Basics of Antennas
(and Transmission Lines)

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EMC Basics + Workshop

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by

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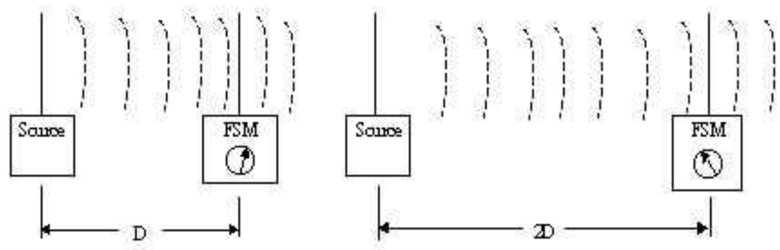
Introduction

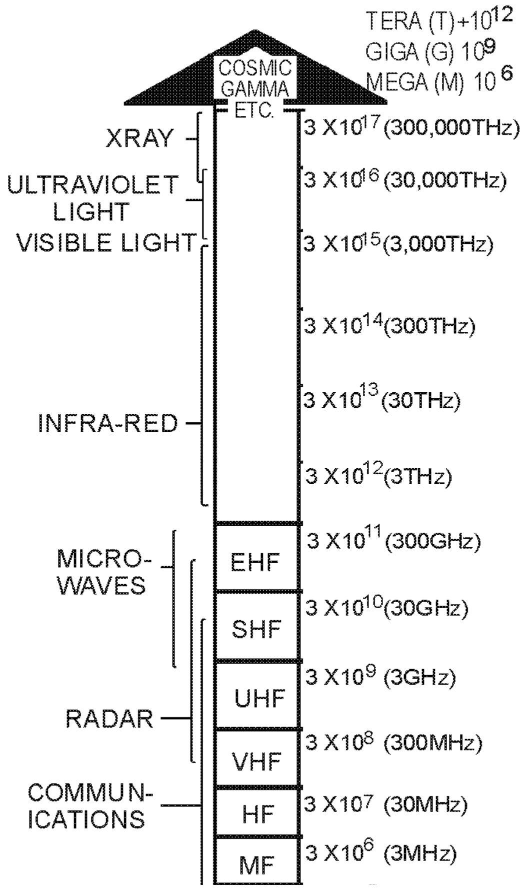
- This discussion covers several key aspects of antenna engineering (and transmission lines):
  - Theory
  - Practical antenna design techniques
  - Overview of actual antennas
  - Goal is to enable you to:
    - Understand antenna basics
    - Know that it's possible to EFFICIENTLY design, model, select and/or evaluate effective antennas
    - Understand transmission line fundamentals.

The “Source-Path-Receiver” Electromagnetic Interaction



- The path of the energy to the receiver may be via radiation or conduction.
- If path is radiated, the intensity is reduced as a function of distance (*similar to a flashlight*)- the intensity is lower the greater the distance away - the “inverse distance” property.

Electromagnetic Frequency Bands



- Much of today's communication occurs from MF to UHF.
- MF/VHF/UHF used for broadcasting.
- UHF is used for handheld and mobile devices (phones, Wi-Fi).

Terminology in EMC – RF Signals

- Radio Frequency (RF) – E/M wave frequencies used typically for communication.
- kHz – 1 x 10^3 Hertz (cycles per second)
- MHz – 1 x 10 ^6 Hertz
- GHz – “1000 MHz”, or 1 x 10^6 Hertz
- THz – 1 x 10^12 Hertz

Circuit Theory Truths and Lie

- 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” ____________________.

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  - LIE: Resistance

Circuit Theory Truths and Lie

- TRUTH: Every current must return to it's source.
- TRUTH: The path of the "source" and "return" current should be determined.
- Current "takes the path of least"
  - LIE: Resistance
  - TRUTH: IMPEDANCE

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
  - Determines the physical dimensions of antennas
- Decibel – "dB"
  - Used to measure ratio
  - Significance of "3 dB"
  - Significance of "6 dB"

“Wavelength”

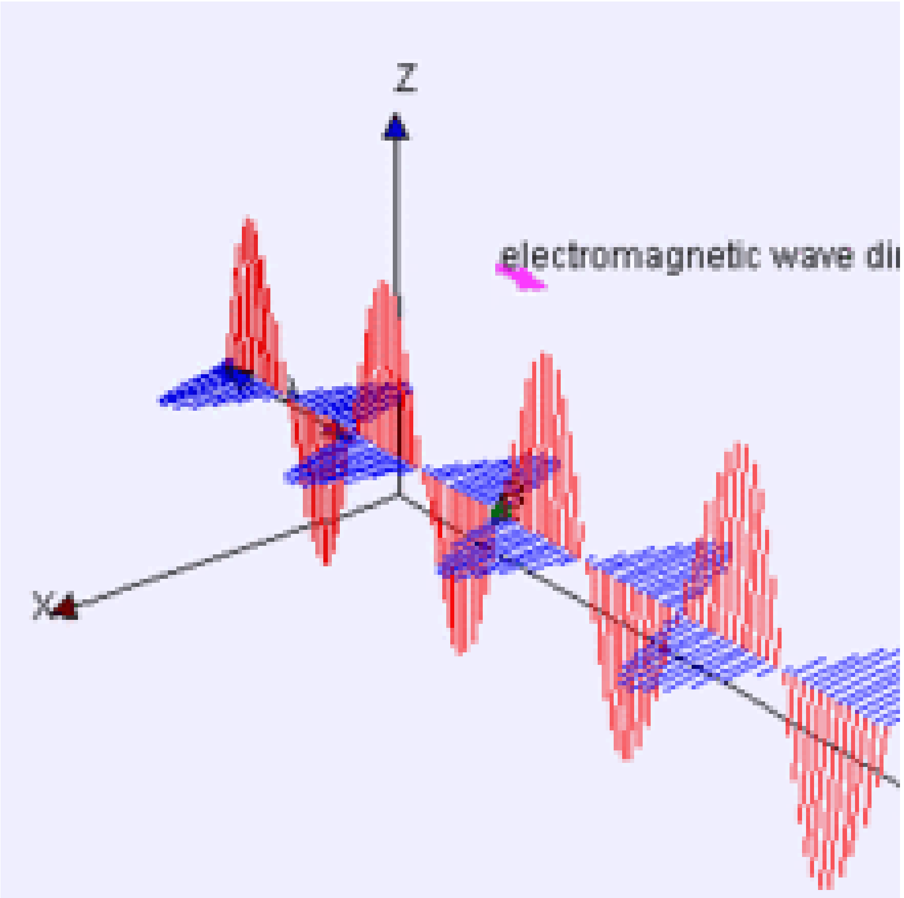
- “Wavelength”- based upon speed of light in vacuum (free space) divided by frequency of the E/M wave.
  - Length decreases as the frequency increases.
  - “Wavelengths” are used to refer to frequency bands.

The Decibel

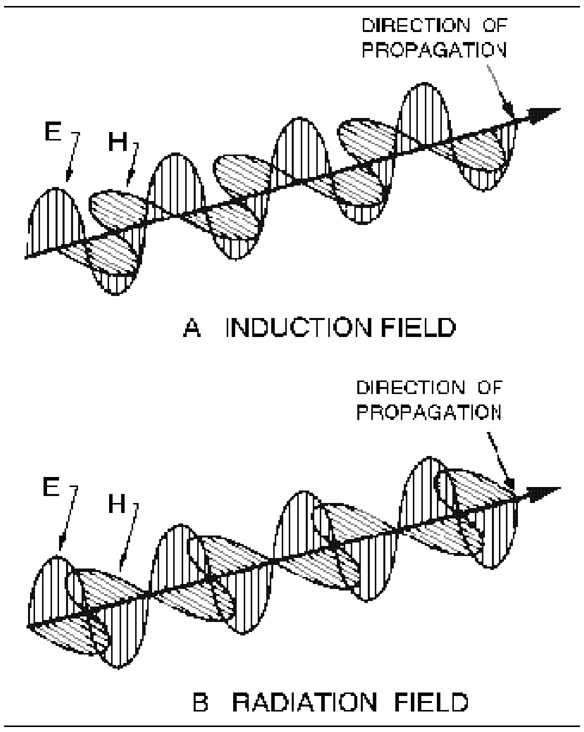
- Used to express the ratio of two quantities
- Typically used for voltage, current, and power ratios
- Based upon a logarithmic relationship
  - For power: dB = 10 log (P1 / P2)
  - For voltage or current: dB = 20 log (X1 / X2), *providing that the impedance is constant*

Electric/Magnetic (E/M) Vectors

- E and H orthogonal to each other
- E and H orthogonal to direction of propagation
- Typical E/H fields consist of 100 kHz to 10’s of GHz.

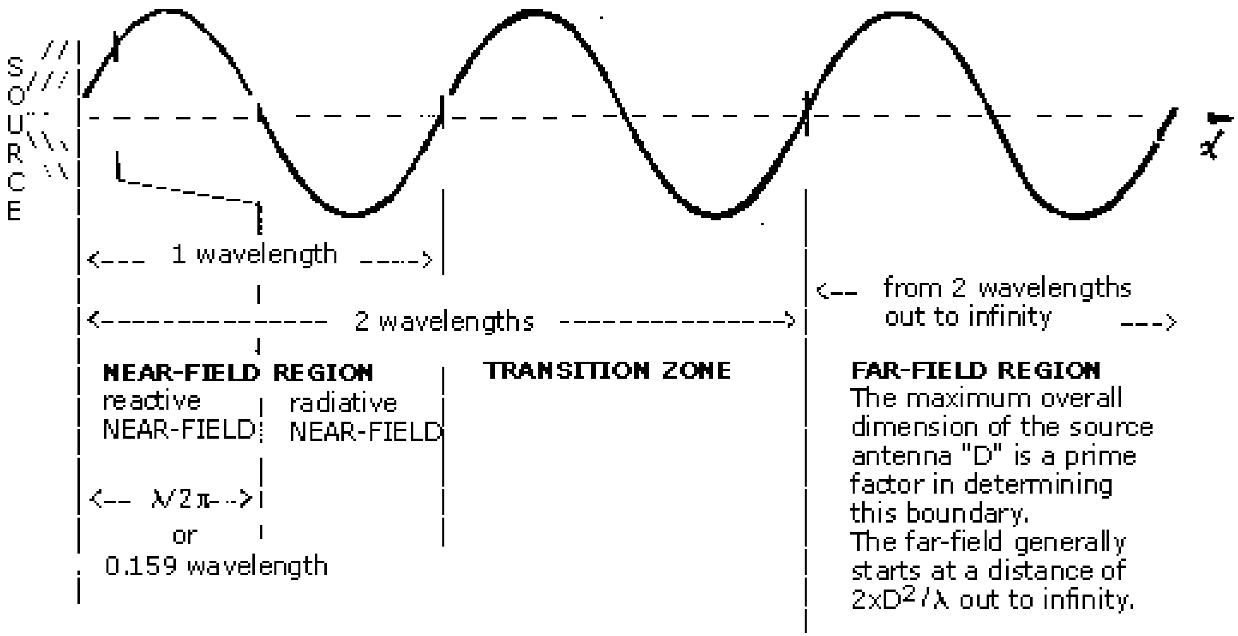


E/M Wave "Polarization"



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

Antenna “Regions”



- 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, *which means the electric field magnitude is 377 times the magnitude of the magnetic field!*

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.

Physics of Electromagnetic (E/M) Waves

- Revolutionary discovery of conditions that were considered impossible.
- Explained in "Maxwell's Equations".
- Detailed by Professor Maxwell in his 1864 paper: *"A Dynamical Theory of the Electromagnetic Field"*

Provided foundation for advancement in science into 20th century…

As Professor Maxwell stated…

VIII. *A Dynamical Theory of the Electromagnetic Field.* By J. Clerk Maxwell, *F.R.S.*

Received October 27,—Read December 8, 1864.

PART I.—INTRODUCTORY.

(1) The most obvious mechanical phenomenon in electrical and magnetical experiments is the mutual action by which bodies in certain states set each other in motion while still at a sensible distance from each other. The first step, therefore, in reducing these phenomena into scientific form, is to ascertain the magnitude and direction of the force acting between the bodies, and when it is found that this force depends in a certain way upon the relative position of the bodies and on their electric or magnetic condition, it seems at first sight natural to explain the facts by assuming the existence of something either at rest or in motion in each body, constituting its electric or magnetic state, and capable of acting at a distance according to mathematical laws.

…Prof. Maxwell continued…

PART VI.—ELECTROMAGNETIC THEORY OF LIGHT.

(91) At the commencement of this paper we made use of the optical hypothesis of an elastic medium through which the vibrations of light are propagated, in order to show that we have warrantable grounds for seeking, in the same medium, the cause of other phenomena as well as those of light. We then examined electromagnetic phenomena, seeking for their explanation in the properties of the field which surrounds the electrified or magnetic bodies. In this way we arrived at certain equations expressing certain properties of the electromagnetic field. We now proceed to investigate whether these properties of that which constitutes the electromagnetic field, deduced from electromagnetic phenomena alone, are sufficient to explain the propagation of light through the same substance.

…and then said…

(3) The theory I propose may therefore be called a theory of the *Electromagnetic Field*, because it has to do with the space in the neighbourhood of the electric or magnetic bodies, and it may be called a *Dynamical* Theory, because it assumes that in that space there is matter in motion, by which the observed electromagnetic phenomena are produced.

- Or – in other words…..

https://www.youtube.com/watch?v=SS4tcajTsW8

$$\iint \mathbf{E} \cdot d\mathbf{A}$$

Differential Form of 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 shows current can "flow" in empty space* due to "displacement current" (same as in a capacitor).

Summary of Electromagnetic (E/M) Wave Physics

- "Maxwell's Equations" show:
  - A changing magnetic (H) field creates a changing electric field.
  - A changing electric (E) field creates a changing magnetic field.
  - An enclosed charge creates an electric field.
  - There can not be magnetic "monopoles".

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

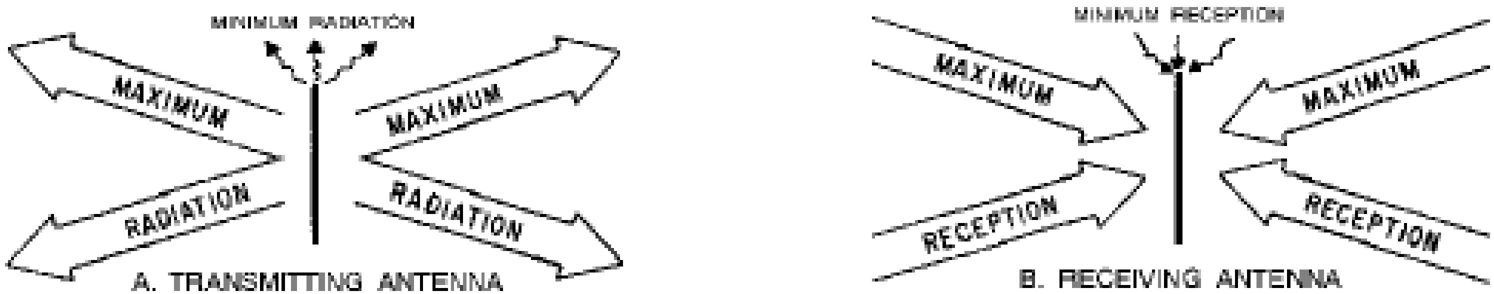
- Used to transfer energy
- Antenna performance based upon physical parameters
- Goal is to understand antenna performance as a function of each parameter
- Analogies to light sources are helpful in understanding antenna theory

Wireless System Antennas

- Typical schematic symbol for antenna is shown at left.
- This is used to represent a general antenna – additional information may be included based on application (such as “gain” attributes).

Antenna Performance

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



E/M Field Strength Factors

$$E = \frac{\sqrt{30PG}}{r}$$

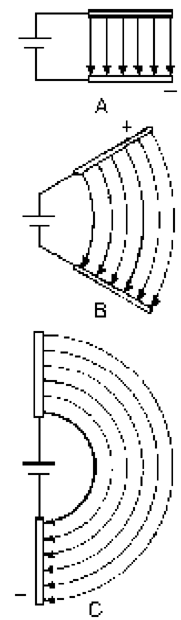
- Electric field strength is measured in terms of "Volts/meter" and is function of transmitter power, antenna gain, and distance from source.

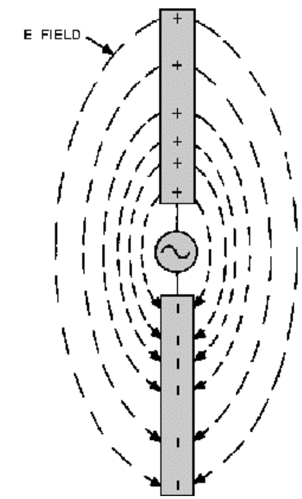
Antenna Physics

- 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 resonate circuits

E-Field Antenna

- Most wireless system antennas are designed to utilize the *electric field component* of E/M wave for communication.
- True or False?: This type of antenna can be represented as an “open” capacitor. (Answer on next slide.)





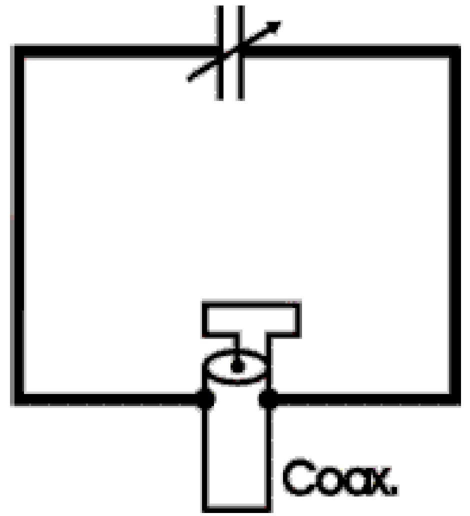
https://www.youtube.com/watch?v=4xF1Fq2wB1I

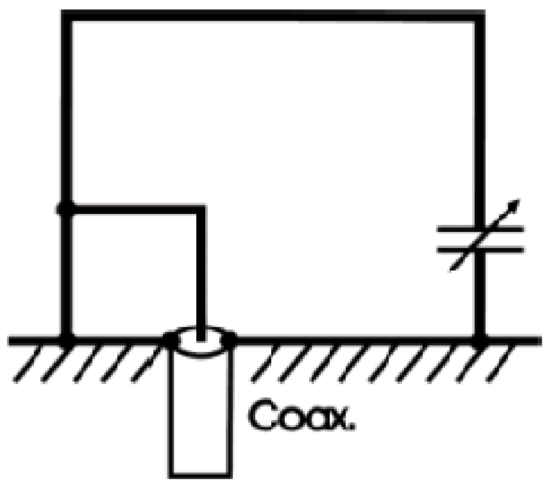
Dipole Antenna

MIT Physics Lecture Demonstration Group

Magnetic Field Antennas

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





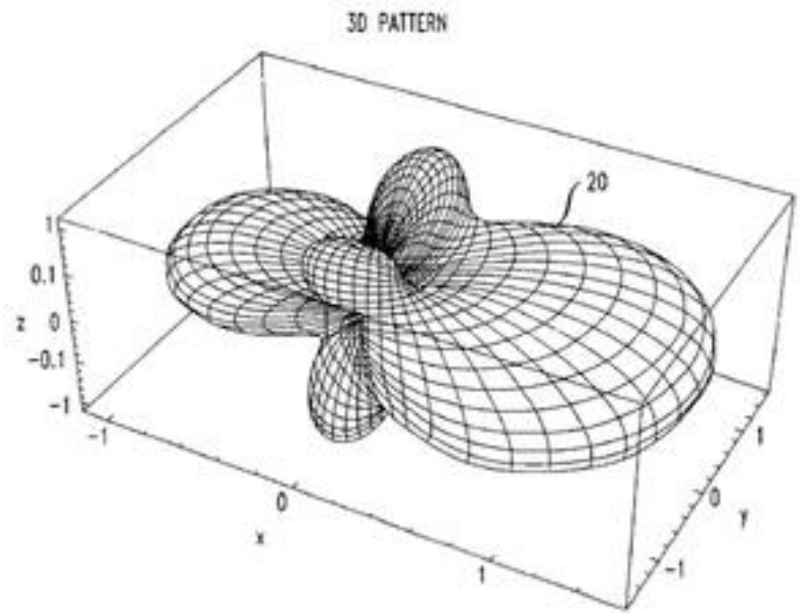
Key Parameters

- 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 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:

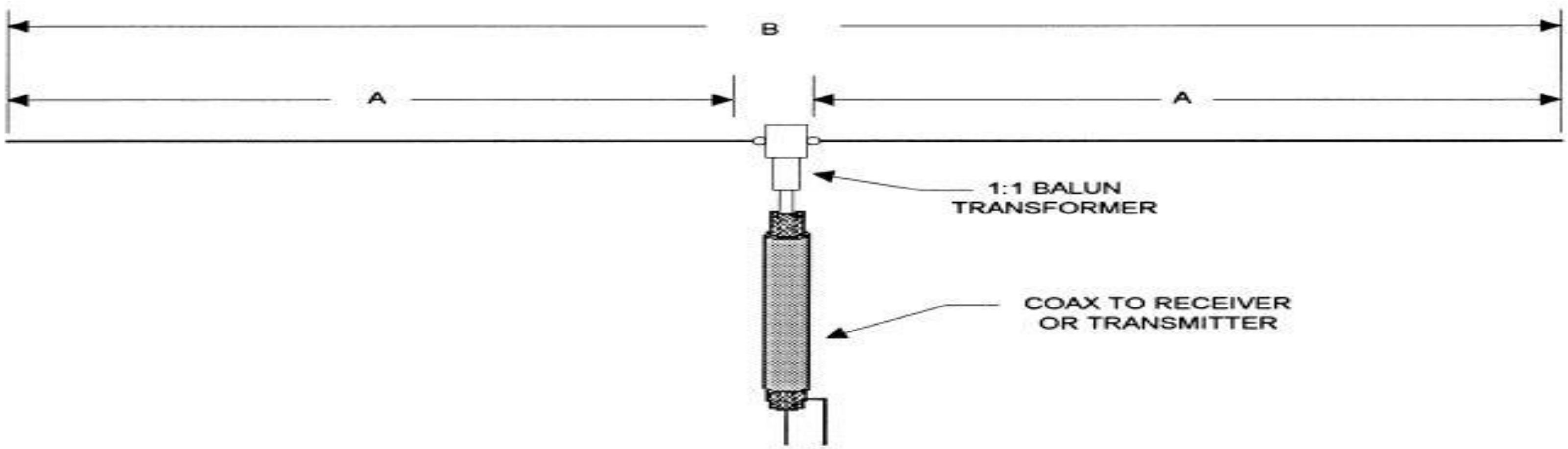
$Z_{ant} = R_r + jX$ (ohms)

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).

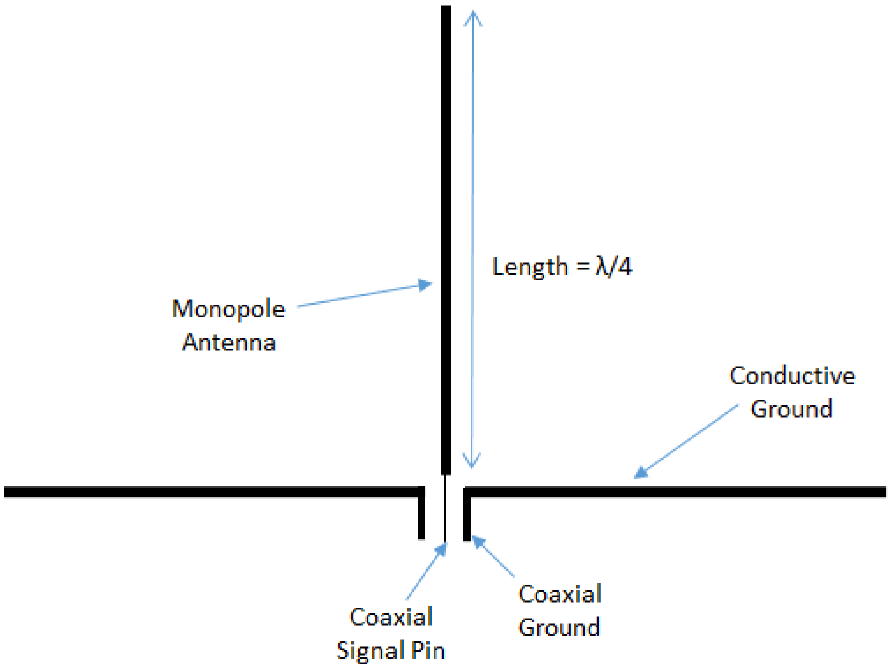
Dipole



- Basic antenna is a dipole, which has a physical length of "½ wave".
- Can reduce physical length to accommodate packaging, space, etc….

Monopole

- Basic antennas can also be constructed using a single radiating element (along with a current return structure).
- These are known as "monopole" antennas.
- Length is ¼ wavelength at the frequency of operation.



¼ Wave Antenna Application

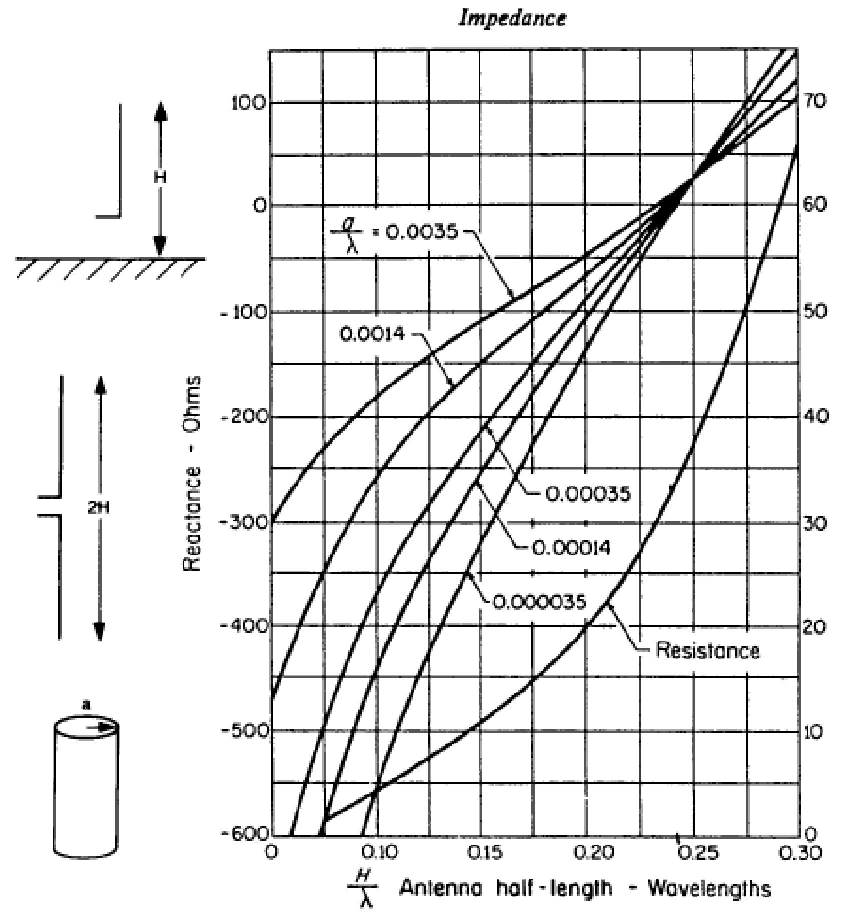
- Hand held transceivers typically use ¼ wave antennas due to simplicity of design.
- 27 MHz transceiver shown at right has an ¼ wave (electrical length) antenna – and has been reduced in size physically.

Description of Antenna Parameters

- Antenna performance determined by its "Radiation resistance" (R_r).
  - Dipole Rr = 73 ohms
  - Monopole Rr = 37 ohms
- Antenna reactance is the "jX", and is *the same as a series resonant circuit.*
  - *When the antenna length is physically short, jX is negative and antenna "looks" capacitive.*
  - *When "jX = 0" the antenna is "resonant".*

Physical “Short” Antennas

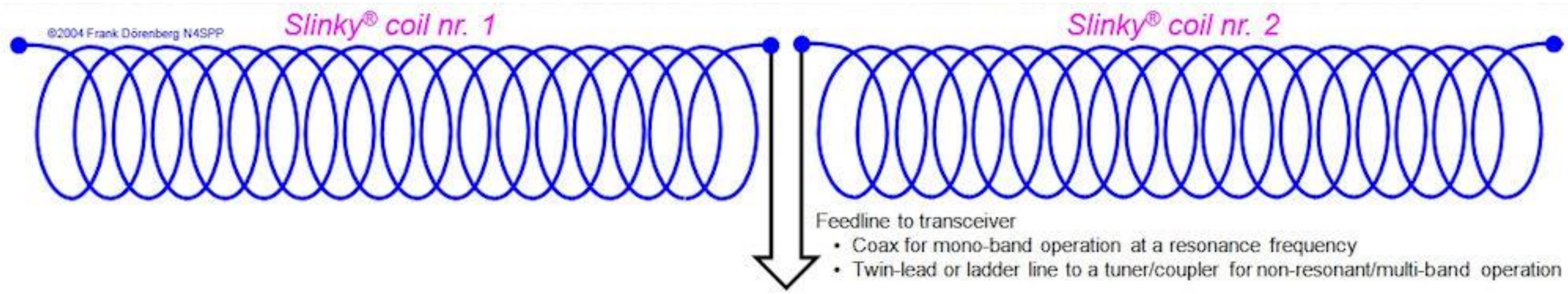
- If the physical length is reduced, this affects both radiation resistance and reactance.
- Applies to both monopoles and dipoles.
- Reduces “efficiency” of antenna (radiation resistance) and requires “tuning” to be done.



“Tuning” an Antenna

- Ideal antenna:
  - $Z = R + j\,0$
  - “Short one” is $Z = R - jX$
- Problem:
  - Need to add “jX” to obtain $Z = R - jX + jX$
- Solution: Add “jX” by adding inductance
- The problem is solved – it now “looks like” a series resonant circuit!

Small Dipole / Monopole



- Size reduction impacts performance
- Reduction in length makes elements look "capacitive"
- Can be "tuned" by adding inductance

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.

Original Type of Automotive Antenna

- Many were “telescoping styles” for better AM reception.

- Widespread use of FM radio resulted in standard 30 inch antenna

Mobile Two-way Radio Antennas

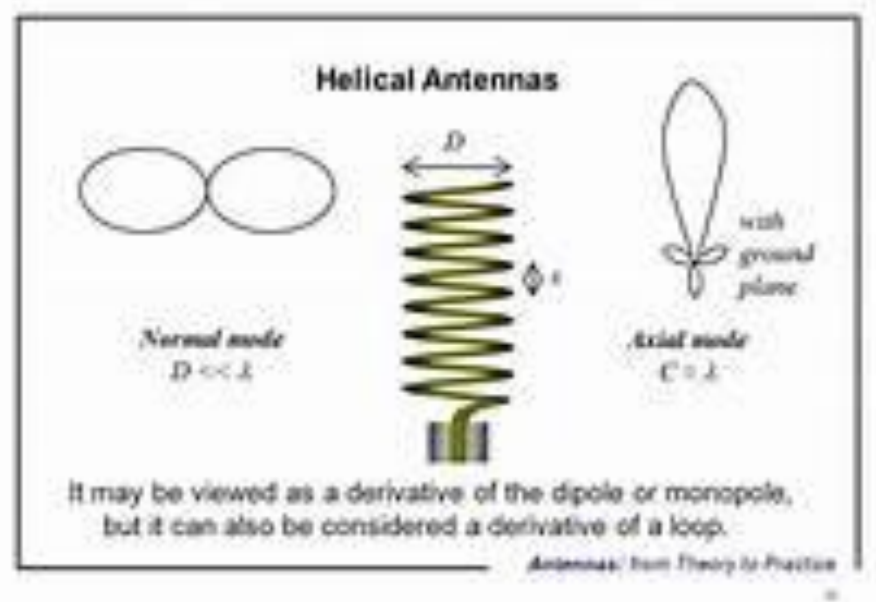
- Primary communications for public services
- Frequencies in use required smaller antennas than standard length
- “Loaded” antennas used to reduce size

Helical Antennas

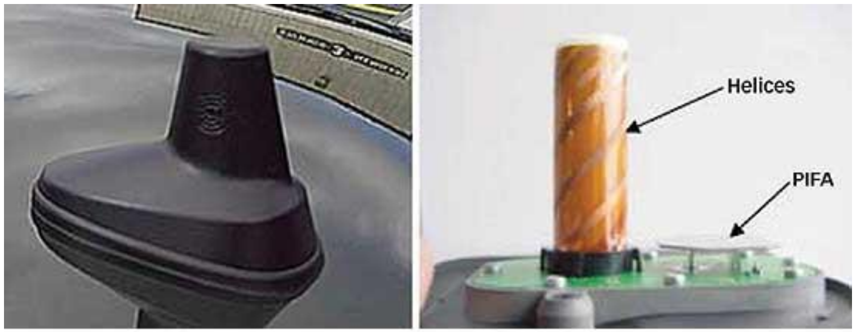
- Similar to continuous or distributed inductance antennas

- Two types:
  - “Axial” mode
  - “Normal” mode

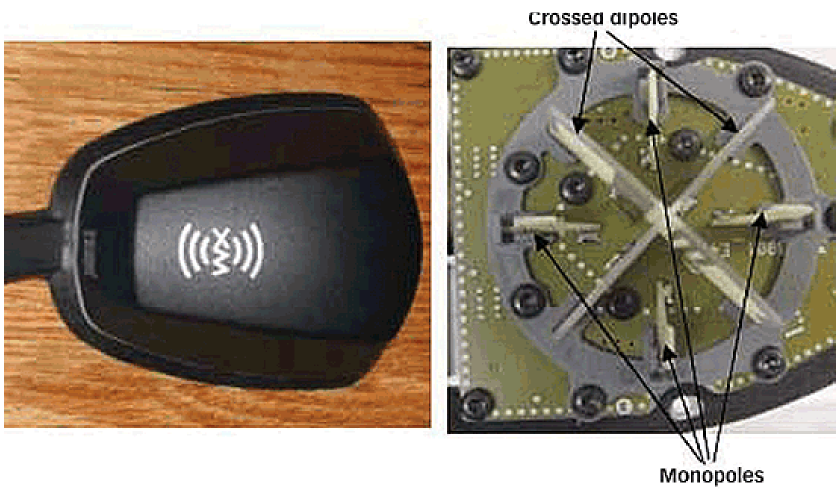
- Normal mode is used in automotive applications



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.

Other Antenna Applications

- Used for one way signaling (RKE)
- GPS and satellite entertainment radio systems
- Vehicle radar for collision and obstacle detection ability
- Traditional two way communications

“Reduced Size” Antennas

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

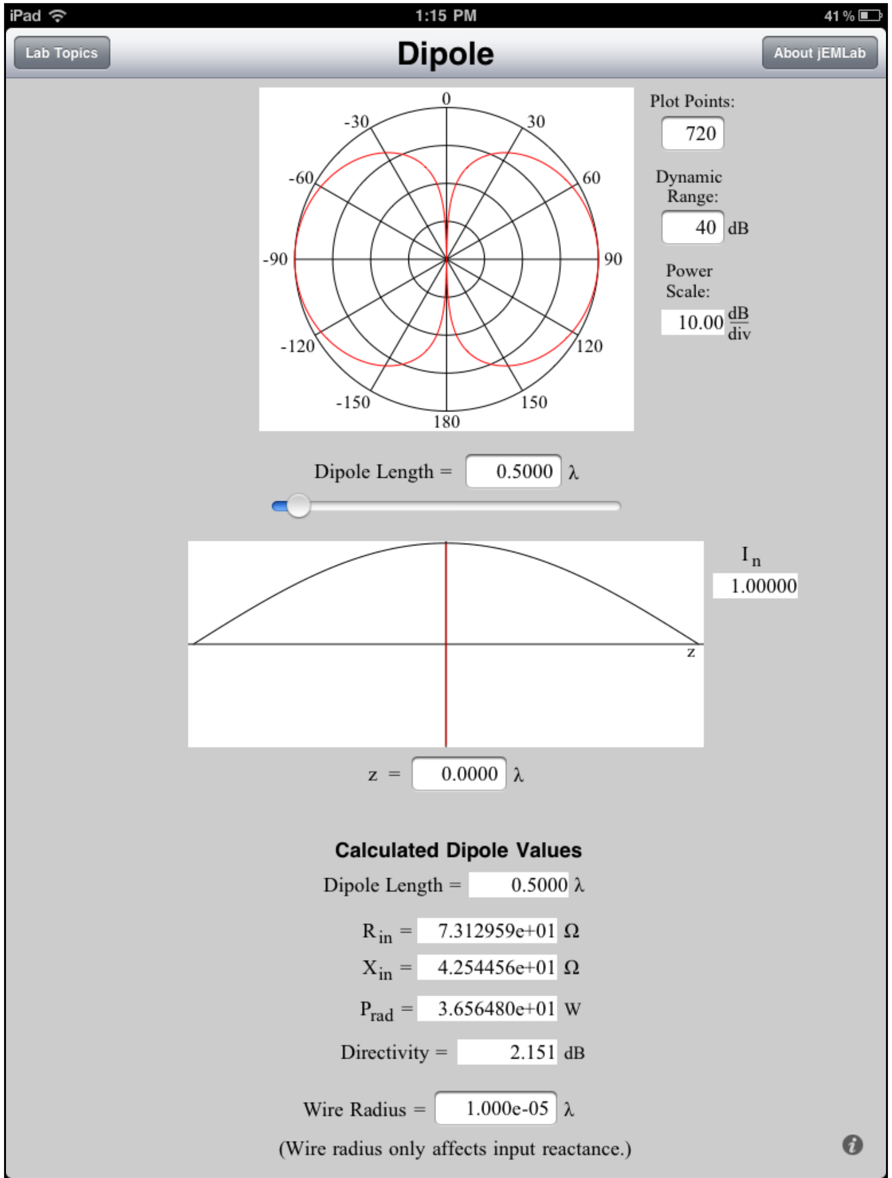
Antenna Measurements

- 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

Antenna Simulation Methods

- Antenna simulation are becoming more common and utilize numerical integration to performed to solve complex problems.
- Examples of tools:
  - PC-based: Numerical Electromagnetics Code (NEC)
  - Mainframe based: FEKO, CST, ANSYS (and others)
  - jEMLab (iPad based!)

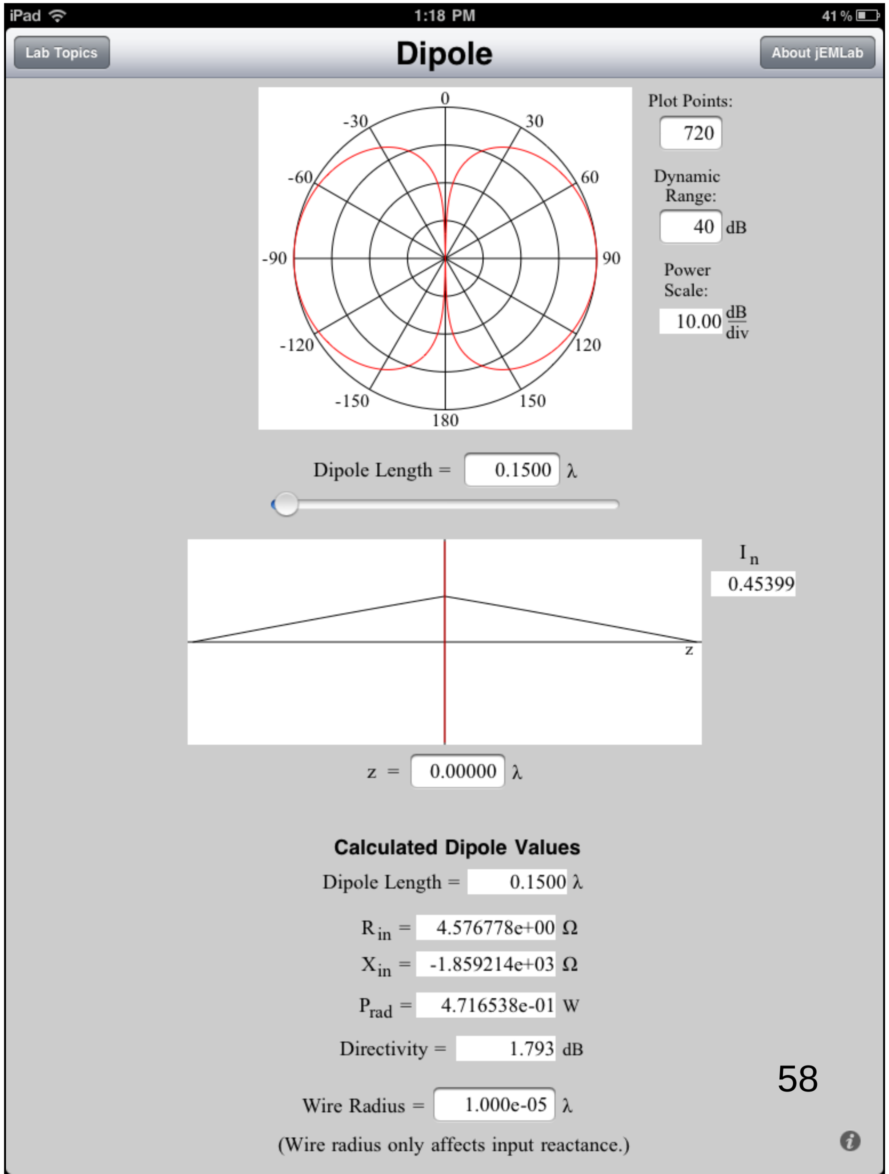
jEMLab Half-Wave Dipole



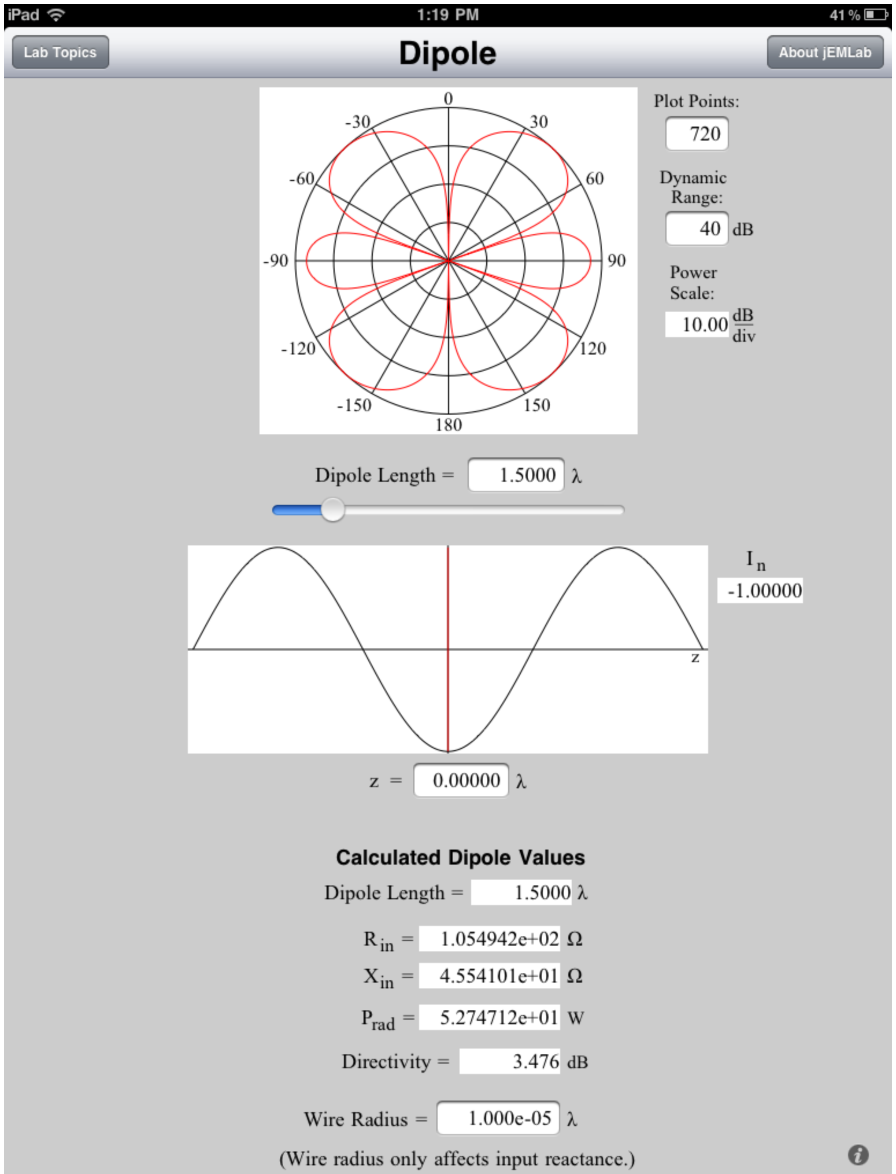
- Traditional ½ wave "resonant antenna".
- Analysis shows antenna pattern, current distribution, gain, and complex impedance expected.

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.

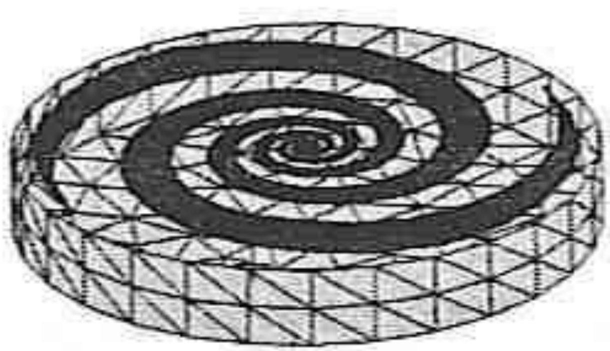


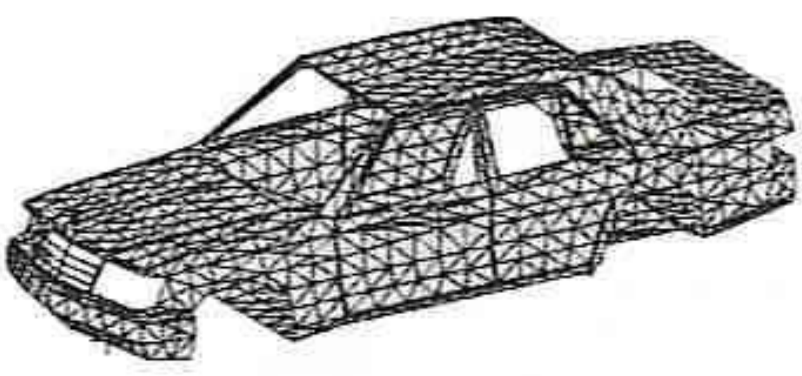
jEMLab Lengthened Dipole

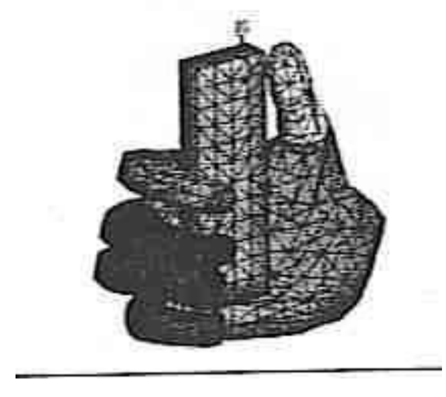


- At length equal 1 ½ wavelengths, there is a very complex radiation pattern that results.
- Radiation resistance increases (antenna is more "efficient").
- Is difficult to "match" to transmission line.

Examples of Antenna Structures



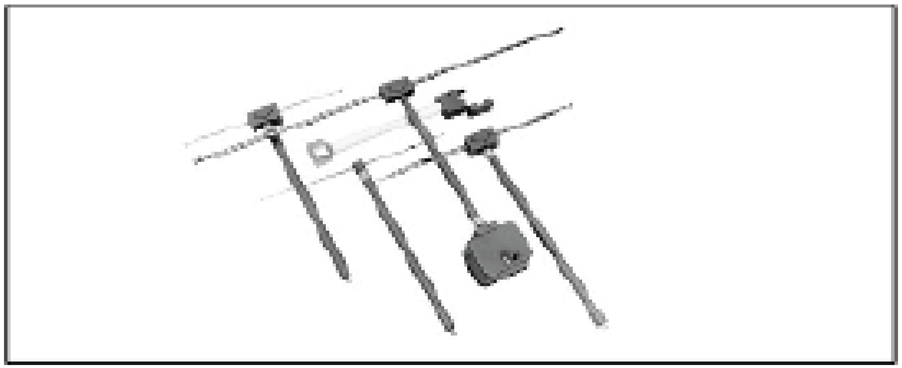


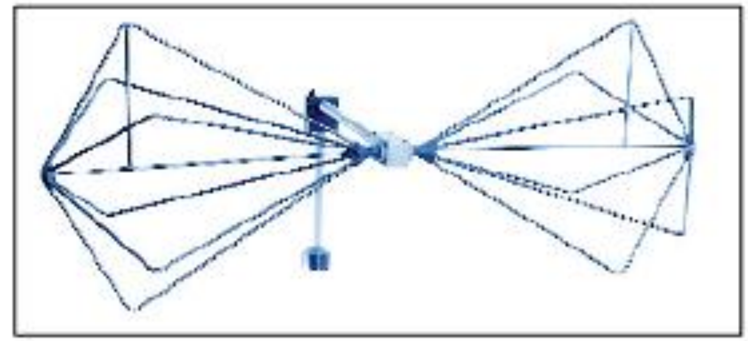


Types of Antennas in EMC

- 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.

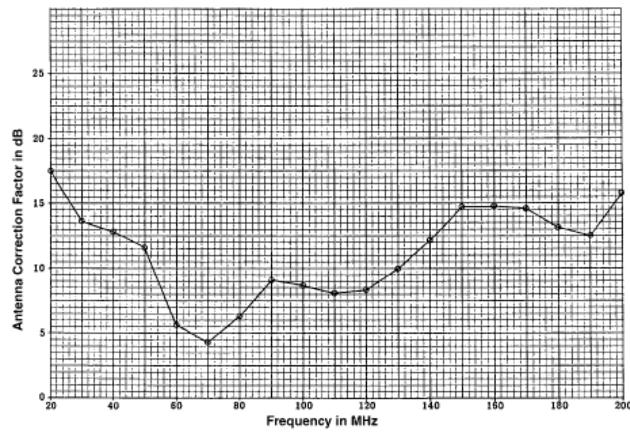
Gain Antennas In EMC

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

“Antenna Factor”

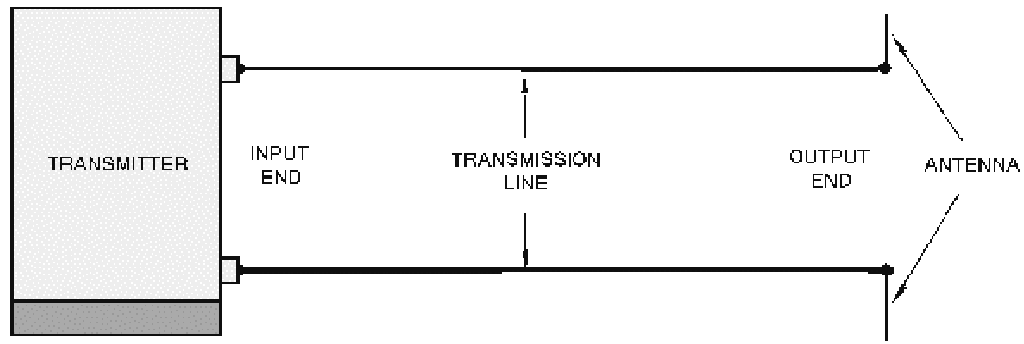
$$AF = \frac{E}{V},$$

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}.



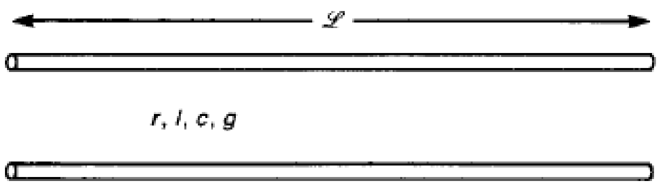
- “Antenna Factor” is a measure of how efficient an antenna is in converting field strength to voltage.
- The lower the antenna factor – more efficient the antenna is in producing an output voltage.

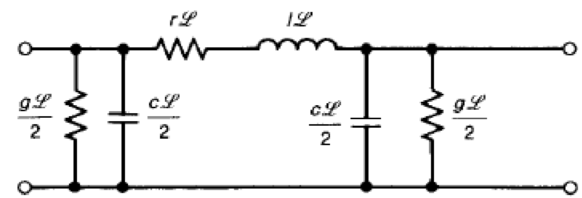
Antenna System Interface



- 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.

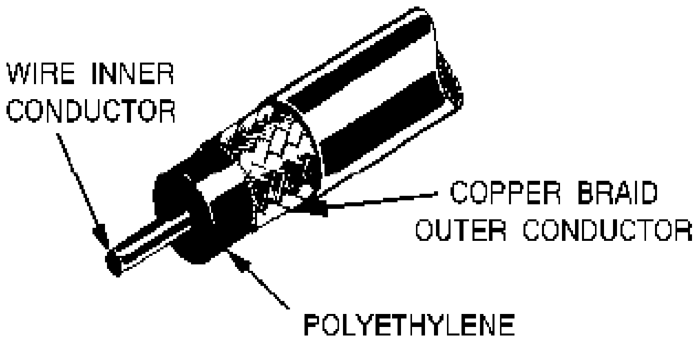
Transmission Line Development

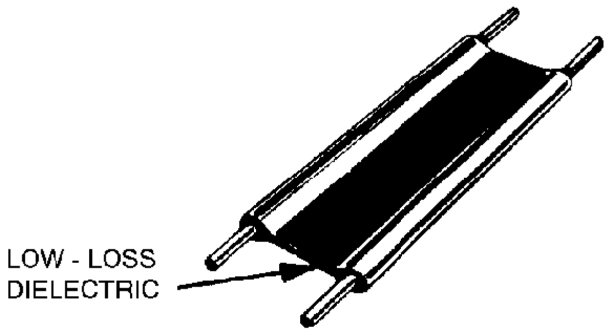




- Heaviside realized that the use of two conductors in the telegraph “transmission” line resulted in capacitive and inductive properties of the line.
- He understood that the capacitance and inductance was continuous along the length of the pair of conductors.

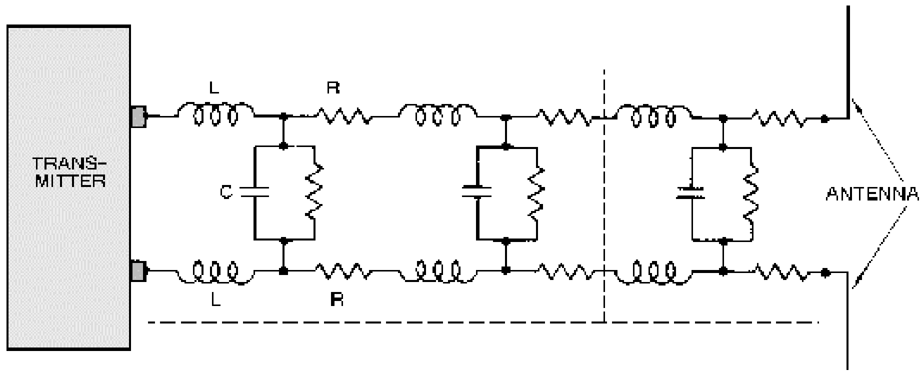
Transmission Line Types





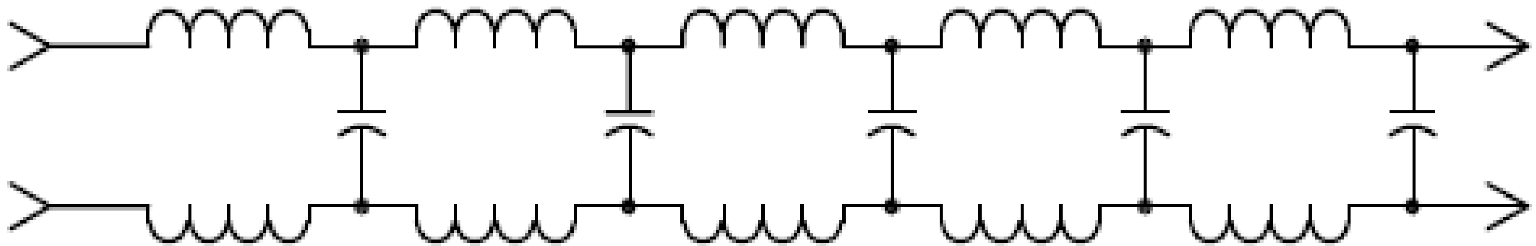
- "Coaxial" cable consists of an inner conductor and an outer conductor *that also functions as a shield*.
- "Twin Lead" consists of two identical conductors and is a "balanced" cable.

Transmission Line Model



- Electrical representation of a transmission line consists of distributed inductance, capacitance, and resistance.
  - Is a result of cable geometry, and conductor material.
  - Transmission line impedance determined by values of the equivalent circuit.

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!

Antenna Summary

- Have covered antenna engineering through the application of basic physics and electric circuits.
- In-class problem solving and simulation have provided valuable insight.
- By using the tools and methods from this course – antenna design and development can be done efficiently and effectively!