Antennas and Transmission Lines

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by

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Introduction

- This presentation covers several key aspects of antenna engineering:
  - Theory
  - Practical antenna design techniques
  - Overview of actual antennas
  - Goal is to enable participants to:
    - Understand antenna basics
    - Efficiently design, model, select and/or evaluate antennas

Circuit Theory “Quiz”

- Every current must return to it’s source.
- The path of the “source” and “return” current should be determined.
- Current “takes the path of least” _______________________.

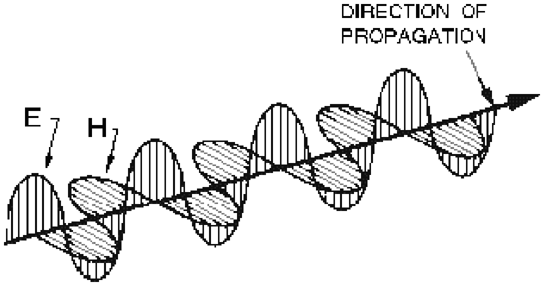
Circuit Theory Realities!

- Path is by “conduction” or “displacement”.
- The majority of the current takes the path of least *impedance*.
  - If current is DC (impedance is determined by resistance).
  - If current is not DC (including pulsed DC), impedance is determined by reactance.
    - Capacitance determined by conductor proximity
    - Inductance determined by current loop path

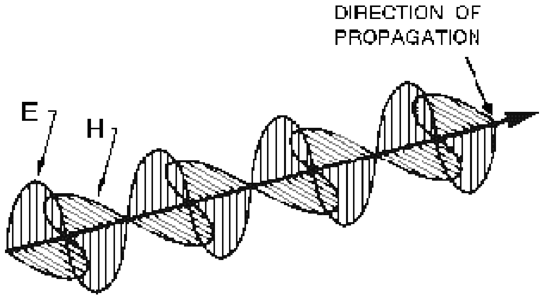
Background

- Frequency and wavelength
  - Drives fundamentals of antenna design
  - Related to physical dimensions of antennas
- Decibel – "dB"
  - Used to measure ratio
  - Significance of "3 dB"
  - Significance of "6 dB"

E/M Wave "Polarization"



A INDUCTION FIELD



B RADIATION FIELD

- Transmitter and receiver antenna polarization refers to the E field vector orientation.
- A monopole on a typical wireless device uses vertical polarization.

Maxwell's Equations

Maxwell's Equations

$$\nabla \times \mathbf{E}(\mathbf{r}, t) = -\frac{\partial \mathbf{B}(\mathbf{r}, t)}{\partial t}$$

$$\nabla \times \mathbf{H}(\mathbf{r}, t) = \frac{\partial \mathbf{D}(\mathbf{r}, t)}{\partial t} + \mathbf{J}(\mathbf{r}, t)$$

$$\nabla \cdot \mathbf{D}(\mathbf{r}, t) = \rho(\mathbf{r}, t)$$

$$\nabla \cdot \mathbf{B}(\mathbf{r}, t) = 0$$

where

$$\mathbf{B}(\mathbf{r}, t) = \mu \mathbf{H}(\mathbf{r}, t)$$

$$\mathbf{D}(\mathbf{r}, t) = \varepsilon \mathbf{E}(\mathbf{r}, t)$$

r – position vector
t – time
E – Electrical Field intensity (Volts/meter)
H – Magnetic Field Intensity (Amps/Meter)
B – Magnetic flux density
J – Conduction current density
ρ – volume charge density
μ – permeability
ε- permittivity

- These form the foundation of the "wave equation" which can be used to determine all the parameters in electromagnetic wave propagation.

Metrics of Electromagnetic (E/M) Waves

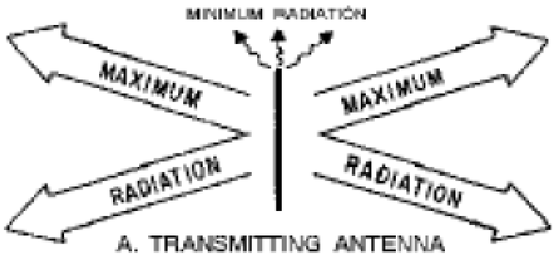
- Travel at/near speed of light (in vacuum/air/free space) = (nearly) 3.00 x 10^8 meters/sec.
- Can be expressed as frequency.
- “Length” of one cycle is expressed as “wavelength”, or “Lambda”.
  - Lambda (λ) = Propagation speed / frequency
  - For 1 MHz, λ = 300 meters
  - As frequency increases, wavelength decreases.
- Frequency and wavelength used interchangeably.
  - E.g. 15 MHz = 20 meter

Antenna Purpose

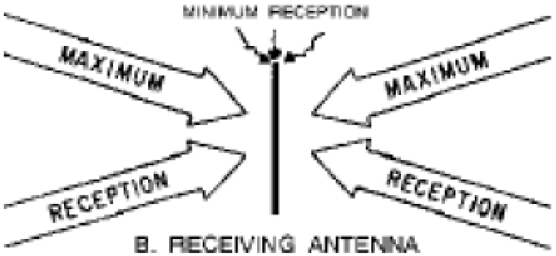
- Used to transfer energy
- Antenna performance based upon physical parameters
- Goal is to understand antenna performance as a function of each parameter
- Analogies to light sources are helpful in understanding antenna theory

Antenna Performance

- Antenna performance is generally a “reciprocal” process – if the antenna works well to transmit a signal, it will work well on receiving a signal.

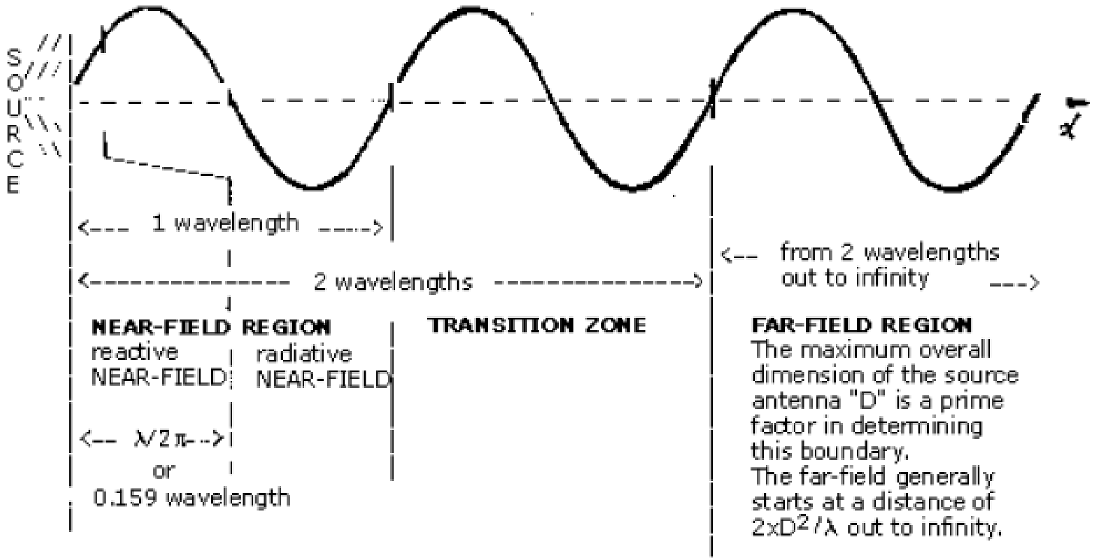


A. TRANSMITTING ANTENNA



B. RECEIVING ANTENNA

Antenna "Regions"



The maximum overall dimension of the source antenna "D" is a prime factor in determining this boundary.
The far-field generally starts at a distance of $2 \times D^2/\lambda$ out to infinity.

- Near field consists of reactive and radiative conditions.
- Far field is the typical condition for antennas.

Near and Far Field Physics

- Location of a receiver in the near field may affect the source and a receiver in the far field has no impact upon the source.
- The E/M wave in each region has a "Characteristic Impedance" of Zw.
- In the far field, the Zw = 377 ohms.

Near Field Physics

- In the near field Zw < 377 or > 377 ohms.
- Wave impedance is determined by:

$$Zw = |E| / |H|$$

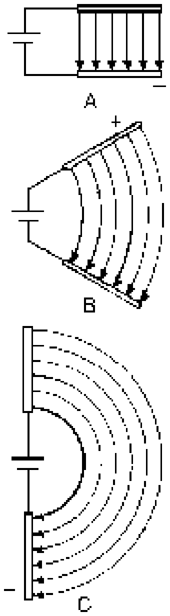
E is the electric field vector.

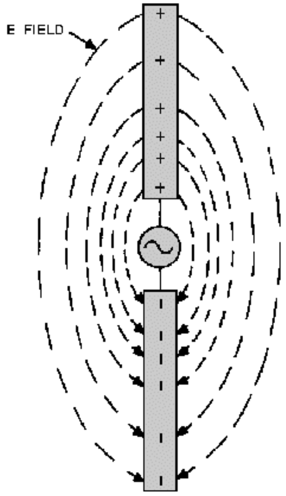
H is the magnetic field vector.

- For a low Z source, H-field dominates.
- For a high Z source, E-field dominates.

E-Field Antenna

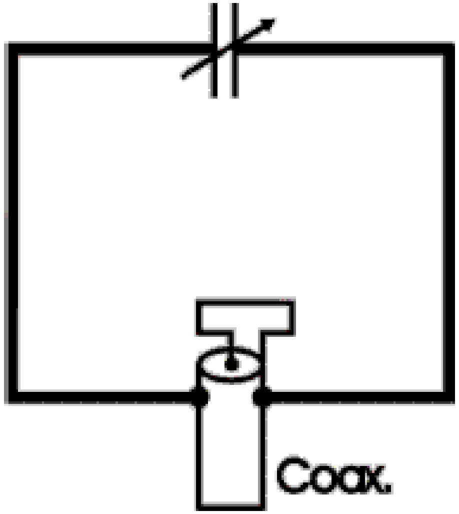
- Most wireless system antennas are designed to utilize the *electric field component* of E/M wave for communication.
- This type of antenna can be represented as an "open" capacitor.

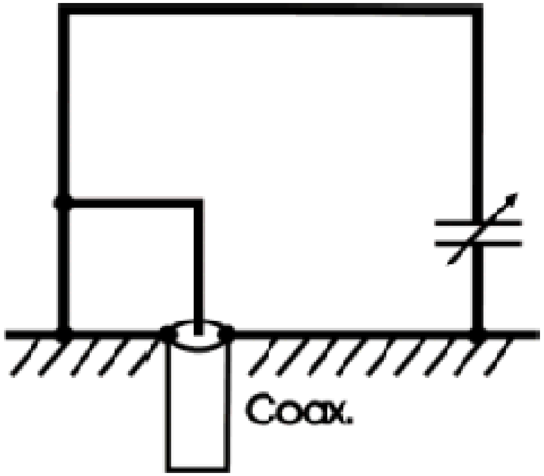




Magnetic Field Antennas

- Another type is the loop antenna.
- This is a closed loop resonant circuit.





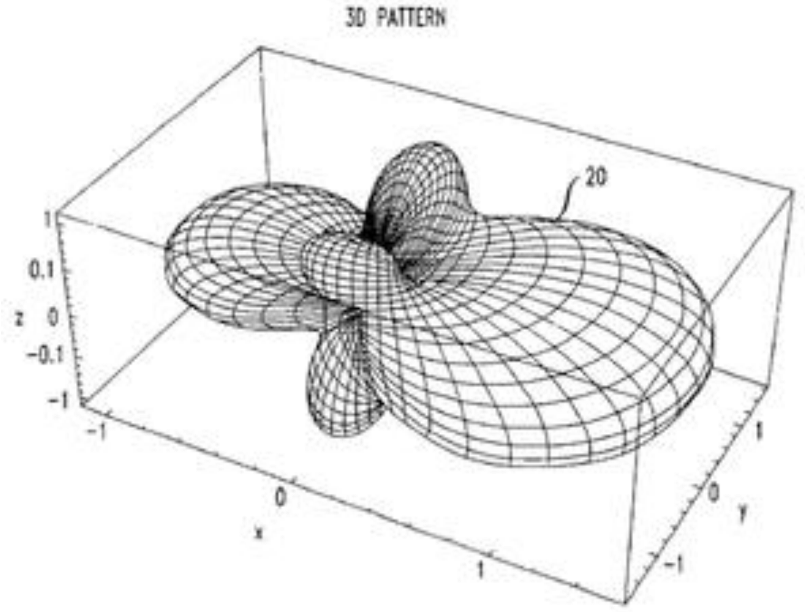
Key Parameters

- Antenna gain and “patterns”
  - “Gain” is a function of geometry
  - Additional metrics are used to express directivity details
    - Beamwidth
    - Sidelobes
- Impedance
  - Complex number
  - Can be used to determine approximate performance

Additional Parameters

- Bandwidth
  - Derived figure of performance
  - Based upon directory and impedance characteristics
  - Used to express characteristics for a particular frequency band
- Efficiency
  - Impacts directivity
  - Reflected in the antenna gain metric
  - Typically only a few percent loss is experienced

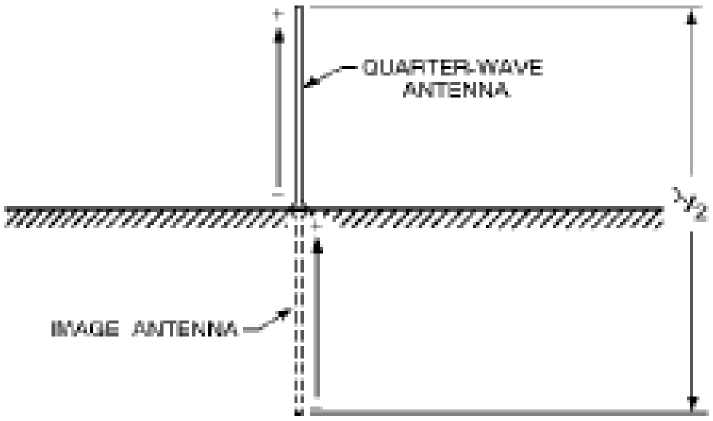
Antenna “Pattern”



- Non-isotropic antenna exhibits “pattern” of gain (field intensity).
- Can take advantage of this property to increase communication range ability.

Electrical and Physical Size

- Many antennas are physically constructed to be a specific length corresponding to the signal wavelength.
- Typical antennas are multiples of ¼ of a wavelength, for “resonant” conditions.



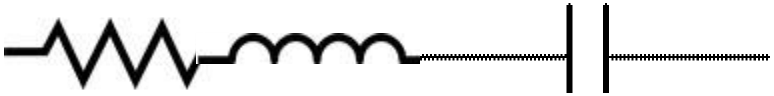
Antenna Physics

- Antennas are conductors.
- Conductors have physical dimensions (length, width, area)
- Physical dimensions result in development of impedance due to inductance and capacitance.
- Reactive elements create resonant circuits.

Electrical Model of Antenna Parameters

- An antenna can be represented just like any other type of electrical component.
- Can be expressed as a complex impedance load:

$Z_{ant} = R_r + jX$ (ohms)



Where:

R_r is the "Radiation Resistance" (a derived value describing how effective the antenna is in transferring power to/from the medium)

jX is the value of the sum of the reactance (due to series inductance and capacitance).

Description of Antenna Parameters

- R_r of ¼ wavelength antenna (typically called a monopole) is about 37 ohms.
- Antenna reactance is the “jX”, and is *the same as a series resonant circuit.*
  - *When the antenna length is physically shorter than ¼ wavelength, jX is negative and antenna “looks” capacitive.*
  - *When “jX = 0” the antenna is “resonant”.*

¼ Wave Antenna??

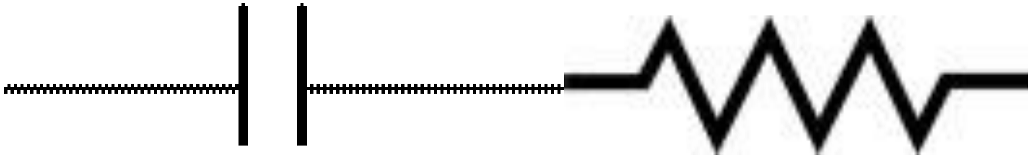
- Hand held transceivers typically use ¼ wave antennas due to simplicity of design.
- 27 MHz transceiver shown at right has an ¼ ¼ wave (electrical length) antenna?

“Reduced Size” Antennas

- Shortened monopole
  - Lumped elements
  - Distributed winding of inductance
- Shortened dipole
  - Lumped elements
  - Distributed winding of inductance
- “Slot” or “patch” antenna

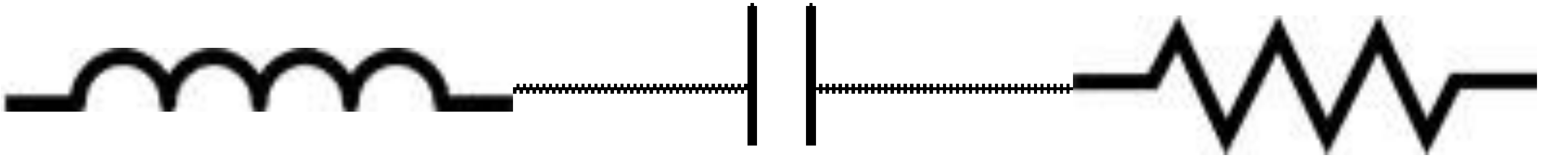
"Tuning" an Antenna - Problem

- Ideal antenna $Z = R + j\,0$, short one is $Z = R - jX$
- Need to somehow add "jX" to obtain $Z = R - jX + jX$



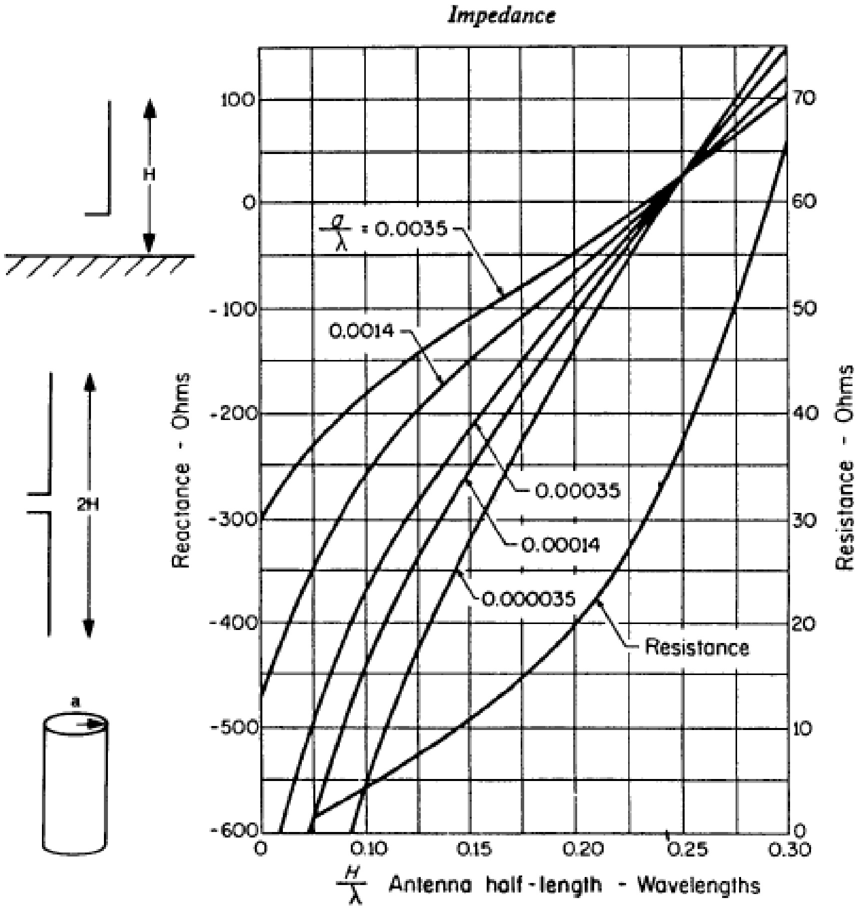
“Tuning” an Antenna – Solution!

- Ideal antenna Z = R + j 0, short one is Z = R –jX
- Need to add “jX” to obtain Z = R – jX +jX
- Add “jX” by adding inductance
- Acts as series resonant circuit



Physical “Short” Antennas

- If the physical length is reduced, this affects both radiation resistance and reactance.
- Applies to both monopoles and dipoles.
- Reduces “efficiency” of antenna (radiation resistance) and requires “tuning” to be done.

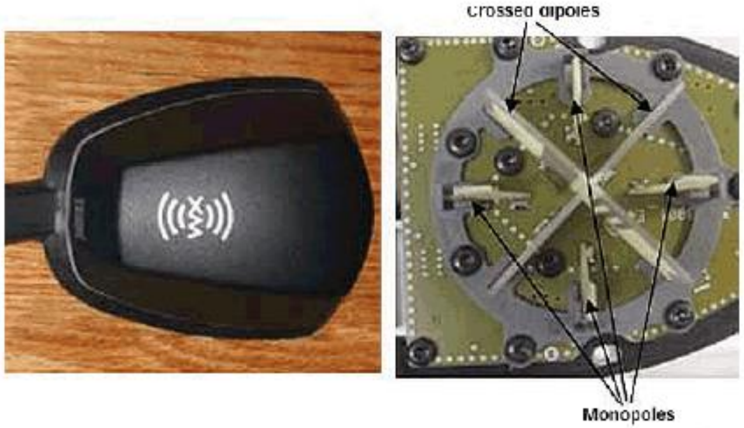


Mobile Two-way Radio Antennas

- Primary communications for public services
- Frequencies in use required smaller antennas than standard length
- "Loaded" antennas used to reduce size

Recent Antenna Examples

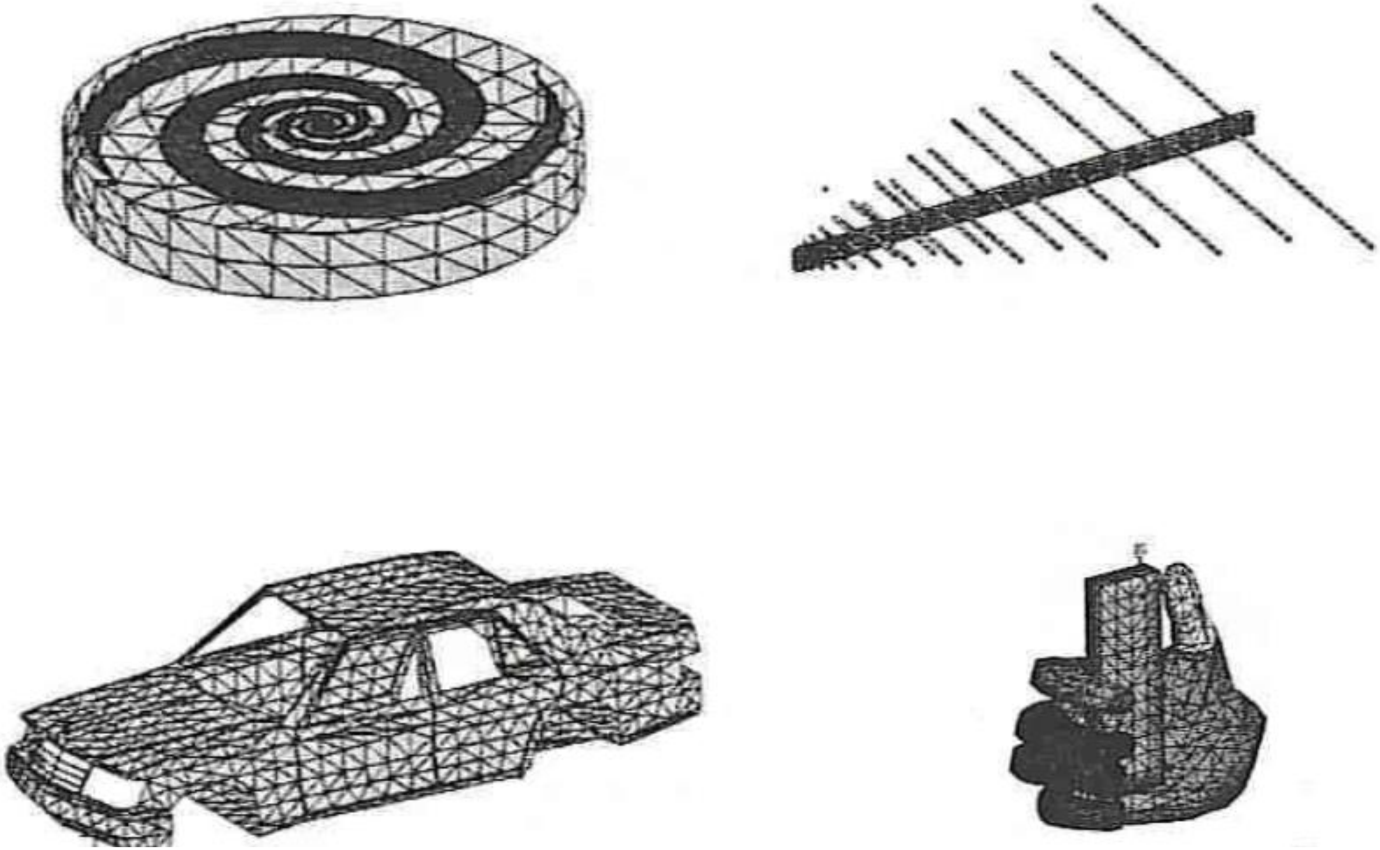
5. This antenna design is a combination of quadrifilar and PIFA structures.



4. This XM antenna features a crossed dipole/monopole array combination.

- New technologies required use of advanced antenna types.
- Some concepts eliminate external antenna and integrate it into vehicle structure.

Examples of Antenna Structures



Antenna Measurements

- Typical measurements consist of gain, pattern, polarizations, bandwidth, and efficiency
- Need to know if in near or far field
- Best method is comparison with a “standard antenna” that has documented characteristics

Basic Antenna Tools

- An electrical oriented “multi-tool” is used to cut wire and tighten connections.
- A tape measure is used to determine physical lengths required for various frequencies.

My Personal Favorite – The “MFJ-269 SWR Analyzer”

- Designed for antenna engineering, this device generates a NB RF signal from 1.7- 174 MHz (and 440 – 450 MHz).
- Measures (at user selected frequencies) complex Z, C, L, and cable loss factors.

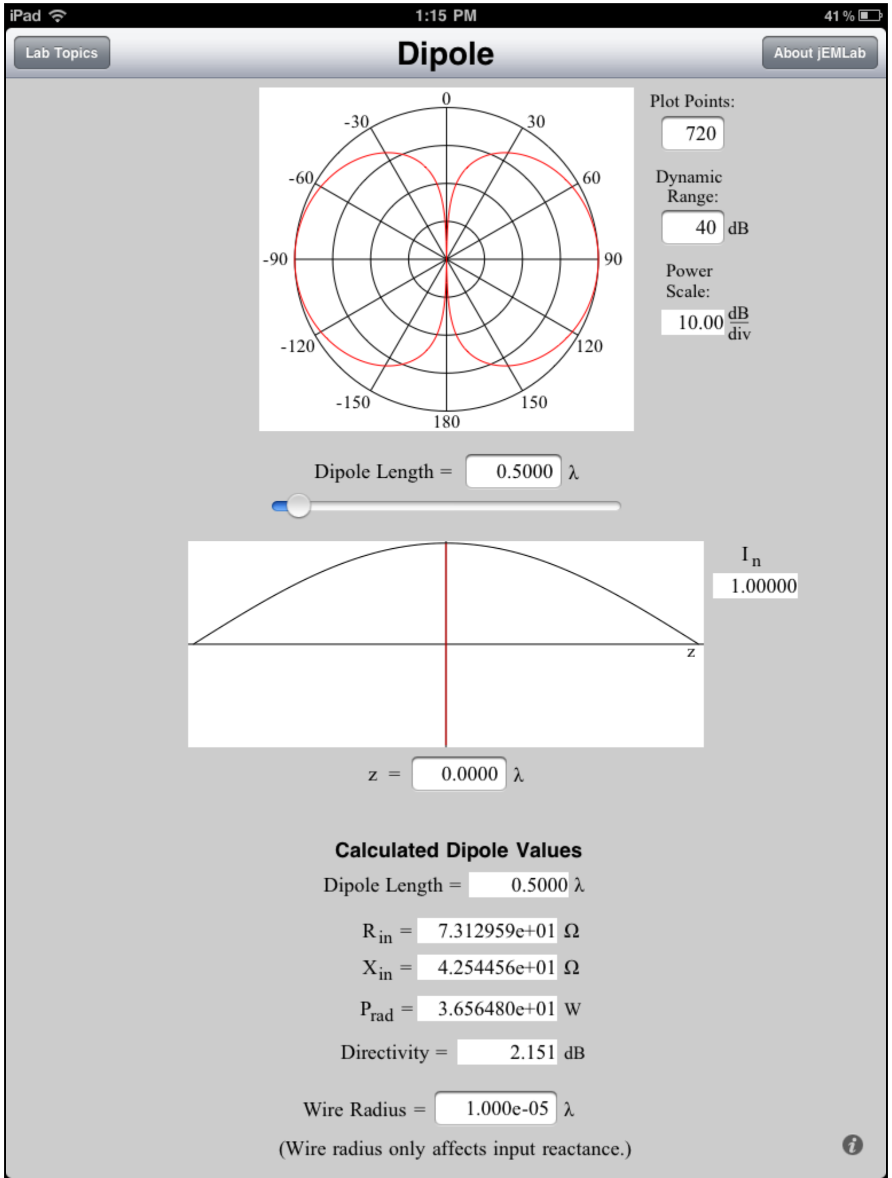
“Reduced Size” Antennas

- Shortened monopole
  - Lumped elements
  - Distributed winding of inductance
- Shortened dipole
  - Lumped elements
  - Distributed winding of inductance
- “Slot” or “patch” antenna

Antenna Simulation Methods

- Antenna simulation are becoming more common and utilize numerical integration to performed to solve complex problems.
- Examples of three packages:
    - Numerical Electromagnetics Code (NEC)
    - Field Computation for Objects of Arbitrary Shape (FEKO)
    - jEMLab (iPad based!)

jEMLab Half-Wave Dipole



Dipole

Plot Points: 720

Dynamic Range: 40 dB

Power Scale: 10.00 dB/div

Dipole Length = 0.5000 λ

I_n 1.00000

z = 0.0000 λ

Calculated Dipole Values

Dipole Length = 0.5000 λ

R_{in} = 7.312959e+01 Ω

X_{in} = 4.254456e+01 Ω

P_{rad} = 3.656480e+01 W

Directivity = 2.151 dB

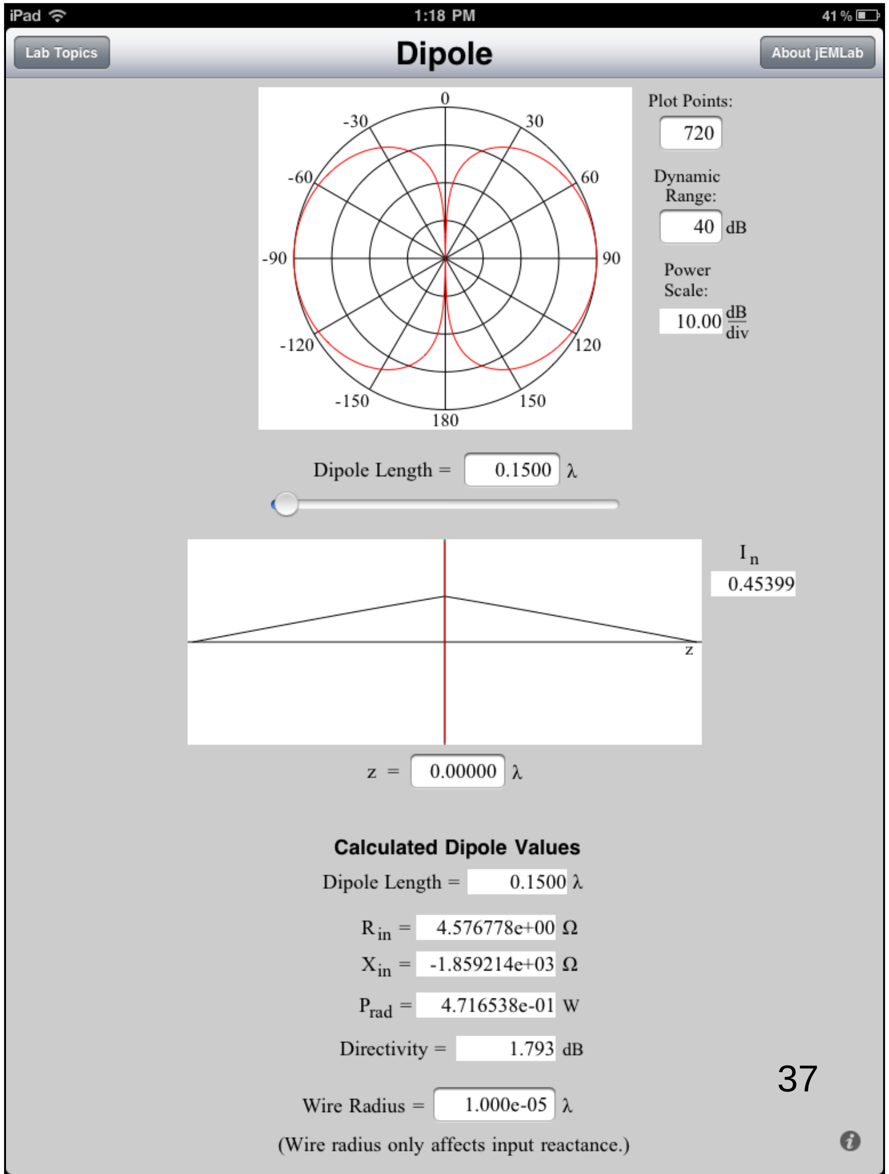
Wire Radius = 1.000e-05 λ

(Wire radius only affects input reactance.)

- Traditional ½ wave “resonant antenna”.
- Analysis shows antenna pattern, current distribution, gain, and complex impedance expected.

jEMLab Shortened Dipole

- Effect of a physically short dipole can be seen.
- Antenna pattern similar to ½ wave dipole.
- Current distribution changed, radiation resistance reduced, and gain is decreased.



Dipole

Plot Points: 720

Dynamic Range: 40 dB

Power Scale: 10.00 $\frac{\text{dB}}{\text{div}}$

Dipole Length = 0.1500 λ

I_n 0.45399

z = 0.00000 λ

Calculated Dipole Values

Dipole Length = 0.1500 λ

R_{in} = 4.576778e+00 Ω

X_{in} = -1.859214e+03 Ω

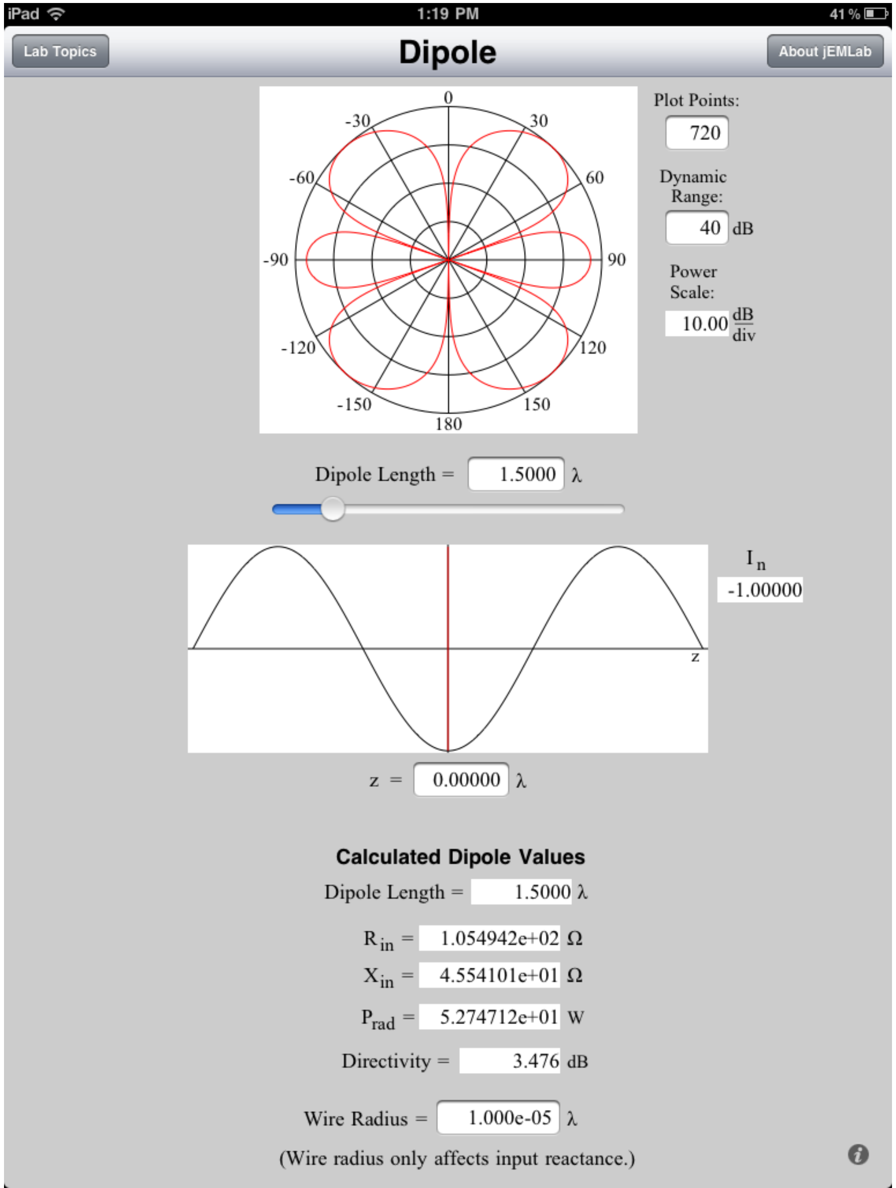
P_{rad} = 4.716538e-01 W

Directivity = 1.793 dB

Wire Radius = 1.000e-05 λ

(Wire radius only affects input reactance.)

jEMLab Lengthened Dipole



Plot Points: 720

Dynamic Range: 40 dB

Power Scale: 10.00 $\frac{\text{dB}}{\text{div}}$

Dipole Length = 1.5000 λ

I_n -1.00000

z = 0.00000 λ

Calculated Dipole Values

Dipole Length = 1.5000 λ

R_{in} = 1.054942e+02 Ω

X_{in} = 4.554101e+01 Ω

P_{rad} = 5.274712e+01 W

Directivity = 3.476 dB

Wire Radius = 1.000e-05 λ

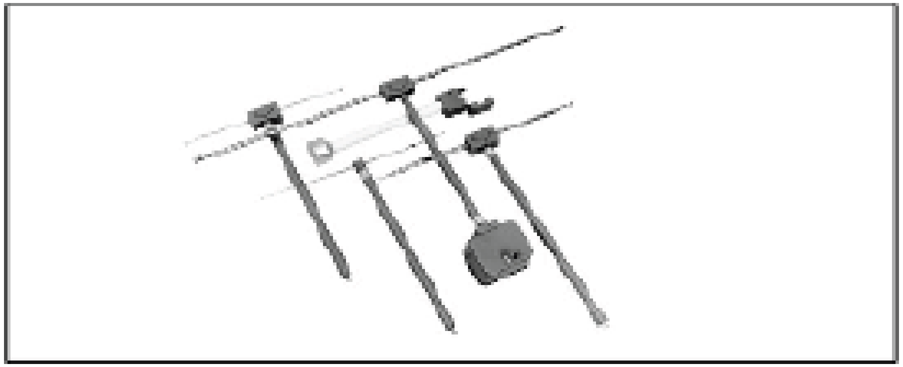
(Wire radius only affects input reactance.)

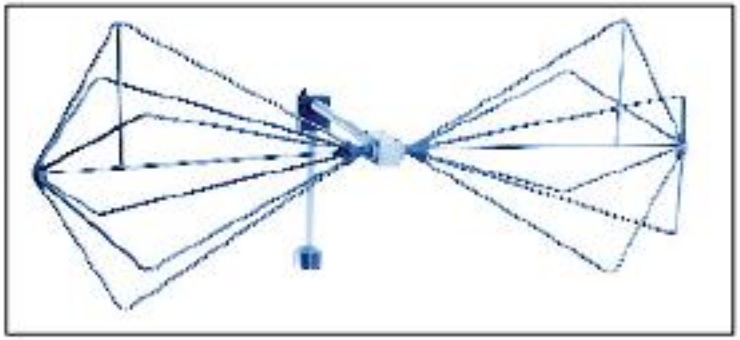
- At length equal 1 ½ wavelengths, there is a very complex radiation pattern that results.
- Radiation resistance increases (antenna is more “efficient”).
- Is difficult to “match” to transmission line.

Types of Antennas in EMC

- Antennas are a critical part of EMC testing.
- It is important to know what type of antenna applies to a particular EMC test.
- EMC antennas are all based on physics (loop antenna on left is for magnetic fields, monopole for E-fields.

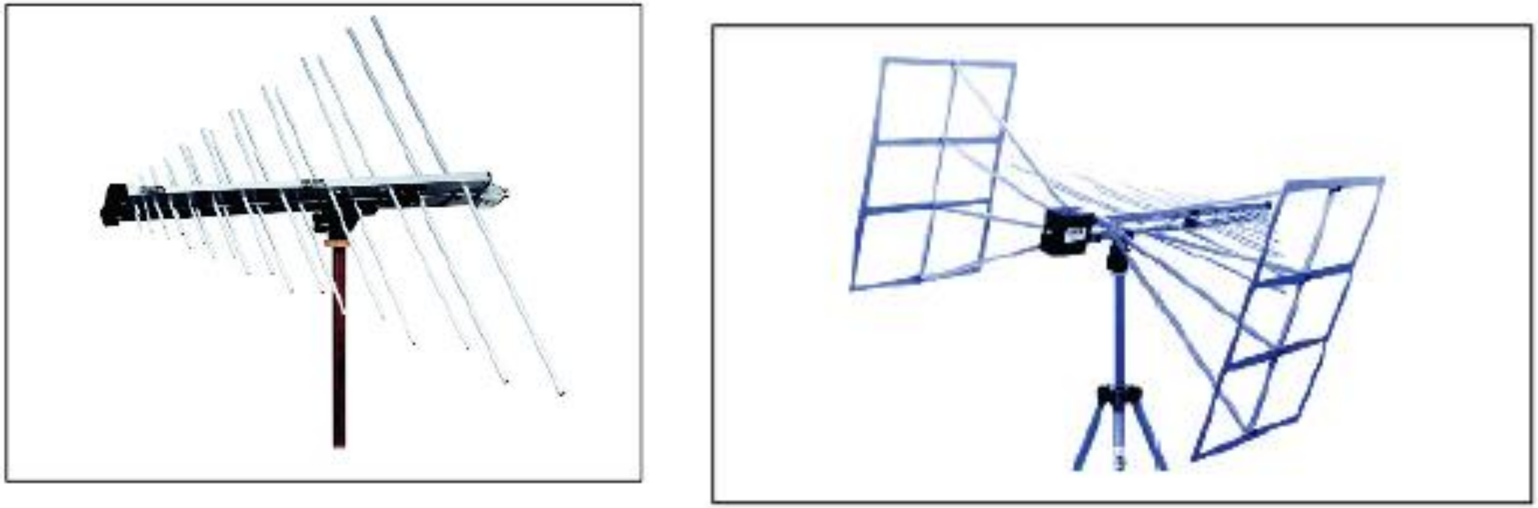
Dipoles in EMC Testing





- EMC testing can be done using dipole antennas.
- If a specific frequency is being tested – conventional dipoles can be used.
- For a wide frequency range a special “broadband” antenna (bi-conical) is typically used.

Gain Antennas In EMC

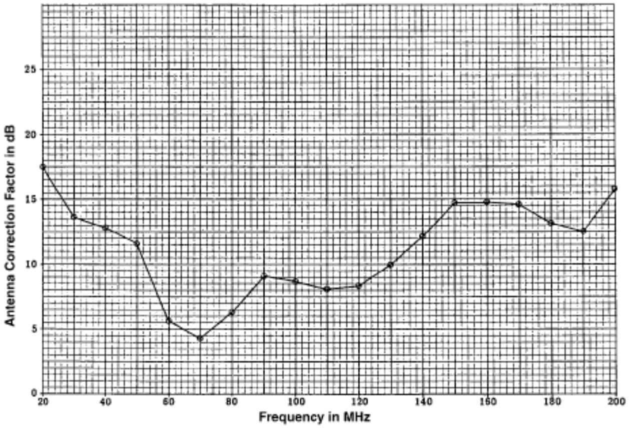


- Gain antennas are also used for emissions and immunity testing.
- Allows for very directional measurements or RF targeting to be accomplished.

“Antenna Factor”

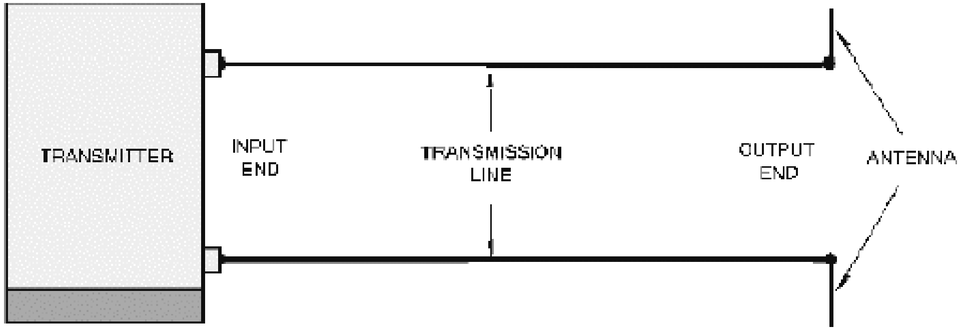
$$AF = \frac{E}{V},$$

where E is the incident electric field, and V is the voltage on the 50 Ω load. AF has a unit of 1/m, or dB m^{-1}.



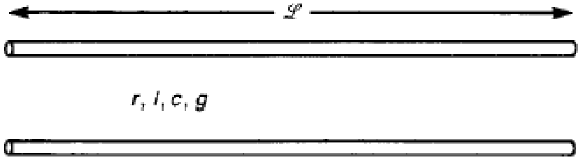
- “Antenna Factor” is a measure of how efficient an antenna is in converting field strength to voltage.
- The lower the antenna factor – more efficient the antenna is in producing an output voltage.

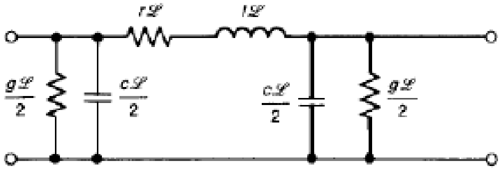
Antenna System Interface



- Antenna (“E-field” antenna shown) is connected to the transmitter via a transmission line.
- Objective is to send/receive power/signal with minimal loss from/to transmitter/receiver.

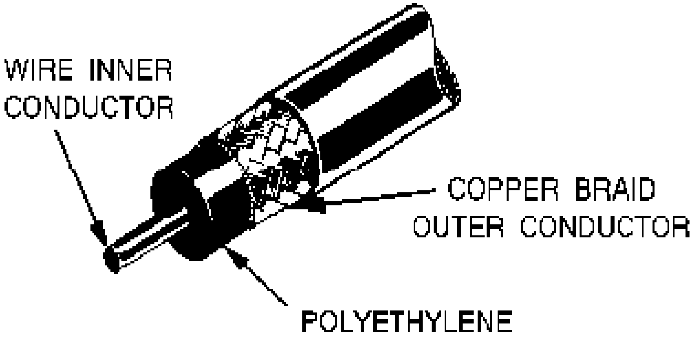
Transmission Line Development

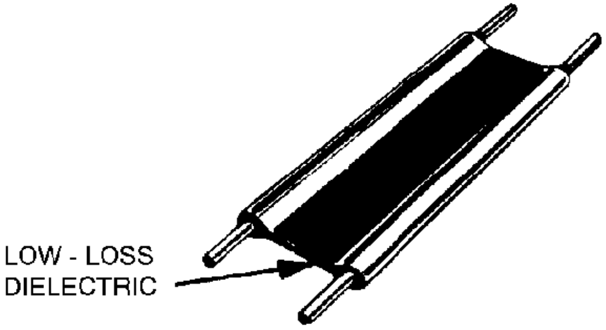




- Heaviside realized that the use of two conductors in the telegraph “transmission” line resulted in capacitive and inductive properties of the line.
- He understood that the capacitance and inductance was continuous along the length of the pair of conductors.

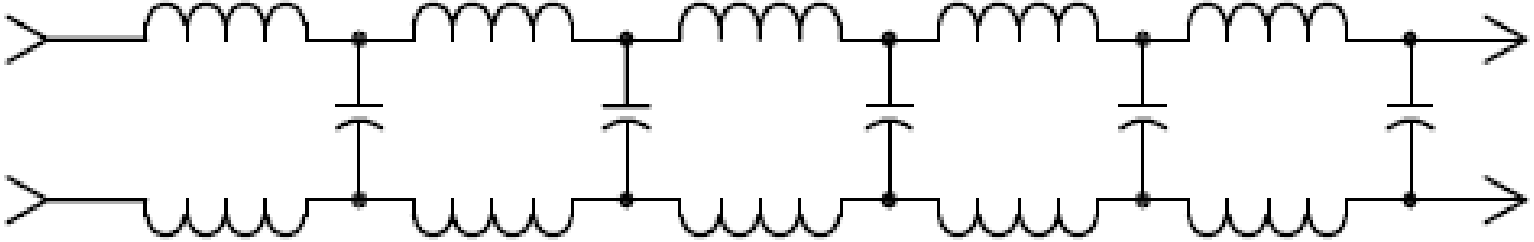
Transmission Line Types





- “Coaxial” cable consists of an inner conductor and an outer conductor *that also functions as a shield*.
- “Twin Lead” consists of two identical conductors and is a “balanced” cable.

Transmission Line Model



- Model that was developed that utilized a line of "distributed" inductance and capacitance..
- It was discovered that the line could be represented by a "surge" (or characteristic) impedance (ignoring small dielectric losses) of:

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

Transmission Line Metrics

- Transmission lines are characterized in terms of impedance, and is a function of a per-unit length of inductance (L), capacitance (C), and resistance.
  - A simplified expression for impedance is (neglecting resistance of the conductors) is $Z = (L/C)^{1/2.}$
  - Note that Z *does not depend on the length of line*.
- Example: RG-58 cable has a specified capacitance of 23 pf/ft , Z= 50 ohms, and “TV Twin lead” has a specified capacitance of 4.5 pf / ft, Z=300 ohms.

Emerging Issues in Antennas

- The continued "miniaturization" of electronic communication systems requires more functionality in smaller spaces.
- Multiple communication methods within the devices (such as Wi-Fi, CDMA, GSM, Bluetooth) require highly efficient antennas for each of the applications – without significant compromises in performance!

Summary

- Basics of antenna engineering and use of transmission lines can be understood through the application of physics and analogies to electric circuits.
- New methods possible in antenna simulation can provide valuable insight.
- Simple tools can enable antenna design and development to be done efficiently and effectively!