by subtracting the voltages on the two wires.

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.

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

Cable Specifications

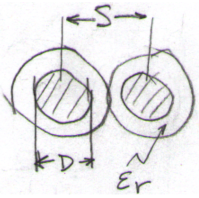
Characteristic Impedance

The characteristic impedance of a transmission line is the ratio of voltage to current for an infinitely long transmission line, or equivalently, the ratio when the transmission line is terminated so that nothing is reflected from the load.

The characteristic impedance of the transmission line is important 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
- minimize reflections that can cause inter-symbol interference

The characteristic impedance of twisted pair transmission line as a function of the wire spacing S, the wire diameter D, and the dielectric constant of the insulation (ε_r):



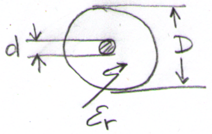
is:

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

Exercise 1: 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.

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:

$$Z_0 \approx \frac{138}{\sqrt{\varepsilon_r}} \log_{10}\left(\frac{D}{d}\right)$$

Exercise 2: 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?

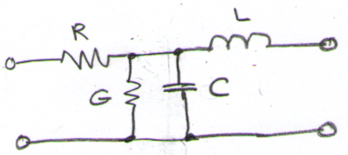
The most common co-ax impedance values are 50 ohm, mainly used for radio equipment and 75 ohm, mainly used for cable TV applications.

Distributed Element Model for Transmission Lines

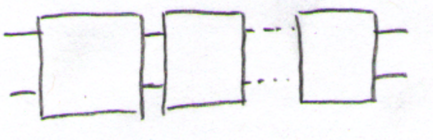
A metalic cable has resistance due to the resistance of the conductors. The cable also has a capacitance because of the charge stored in the electric field between the conductors. The cable also has inductance because of the magnetic field set up around the wires. There insulator can also be lossy, particularly at higher frequencies.

The resistance, capacitance and inductance are uniform and distributed along the whole length of the line so we can specify these values per unit length (pF per meter, for example).

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:



and the complete transmission line as an infinite sequence of the above blocks:



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

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

where the electrical quantities are specified 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:

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

Exercise 3: What is the characteristic impedance of a lossless cable with an inductance of 94 nH per foot and capacitance of 17pF/ft?

Loss

Loss measures how much the transmission line attenuates the signal. It will depend on the dimensions and the materials used to make the transmission line. It is a function of frequency and is specified in dB per unit length. For example "3dB per 100m at 10 MHz".

Exercise 4: 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?

Velocity Factor

The velocity factor is the propagation velocity as a fraction of 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:

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

Exercise 5: 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?

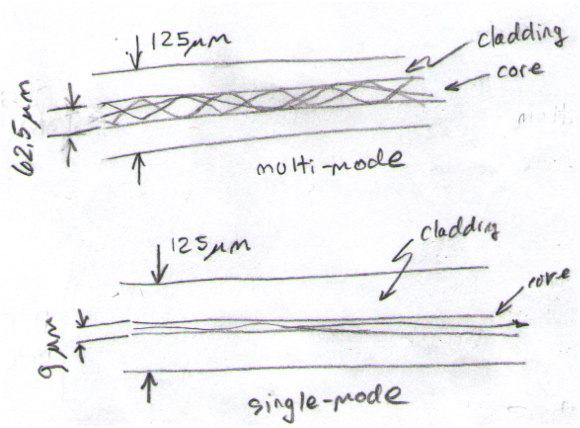
Fiber-Optic Cables

Optical fibers are made from glass fibers whose index of diffraction increases from the center out. This causes light to be refracted (bent) back towards the center of fiber.

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 which limits possible data rates. Multimode fiber is typically limited to 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.

Both types of fiber are typically 125 micron[1] 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 near-infrared region). Most single-mode fiber has a 9 micron inner core and a loss of about 0.25 dB/km at 1330nm. Each fiber is coated with one more layers of plastic to protect the fiber.



Exercise 6: If the optical signal wavelength is 1330nm what is the frequency?

The advantages of optical fiber include lower loss and higher bandwidth than the metalic cable alternatives (UTP and co-ax). Optical fibers are also immune from interference from electric and magnetic fields.

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.

Optical fibers can be connected by fusion splicing (melting the two fibers together to fuse them) or mechanical splicing (butting the ends of two fiber together in a fixture 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).

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 being extended closer to the end-user. 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) which is frequency division multiplexing (FDM) at optical frequencies.

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 and automotive applications where low costs and noise immunity are important but distances are short and data rates relatively low.

Practical Considerations

Wire Gauge

Wire diameters are often quoted in "American Wire Gauge". 24-gauge wire, a common gauge, has a diameter of about 0.5mm. The AWG value *decreases* as the log of the wire's diameter. Reducing (increasing) the wire gauge by 6 approximately doubles (halves) the diameter. For example, 30-gauge wire is about 0.25mm in diameter.

Exercise 7: 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.

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.

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

Fire- and Plenum-Rated Cables

Cables installed in certain locations need to be fire-resistant to minimize the spread of fire. 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.

Free Space Propagation

Wireless communication systems use radio-frequency signals that propagate through free space.

The characteristic impedance of free space is 377 ohms and the velocity of propagation is 3×10^8 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).

The received signal level for a LOS link is given by 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_T and G_R are the gains of the transmit and receive antennas, λ is the wavelength and d is the distance from transmitter to receiver.

Exercise 8: 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 the receiver?

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

Wired vs Wireless Channels

A signal can propagate between the transmitter and receiver over free space (“wireless transmission”) and this enables 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