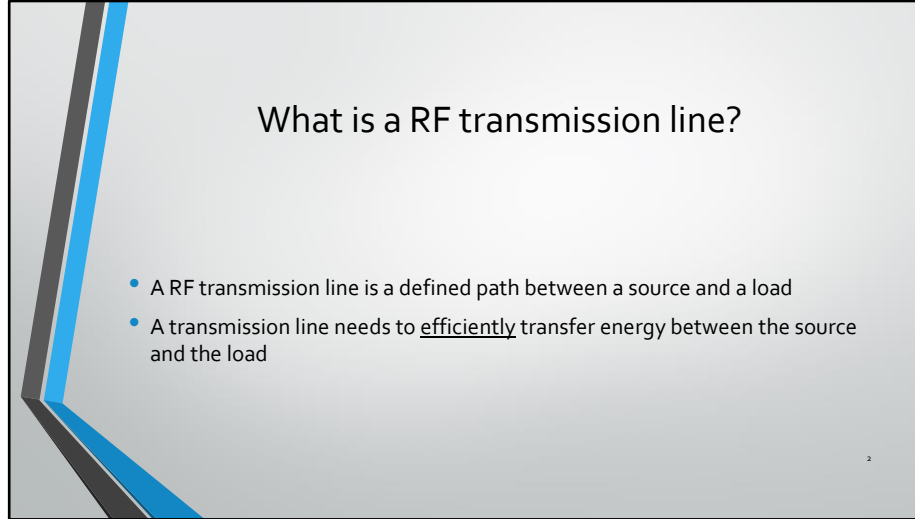




RF Transmission Lines

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Ole Virginia Hams



What is a RF transmission line?

- A RF transmission line is a defined path between a source and a load
- A transmission line needs to efficiently transfer energy between the source and the load

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Transmission lines efficiently transfer energy by CONTAINING the energy INSIDE the line. Transmission lines PREVENT energy from being radiated or lost as heat.

Even this is a transmission line...

- A type of transmission line called a cage line, used for high power, low frequency applications. It functions similarly to a large coaxial cable.
- This example is the antenna feed line for a longwave radio transmitter in Poland, which operates at a frequency of 225 kHz and a power of 1200 kW.



https://en.wikipedia.org/wiki/Transmission_line#/media/File:Solec_Kujawski_longwave_antenna_feeder.jpg

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This is a coaxial transmission line. The central “bundle” of wires forms the center conductor. The outer wires form the outer conductor.

Antenna, Transmission Line and Feed Line

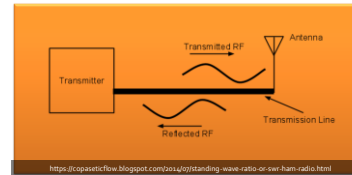
- Feed line is just another name for a transmission line
- For efficient transfer of energy from the transmitter to the feed line and from the feed line to the antenna, the various impedances need to match.
- When there is mismatch of impedances, things may still work, but not as effectively as they could.

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The key to efficient power transfer requires that the source, the load and the transmission line all have the same impedance. Impedance mismatches cause power to be reflected from the load back to the source.

What happens when energy is not perfectly delivered to the load?

- Energy not transferred to the load is reflected toward the source
- Standing Wave Ratio (SWR) is the measurement of the transmitted power to the reflected power



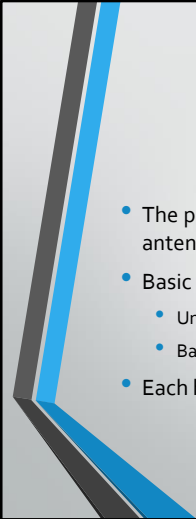
<https://copaseticflow.blogspot.com/2014/07/standing-wave-ratio-or-swr-ham-radio.html>

$$SWR = \frac{1 + \sqrt{P_r/P_f}}{1 - \sqrt{P_r/P_f}}$$

https://en.wikipedia.org/wiki/Standing_wave_ratio

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An impedance mismatch occurs when the antenna impedance is different than the transmission line impedance. The power that is not absorbed by the antenna (either radiated as electromagnetic waves or dissipated as heat) is reflected along the transmission line toward the source. At certain distances along the transmission line (at half-wavelength increments) “hotspots” form where the peak of the transmitted power “lines up” with the peak of the reflected power. You can think of this as ripples in a pond hitting a barrier, causing ripples to propagate back toward the source. At certain locations, these two waves cross, causing peaks in the ripple heights. In a transmission line, these hotspots cause heating at that location which can lead to cable breakdown. As the standing wave ratio (SWR) formula shows, this behavior is related to the reflected power and the forward (transmitted) power.



Feed Line types

- The purpose of the feed line is to get energy from your station to the antenna.
- Basic feed line types.
 - Unbalanced: Coaxial cable (coax).
 - Balanced: Open-wire or ladder line.
- Each has a characteristic impedance, each has its unique application

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Characteristic impedance of a transmission line is based on the physical construction parameters such as conductor diameter, conductor spacing, and the dielectric material between the conductors. A coaxial cable is considered an 'unbalanced' line because the two conductors are not identical in size and thickness. A balanced transmission line has identical conductors.

Characteristic Impedance

- Impedance of transmission line is based on:
 - spacing of conductors
 - diameter of conductors
 - material between the conductors



$$Z_0 = \frac{138}{\sqrt{k}} \log \frac{d_2}{d_1}$$

Where,

Z_0 = Characteristic impedance of line
 d_1 = Inside diameter of outer conductor
 d_2 = Outside diameter of inner conductor
 k = Relative permittivity of insulation between conductors



$$Z_0 = \frac{276}{\sqrt{k}} \log \frac{d}{r}$$

Where,

Z_0 = Characteristic impedance of line
 d = Distance between conductor centers
 r = Conductor radius
 k = Relative permittivity of insulation between conductors

<https://www.allaboutcircuits.com/textbook/alternating-current/chpt-14/characteristic-impedance/> 7

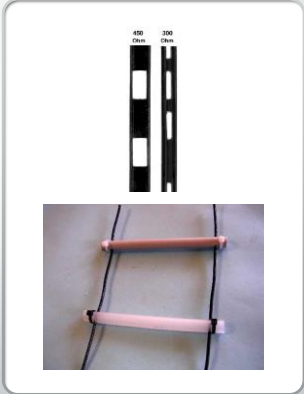
In the above formulas, the variable k is the dielectric constant of the insulating material. Many textbooks will use the variable epsilon (ϵ_r) instead of k, but the meaning is the same. The value for ϵ_r is 1.0 for air. For polyethylene (used in coaxial cable like RG-8X), the value is 2.25.



The dielectric material is an insulator (typically a plastic) that controls the separation between the inner and outer conductors. The outer braid is woven over the dielectric. A cable jacket protects the entire cable assembly.

Open-wire and Ladder Line

- Typically, 300, 450 or 600 ohms
- Plastic versions sometimes called 'window line'



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Open wire line uses air as the dielectric material between the conductors. The spacers have minimal impact on the impedance of the transmission line.

Feed Line Losses

- Feed line losses dissipate energy as heat
 - Losses in the cable's conductors
 - Losses in the cable's dielectric material
- Loss is also called attenuation
 - Expressed in dB per unit length
 - Losses increase with frequency
- Air dielectric cables have the lowest loss

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Feed Line Losses

- In general, larger diameter cables have less loss than smaller diameter cables
 - Larger conductors have lower resistance since they have more surface area
- Cables with solid shields or multiple braids have less loss than poorly constructed single-braid cables
 - Commonly referred to as braid density



<https://nasaunationalcable.com/products/belden-single-conductor-rg-59-u-pe-insulation-double-braided-analog-video-coax-cable>



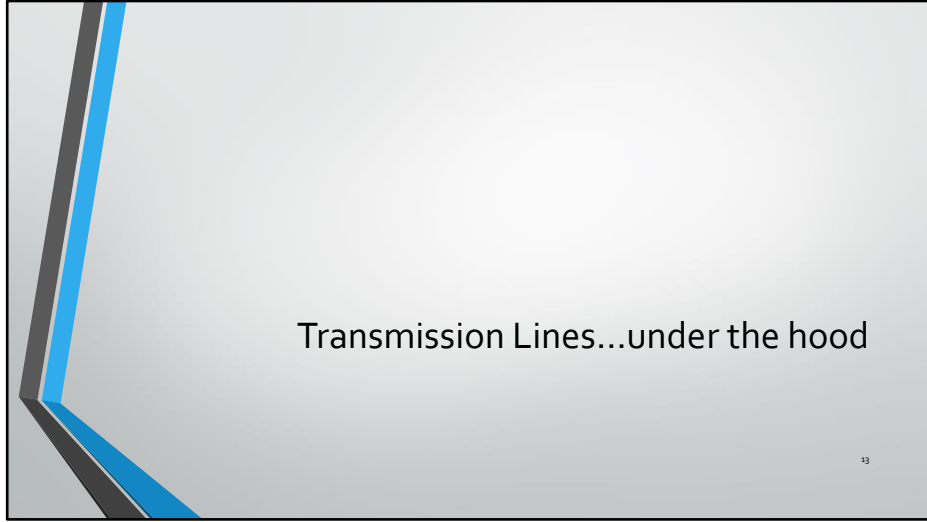
https://www.alldatasource.com/Commscope-H111-50-H111-50-HELJAX-Standard-Air-Dielectric-Coaxial-Cable-corrugated-copper-4-in-black-PE-jacket_p_396114.html

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Care and Feeding of Feed Lines...

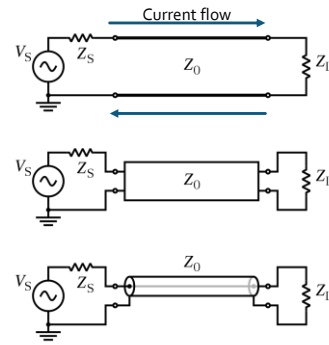
- Keep the lines dry
 - Seal connector/cable joints to keep out moisture
 - Moisture ingress for coaxial cable causes cable deterioration
- UV-rated cable jackets are designed for long-term outdoor exposure
- Do not exceed cable bend radius recommendations
- Do not exceed maximum power rating of feed line

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Transmission Line Nomenclature

- V_s : source voltage
- Z_s : source output impedance
- Z_0 : characteristic impedance of the transmission line
- Z_L : load impedance



https://en.wikipedia.org/wiki/Transmission_line#/media/File:Transmission_line_symbols.svg 14

Electric and Magnetic Fields

- Equal currents in opposite directions create magnetic fields that cancel **OUTSIDE** of the transmission line
- Nomenclature:
- H = magnetic field
- E = electric field
- I = current flow

Balanced Transmission Line

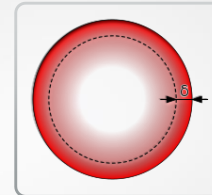
The diagram illustrates a balanced transmission line with two parallel cylindrical conductors. Part (a) shows the conductors with current I_+ flowing in the positive x -direction and I_- flowing in the negative x -direction. A 3D coordinate system with x , y , and z axes is shown. Part (b) shows the electric field \vec{E} lines between the conductors, pointing from the positive to the negative conductor. It also shows the magnetic field \vec{H} lines, which are circular loops around each conductor. The magnetic field lines between the conductors are in opposite directions, leading to cancellation outside the line.

https://www.oreilly.com/library/view/f-and-microwave/9781118349574/co3_level1_x.html
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The magnetic and electric fields are confined between the conductors. Because the conductors are in proximity, the magnetic fields generated by each conductor cancel at distances far from the transmission line.

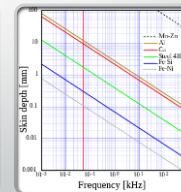
Skin Effect

- AC currents flow on the **outer part** of the conductor
- The higher the frequency, the more the currents are confined to the surface
- Separate currents can flow on the **inside and the outside** of a hollow tube (like a coax cable shield) or the surfaces of a flat conductor (like a circuit board layer)
- Copper foil thickness on a PCB is about 1.4 mils (35.5 μm)
- Diameter of a human hair: 17-181 μm



The skin depth, δ , is defined as the depth where the current density is just $1/e$ (about 37%) of the value at the surface

Skin depth in copper	
Frequency	Skin depth (μm)
50 Hz	9220
60 Hz	8420
10 kHz	652
100 kHz	206
1 MHz	65.2
10 MHz	20.6
100 MHz	6.52
1 GHz	2.06



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https://en.wikipedia.org/wiki/Skin_effect

Common-mode and Differential-mode Currents

- Differential-mode currents: the "intended" current flow
- Common-mode currents: the "unintended" current flow

The diagram illustrates current flow in two scenarios, (A) and (B). In (A), two parallel conductors are shown. The top conductor has a solid arrow pointing left labeled 'Common-mode'. The bottom conductor has a dashed arrow pointing right labeled 'Differential-mode'. Below this, a single conductor has a solid arrow pointing left labeled 'Common-mode'. In (B), a coaxial cable is shown with an outer shield and an inner conductor. The outer shield has a solid arrow pointing left labeled 'Common-mode'. The inner conductor has a dashed arrow pointing right labeled 'Differential-mode'. Labels 'Outer surface', 'Shield', and 'Inner surface' point to the respective parts of the coaxial cable. The text 'ANT1197' is visible in the bottom right of the diagram area.

Figure 23.11 — Common-mode (CM) and differential-mode (DM) current can flow on parallel-conductor and coaxial cables at the same time. CM current can be converted to a DM signal by the cable's transfer impedance.

The ARRL Antenna Book, 24th Edition

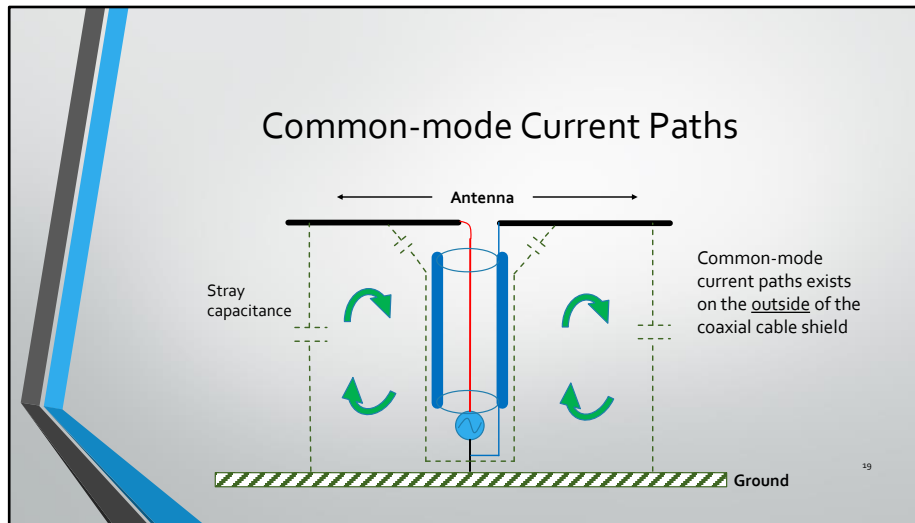
The cable's characteristic impedance is related to the differential currents that flow on the conductors. Cable transfer impedance a measure of how much interaction occurs between currents flowing on the outside of a cable shield vs. inside a cable. It is a measure of the cable's shielding effectiveness.

A description of cable transfer impedance measurements (refer to Figure 2):
<https://global-sei.com/technology/tr/bn79/pdf/79-05.pdf>

Everything's fine...until it isn't...

- If conductors are away from "external" paths the fields remain "contained" inside the transmission line
- What's an "external" path?
 - Other nearby conductors
 - Ground
- Common-mode currents flow on the "external" path

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Due to skin effect, currents can flow on the **OUTSIDE** of the shield. The antenna radiates, creating currents that flow to ground through capacitive coupling (the stray capacitance shown). Since the outside of the coaxial cable has currents flowing through it, the outer portion of the shield can radiate, just like the antenna.

Ideal Case

- Ideally only differential currents exists
 - Center conductor
 - Inside of outer conductor
- No common mode currents

Common-Mode-Current on a Dipole
(In a "Perfect" World)

(NONE)

Drawing: 0301P

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<https://www.djoip.de/rf-cmc-chokes/simple-basic-theory/cmc-detailed/>

Ideally, only differential mode currents would flow from the source to the load (i.e., the antenna). There would be no common mode currents flowing on the outside of the shield.

Real Case

- Differential currents still exist but are imbalanced
- Capacitive coupling causes common mode currents to flow on the **OUTSIDE** of the coaxial cable shield
- The outside of the cable shield can radiate

Common-Mode-Current on a Dipole
(in the "Real" World)

Drawing: D281P

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<https://www.djoip.de/rf-cmc-chokes/simple-basic-theory/cmc-detailed/>

The outside of the coaxial cable can support common mode current flow. Note that the direction of the common mode current is opposite of the internal current flow (i.e., the inside surface of the shield) in this example because the outside of the shield is connected to the reference point (i.e., the ground connection). The common mode current is generally much weaker than the differential mode current. Regardless of current mode direction, the common mode current causes the current flow in one 'arm' of the antenna to be different than the other arm. This causes the antenna radiation pattern to become asymmetrical.

How do you stop common mode currents?

Use a balun!



<https://www.on7fuferriteapplications.com/index.php/gallery-2/>



<https://www.hamuniverse.com/balun.html>



https://www.qsl.net/tazdv/amator/broadband_baluns.htm



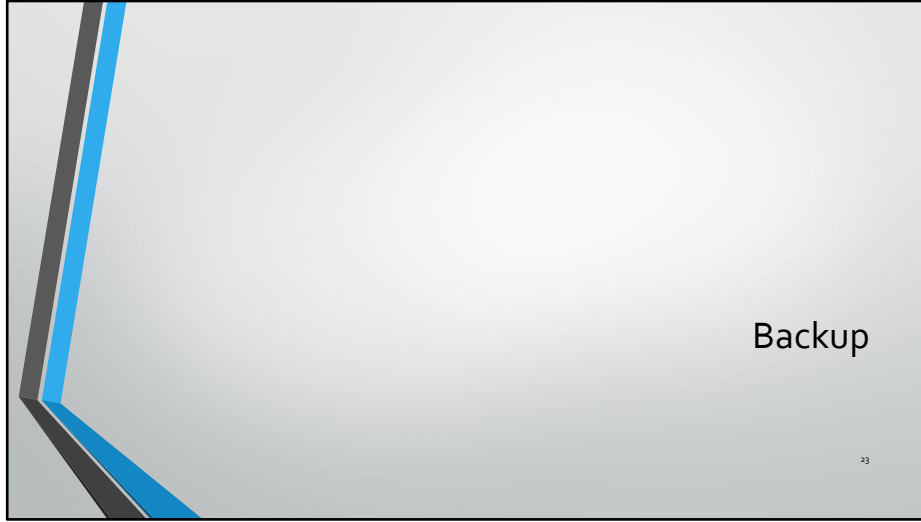
<https://www.dj0ip.de/f-cmc-choke/different-kinds-of-choke/d2-guanella-choke/>



<https://palomar-engineers.com/antenna-products/1-1-balun-kits>

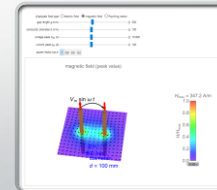
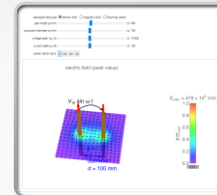
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Regardless of the construction method, a balun provides a transition from a balanced connection (i.e., the antenna) to an unbalanced connection (i.e., the coaxial cable). By winding the coaxial cable into a loop, the OUTSIDE of the shield (i.e., where the common mode currents flow) forms an inductor. This inductance greatly reduces the flow of current along the outside of the shield. This inductance can also be substantially increased by using magnetic materials such as ferrite.




Simulation

- <https://demonstrations.wolfram.com/ElectricAndMagneticFieldsNearATransmissionLine/>
- You will need to download the Wolfram Viewer tool when prompted.
- The 'Poynting Vector' is the direction of propagation along the transmission line.
- The small arrows represent the direction of the field lines (electric and magnetic).



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It's difficult to see the simulation results in this slide; running the simulation directly makes the results more visible. The small arrows show the direction of the electric and magnetic field lines. For the magnetic lines, the arrows point in opposite directions far from the transmission line. This behavior is what causes the magnetic fields to 'cancel' far away from the transmission line. The electric fields are 'tightly' confined between the two conductors.



Velocity Factor

- The velocity factor is the speed at which an RF signal travels through a material compared to the speed the same signal travels through a vacuum. The velocity of propagation is inversely proportional to the dielectric constant. Lowering the constant increases the velocity.
- Typically, the higher the velocity factor, the lower the loss through the cable.
- Raising the D/d has no effect on V_p
- Raising the dielectric constant lowers V_p

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Velocity factor is important when using specific lengths of transmission lines for impedance matching, resonant stubs, etc. A wavelength in the cable is 'shortened' or 'compressed' based on the velocity factor. For example, if the wavelength in free-space is 10 meters, the same 'wavelength' in a cable with a velocity factor of 66% is only 6.6 meters long. Compared to air (or a vacuum), a dielectric has higher 'inherent' loss due to dissipation in the material itself. For a dielectric material this is referred to as the loss tangent.

Velocity Factor

Typical velocity factors of common transmission lines

VF%	Transmission line type
95	ladder line
82	twin-lead
79	coaxial cable / foam dielectric
75	RG-6 and RG-8 coax (thick)
66	RG-58 and RG-59 coax (thin)

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

Note: multiply VF by 100% to express velocity factor as a percentage

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