Topic 6. Radiation Fundamentals

Telecommunication Systems Fundamentals

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Concepts in this Chapter

- *Antennas: definitions and classification*
- *Antenna parameters*
- *Fundamental Theorems: uniqueness and reciprocity. Images' method*
- *Friis' equation*
- *Link Budget of a Radio-Link*

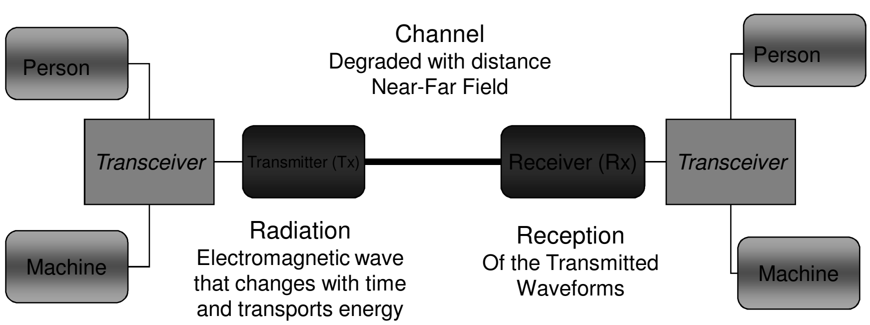
Theory classes: 1.5 sessions (3 hours)
Problems resolution: 0.5 session (1 hours)

Bibliography

Antenna Theory and Design. W.L. Stutzman, G.A. Thiele. John Wiley & Sons

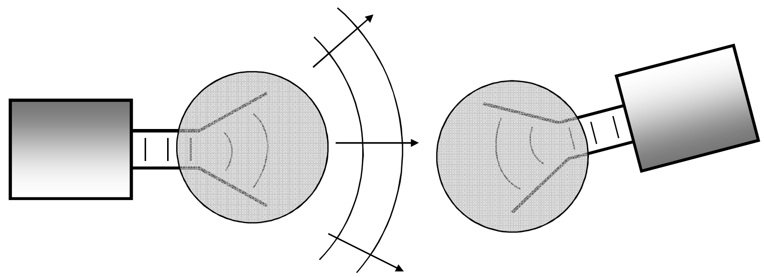
Introduction: Radio-Telecommunication Systems

- Info transmission implies to transmit a signal (with a given energy) through a radio-channel



Introduction: Transmitting and Receiving Antenna

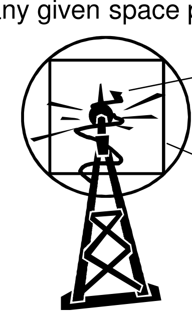
- An antenna can either transmit (radiate) energy in Transmission



- Or capture energy in Reception

Radiation Performance of an Antenna

- Radiation is the electromagnetic energy flux outward form a source
- Basic Problem in electromagnetic theory:
  - Calculus of the electromagnetic field produced by a structure in any given space point



From Electrical Currents within the Tx’ing antenna structure

From the Electromagnetic Field distribution along a closed surface that surrounds the Tx’ing antenna

Efficiency as Main Objective in Antennas

- Efficiency is the main objective when designing/ selecting an antenna
  - Maximize the electromagnetic field power in a given point given an amount of power provided to the antenna
- Which antenna parameters should we consider
  - Phase Center
  - Power Parameters
    - » Radiated power flux density
    - » Radiation intensity
    - » Directivity
    - » Power Gain
  - Gain diagram
  - Polarization
  - Bandwidth

Power Parameters: Poynting's Theorem

- **Complex Poynting's Vector**: electromagnetic energy flux density through a given surface

$$S = \frac{1}{2}\mathrm{Re}\left\{\overline{E} \times \overline{H}^*\right\}$$

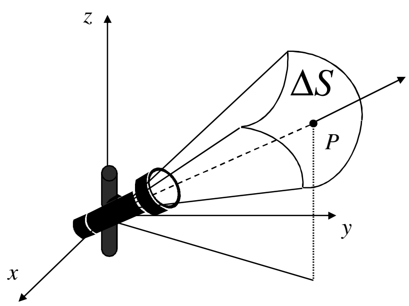
- **Average Power**: Poynting's vector flux

$$P_{media} = \iint S \cdot dS \ \ [\mathrm{W}]$$

Power Parameters: Radiation Density

- Average radiated power **per surface unit** in a given direction

$$\phi(\theta,\varphi) = \frac{1}{2}\mathrm{Re}\left\{\overline{E}\times\overline{H}^{*}\right\} \left[\frac{W}{m^{2}}\right]$$

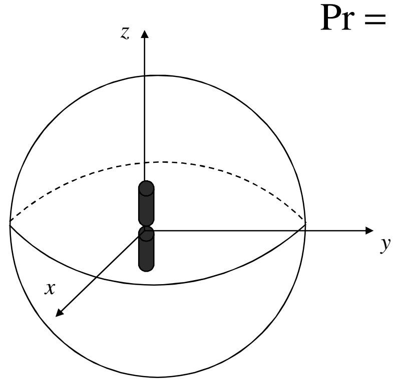


$$\phi(\theta,\varphi) = \frac{\Delta p(\theta,\varphi)}{\Delta S}$$

Power Parameters: Radiated Power

- ***Sum up*** radiated flux density along a sphere surface that circumscribe the antenna

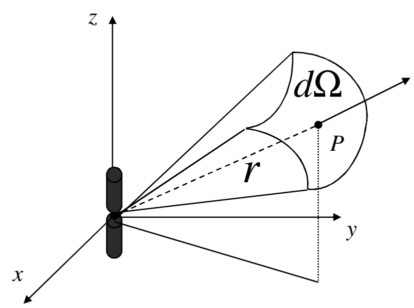
$$\Pr = \int\int \phi(\theta,\varphi)\cdot dS \ \ [\mathrm{W}]$$



Power Parameters: Radiation Intensity

- Average radiated power **per solid angle unit** in a given direction

$$i(\theta,\varphi)=\frac{\Delta p(\theta,\varphi)}{\Delta\Omega} \quad \left[\frac{W}{esteroradian}\right]$$



$$\Pr=\iint i(\theta,\varphi)\cdot d\Omega$$

Power Parameters: Radiation Intensity

- **Independently of the distance** from the antenna

$$\Delta S = r^2\Delta\Omega \Rightarrow \phi(\theta,\varphi)\cdot r^2 = i(\theta,\varphi)$$

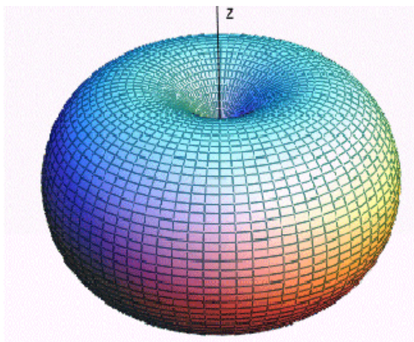
- The Power Flux Density decreases with distance inversely proportional to the area of the spherical solid angle
- Radiation Diagram (power-wise)

$$r(\theta,\varphi)=\frac{i(\theta,\varphi)}{i_{\max}}$$

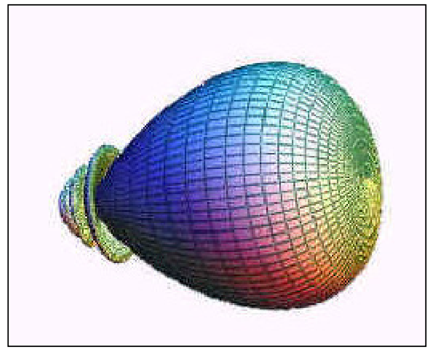
Power Parameters: Radiation Intensity

Omnidirectional (on Azimuth)

Directive



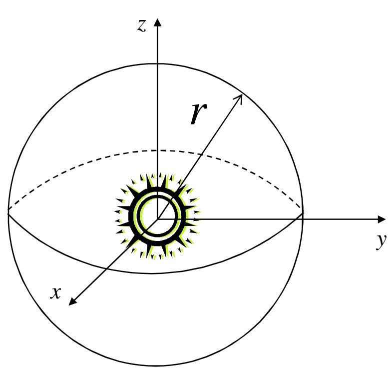
Dipolo: typical on cellular terminals



Yagi: typical for television receivers

Power Parameters: Isotropic Antenna

- **Ideal** point source that radiates **uniformly** in all directions



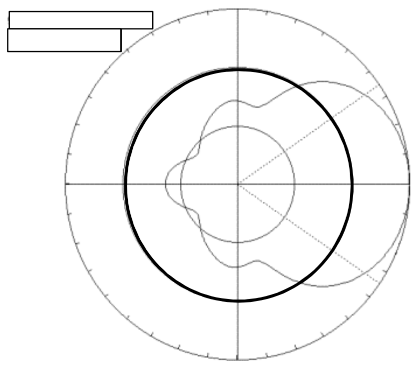
$$i_{iso} = \frac{\Pr}{4\pi}$$

$$\phi_{iso} = \frac{\Pr}{4\pi \cdot r^2}$$

Reference to compare rest of Antennas

Power Parameters: Isotropic Antenna

$i(\theta,\varphi)$



Same area under the curve

Assuming the same transmitted power by both antennas…which *focalizes* better?

Power Parameters: Directivity (function of direction)

- Ratio between the power density flux an antenna radiates and the one an isotropic (omnidirectional) antenna would do, as a function of the radiating direction

$$\boxed{D(\theta,\varphi) = \frac{i(\theta,\varphi)}{i_{iso}} = 4\pi\frac{i(\theta,\varphi)}{\mathrm{Pr}}}$$

$$i(\theta,\varphi) = \frac{\mathrm{Pr}}{4\pi}D(\theta,\varphi) \qquad \phi(\theta,\varphi) = \frac{\mathrm{Pr}}{4\pi\cdot r^2}D(\theta,\varphi)$$

Power Parameters: Directivity

- Directivity is defined as the maximum value of the Directivity function

$$\boxed{D = 4\pi \frac{i_{\max}}{\Pr}}$$

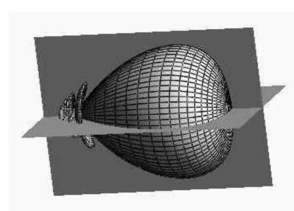
  – Because $\Pr = \int\int i(\theta,\varphi)\cdot d\Omega \qquad r(\theta,\varphi) = \frac{i(\theta,\varphi)}{i_{\max}}$

$$\boxed{D = \frac{4\pi}{\Omega_A} \quad \text{being} \quad \Omega_A = \int\int r(\theta,\varphi) d\Omega}$$

Power Parameters: Directivity

- When the Bean is narrow

$$\boxed{D \approx \frac{4\pi}{\theta_1\theta_2}}$$



- Conclusions
  - Directivity provides information about how the radiated power is distributed with direction (elevation and azimuth)
  - Directivity does not provide information about the actual transmited power

Power Parameters: Gain Function

- **Ratio** between the power intensity radiated in a direction and the radiated intensity of an isotropic antenna, given a power available to the antenna

$$\boxed{G(\theta,\varphi) = 4\pi \frac{i(\theta,\varphi)}{P_{in}}}$$

being P_{in} the power available at the antenna input

Power Parameters: Gain

- Gain is the maximum value of the Gain Function

$$\boxed{G = 4\pi \frac{i_{\max}}{P_{in}}}$$

  – Because it is a ratio, the units are dBs

Power Parameters: Examples of Gain

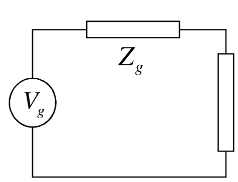
ANTENNA TYPE	GAIN (dBi)
Isotropic	**0,0**
Ground Plane 1/4 wavelength	**1,8**
Dipole 1/2 wavelength	**2,1**
Monopole 5/8 wavelength	**3,3**
Yagui 2 elements	**7,1**
Yagui 3 elements	**10,1**
Yagui 4 elements	**12,1**
Yagui 5 elements	**14,1**

Power Parameters: Efficiency

- P_{in} and **Pr** are related to each other around radiating ***Efficiency*** of the antenna

$$\boxed{\mathrm{Pr} = \eta \cdot P_{in}}$$

$$\eta_{cd} = \frac{R_r}{R_r + R_L} \qquad \eta_{cd} \qquad \eta_d = 1 - \left|\Gamma^2\right| \qquad \Gamma = \frac{Z_a - Z_g}{Z_a + Z_g}$$



$$Z_a = R_r + R_L + jX_a$$

Power Parameters: Efficiency

- From the above definition of Efficiency, the relationship between Gain and Directivity of an antenna can be derived

$$\boxed{G = \eta \cdot D}$$

- Can the Gain of an antenna be increased by increasing the Directivity?

Example

- A dipole of half wavelength without losses, with input impedanze of 73Ω is connected to a transmission line with characteristic impedance of 50Ω. Assuming the radiating intensity of the antenna is

$$i(\theta) = B_0 sen^3(\theta)$$

Compute the Gain of the Antenna

$$i_{\max} = i_{\max}(\theta) = B_0$$

$$P_r = \int_0^{2\pi}\int_0^{\pi} D(\theta) sen\theta = 2\pi B_0 \int_0^{\pi} sen^4\theta \, d\theta = B_0\left(\frac{3\pi^2}{4}\right)$$

$$D = 4\pi \frac{i_{\max}}{P_r} = 1.697$$

$$G = \eta \cdot D = \left(1 - |\Gamma|^2\right) D = \left(1 - \left|\frac{73-50}{73+50}\right|^2\right) 1.697 = 0.965 \cdot 1.697 = 1.638 = 2.14dB$$

Example Answer

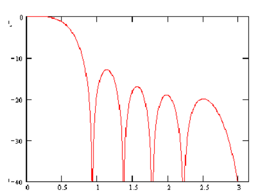
$$i_{\max} = i_{\max}(\theta) = B_0$$

$$P_r = \int_0^{2\pi}\int_0^{\pi} D(\theta)\, sen\,\theta = 2\pi B_0 \int_0^{\pi} sen^4\theta\, d\theta = B_0\left(\frac{3\pi^2}{4}\right)$$

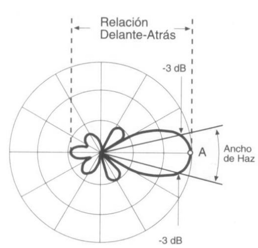
$$D = 4\pi \frac{i_{\max}}{P_r} = 1.697$$

$$G = \eta \cdot D = \left(1 - |\Gamma|^2\right) D = \left(1 - \left|\frac{73-50}{73+50}\right|^2\right) 1.697 = 0.965 \cdot 1.697 = 1.638 = 2.14dB$$

Radiation Diagram

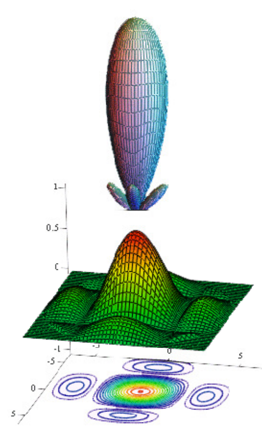


Cartesian



Polar

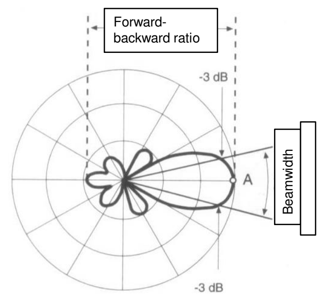
What parameter are usefull?



Joint

Radiation Diagram

- Parameters to characterize the lobe structure
  - Beamwidth
    - Null to Null Beamwidth
    - Half Power Beamwidth (HPBW) – 3dBs
    - 10 dB Beamwidth
  - Lobes
    - Main lobe
    - Side lobes
      - First lobe
    - Backlobe
  - Forward-backward ratio

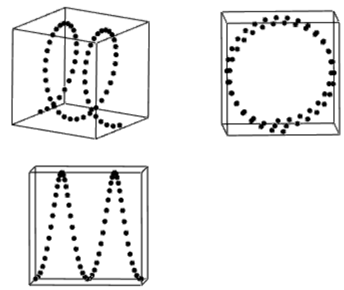


Radiation Diagram: Classification

- Isotropic
- Omnidirectional
- Directive
- Multi-beam

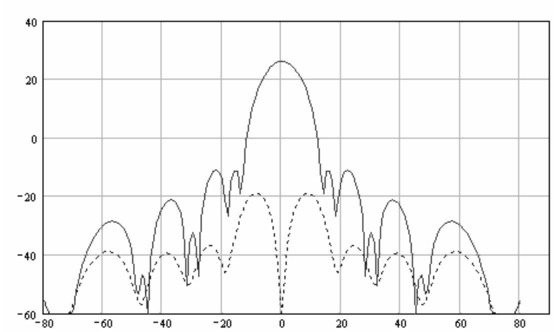
Polarization

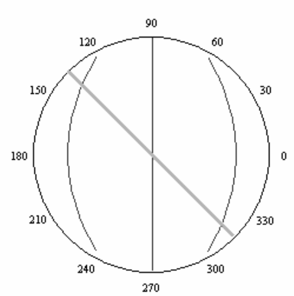
- Of a **Plane-wave**, it refers to the spatial orientation of the time-variation of the electric field
- Of an **antenna**, it refers to the polarization of the radiated field
  - Generally speaking polarization is defined acording to the propagation direction



Polarization

- Co-Polar and Cross-Polar components



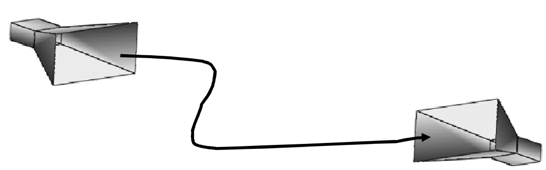


Antenna Bandwidth

- Frequency margin where the defined parameters for the antenna remain valid (impedance, beamwidth, sidelobes ratio, etc.)
  – Narrowband Antennas (<10% central frequency)
  – Broadband Antennas (>10% central frequency)

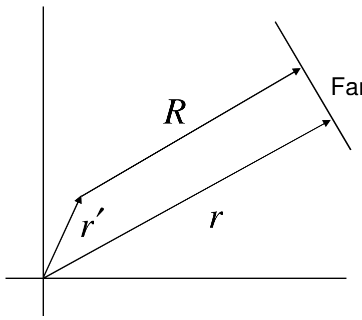
Antenna Radiation on Free-Space Condition

- What is Free-Space condition: no obstacles or material to influence the radiation patern – not even the ground



Radiation Zones

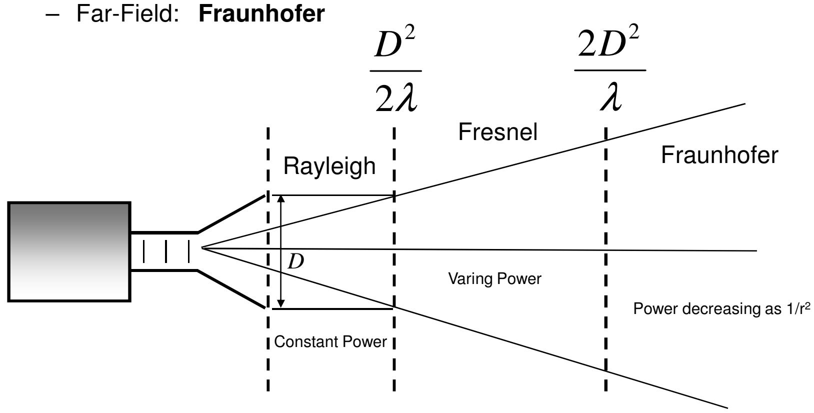
- When the distance is much greater than the wavelength, **R>> λ**, the observed wave behaves as a Plane-Wave.
- When can we consider we are "far enough"?



Far-Field zone: $R \approx r$

Radiation Zones

- Simplifying but useful approach: three zones are defined:
  - Near-Field: **Rayleigh** (spheric propagation)
  - Intermediate-Field: **Fresnel** (interferences)
  - Far-Field: **Fraunhofer**



Radiation Zones: Far-Field

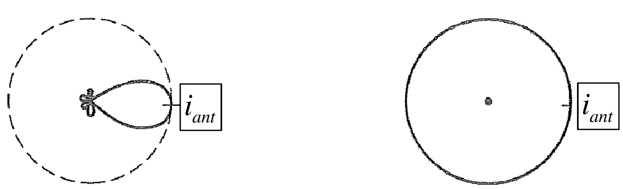
- Conclusions:
  – Power decreases as **square of the distance**
  – Satisfy condition of **Plane-Wave**
    - E and H fields are perpendicular
    - Amplitude of E and H fields are related to each other through the transmission mean impedance
  – The type of the transmitting antenna afects only on the angular variation of the transmitted power flux (**Radiation Diagram**)
  – **Transmission direction of the wave propagation** coincides with **line of sight** of the transmitting antenna

EIRP - Equivalent Isotropic Radiated Power

- The product of the antenna Gain by the available Power

$$\boxed{PIRE = G \cdot P_{in}}$$

$$i_{iso} = \frac{P_{in}}{4\pi} \qquad i_{ant} = \frac{G \cdot P_{in}}{4\pi} = \frac{PIRE}{4\pi}$$



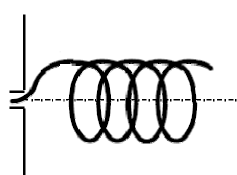
EIRP

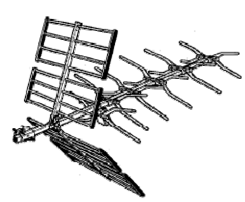
- Its units are dBW (or dBm)
- We will see later, this parameter (expressed on dBW) is quite usefull when computing the “availability” of the radio-link
- Example: if the Gain of an antenna is 2dBi and it gets a power of 10W, How much is its EIRP?

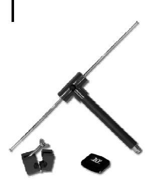
$$
\boxed{\begin{aligned}
&G = 2\,\mathrm{dB}\\
&P_{in} = 10\cdot\log(10) = 10\ \ \mathrm{dB}\\
&PIRE = 12\,\mathrm{dB}
\end{aligned}}
$$

Lineal Antennas

- Antennas built with thin electrically conductive wires (very small diameter compared to λ).
- They are used extensively in the MF, HF, VHF and UHF bands, and mobile communications.
- Among others:
  - Dipole
  - Monopole
  - Yagi antenna
  - Loops
  - Helixes

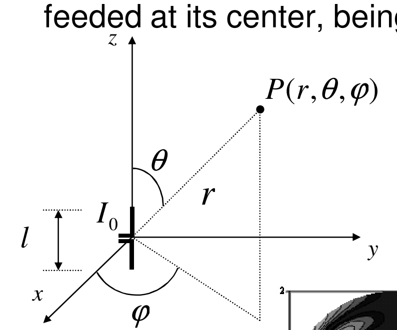






Lineal Antennas: Infinitesimal Dipole

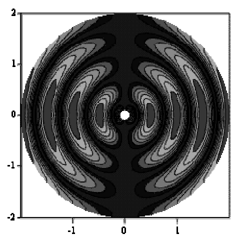
- Formed by two short conductive wires simetrically feeded at its center, being $l << \lambda$.

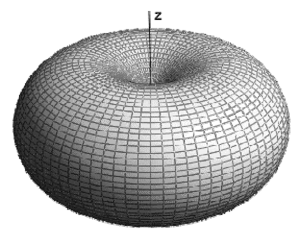


$$E_\theta = jZ_0 \frac{l \cdot I_0}{2\pi \cdot \lambda \cdot r} sen(\theta) \cdot e^{-j\frac{2\pi r}{\lambda}}$$

With Linear Polarization

And radiation diagram





Lineal Antennas: Infinitesimal Dipole

- Computing the magnetic field form the electrical, calculating the power flux and integrating for all θ we get

$$\text{Pr} = Z_0 \left(\frac{2\pi}{3}\right)\left(\frac{l \cdot I_0}{\lambda}\right)^2 = I_0^2 R_r$$

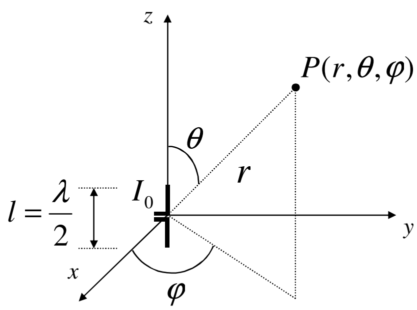
$$R_r = 80\pi^2 \left(\frac{l}{\lambda}\right)^2$$

  - and consecuently $D = \frac{3}{2}$

- What is the Gain of this antenna?

Lineal Antennas: Half-Wavelength Dipole

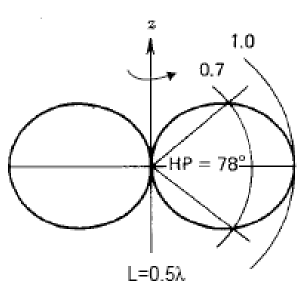
- Very common antenna, with a “convenient” radiation impedance of 73Ω



$$E_\theta = jZ_0 \frac{I_0 e^{-j\frac{2\pi r}{\lambda}}}{2\pi \cdot r} \left[\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta} \right]$$

Lineal Antennas: Half-Wavelength Dipole

- Radiation parameters



Directividad: $D_0 = 1{,}64 = 2{,}15$ dBi

$R_{radiación}$: $R_{rad} = 73\ \Omega$

Radiated Field over a Perfect Conductor

- Up to this point we have assumed the antennas are in the free-space environment. However they usually are close to the ground
- When the distance to ground is comparable to the wavelength, and the beamwidth is large, antenna radiation is heavily affected by the presence of the ground
- For these scenarios, we will assume the ground is a perfect conductor, infinite and plane

Image Theory

- Intuitively, the field is reflected on the ground
  - Perfect conductor: the transmitted wave is reflected
  - The field P is the result of the sum of the direct and reflected waves
  - Fiend P is the result of the primary and image waves in the equivalent free-space scenario
    - Which is valid only for the upper half semi-space

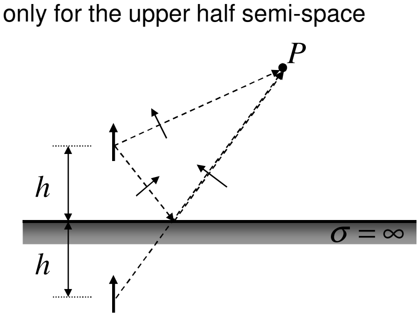
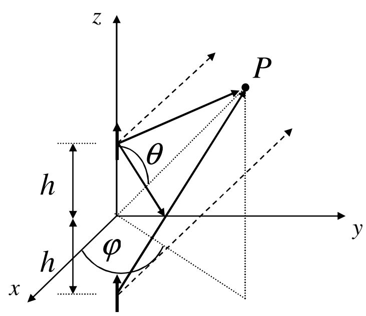


Image Theory

- Example: field produced by a Infinitesimal dipole



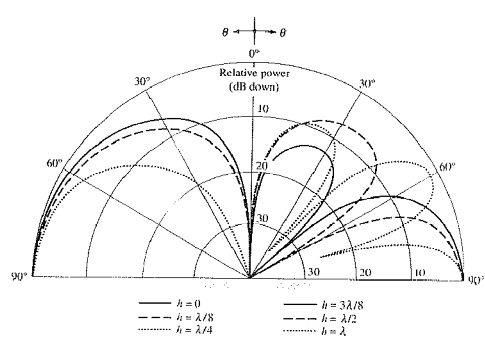
$$\boxed{E_\theta \approx \underbrace{jZ_0 \frac{I_0 e^{-j\frac{2\pi r}{\lambda}}}{2\pi \cdot r} \sin\theta}_{\text{Isolated Dipole Field}} \underbrace{\left[2\cos\left(\frac{2\pi \cdot h}{\lambda} \cos\theta \right) \right]}_{\text{Joint Contribution of two Antennas}}}$$

Radiation Properties change as function of the ratio

$$h/\lambda$$

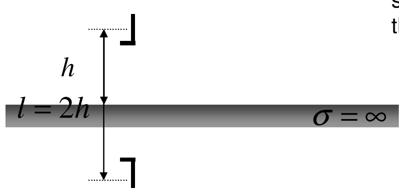
Image Theory

- Example (cont.)
  - If $\lambda >> h$ then, directivity increases by 3dB! -> decrease the size
  - Otherwise….



Monopole

- Vertical Dipole divided to its half, that is fed between wire end and a conductive plane



- Applying Image theory, it can be proven that a monopole above a conductive plane exhibit the same behavior than a dipole with a length twice the height of the monopole

Consider only $z > 0$ and $\lambda >> h$

$$\boxed{i_{mono} = i_{dipolo}}$$

$$\boxed{\mathrm{Pr}_{mono} = \frac{1}{2}\mathrm{Pr}_{dipolo}} \quad \boxed{R_{r,mono} = \frac{1}{2}R_{r,dipolo}} \quad \boxed{D_{mono} = 2D_{dipolo}}$$

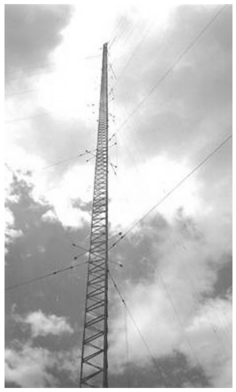
Monopole

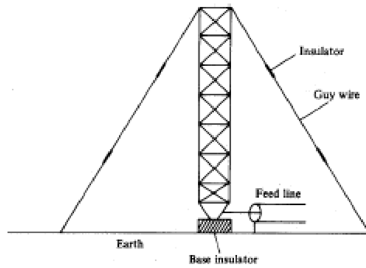
- Example: λ/4 monopole
  - As shown before, the monopole exhibit the same performances than a λ/2 dipole and therefore its directivity is

$$\boxed{D = 5.15 \text{ dBi}}$$

- At low frequencies, this antenna has quite large physical dimensions
  - Example: the standard AM transmitter for frequency carrier around 1MHz, corresponds to a wavelength of 300 m, and therefore this λ/4 monopole has a heigth of 75 m.

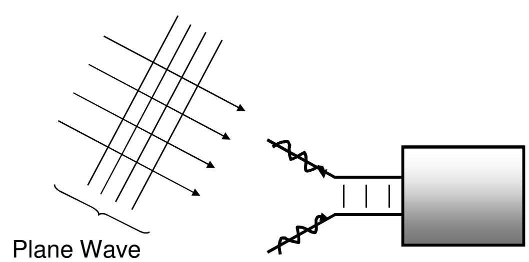
Monopole





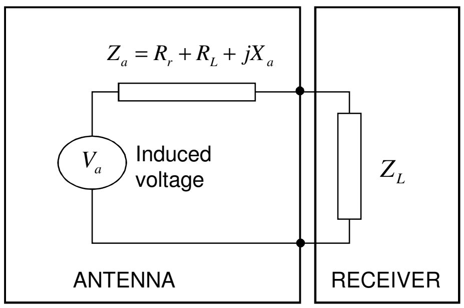
Reception of an Electromagnetic Field

- If and electromagnetic wave, with a plan-wave like propagation, runs over a conductor (antenna) it generates a current distribution over it



Equivalent Circuit Model for a Receiving Antenna

- An antenna at reception is designed to optimize the power handed out at its terminal



- Available power at antenna

$$P_a = \frac{|V_a|^2}{8R_a}$$

- Power handed out

$$P_L = \frac{1}{2}|I_L|^2 R_L = P_a\left(1 - |\Gamma^2|\right)$$

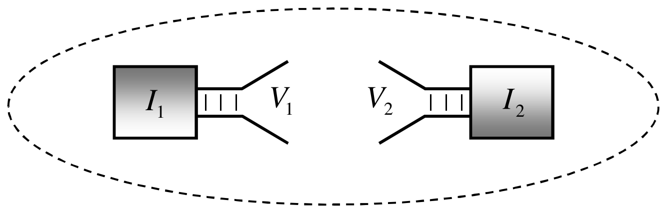
$$\Gamma = \frac{Z_a - Z_L}{Z_a + Z_L}$$

Reciprocity Theorem

- It allows to relate the properties of an antenna when receiving and transmitting
- “The relationship between an oscillating current and the resulting electric field is unchanged if one interchanges the points where the current is placed and where the field is measured”
  – For the specific case of an electrical network, it is sometimes phrased as the statement that voltages and currents at different points in the network can be interchanged”

Reciprocity Theorem

- Suppose an anechoic chamber (no echo) in which are placed two antennas, both can transmit and receive, and operating at the same frequency



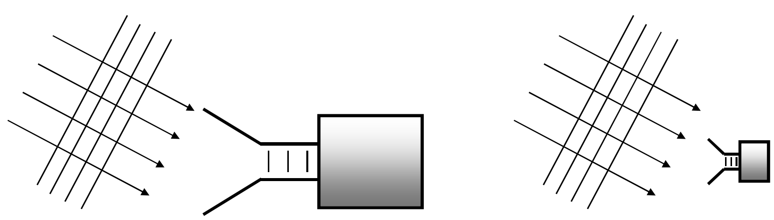
- The roles of sending and receiving can exchanged. Thus, the radiation patterns of transmitting and receiving are the same

$$\boxed{\text{If } I_1 \rightarrow V_{2,ca} \Rightarrow V_{1,ca} = V_{2,ca} \text{ when } I_2 \rightarrow V_{1,ca}}$$

$$\boxed{I_1 = I_2}$$

Effective Aperture

- Effective Aperture of an antenna characterizes the electromagnetic energy that it is able to capture
- Intuitively a large antenna captures more power, as it has more area



Effective Aperture

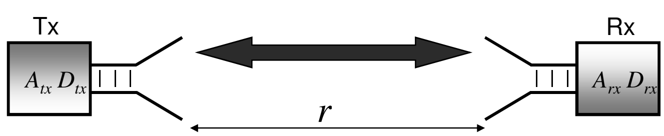
- Equivalent aperture is defined as

$$\boxed{A_{ef} = \frac{\text{Potencia entregada}}{\text{Densidad de potencia incidente}} = \frac{P_L}{\phi_i} = \frac{|I_L|^2 R_L / 2}{\phi_i}}$$

- The value does not have to match the dimensions (physical) of the antenna.
- When the antenna is flat, the physical relationship between the opening (A_f) and the effective aperture (A_{eff}) is known as aperture efficiency, verifying that:

$$\boxed{A_{eff} = \varepsilon_{ap} A_f \qquad \text{con } 0 \le \varepsilon_{ap} \le 1}$$

Directivity vs Maximum Effective Aperture



$$\phi_{tx} = \frac{P_{tx}}{4\pi \cdot r^2} D_{tx}$$

$$P_{rx} = \phi_{tx} A_{rx} = \frac{P_{tx} D_{tx} A_{rx}}{4\pi \cdot r^2} \longrightarrow D_{tx} A_{rx} = \frac{P_{rx}}{P_{tx}} \left(4\pi r^2\right)$$

$$D_{rx} A_{tx} = \frac{P_{tx}}{P_{rx}} \left(4\pi r^2\right)$$

Directivity vs Maximum Effective Aperture

$$\boxed{\frac{D_{tx}}{A_{tx}} = \frac{D_{rx}}{A_{rx}} \Rightarrow \frac{D_{tx}}{A_{tx,m}} = \frac{D_{rx}}{A_{rx,m}}}$$

- The above solution is valid for any antenna. For an infinitesimal dipole it can be proof that

$$\boxed{A_{ef} = \frac{3\lambda^2}{8\pi} = \frac{\lambda^2}{4\pi} D}$$

Directivity vs Maximum Effective Aperture

- In case of losses associated to the antenna, the maximum effective aperture is

$$\boxed{A_{ef} = \eta_{cd}\left(1 - |\Gamma|^2\right)\frac{\lambda^2}{4\pi} D = \frac{\lambda^2}{4\pi} G}$$

$$\boxed{G = \frac{4\pi}{\lambda^2} A_{ef}}$$

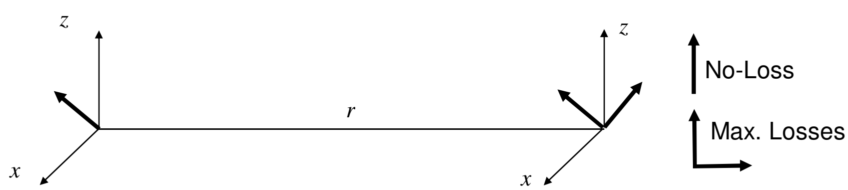
Polarization Mismatch

- The difference of polarization between transmitting and receiving antennas, it is known as ***Polarization Loss Factor***

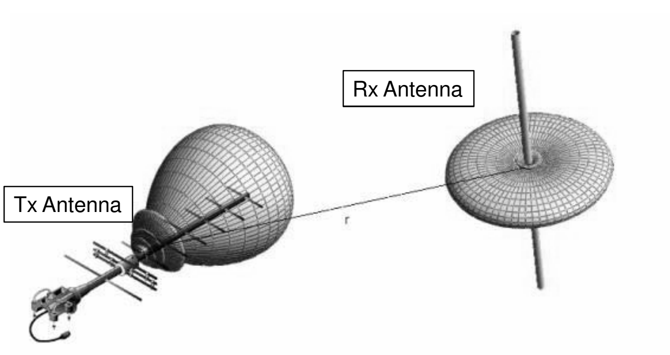
$$\boxed{L_{polarization} = \left| \overline{e}_{tx} \cdot \overline{e}^{*}_{rx} \right|^2}$$

Polarization Vector For Tx antenna

Polarization Vector For Rx antenna



Gains in the Radio Link: Tx and Rx Gains

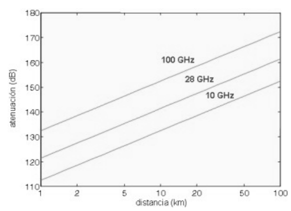


$$\phi_{tx} = \frac{P_{tx} G_{tx}}{4\pi r^2} = \frac{PIRE}{4\pi r^2} \qquad P_{rx} = \phi_{tx} A_{rx} = \phi_{tx} \frac{\lambda^2}{4\pi} G_{rx} = \frac{P_{tx} G_{tx} G_{rx} \lambda^2}{(4\pi r)^2}$$

Friis Transmission Equation

- For Isotropic antennas and free-space propagation
  ➔ The basic losses are

$$\left.\begin{aligned} p_{Rx} &= \phi_{iso}\cdot s_{eq_{iso}} = \phi_{iso}\cdot\frac{\lambda^2}{4\pi} \\ \phi_{iso} &= \frac{p_{Tx}}{4\pi d^2} \end{aligned}\right\} \Rightarrow l_{bf} = \frac{p_{Tx}}{p_{Rx}} = \left(\frac{4\pi d}{\lambda}\right)^2$$



$$L_{bf}(dB) = 32{,}45 + 20\log f(MHz) + 20\log d(km)$$

$$L_{bf}(dB) = 92{,}45 + 20\log f(GHz) + 20\log d(km)$$

Friis Transmission Equation

- For any pair of antennas and free-space propagation
  ➔ The basic losses are

$$l_{tf} = \frac{p_{et}}{p_{dr}} \quad \begin{cases} p_{et}: \text{power handed in to Tx antenna} \\ p_{dr}: \text{power handed in to Rx antenna} \end{cases}$$

$$\left.\begin{aligned} p_{dr} &= \phi\cdot s_{eq} = \phi\cdot\frac{\lambda^2}{4\pi}\cdot g_{Rx} \\ \phi &= \frac{p_{et}}{4\pi d^2}\cdot g_{Tx} \end{aligned}\right\} \Rightarrow l_{tf} = \frac{p_{Tx}}{p_{Rx}} = \left(\frac{4\pi d}{\lambda}\right)^2 \cdot \frac{1}{g_{Tx}\cdot g_{Rx}} = \frac{l_{bf}}{g_{Tx}\cdot g_{Rx}}$$

$$p_{Rx} = \frac{p_{Tx} g_{Tx}\cdot g_{Rx}}{\left(\frac{4\pi d}{\lambda}\right)^2}$$

$$L_{tf}(dB) = L_{bf}(dB) - G_{Tx}(dB) - G_{Rx}(dB)$$

Friis Transmission Equation

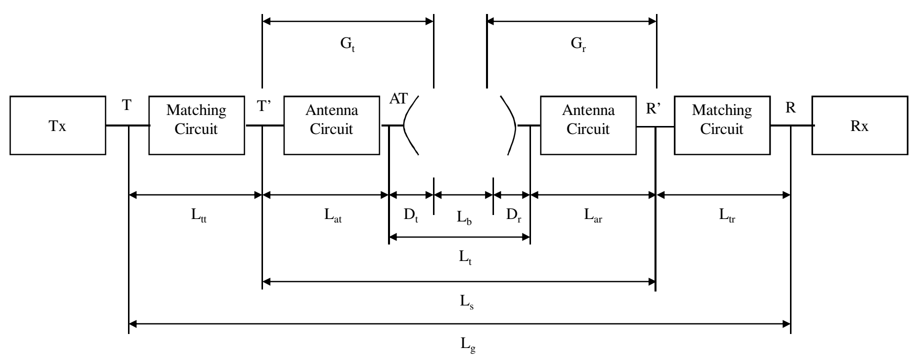
- Sumarizing, for any antenna

$$l_t = \frac{p_{Tx}}{p_{Rx}} = a_e \cdot \left(\frac{4\pi d^2}{\lambda}\right) \cdot \frac{1}{g_{Tx} \cdot g_{Rx}}$$

$$\boxed{L_t = L_{bf} + A_e - G_t - G_r = L_b - G_t - G_r}$$

	Usual Notation	Definition	
		Antennas	Mean
Free-Space Basic Loss	L_{bf}	Isotripic	Free-Space
Basic Loss	L_b	Isotripic	Any
Free-Space Transmission Loss	L_{tf}	Any	Free-Space
Transmission Loss	L_t	Any	Any

Friis Transmission Equation



Link Budget

- Link Budget = expression for available power at the receiver as a function of
  - Transmitted Power
  - Rx andTx Antenna Gains
  - All the losses in the link

$$P_{Rx} = P_{Tx} - L_{bf} + G_{Tx} + G_{Rx} - A_e$$

Link Budget

- Other factors affecting the link
  - Normalized Noise Power
    - SNR
    - Power-limited Systems
      - Minimum Received Power (Sensibility) + Fading Margin
      - The maximum distance between Tx and Rx is calculated by the Link Budget

$$p_n = k \cdot T_0 \cdot b \cdot f_{sis} \qquad P_n(dBm) = F_{sis}(dB) + 10\log b(Hz) - 174$$

  - Interference

$$p_n = k \cdot T_{eq} \cdot b$$

    - C/I; SINR
    - Interference-limited Systems
  - Performances: BER, PER, $P_{\text{out}}\ldots$

Important Concepts in this Topic

- Poynting Vector
- Radiated Power Flux Density
- Antenna Directivity
- Antenna Gain
- Antenna Efficiency
- Antenna Effective Aperture
- Polarization
- Reciprocity Theorem
- Most common simple antennas
- Friis Equation and Link Budget
- Free-Space Basic Propagation Loss