Transmission Line Forum

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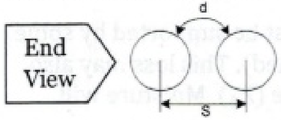
Transmission Lines: Some Common Types

▶ BALANCED CONDUCTOR LINE ◀

Open Wire Line, Ladder Line, Window Line, Twisted-Pair Line, Twin-Lead, etc.
Balanced currents in conductors: Equal and opposite.



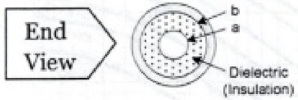
$$Z_\varnothing = 276 \log_{10}\left(\frac{2S}{d}\right), \text{ where}$$

$Z_\varnothing$ = Characterisitc Impedance
S = Center – to – Center Spacing
d = Conductor Diameter

Any dielectric (insulation, spacers, ...) will **lower** $Z_\varnothing$. Practical values for $Z_\varnothing$ range from 75Ω to 900Ω. Balanced lines can have very low-loss, but are affected by weather (moisture, ice, dirt), and proximity to other conductors.

▶ COAXIAL CABLE ◀

Solid-Dielectric, Foam-Dielectric, Semi-Rigid, "Hard Line", etc.
Unbalanced - outer conductor acts as a shield.



$$Z_\varnothing = \frac{138}{\sqrt{\epsilon_r}} \log_{10}\left(\frac{b}{a}\right), \text{ where}$$

$Z_\varnothing$ = Characterisitic Impedance
a = Outer – Diameter of Inner Conductor
b = Inner – Diameter of Outer Conductor
ϵ_r = Dielectric Constant ("Relative Permittivity")

Coaxial cables can have higher loss than Balanced-Lines, but are not affected by weather and proximity to other conductors. Practical values for $Z_\varnothing$ range from 20Ω to 200Ω. Minimum attenuation occurs when $Z_\varnothing \approx 75\Omega$, however, maximum power-handling occurs when $Z_\varnothing \approx 30\Omega$! 50Ω is a good compromise for amateur radio!

Common 50Ω types: RG-8 / RG-58 / 9913 / LMR-400
Common 75Ω types: RG-11 / RG-59

Common Dielectrics

Velocity Factor is velocity of signal in cable relative to speed of light.

$$V.F. = \frac{1}{\sqrt{\epsilon_r}}$$

Vacuum or Dry Air:	$(\epsilon_r = 1.0, V.F. = 1.0)$
Foamed Polyethylene:	$(\epsilon_r = 1.3 - 1.7, V.F. = 0.78 - 0.88)$
PTFE (Teflon®):	$(\epsilon_r = 2.1, V.F. = 0.69)$
Solid Polyethylene:	$(\epsilon_r = 2.3, V.F. = 0.66)$

▶ STRIP LINE ◀

Flat metal strip between ground planes.

For power amplifiers, filters, tuners, ...

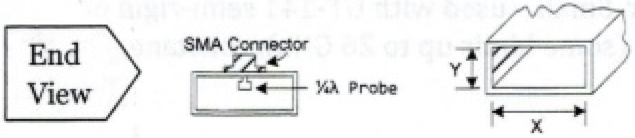
▶ MICRO STRIPLINE ◀

For VHF/UHF/Microwave circuit boards.

Example: For 50Ω line on glass-epoxy substrate ($\epsilon_r = 4.8$),
$H = \frac{1}{16}$ in. (0.062 in.), W = 0.105 in.

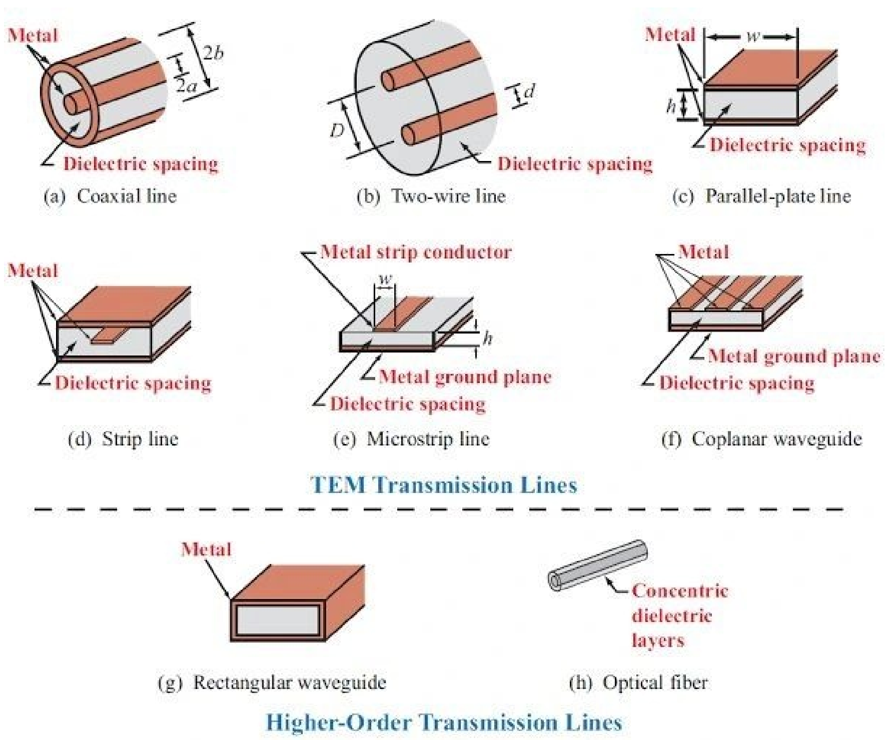
▶ WAVE GUIDE ◀

Useful for UHF & Microwaves.



Very low loss (Amateur use > 1 GHz)
Example: WR-90 (X=0.90 in., Y=0.40 in.)
Good for 8-12 GHz. Loss @ 10GHz ≈ 3 dB/100ft.
X > ½λ (X,Y are inner dimensions)

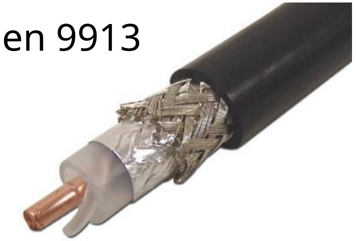
Types of RF Transmission Lines



https://www.linkedin.com/posts/pradeep-khannur-a7b4358a_rf-basics-rf-transmission-lines-rf-transmission-activity-7352850289105756161-t0Ce

Times LMR-400

Belden 9913



https://avarc.ca/wp-content/uploads/online-basic-course/Ch7-Transmission-Lines.pdf

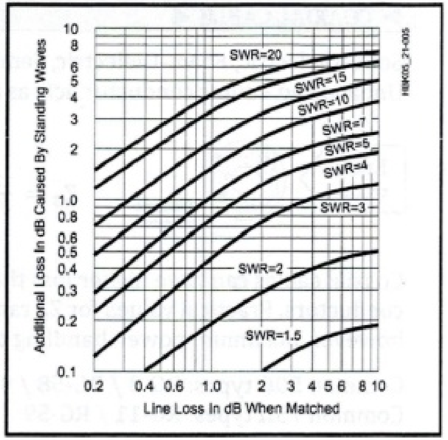
Transmission Line Losses

Attenuation is often rated in dB per 100 ft.

1. OHMIC LOSS in conductors increases with frequency, since electrons concentrate more on the surface ("skin effect").

2. DIELECTRIC LOSS. A vacuum or inert gas is best, but in practice the conductors must be supported by some insulating material. Good choices are PTFE (Teflon®), or polyethylene (solid or foamed). This loss may also increase with frequency. Dielectric Constant (ϵ_r) will affect Characteristic Impedance ($Z_\emptyset$). Moisture will drastically increase losses.

3. RADIATION LOSS. Parallel-conductor line will radiate if currents are unequal, or if conductor spacing is large (> 1%λ). Coaxial cable will radiate if the shield has holes or gaps, or if connectors are not tight. Also, feeding a balanced antenna can result in current flow outside the coaxial shield – prevent this with a BALUN ("Balanced-to-Unbalanced" Transformer).



4. MISMATCH LOSS. Reflected power (high SWR) causes additional loss over that when the line is matched (SWR = 1). The higher the matched loss is, the more significant this additional loss becomes. For long runs of coaxial cable at VHF or UHF, the Load Impedance (R_L) of the antenna should equal the Characteristic Impedance ($Z_\emptyset$) of the cable. For low loss ladder-line at HF, a high SWR may not matter much as long as your transmitter or tuner can operate into the load!

5. CONNECTOR LOSSES result from impedance mismatches and poor interfaces (moisture, dirt, ...).

REDUCE LOSSES! Increase conductor size (doubling diameter ≈ half the loss). Shorten the line (move the radio closer to the antenna!). Keep moisture and corrosion away!

ESTIMATING LINE LOSS: If loss in dB at one frequency (f_1) is known, then loss in dB at another frequency (f_2) can be calculated: $f_2 \approx \text{dB at } f_1 \times \sqrt{f_2/f_1}$

(This may be optimistic, since it does not account for change in dielectric loss with frequency.)

► COAXIAL CONNECTORS: Some Common Types ◄

UHF Most popular for HF – can handle 1.5 KW. Easy to install, but **not waterproof**. Good up to 200 MHz not constant impedance (UHF is a misnomer). Can be used with RG-8, RG-8X, RG-58, RG-59 cables.
Plug: PL-259   Socket: SO-239

N Can handle 1.5 KW at HF and VHF – constant impedance. Good up to 12 GHz, **waterproof**. Available in 50Ω and 75Ω versions.

BNC Good for test equipment, small or portable gear; for RG-58 cable. **Not waterproof** – indoor use only. Constant impedance – good to 1 or 2 GHz. Quick disconnect (a threaded version, type TNC, operates up to 12 GHz).

SMA (Sub-Miniature, Type A) – most popular microwave connector. Small – used with UT-141 semi-rigid or RG-58 flexible cables. Fragile – difficult to install. Good up to 18 GHz (some kinds up to 26 GHz), constant impedance. Found on some miniature portable radios.

Transmission Lines as Circuit Components

Transmission Line Sections may be used instead of discrete components ("Lumped Elements") for tuning, phasing, or matching of antennas, feed-lines, or circuits.

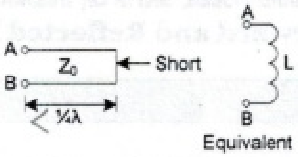
Parallel-Conductor line can be affected by nearby objects; coaxial cables are shielded and may be coiled up without effect.

Assuming Loss-Less Line:

X_L = Inductive Reactance (Ω) — $X_L = 2\pi fL$, where L = Inductance
X_C = Capacitive Reactance (Ω) — $X_C = \frac{1}{2\pi fC}$, where C = Capacitance
θ = Electrical Length in Degrees
$Z_\emptyset$ = Characteristic Impedance (Ω) of a Transmission Line
Z_1 = Input Impedance (Ω) — λ = Wavelength
Z_2 = Output Impedance (Ω) — 1λ corresponds to $\theta = 360°$
f = Frequency (Hz)

Note that Line Lengths must include Velocity Factor (V.F.). Any dielectric (insulation) will slow down velocity relative to the speed of light, and reduce the wavelength in the line to less than that in free space.
$V.F. = \frac{1}{\sqrt{\epsilon_r}}$, where ϵ_r is the dielectric constant of the material. For a vacuum or dry air, $\epsilon_r = 1.0$.

INDUCTOR

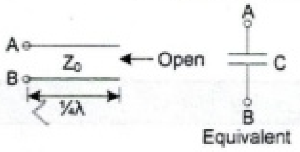


$\theta < 90°$

$$X_L = \tan\theta \, Z_\phi$$

Special Case: For $\frac{1}{8}\lambda$, $\tan 45° = 1$, and $X_L = Z_\emptyset$

CAPACITOR

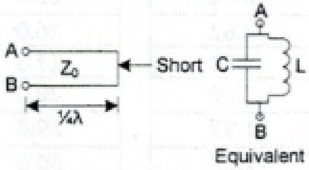


$\theta < 90°$

$$X_C = Z_\emptyset \operatorname{ctn}\theta$$

Special Case: For $\frac{1}{8}\lambda$, $\operatorname{ctn} 45° = 1$, and $X_C = Z_\emptyset$

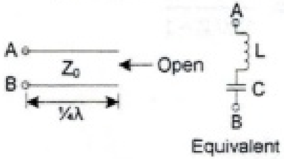
PARALLEL RESONANCE



$\theta = 90°$

$X_L = X_C$ $\quad A - B = Hi - Z$

SERIES RESONANCE



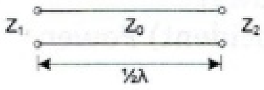
$\theta = 90°$

$X_L = X_C$ $\quad A - B = Lo - Z$

"IMPEDANCE INVERTER"

"$\frac{1}{4}\lambda$ Transformer" $\quad Z_1 = \frac{{Z_\emptyset}^2}{Z_2}$ or $Z_\emptyset = \sqrt{Z_1 Z_2}$

"IMPEDANCE REPEATER"



$Z_1 = Z_2$ regardless of $Z_\emptyset$

Transmission Line Measurements

Transmission Line Sections may be used instead of discrete components (Lumped Elements) for tuning, phasing, or matching of antennas, feed-lines, or circuits.

▶ STANDING-WAVE RATIO (SWR) ◀

$$SWR = \frac{E_{max}}{E_{min}}$$

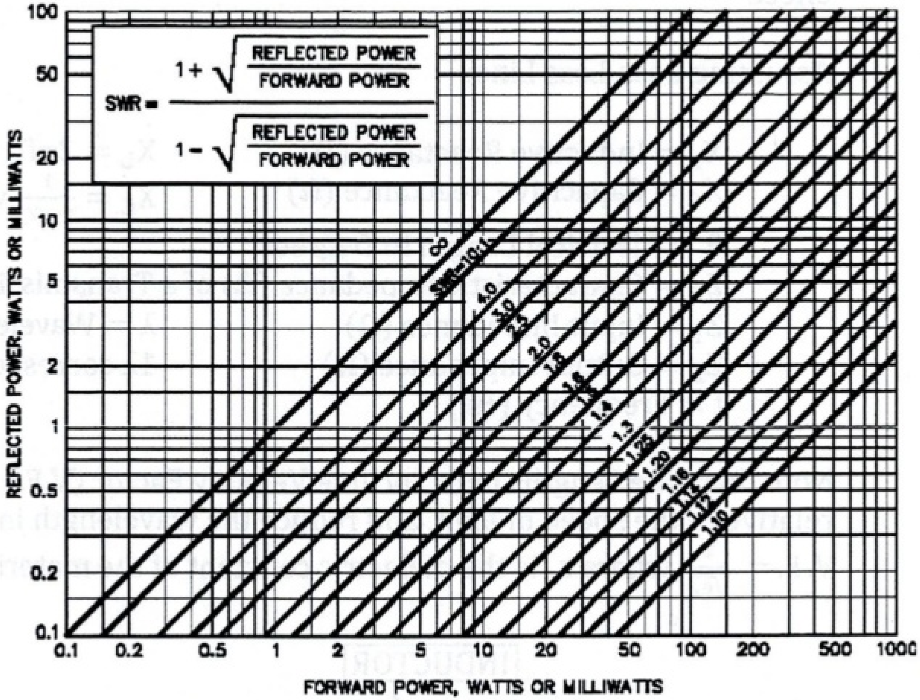
Note: SWR is always ≥ 1!

For a Resistive Load (R_{Load}):

$SWR = \frac{Z_{\emptyset}}{R_{Load}}$ -or- $SWR = \frac{R_{Load}}{Z_{\emptyset}}$, whichever is > 1.

$Z_{\emptyset}$ = Characteristic Impedance (Ω) of a Transmission Line.

When $R_{Load} = Z_{\emptyset}$, the line is perfectly matched.



SWR vs Forward and Reflected Power

► RETURN LOSS ◄

This is much more accurate than SWR for determining small changes in mismatch.

$$RL = -20 \log_{10} |\rho|$$

$$\rho = \frac{E_r}{E_f} \rightarrow |\rho| = \sqrt{\frac{P_r}{P_f}} = \frac{SWR-1}{SWR+1}$$

Where
RL = Return Loss (in dB)
ρ = Voltage Reflection Coefficient
$|\rho|$ = Reflection Coefficient Magnitude
E_r = Reflected Voltage
E_f = Forward (Incident) Voltage
P_r = Reflected Power
P_f = Forward (Incident) Power

RL (dB)	SWR
0.0	∞
1.0	17.39
2.0	8.72
3.0	5.85
4.0	4.42
5.0	3.57
6.0	3.01
7.0	2.62
8.0	2.32
9.0	2.10
10.0	1.93
11.0	1.79
12.0	1.67
13.0	1.57
14.0	1.50
15.0	1.43
16.0	1.38
17.0	1.33
18.0	1.29

RL (dB)	SWR
19.0	1.25
20.0	1.22
21.0	1.20
22.0	1.17
23.0	1.15
24.0	1.14
25.0	1.12
26.0	1.11
27.0	1.09
28.0	1.08
29.0	1.07
30.0	1.07
31.0	1.06
32.0	1.05
34.0	1.04
37.0	1.03
40.0	1.02
45.0	1.01
∞	1.00

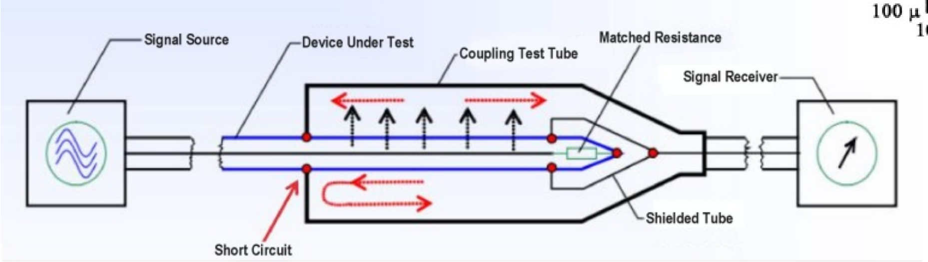
A simple **Return-Loss Bridge** and **Detector** can be used to accurately measure coaxial cable lengths for phasing antennas.

Measuring coaxial cable loss:
Short or open the far end (an open end may give an error at high frequencies due to fringing capacitance).

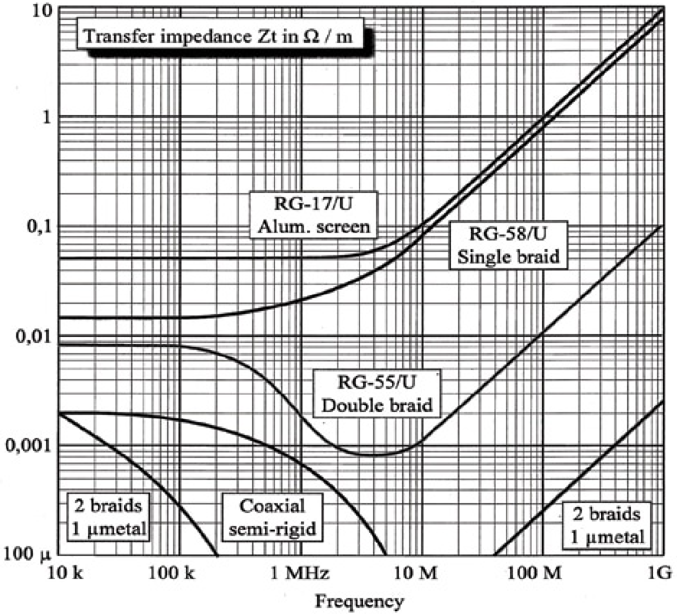
$$\text{Cable Loss (dB)} = \frac{RL}{2}$$

Shielding Effectiveness / Isolation

- Measuring the Shielding Effectiveness (SE) of a coaxial cable involves quantifying how well its outer conductor (shield) prevents internal signals from leaking out and external electromagnetic interference (EMI) from leaking in. This is typically expressed in decibels (dB), where a higher value indicates better performance.
  - Tri-axial Fixture
  - Mode-Stirred Chamber
  - Transverse ElectroMagnetic Cell
  - Line Injection Method



https://vinstronics.com/waht-is-triaxial-method/



https://interferencetechnology.com/simple-method-for-predicting-a-cable-shielding-factor-based-on-transfer-impedance/

TABLE IV

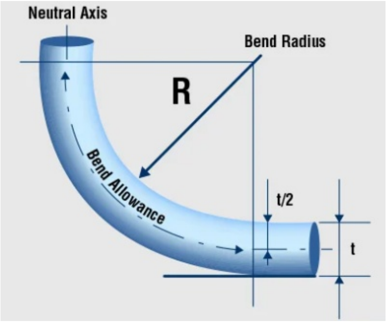
COMPARISON OF VARIOUS OUTER CONDUCTOR SHIELDING CONSTRUCTIONS

Ranking by Best Atten. Perf.	Ranking by Best Shielding Perf.	Ranking by Best Physical Toughness	Ranking by Flexibility	Outer Conductor Style
1	1 >100 dB	4	3	Wrapped Foil + Woven Round Braid
2	2 >90 dB	1	5	Woven Flat Braid + Wrapped Foil + Woven Round Braid
3	3 >80 dB	2	4	Woven Flat Braid + Woven Round Braid
4	4 >65 dB	3	2	Two Woven Round Braids
5	5 >40 dB	5	1	One Single Woven Round Braid

https://www.microwavejournal.com/articles/9169-choosing-the-optimal-high-frequency-coaxial-cable

Bend Radius

- The minimum bend radius of a coaxial cable is the tightest curve it can handle without damaging its internal structure or degrading signal performance. Bending a cable too sharply can crush the dielectric, displace the center conductor, or deform the shield, leading to increased signal loss (attenuation) and impedance mismatches.
- If a manufacturer's specification is unavailable, you can use these common industry standards based on the cable's Outside Diameter (O.D.):
  - Static (Fixed) Installations: 5 to 10 times the cable O.D..
  - Dynamic (Repeated Flexing): 15 to 20 times the cable O.D..
  - Micro-coax (e.g., U.FL cables): Typically around 6 times the O.D.

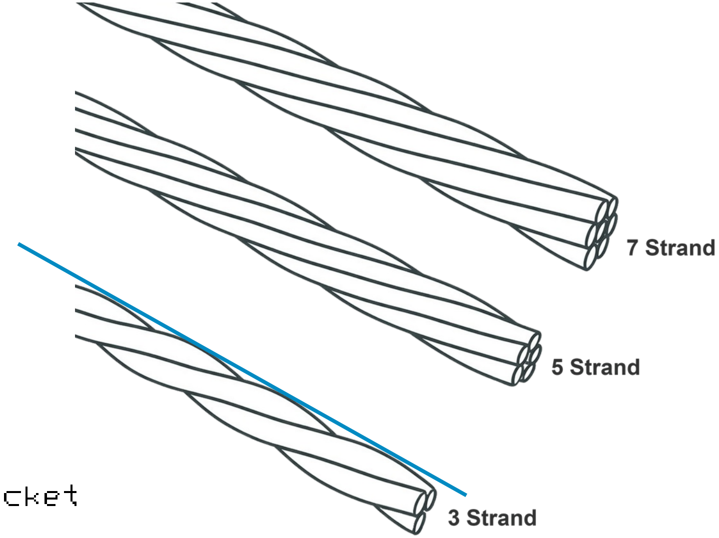


Cable Type	Typical O.D.	Min. Bend Radius (Static)
RG-174	0.100 in (2.54 mm)	0.4 – 0.5 in (10 – 12.7 mm)
RG-58	0.195 in (4.95 mm)	1.0 in (25.4 mm)
RG-6	0.275 in (6.80 mm)	1.375 – 2.0 in (35 – 50 mm)
RG-59	0.242 in (6.15 mm)	1.2 in (30.5 mm)
LMR-100	0.110 in (2.79 mm)	0.25 in (6.4 mm)
LMR-200	0.195 in (4.95 mm)	0.5 in (12.7 mm)
LMR-400	0.405 in (10.29 mm)	1.0 – 4.0 in (25 – 100 mm)*

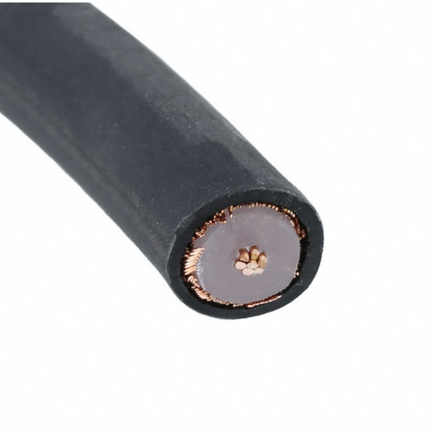
**Note: LMR-400 specifically varies based on whether it is a one-time bend (1") or a general installation (4").* Rokland +1

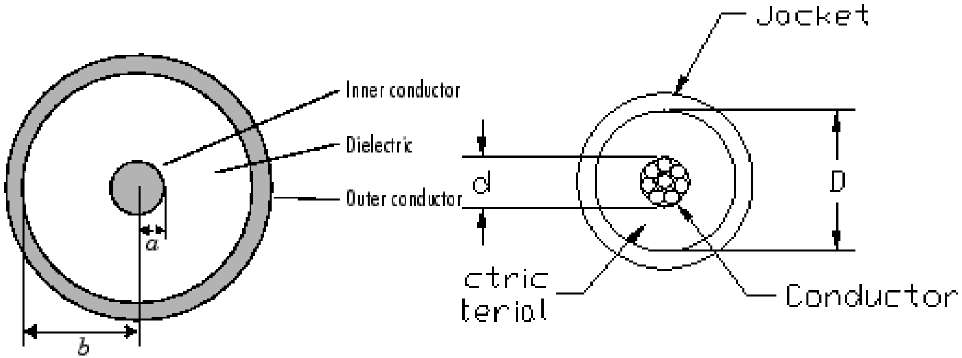
Solid vs. Stranded Center Conductor

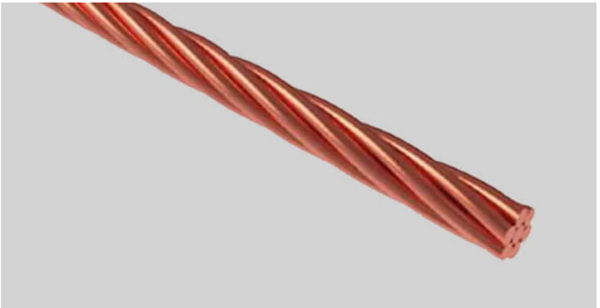
- Times Microwave Systems, LMR-400 Cable as an example
  - LMR-400 Standard (Solid) at 900 MHz is 0.13 dB/meter
  - LMR 400 -UF (Stranded) at 900 MHz is 0.16 dB /meter



RG-213



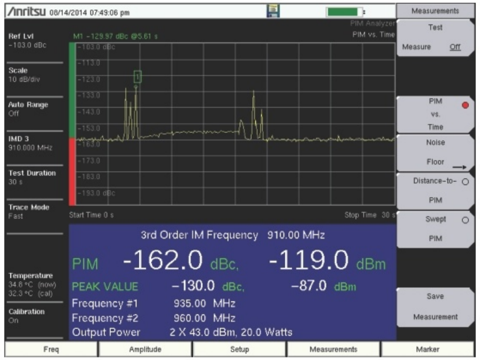




Passive InterModulation (PIM)

(PIM) in RF connectors and transmission lines is a form of signal interference caused by non-linear junctions in the signal path, such as loose, damaged, or corroded connections. It occurs when two or more high-power signals interact, creating unwanted, interfering frequencies that degrade receiver sensitivity and lower network capacity, particularly in 5G and cellular systems.

- Poorly Torqued Connectors: The most common cause, where insufficient pressure creates a non-linear contact.
- Contamination: Dirt, moisture, metal filings, or oxidation within the connector interface.
- Damaged Components: Scratched mating surfaces, damaged center pins, or kinked cables.
- Material Discontinuity: Using dissimilar metals or ferromagnetic materials (e.g., nickel) in the conductor path.
- Cold Solder Joints: Poor soldering in connectors or cable assemblies.



High-Risk Metals and Materials:

Nickel (Ni): Widely used in plating (e.g., nickel-plated connectors or gold-over-nickel plating). Nickel is ferromagnetic and acts as a major PIM source, potentially adding 20 to 40 dB of PIM to the signal.

Iron (Fe) & Steel: Common in structural components, connectors (especially stainless steel), and hardware (screws, bolts). Rusty iron or steel creates "rusty bolt" PIM, an exceptionally strong form of PIM.

Cobalt (Co): Similar to nickel, cobalt is ferromagnetic and should be avoided in RF paths.

Ferrites: Used in components like isolators and circulators. While necessary, they can produce higher PIM if cracked.

Aluminum (Al): Aluminum oxide, which forms rapidly on exposed surfaces, is a non-linear dielectric that can cause PIM through electron tunneling.

Copper (Cu) with Corrosion/Solder Flux: While pure copper is generally good, copper oxides or contaminated solder joints (if not properly cleaned) can create non-linear, diode-like effects.

Connector Torque

Key Guidelines for Torque Application

Use a Torque Wrench: Always use a calibrated torque wrench to ensure proper mating force, specifically designed for the connector type (e.g., break-over wrenches).

Rotate Only the Nut: When connecting, turn only the coupling nut, not the cable or the connector body, to avoid damaging the center conductor.

Over-tightening Issues: Excessive torque can deform threads, crush the dielectric material, and destroy the connector interface.

Under-tightening Issues: Insufficient torque leads to poor grounding, high insertion loss, and intermittent signals.

Finger Tightening: Only suitable for temporary or low-frequency connections; it is generally insufficient for high-performance applications.

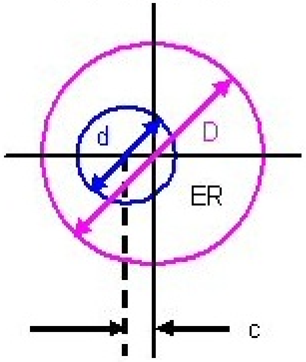
Connector Type	Connector Body /Nut Material	Recommended Torque Value (in-lbs)	Recommended Torque Value (N.M)
1mm	Stainless steel	4 in-lbs	0.45 N.M
1.85mm	Stainless steel	8 in-lbs	0.90 N.M
2.4mm	Stainless steel	8 in-lbs	0.90 N.M
2.92mm	Stainless steel	8 in-lbs	0.90 N.M
3.5mm	Stainless steel	8 in-lbs	0.90 N.M
SMA	Stainless steel	8 in-lbs	0.90 N.M
SMA	Brass	4 in-lbs	0.45 N.M
4.3-1.0	Brass	44.25 in-lbs	5N.M
4.1-9.5	Brass	88.5 in-lbs	10.N.M
7/16 DIN	Brass	221 in-lbs	25 N.M
N	Stainless steel	12 in-lbs	1.36 N.M
N	Brass	8 in-lbs	0.90 N.M
TNC	Stainless steel	12 in-lbs	1.36 N.M
TNC	Brass	5 in-lbs	0.56 N.M
SMC	Brass	2~3 in-lbs	0.23 N.M~0.34 N.M
SSMA	Stainless steel	8 in-lbs	0.90 N.M
SSMA	Brass	4 in-lbs	0.45 N.M

https://www.rfone.cn/articles/frequently-asked-questions-for-torque-wrenches

Concentricity

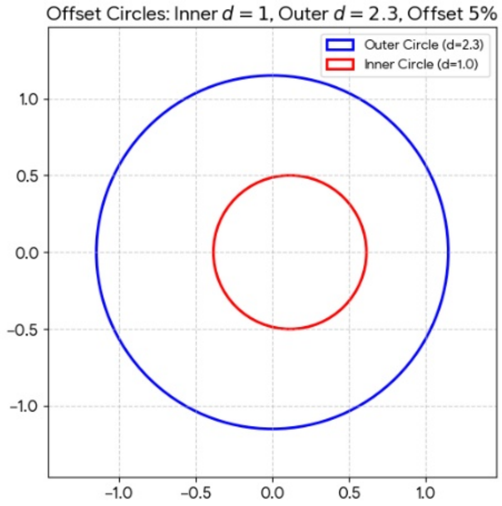
- As the center conductor moves off-center, the characteristic impedance can only decrease; it will never increase. However, the change is relatively small compared to the physical displacement. For instance, a 50% deviation from the center typically results in only about a 10% drop in impedance.

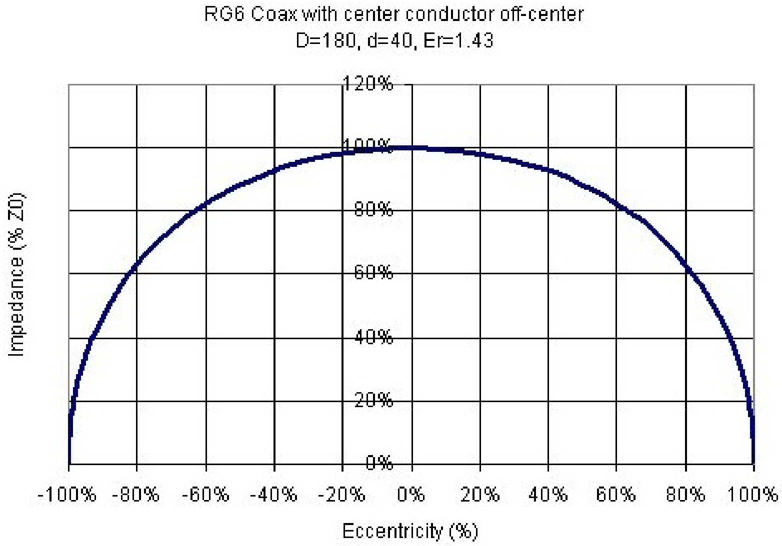
For outer diameter D, inner diameter d, and eccentricity c:
Z0=[60/sqrt(ER)] x acosh[(1/2)x(D/d+d/D-4c^2/(dxD)]



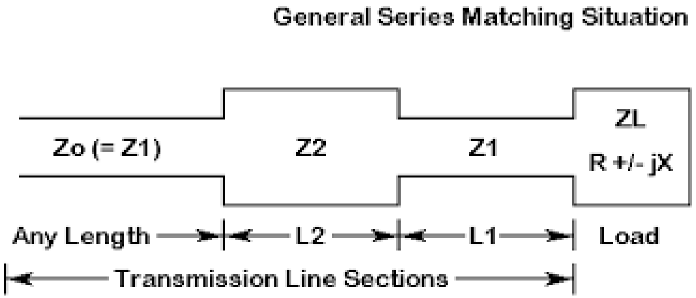
https://www.microwaves101.com/encyclopedias/off-center-coax

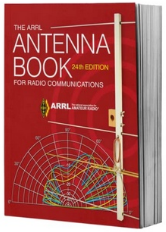
5%





Transmission Line Impedance Matching





ARRL Antenna Book
24th Edition
Section 24.4.3

It sounds like you're looking for the specific design equations for the **Regier series-section transformer**, which uses two lines of impedances Z_1 and Z_2 to match a complex load $Z_L = R_L + jX_L$ to a main line Z_0.

If you are using two sections of lines with impedances Z_1 and Z_2 in series, the electrical lengths θ_1 and θ_2 (in radians) are found using these specific steps:

1. Calculate the Intermediate Ratios

Define the normalized resistance (r) and reactance (x) of the load relative to the first section (Z_1):

$$r = \frac{R_L}{Z_1}, \quad x = \frac{X_L}{Z_1}$$

And the ratio of the two transformer line impedances:

$$n = \frac{Z_2}{Z_1}$$

2. Solve for the Length of Section 1 (θ_1)

Section 1 is the line connected directly to the load. Its length is:

$$\tan\theta_1 = \frac{(n-r) \pm \sqrt{(n-r)^2 - (1-n)(r^2 + x^2 - nr)}}{x(1-n)}$$

Note: If the term inside the square root is negative, a match is physically impossible with those specific choices of Z_1 and Z_2.

3. Solve for the Length of Section 2 (θ_2)

Section 2 connects Section 1 to the main feed line (Z_0). Its length is:

$$\tan\theta_2 = \frac{Z_2(Z_0 - R_{in1})}{X_{in1}Z_0}$$

Where $R_{in1} + jX_{in1}$ is the input impedance of Section 1 when terminated by Z_L.

Smith Chart