Coaxial Cable

Theory & Practice

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AJ4TF

- Coaxial Cable History
- Theory
- Theory reduced to practice
- Where can I find more information about it?

What is Coaxial Cable?

- "Co-axial" – sharing the same axis
- First mention of this type of cable was by the famous English mathematician Oliver Heaviside, who patented it in 1880.
  - Other accomplishments by Heaviside (in case you haven't heard of him):
    - rewrote the fundamental equations of electromagnetism (Maxwell's Equations) into the forms that are used today
    - Predicted the existence of the E-layer of the ionosphere
    - Developed theories of transmission line propagation
    - Invented the following terms:
      - Impedance, inductance, conductance, permeability, reluctance, admittance

What is Coaxial Cable?

- In the 1920's, AT&T was looking for new methods of transmission for telephone traffic, and re-evaluated Heaviside's work
- This led to the patenting of what we would consider "modern" coaxial cable by AT&T's Bell Laboratories in 1931.

Patented Dec. 8, 1931 **1,835,031**

UNITED STATES PATENT OFFICE

LLOYD ESPENSCHIED, OF KEW GARDENS, NEW YORK, AND HERMAN A. AFFEL, OF RIDGEWOOD, NEW JERSEY, ASSIGNORS TO AMERICAN TELEPHONE AND TELEGRAPH COMPANY, A CORPORATION OF NEW YORK

CONCENTRIC CONDUCTING SYSTEM

Application filed May 23, 1929. Serial No. 365,526.

This invention relates to transmission systems, and more particularly to a novel form of conductor structure and associated apparatus for the guided transmission and utilization of a very wide band of frequencies whose width may be of the order of a millon cycles or more.

The art of television in particular has emphasized the need for transmission line systems having enormously wide frequency range requirements. Whereas individual channel requirements of telegraphy are of the order of a few hundred cycles at most, and telephony perhaps a few thousand cycles, television may require transmission of bands hundreds of thousands of cycles in width to insure a reasonable degree of picture detail. At the same time, of course, a transmission channel satisfying television requirements, gives opportunity for breaking up a very wide frequency band into perhaps hundreds of telephone channels.

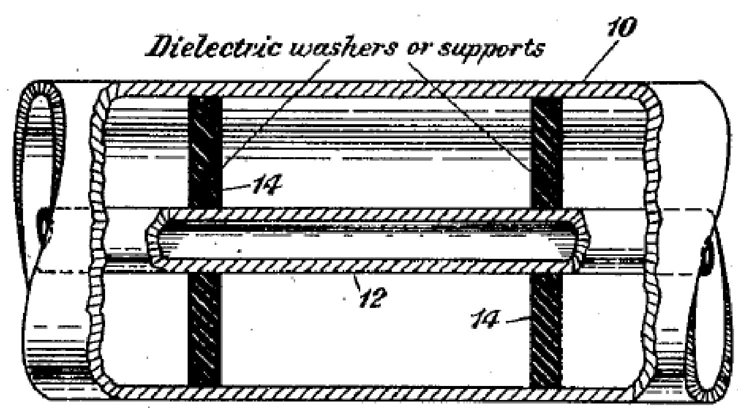
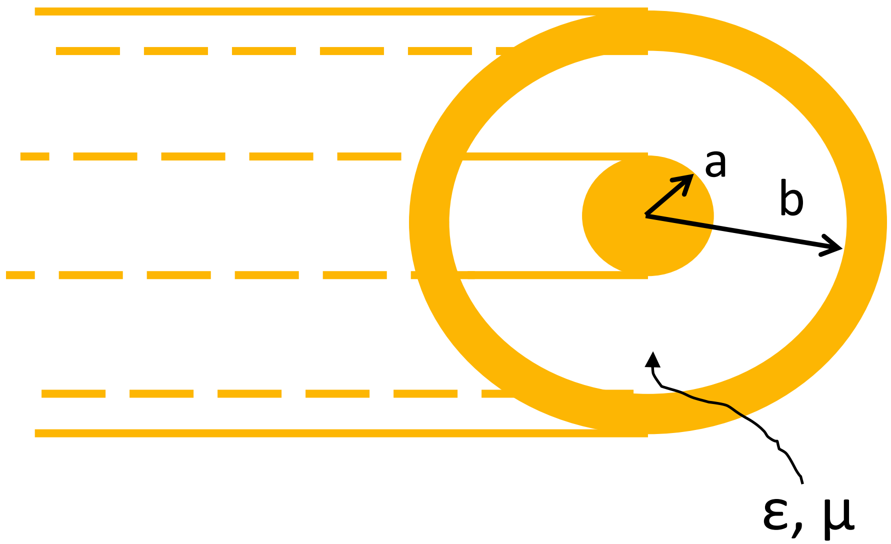


Fig. 2, Longitudinal Section

Coaxial Cable Theory

➢ Specialized form of a general two-conductor transmission line, consisting of an outer and inner conductor, with an insulating dielectric between the conductors



➢ Dimensions:

- a = outside radius of inner conductor (1/2 the diameter)
- b = inside radius of outer conductor (1/2 the diameter)
- Dielectric properties:
  ε = electric permittivity,
  μ = magnetic permeability

Coaxial Cable Theory

- Dielectric Properties

Dielectric can be described, in general, by the relative electric permittivity (ε_r) and magnetic permeability (μ_r), as compared to the "perfect" dielectric, which is free space (i.e. a vacuum with nothing around it).

$\varepsilon_r = \varepsilon / \varepsilon_o$

$\mu_r = \mu / \mu_o$

- $\varepsilon_o = 8.85 \times 10^{-11}$ permittivity of free space
- $\mu_o = 1.26 \times 10^{-5}$ permeability of free space

Coaxial Cable Theory

- Dielectric Properties

$\varepsilon_r = \varepsilon \,/\, \varepsilon_o$ also known as the 'dielectric constant'

$\mu_r = \mu \,/\, \mu_o$

- Dielectrics are (generally) non-magnetic, $\mu_r = 1$
- Non-ferrous conductors (such as copper) are also non magnetic, and since they are not dielectrics, $\varepsilon_r = 1$
- It can be shown that the intrinsic wave impedance of an electromagnetic wave in free space is:

$$\sqrt{\frac{\mu_0}{\varepsilon_0}} \cong 120\pi \cong 377\Omega$$

Coaxial Cable Theory

➢ It can also be shown that the characteristic impedance of a coaxial structure is:

$$Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu_0\mu_r}{\varepsilon_0\varepsilon_r}}\ln\frac{b}{a}$$

Since we already know $\mu_r = 1$ $\sqrt{\frac{\mu_0}{\varepsilon_0}} \cong 120\pi$ and $\log(x) = \frac{\ln(x)}{\ln(10)} = 2.302\ln(x)$

This simplifies into: $$Z_0 = \frac{138}{\sqrt{\varepsilon_r}}\log\frac{b}{a}$$

Note that the value of *b* and *a* is not important, only the logarithm of the ratio between them

Coaxial Cable Theory

- Per unit length capacitance $$C = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln\frac{b}{a}}$$

- Per unit length inductance $$L = \frac{\mu_0\mu_r}{2\pi}\ln\frac{b}{a}$$

- With some manipulation, this can be reduced to:

$$C = \frac{7.26\varepsilon_r}{\log\left(\frac{b}{a}\right)}$$ pF/foot

$$L = 0.14\log\left(\frac{b}{a}\right)$$ uH/foot

$$Z_0 = \sqrt{\frac{L}{C}}$$

Characteristic Impedance

Coaxial Cable Theory

- Propagation velocity (aka Velocity Factor)

$Vp = \frac{c}{\sqrt{\varepsilon_r}}$ or as a percentage of the speed of light: $VF = \frac{1}{\sqrt{\varepsilon_r}}$

- This is the speed at which the electric and magnetic fields travel through the cable

- This is important when determining the length in wavelengths of a section of coaxial cable, since the *electrical length* is shorter than the physical length, proportional to the velocity factor.

Coaxial Cable Theory

- Attenuation

• Power loss in coax cable comes from dielectric losses, conductor resistance, and a small amount that is radiated from the line.

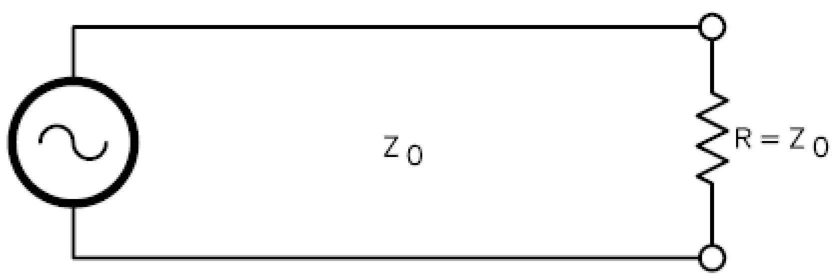
• Losses are not proportional to the length of the line, but vary by the logarithm of the length. Since the decibel is a logarithmic unit, expressing losses as dB per unit length makes calculations easier.

• Usually specified in dB per 100 ft, or dB per 100 meters

  - Watch carefully for the units… 100 m > 3X 100 ft!

Reflection Theory

- When a coaxial cable (or any other transmission line) is terminated with a load equal to its characteristic impedance, it is said to have a ***matched*** load.
- When the load is not equal to the characteristic impedance, it is ***mismatched.*** In this case, the power is only partially absorbed by the load, the rest of it is ***reflected*** back towards the source.

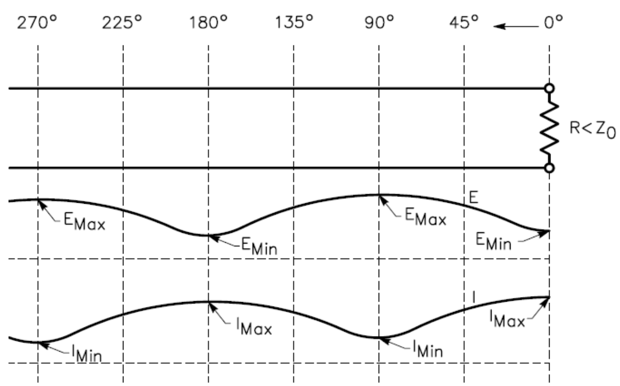


Reflection Theory

- The reflection coefficient ρ is defined as:

$$\rho = \frac{V_R}{V_F} = \frac{I_R}{I_F} = \sqrt{\frac{P_R}{P_F}}$$

- Reflected waveforms mix with the incident waveforms and add and subtract from each other, creating maximums and minimums on the line.



Reflection Theory

➢ The ratio of the maximum voltage on the line and the minimum voltage is called the *voltage standing wave ratio*, VSWR, or just SWR. Going back to the reflection coefficient:

$$SWR = \frac{1+|\rho|}{1-|\rho|} = \frac{1+\sqrt{\dfrac{P_R}{P_F}}}{1-\sqrt{\dfrac{P_R}{P_F}}}$$

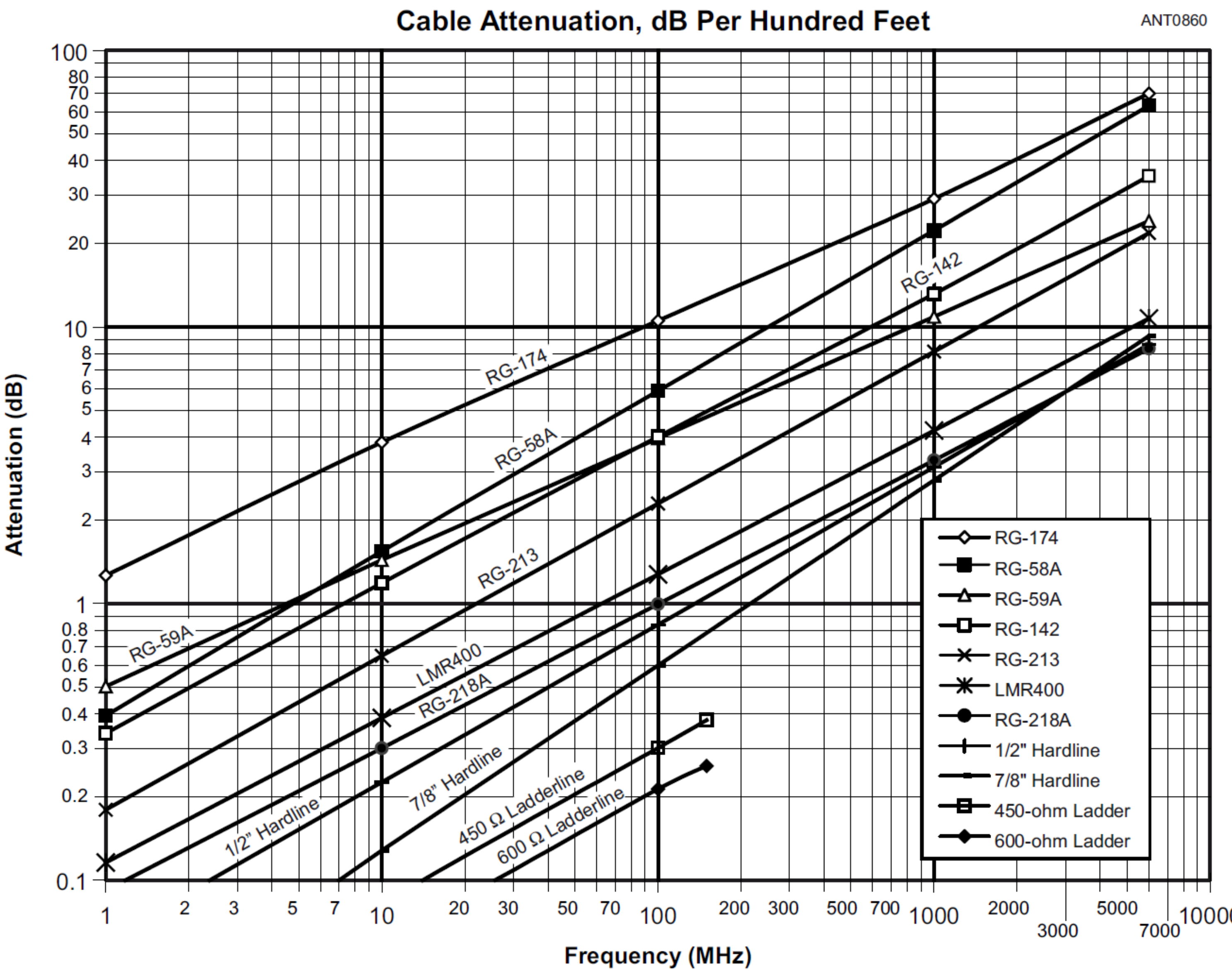
➢ So, if you know the forward and reflected power, you can calculate the SWR. A directional wattmeter, such as a Bird 43 can measure both forward and reflected power.

➢ High SWR causes additional loss over and above the line loss, and high levels of reflected power can damage your transmitter.

Practical Coax Cables

- There are many factors that go into the choice of a coax cable:
  - Loss (usually specified in dB per 100 ft or 100 m)
  - Peak power rating (which is related to the maximum breakdown voltage)
  - Average power rating (which is related to the long-term temperature rating of the dielectric material)
  - Ease of handling (diameter, bend radius, solid or stranded conductor)
  - And, of course, $$

Practical Coax Cables



Practical Coax Cables

Nominal Characteristics of Commonly Used Transmission Lines

RG or Type	*Part Number*	*Nom. Z_0 Ω*	*VF %*	*Cap. pF/ft*	*Cent. Cond. AWG*	*Diel. Type*	*Shield Type*	*Jacket Matl*	*OD inches*	*Max V (RMS)*	*Matched Loss (dB/100') 1 MHz*	*10*	*100*	*1000*
RG-6	Belden 1694A	75	82	16.2	#18 Solid BC	FPE	FC	P1	0.275	300	0.3	.7	1.8	5.9
RG-6	Belden 8215	75	66	20.5	#21 Solid CCS	PE	D	PE	0.332	2700	0.4	0.8	2.7	9.8
RG-8	Belden 7810A	50	86	23.0	#10 Solid BC	FPE	FC	PE	0.405	300	0.1	0.4	1.2	4.0
RG-8	TMS LMR400	50	85	23.9	#10 Solid CCA	FPE	FC	PE	0.405	600	0.1	0.4	1.3	4.1
RG-8	Belden 9913	50	84	24.6	#10 Solid BC	ASPE	FC	P1	0.405	300	0.1	0.4	1.3	4.5
RG-8	CXP1318FX	50	84	24.0	#10 Flex BC	FPE	FC	P2N	0.405	600	0.1	0.4	1.3	4.5
RG-8	Belden 9913F	50	83	24.6	#11 Flex BC	FPE	FC	P1	0.405	300	0.2	0.6	1.5	4.8
RG-8	Belden 9914	50	82	24.8	#10 Solid BC	FPE	FC	P1	0.405	300	0.2	0.5	1.5	4.8
RG-8	TMS LMR400UF	50	85	23.9	#10 Flex BC	FPE	FC	PE	0.405	600	0.1	0.4	1.4	4.9
RG-8	DRF-BF	50	84	24.5	#9.5 Flex BC	FPE	FC	PE	0.405	600	0.1	0.5	1.6	5.2
RG-8	WM CQ106	50	84	24.5	#9.5 Flex BC	FPE	FC	P2N	0.405	600	0.2	0.6	1.8	5.3
RG-8	CXP008	50	78	26.0	#13 Flex BC	FPE	S	P1	0.405	600	0.1	0.5	1.8	7.1
RG-8	Belden 8237	52	66	29.5	#13 Flex BC	PE	S	P1	0.405	3700	0.2	0.6	1.9	7.4
RG-8X	Belden 7808A	50	86	23.5	#15 Solid BC	FPE	FC	PE	0.240	300	0.2	0.7	2.3	7.4
RG-8X	TMS LMR240	50	84	24.2	#15 Solid BC	FPE	FC	PE	0.242	300	0.2	0.8	2.5	8.0
RG-8X	WM CQ118	50	82	25.0	#16 Flex BC	FPE	FC	P2N	0.242	300	0.3	0.9	2.8	8.4
RG-8X	TMS LMR240UF	50	84	24.2	#15 Flex BC	FPE	FC	PE	0.242	300	0.2	0.8	2.8	9.6
RG-8X	Belden 9258	50	82	24.8	#16 Flex BC	FPE	S	P1	0.242	300	0.3	0.9	3.2	11.2
RG-8X	CXP08XB	50	80	25.3	#16 Flex BC	FPE	S	P1	0.242	300	0.3	1.0	3.1	14.0
RG-9	Belden 8242	51	66	30.0	#13 Flex SPC	PE	SCBC	P2N	0.420	5000	0.2	0.6	2.1	8.2
RG-11	Belden 8213	75	84	16.1	#14 Solid BC	FPE	S	PE	0.405	300	0.1	0.4	1.3	5.2
RG-11	Belden 8238	75	66	20.5	#18 Flex TC	PE	S	P1	0.405	300	0.2	0.7	2.0	7.1
RG-58	Belden 7807A	50	85	23.7	#18 Solid BC	FPE	FC	PE	0.195	300	0.3	1.0	3.0	9.7
RG-58	TMS LMR200	50	83	24.5	#17 Solid BC	FPE	FC	PE	0.195	300	0.3	1.0	3.2	10.5
RG-58	WM CQ124	52	66	28.5	#20 Solid BC	PE	S	PE	0.195	1400	0.4	1.3	4.3	14.3
RG-58	Belden 8240	52	66	29.9	#20 Solid BC	PE	S	P1	0.193	1400	0.3	1.1	3.8	14.5
RG-58A	Belden 8219	53	73	26.5	#20 Flex TC	FPE	S	P1	0.195	300	0.4	1.3	4.5	18.1
RG-58C	Belden 8262	50	66	30.8	#20 Flex TC	PE	S	P2N	0.195	1400	0.4	1.4	4.9	21.5
RG-58A	Belden 8259	50	66	30.8	#20 Flex TC	PE	S	P1	0.192	1400	0.5	1.5	5.4	22.8
RG-59	Belden 1426A	75	83	16.3	#20 Solid BC	FPE	S	P1	0.242	300	0.3	0.9	2.6	8.5
RG-59	CXP 0815	75	82	16.2	#20 Solid BC	FPE	S	P1	0.232	300	0.5	0.9	2.2	9.1
RG-59	Belden 8212	75	78	17.3	#20 Solid CCS	FPE	S	P1	0.242	300	0.2	1.0	3.0	10.9
RG-59	Belden 8241	75	66	20.4	#23 Solid CCS	PE	S	P1	0.242	1700	0.6	1.1	3.4	12.0
RG-62A	Belden 9269	93	84	13.5	#22 Solid CCS	ASPE	S	P1	0.240	750	0.3	0.9	2.7	8.7
RG-62B	Belden 8255	93	84	13.5	#24 Flex CCS	ASPE	S	P2N	0.242	750	0.3	0.9	2.9	11.0
RG-63B	Belden 9857	125	84	9.7	#22 Solid CCS	ASPE	S	P2N	0.405	750	0.2	0.5	1.5	5.8
RG-142	CXP 183242	50	69.5	29.4	#19 Solid SCCS	TFE	D	FEP	0.195	1900	0.3	1.1	3.8	12.8
RG-142B	Belden 83242	50	69.5	29.0	#19 Solid SCCS	TFE	D	TFE	0.195	1400	0.3	1.1	3.9	13.5
RG-174	Belden 7805R	50	73.5	26.2	#25 Solid BC	FPE	FC	P1	0.110	300	0.6	2.0	6.5	21.3
RG-174	Belden 8216	50	66	30.8	#26 Flex CCS	PE	S	P1	0.110	1100	0.8	2.5	8.6	33.7
RG-213	Belden 8267	50	66	30.8	#13 Flex BC	PE	S	P2N	0.405	3700	0.2	0.6	2.1	8.0
RG-213	CXP213	50	66	30.8	#13 Flex BC	PE	S	P2N	0.405	600	0.2	0.6	2.0	8.2
RG-214	Belden 8268	50	66	30.8	#13 Flex SPC	PE	D	P2N	0.425	3700	0.2	0.7	2.2	8.0
RG-216	Belden 9850	75	66	20.5	#18 Flex TC	PE	D	P2N	0.425	3700	0.2	0.7	2.0	7.1
RG-217	WM CQ217F	50	66	30.8	#10 Flex BC	PE	D	PE	0.545	7000	0.1	0.4	1.4	5.2
RG-217	M17/78-RG217	50	66	30.8	#10 Solid BC	PE	D	P2N	0.545	7000	0.1	0.4	1.4	5.2
RG-218	M17/79-RG218	50	66	29.5	#4.5 Solid BC	PE	S	P2N	0.870	11000	0.1	0.2	0.8	3.4
RG-223	Belden 9273	50	66	30.8	#19 Solid SPC	PE	D	P2N	0.212	1400	0.4	1.2	4.1	14.5
RG-303	Belden 84303	50	69.5	29.0	#18 Solid SCCS	TFE	S	TFE	0.170	1400	0.3	1.1	3.9	13.5
RG-316	CXP TJ1316	50	69.5	29.4	#26 Flex BC	TFE	S	FEP	0.098	1200	1.2	2.7	8.0	26.1
RG-316	Belden 84316	50	69.5	29.0	#26 Flex SCCS	TFE	S	FEP	0.096	900	0.8	2.5	8.3	26.0
RG-393	M17/127-RG393	50	69.5	29.4	#12 Flex SPC	TFE	D	FEP	0.390	5000	0.2	0.5	1.7	6.1
RG-400	M17/128-RG400	50	69.5	29.4	#20 Flex SPC	TFE	D	FEP	0.195	1400	0.4	1.3	4.3	15.0

Practical Coax Cables

- Power Handling
  - The dielectric material and losses are the main contributor to the power handling ability of a given cable type for long-term operation
  - For example, a 200 foot piece of RG-8 has a loss of around 3 dB. If you put 500 watts into this cable, 250 watts, or *half of the power,* is lost in the cable. This is dissipated as heat, and can be enough to soften the plastic materials.
  - Pay attention to the maximum RMS voltage rating of the cable: A solid dielectric will handle a higher voltage (more power), but, with higher losses than a foam dielectric

Approximate Power Handling Capability (1:1 SWR, 40°C Ambient):

	1.8 MHz	*7*	*14*	*30*	*50*	*150*	*220*	*450*	*1 GHz*
RG-58 Style	1350	700	500	350	250	150	120	100	50
RG-59 Style	2300	1100	800	550	400	250	200	130	90
RG-8X Style	1830	840	560	360	270	145	115	80	50
RG-8/213 Style	5900	3000	2000	1500	1000	600	500	350	250
RG-217 Style	20000	9200	6100	3900	2900	1500	1200	800	500
LDF4-50A	38000	18000	13000	8200	6200	3400	2800	1900	1200
LDF5-50A	67000	32000	22000	14000	11000	5900	4800	3200	2100
LMR500	18000	9200	6500	4400	3400	1900	1600	1100	700
LMR1200	52000	26000	19000	13000	10000	5500	4500	3000	2000

Practical Coax Cables

- Bend Radius
  - The minimum bend radius is the radius (or ½ the diameter) of the smallest circle the cable should be coiled or bent into
  - A common rule of thumb for braided shield cables is a minimum bend radius of 8 x the outside diameter.
    - RG-8: ~ ½” outside diameter x 8 = 4” minimum bend radius or no smaller than an 8” diameter coil
  - For solid shield cable (hardline) the minimum bend radius will be larger
  - Cables that will be frequently bent or flexed, such as with antenna rotators, should have a stranded center conductor; a solid conductor will likely break as a result of repeated flexing

Practical Coax Cables

- Outside Use
  - Water Infiltration – through jacket cuts and connectors (common amateur coaxial connectors are NOT waterproof!)
    - Water causes corrosion and breakdown of the shield, and contamination of the dielectric material, which will increase the cable loss significantly
  - Outer Jacket Damage
    - Sunlight can cause PVC jackets to break down and eventually fail, contaminating the shield and dielectric
    - For outside use, select a "Non-Contaminating" jacket material

Practical Coax Cables

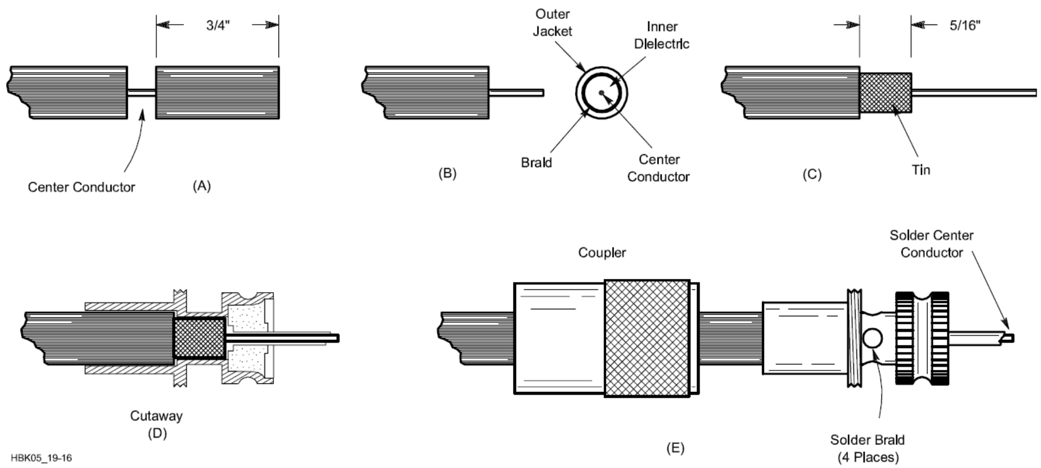
- Outside Use
  - Direct Burial
    - Burying a feedline can provide:
      - Protection from sunlight or storm damage
      - Reduction of common mode currents on the shield
      - Protection from the neighbors
    - For a cable that is to be buried directly in the ground, select a type that is rated for this; direct burial cables usually have a tough polyethylene jacket that resists damage.
    - Some are ‘flooded’ with a water-blocking material that will prevent water intrusion if the jacket is cut

Practical Coax Cables

- Outside Use
  - Direct Burial
    - Consider using sand in your burial trench to help prevent cable damage and protection from rocks
    - Or, use a plastic pipe that the cable is pulled through
      - The pipe needs to have drainage holes to allow moisture to escape
    - Bury deep enough that digging, aerating, etc won't affect the cable (12-18 inches)

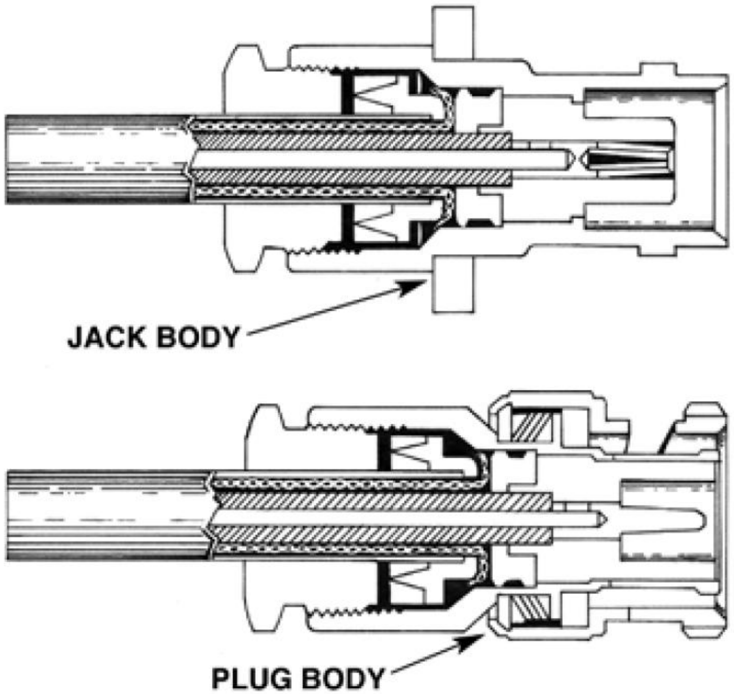
Practical Coax Cables

- Coaxial Connectors
  - Most common is the UHF, or PL-259/SO-239
    - Despite the name, UHF connectors are not very good at UHF frequencies, the U means “universal” instead of “ultra”
    - UHF connectors do not maintain a constant impedance at high frequencies
    - However, they remain very popular for HF equipment



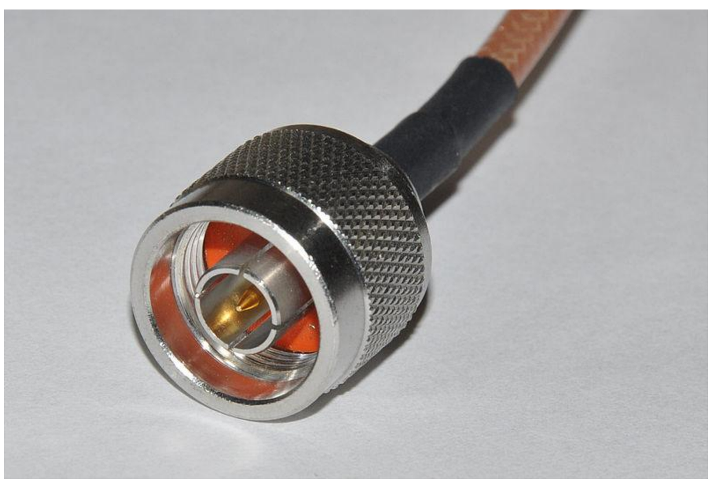
Practical Coax Cables

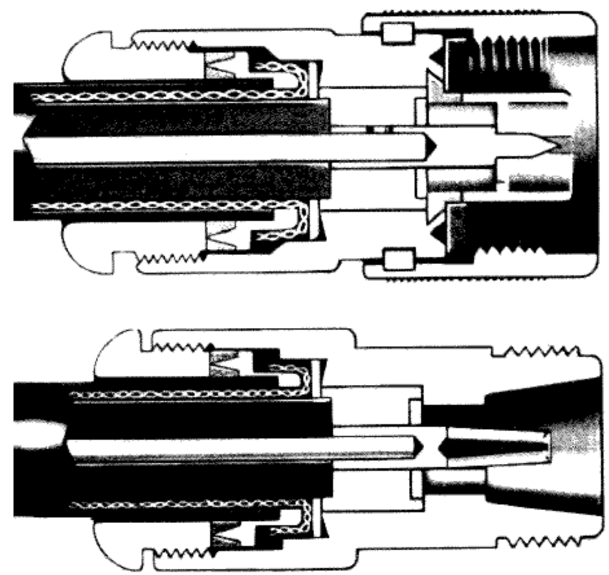
- Coaxial Connectors
  - BNC (Bayonet Neill-Concelman) connectors are used for VHF/UHF at low to moderate power levels
  - Named after its bayonet locking mechanism and its inventors, Paul Neill of Bell Laboratories, and Carl Concelman of Amphenol.
  - Patented in 1951
  - Good up to 2 GHz



Practical Coax Cables

- Coaxial Connectors
  - N connectors are used for VHF/UHF at high power levels
  - Also invented by Paul Neill of Bell Laboratories
  - Good up to 11 GHz
  - ≈5000 W at 20 MHz and ≈500 W at 2 GHz





More Information

- Much of this material was taken from the *ARRL Antenna Book*, which is a valuable resource
- Coax manufacturers also have good information, example:

http://www.belden.com/pdfs/Techpprs/CoaxialCablesandApplications.pdf

- Web searches can locate a lot of good info on coax cable

Questions?