EE540 Advance Electromagnetic Theory & Antennas

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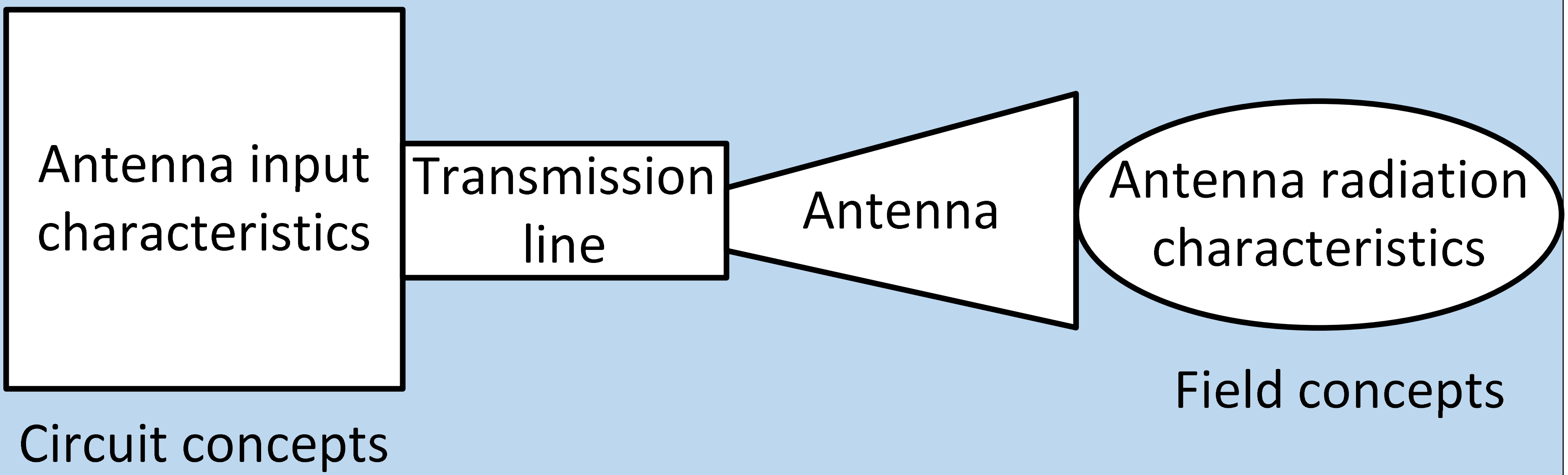
Antenna pattern and parameters

- Which parameters are used for specifying an antenna?
- What parameters differentiate one antenna from others?
- How do one characterize an antenna?
- Antenna has two types of characteristics from
  - Field concepts
  - Circuit concepts

Antenna pattern and parameters

- An antenna can launch free space wave in a desired direction
  - This directional characteristics of an antenna can be interpreted from its radiation characteristics
- We also know that an antenna is connected to a transmission line
  - and it converts guided wave to free space wave
  - Hence it can be thought as a load to the transmission line
  - One can find its equivalent circuit (input characteristics)

Antenna pattern and parameters



- Fig. Antenna characteristics: (a) Radiation characteristics (b) input characteristics

Antenna pattern and parameters

- Radiation characteristics
  - Radiation pattern
  - Directivity
  - Gain
  - Polarization, etc.

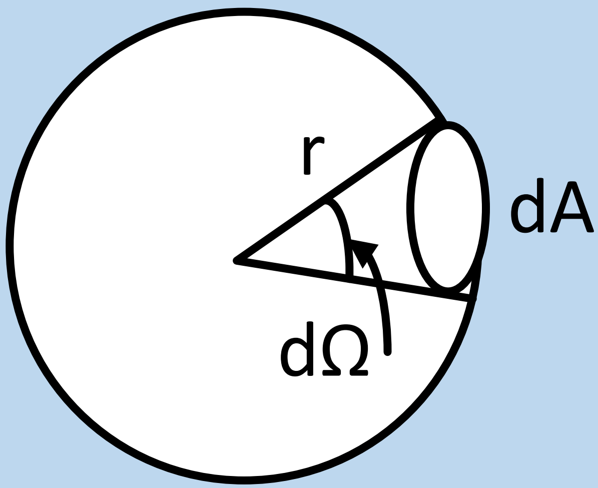
Antenna pattern and parameters

- Input characteristics
  - Input impedance
  - Bandwidth
  - Reflection coefficient
  - Voltage standing wave ratio, etc.

Antenna pattern and parameters

- Radiation characteristics
  - Radiation intensity:
    - The most fundamental parameter is its radiation intensity
    - Based on this parameter,
      - gain and
      - directivity
    - of the antenna will be defined

Antenna pattern and parameters



$$d\Omega = \frac{dA}{r^2}$$

- Fig. Solid angle (Ratio of the area subtended by the solid angle to the squared radius)

Antenna pattern and parameters

- Radiation intensity is defined as power crossing per unit solid angle
- Power crossing over the area dA is $S(\theta,\phi)dA$

$$U(\theta,\phi)=\frac{S(\theta,\phi)dA}{d\Omega}=S(\theta,\phi)r^2\left(W/Sr\right)$$

- Radiation intensity can be calculated by
  - multiplying the Poynting vector by r^2

Antenna pattern and parameters

- For example
- Hertz dipole

$$U(\theta,\phi)=S(r,\theta,\phi)r^2=\frac{\beta^2 I_0^2 dl^2 \sin^2\theta}{32\pi^2\eta_0}$$

  - Note that U(θ,φ) is independent of r
- Normalized radiation intensity is a dimensionless quantity

$$U_n(\theta,\phi)=\frac{U(\theta,\phi)}{U_{\max}(\theta,\phi)}$$

  - For Hertz dipole $U_n(\theta,\phi)=\sin^2\theta$

Antenna pattern and parameters

- It is usually expressed in dB
  - For Hertz dipole

$$U_{n_{dB}}(\theta,\phi)=10\log_{10}\left(\sin^2\theta\right)$$

- The power or radiation intensity pattern is
  - the angular distribution of antenna's radiated power
  - per unit solid angle

Antenna pattern and parameters

- One could also find the total radiated power of an antenna as

$$P_{rad} = \int_{\Omega=4\pi} U(\theta,\phi)\,d\Omega = \int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} U(\theta,\phi)\sin\theta\,d\theta\,d\phi$$

- Average radiation intensity is defined as

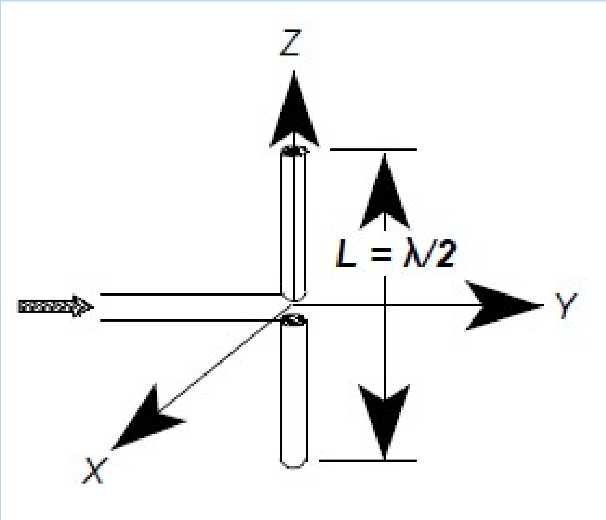
$$U_{avg} = \frac{P_{rad}}{4\pi} = \frac{1}{4\pi}\int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} U(\theta,\phi)\sin\theta\,d\theta\,d\phi$$

Antenna pattern and parameters

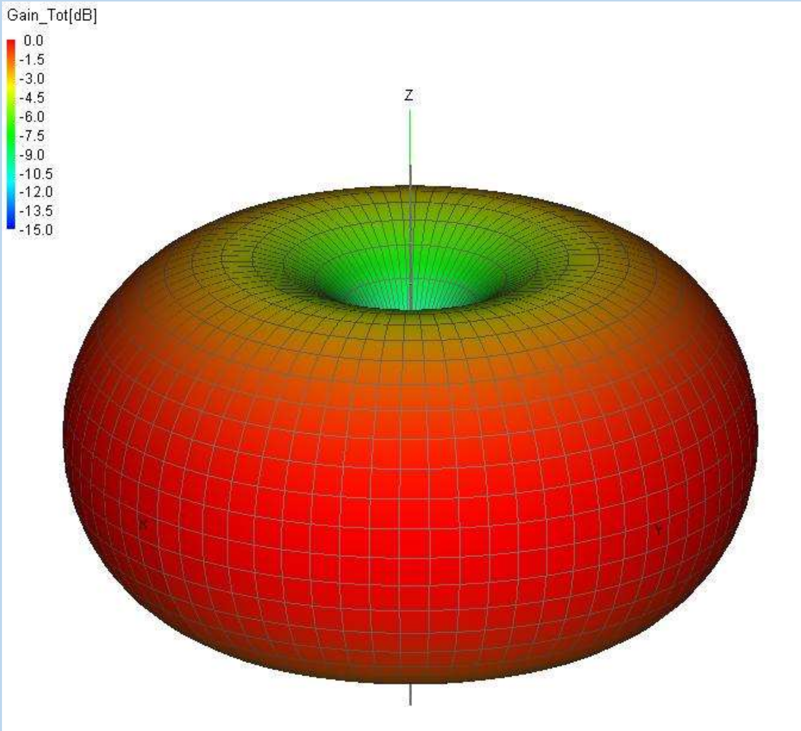
What is antenna radiation pattern?

- The radiation pattern of an antenna is a 3-D graphical representation of the radiation properties of the antenna as a function of position (usually in spherical coordinates)
- If we imagine an antenna is placed at the origin of a spherical coordinate system,
  - its radiation pattern is given by measurement of the magnitude of the electric field over a surface of a sphere of radius r

Antenna pattern and parameters

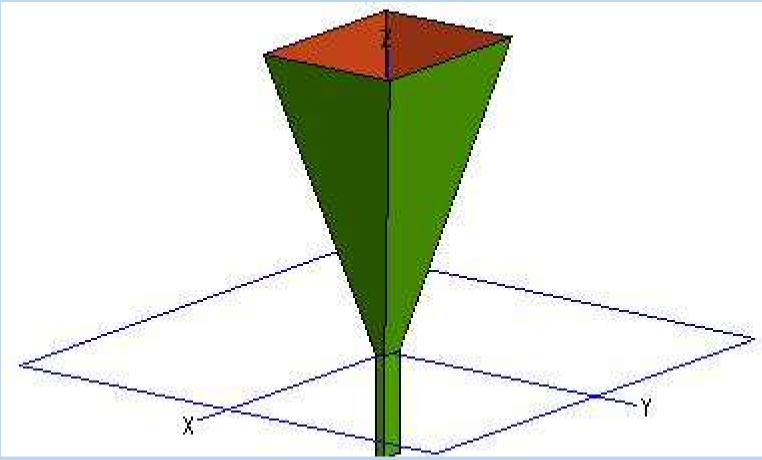


Dipole Antenna

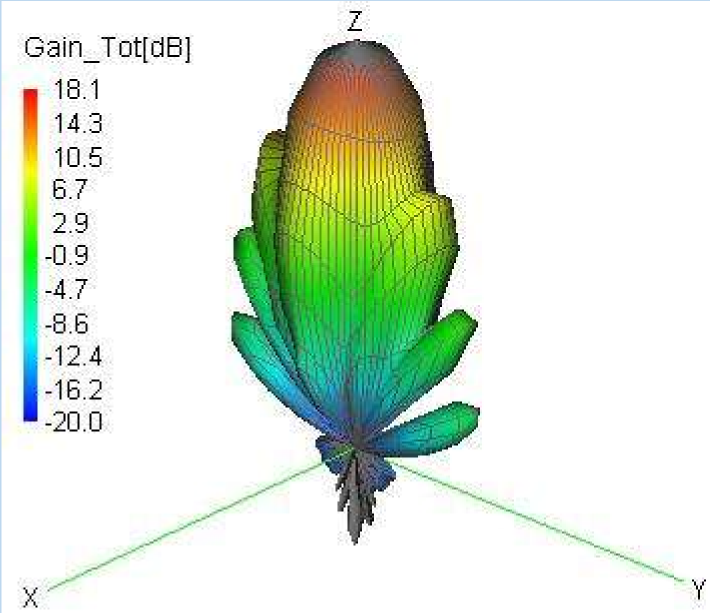


Omni-directional radiation pattern

Antenna pattern and parameters



Horn Antenna



Directional radiation pattern

Antenna pattern and parameters

- For a fixed r, electric field is only a function of θ and ϕ

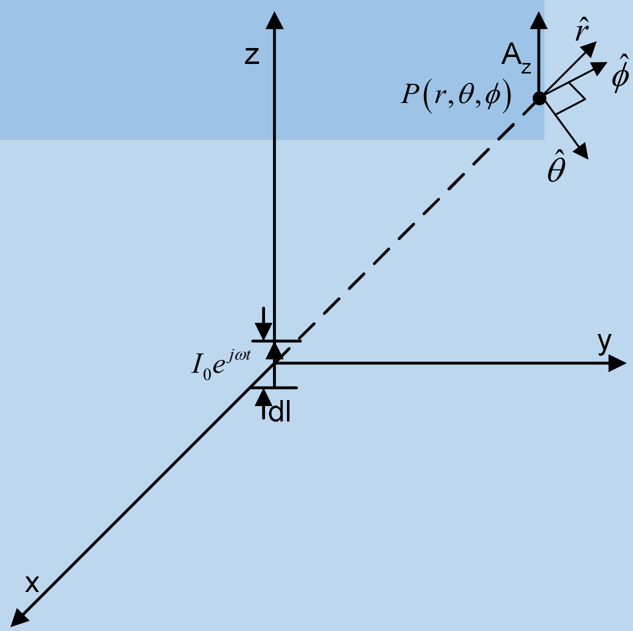
$$\vec{E}(\theta,\phi)$$

- Two types of patterns are generally used:
  - (a) field pattern (normalized $|\vec{E}|$ or $|\vec{H}|$ versus spherical coordinate position) and
  - (b) power pattern (normalized power versus spherical coordinate position).

Antenna pattern and parameters

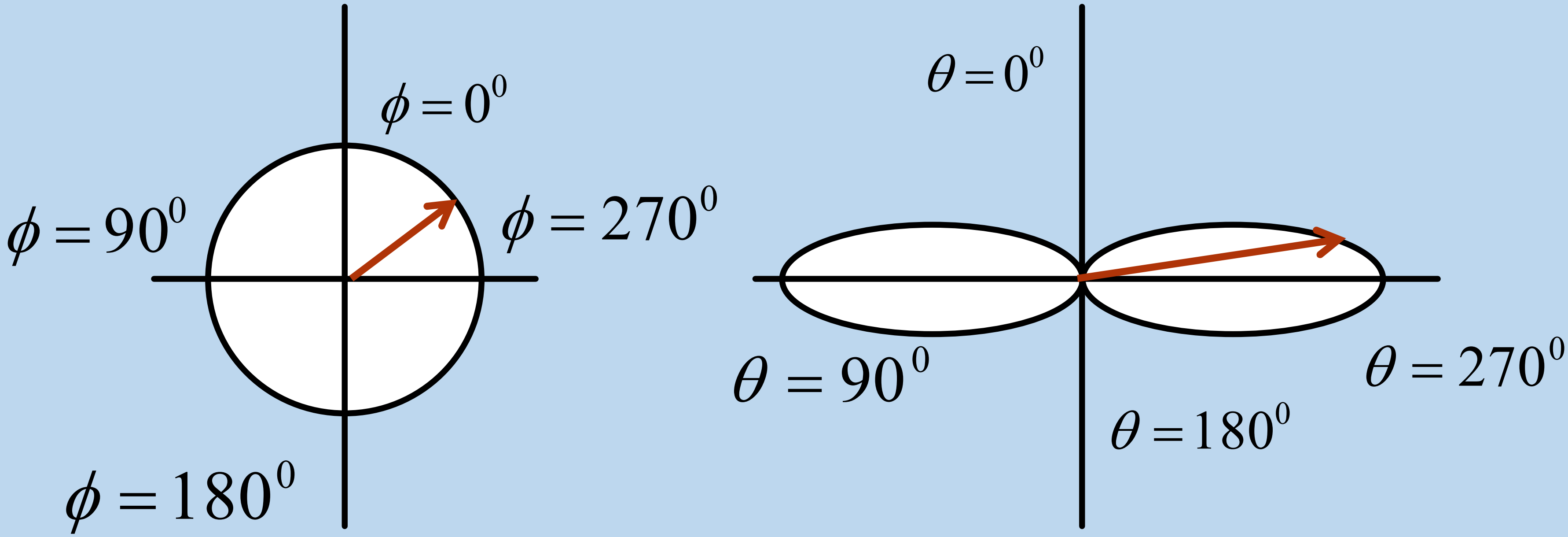
- 3-D radiation patterns are difficult to draw and visualize in a 2-D plane like pages of this book
- Usually they are drawn in two principal 2-D planes which are orthogonal to each other
  - Generally, xz- and xy- plane are the two orthogonal principal planes
  - E-plane (H-plane) is the plane in which there are maximum electric (magnetic) fields for a linearly polarized antenna

Antenna pattern and parameters



- For example,
  - Hertz dipole
- How to decide E- and H- planes?
  - Current is flowing in z-direction
  - Magnetic vector potential follows the current direction
  - Magnetic field will be along φ-direction (H-plane is in x-y plane)
  - Electric field will be along θ-direction (E-plane is in x-z plane)

Antenna pattern and parameters

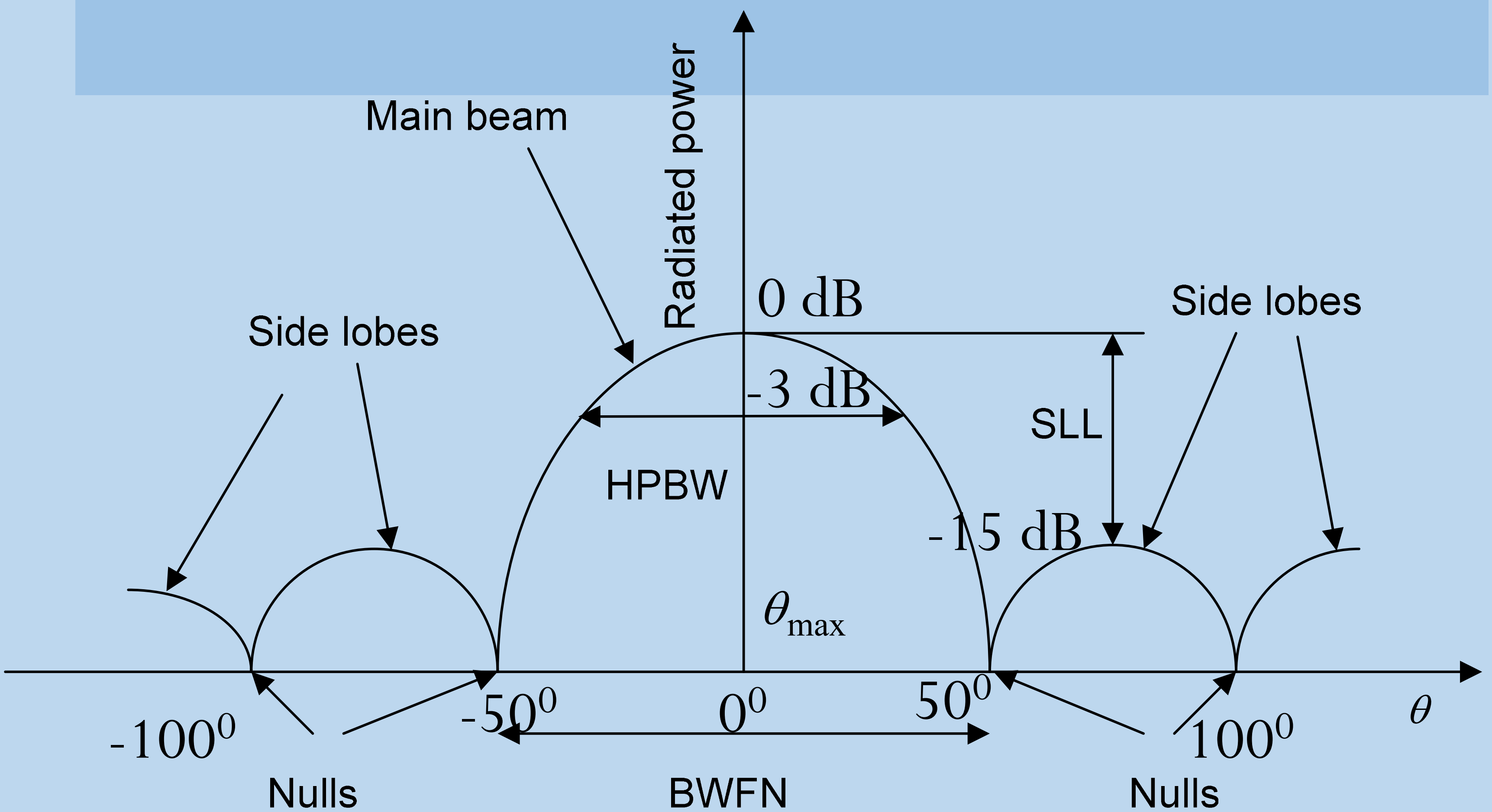


- Fig. H-plane (x-y plane) and E-plane (x-z plane) radiation patterns of Hertz dipole

Antenna pattern and parameters

- Besides 2-D and 3-D polar plots,
  - radiation pattern may be plotted as rectangular plots
- In this case,
  - horizontal axis is in degrees
  - vertical axis is normalized radiated power in dB

Antenna pattern and parameters



- Fig. Typical radiation pattern of an antenna (rectangular plots)

Antenna pattern and parameters

- A typical antenna radiation pattern looks like as in shown Fig.
- It could be a polar plot as well
- An antenna usually has either one of the following patterns:
  - (a) isotropic (uniform radiation in all directions, it is not possible to realize this practically)
  - (b) directional (more efficient radiation in one direction than another)
  - (c) omnidirectional (uniform radiation in one plane)

Antenna pattern and parameters

Direction of the main beam (θ_{max})

- A radiation lobe is a clear peak in the radiation intensity surrounded by regions of weaker radiation intensity
  - Main beam is the biggest lobe in the radiation pattern of the antenna
- It is the radiation lobe in the direction of maximum radiation

Antenna pattern and parameters

- θ_{max} is the direction in which maximum radiation occurs
  - Any lobe other than the main lobe is called as minor lobe
  - The radiation lobe opposite to the main lobe is also termed as back lobe
  - This will be more appropriate for polar plot of radiation pattern

Antenna pattern and parameters

Half power beam width (HPBW)

- It is the angular separation between the half of the maximum power radiation in the main beam
- At these points, the radiation electric field reduces by $\frac{1}{\sqrt{2}}$ of the maximum electric field
- Its shows how sharp is the beam
- Half power is also equal to -3-dB
  - We also call HPBW as -3-dB beamwidth
  - They are measured in the E-plane and H-plane radiation patterns of the antenna

Antenna pattern and parameters

Beam width between first nulls (BWFN)

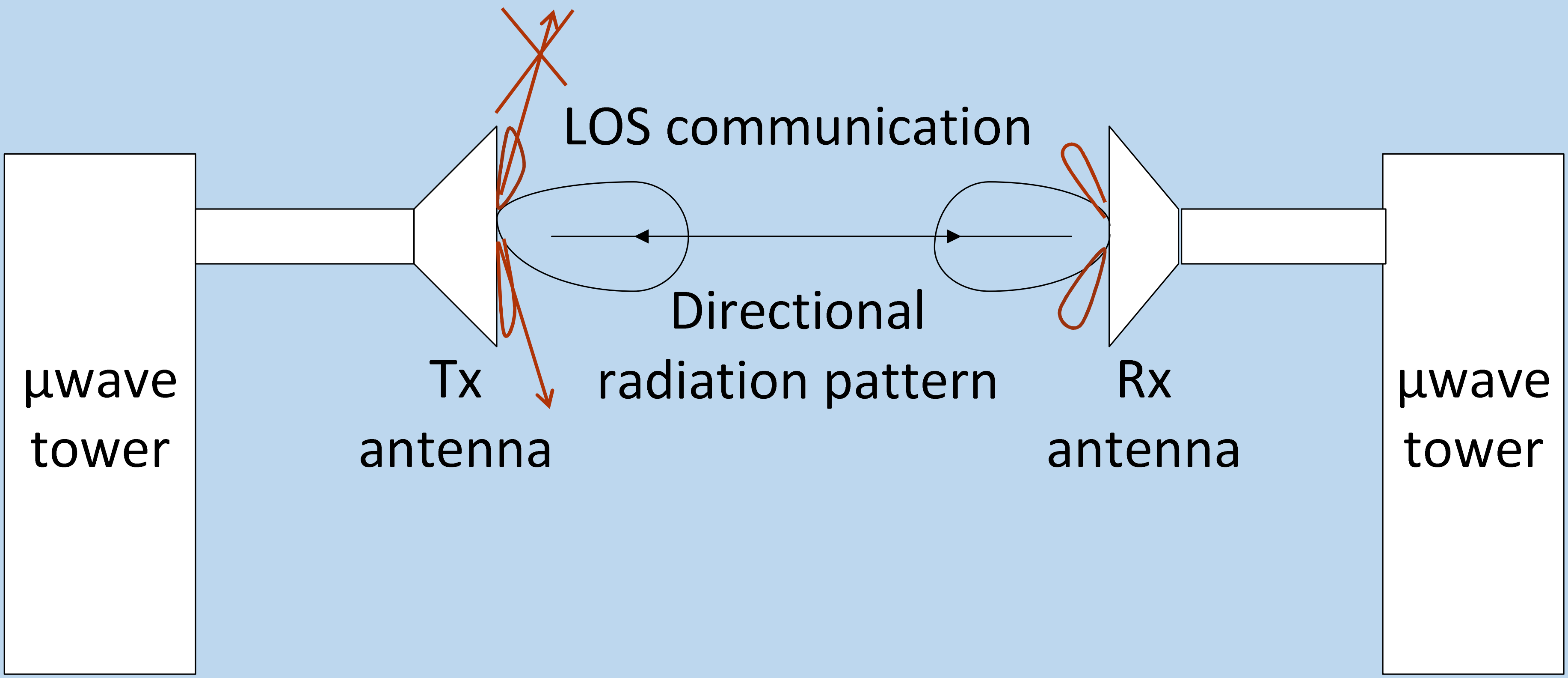
- It is the angular separation between the first two nulls on either side of the main beam
- For same values of BWFN, we can have different values of HPBW for narrow beams and broad beams
- HPBW is a better parameter for specifying the effective beam width
- It gives an idea of the main beam shape

Antenna pattern and parameters

Side lobe level (SLL)

- The side lobes are the lobes other than the main beam and
  - it shows the direction of the unwanted radiation in the antenna radiation pattern
- The amplitude of the maximum side lobe in comparison to the main beam maximum amplitude of the electric field is called as side lobe level (SLL)
- ***It is normally expressed in dB and a SLL of -30 dB or less is considered to be good for a communication system***

Antenna pattern and parameters

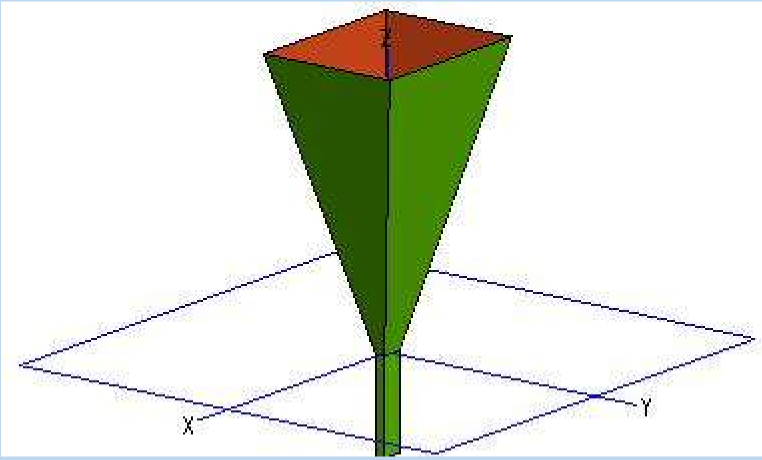


- Fig. Microwave tower: LOS communication (*lower SLL is better for communications since power gone to side lobe is wasted power*)

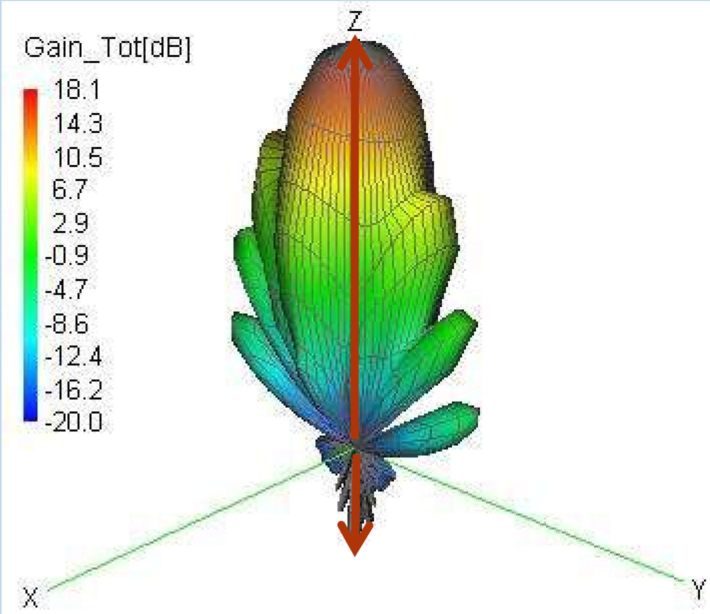
Antenna pattern and parameters

- Back lobe
- Sometimes antenna may have back lobe radiation
  - It is specified by front-to-back ratio
  - It is basically the ratio of the peak of the main lobe over the peak of the back lobe
  - ***Higher front-to-back ratio is better for communications***
- It gives an idea abut the directivity of an antenna
  - Like side lobe, back lobe is also an unwanted radiation

Antenna pattern and parameters



Horn Antenna

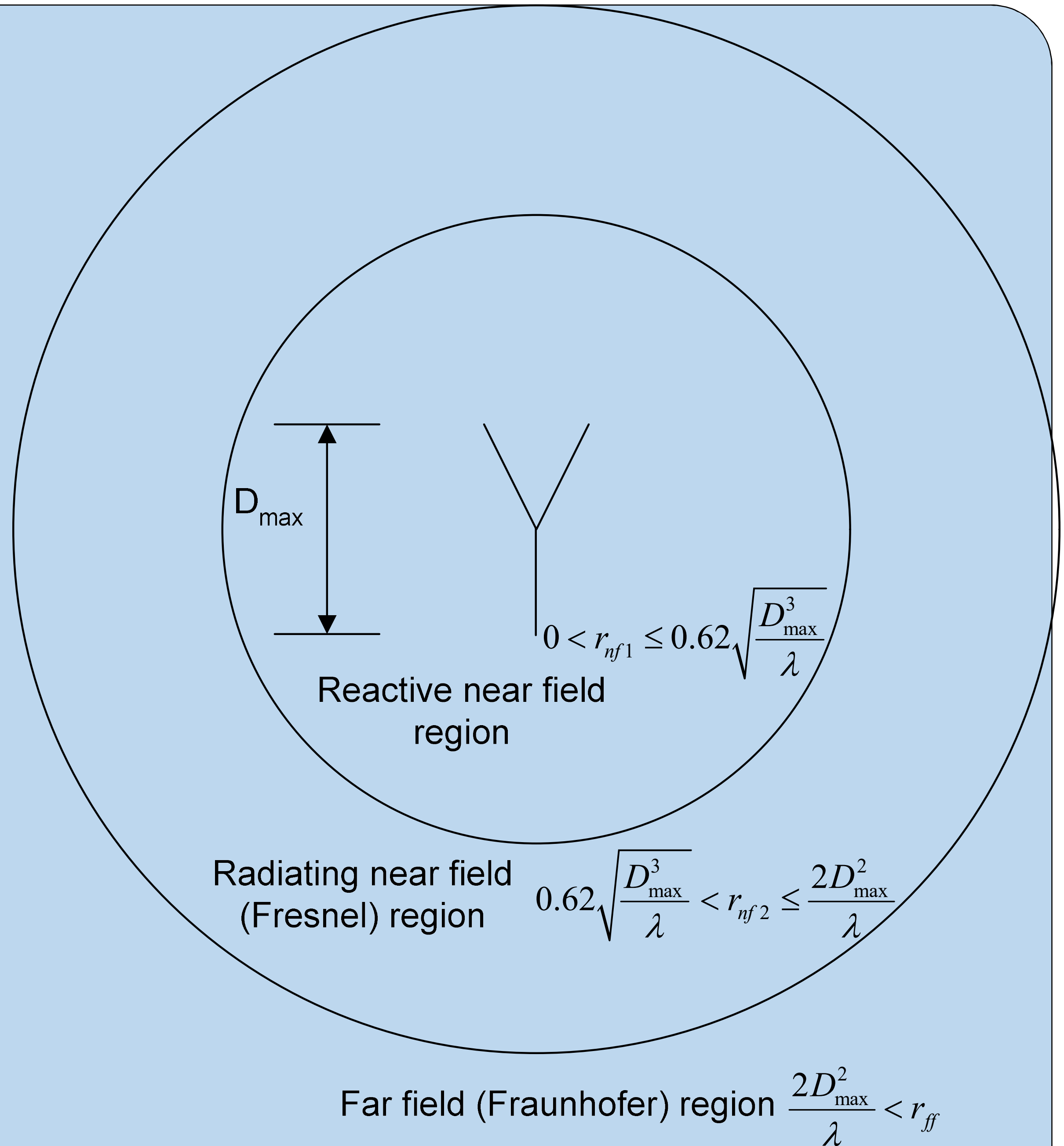


Directional radiation pattern

Antenna pattern and parameters

- At what distance from the antenna, we may assume far field region
- Region surrounding an antenna may be divided into three regions:
  - Reactive near field
  - Radiating near field
  - Far field

Antenna field regions



Antenna pattern and parameters

- The antenna field regions could be divided broadly into three regions (see Fig.):

Reactive near field region:

- This is the region immediately surrounding the antenna where the reactive field (stored energy-standing waves) dominates
- Reactive near field region is for a radius of

$$0 < r_{nf1} \leq 0.62\sqrt{\frac{D_{\max}^3}{\lambda}}$$

- where D_{max} is the maximum antenna dimension

Antenna pattern and parameters

Radiating near field (Fresnel) region:

- The region in between the reactive near field and the far-field (the radiation fields are dominant)
- the field distribution is dependent on the distance from the antenna
- Radiating near field (Fresnel) region is usually for a radius of

$$0.62\sqrt{\frac{D_{\max}^{3}}{\lambda}} < r_{nf2} \leq \frac{2D_{\max}^{2}}{\lambda}$$

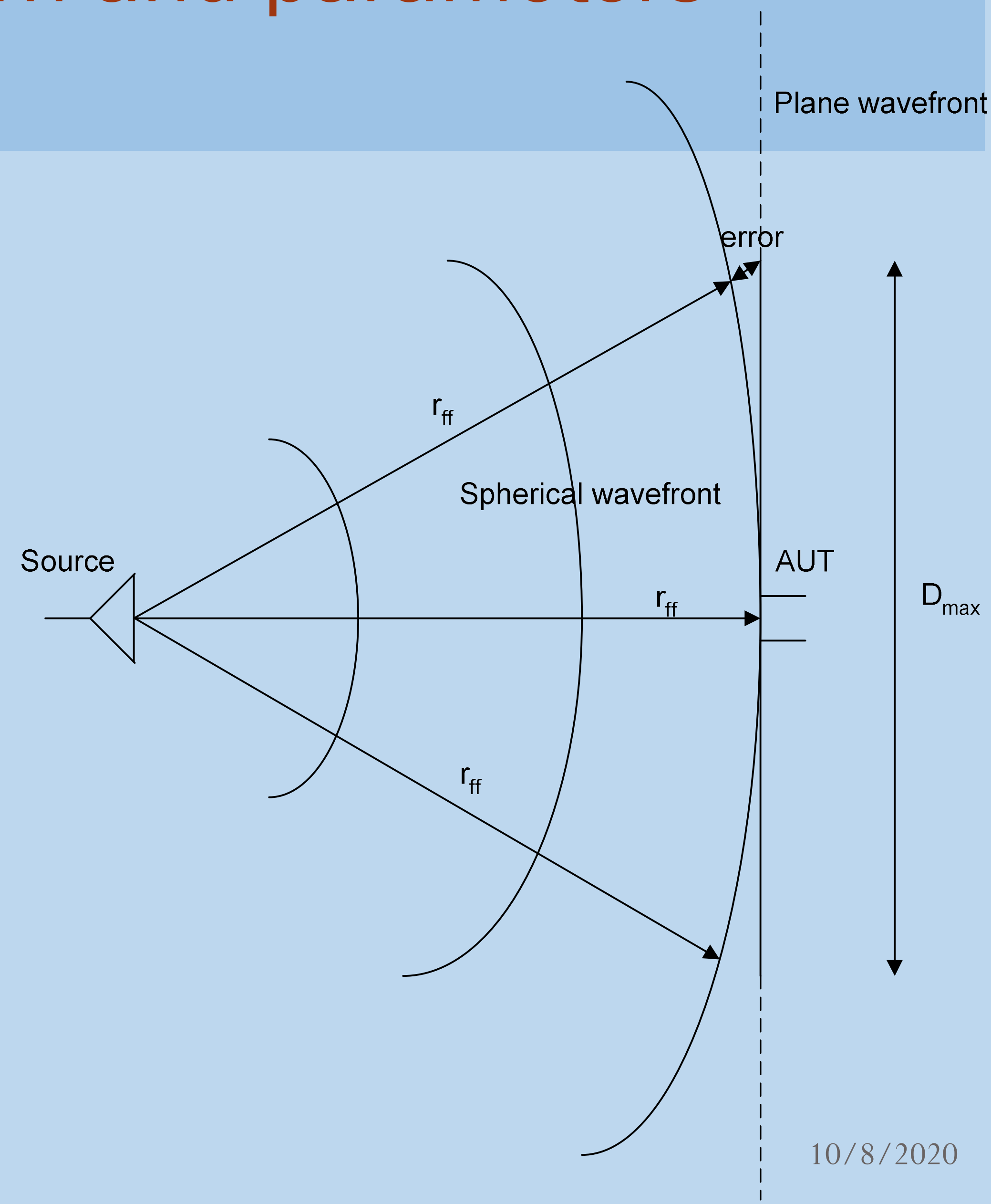
Antenna pattern and parameters

Far field (Fraunhofer) region:

- This is the region farthest from the antenna where the field distribution is essentially independent of the distance from the antenna (propagating waves)
- Fraunhofer far field region is usually for a radius of $\left(\frac{2D_{\max}^2}{\lambda} < r_{ff} \right)$
- In the far field region, the spherical wavefront radiated from a source antenna can be approximated as plane wavefront
- The phase error in approximating this is $\pi/8$

Antenna pattern and parameters

- Fig. Illustration of far field region (antenna under test: AUT)



Antenna pattern and parameters

- We can calculate the distance r_{ff} by equating the maximum error (which is at the edges of the AUT of maximum dimension D_{max}) in the distance r by approximating spherical wavefront to plane wavefront to $\lambda/16$ (Exercise 8.1)

Antenna pattern and parameters

Directivity

- The directivity of an antenna is defined as
  - the ratio of the radiation intensity in a given direction from the antenna
  - to the radiation intensity averaged over all directions
    - which equivalent to the radiation intensity of an isotropic antenna

$$D(\theta,\phi) = \frac{U(\theta,\phi)}{U_{avg}} = \frac{4\pi U(\theta,\phi)}{\int_{\theta=0}^{\pi}\int_{\phi=0}^{2\pi} U(\theta,\phi)\sin\theta d\theta d\phi}$$

Antenna pattern and parameters

- D (θ, ϕ) is maximum at θ_{max} and minimum along θ_{null}

$$D_{\max}(\theta,\phi)=\frac{U_{\max}}{\mathrm{U}_{\mathrm{avg}}}=\frac{4\pi U_{\max}(\theta,\phi)}{\int\limits_{\theta=0}^{\pi}\int\limits_{\phi=0}^{2\pi}U(\theta,\phi)\sin\theta d\theta d\phi}=\frac{4\pi}{\Omega_A}$$

- Ω_A is also known as beam solid angle
- It is also defined as the solid angle through which all the antenna power would flow
  - if the radiation intensity was $U_{\max}(\theta,\phi)$ for all angles in Ω_A

Antenna pattern and parameters

- Given an antenna with one narrow major beam, negligible radiation in its minor lobes

$$\Omega_A \approx \theta_{HPBW}^{rad} \times \phi_{HPBW}^{rad}$$

- where θ_{HPBW} and ϕ_{HPBW} are the half-power beam widths in radians which are perpendicular to each other
- For narrow beam width antennas $(\theta_{HPBW}, \phi_{HPBW} << 1)$
- It can be shown that the maximum directivity is given by

$$D_{\max} \cong \frac{4\pi}{\theta_{HPBW}^{rad} \times \phi_{HPBW}^{rad}}$$

Antenna pattern and parameters

- If the beam widths are in degrees, we have

$$D_{\max} \cong \frac{4\pi\left(\frac{180}{\pi}\right)^2}{\theta_{HPBW}^{\deg} \times \phi_{HPBW}^{\deg}} = \frac{41,253}{\theta_{HPBW}^{\deg} \times \phi_{HPBW}^{\deg}}$$

Gain

- In defining directivity, we have assumed that the antenna is lossless
- But, antennas are made of conductors and dielectrics

Antenna pattern and parameters

- It has same in-built losses accompanied with the conductors and dielectrics
- Thereby, the power input to the antenna is partly radiated and
  - remaining part is lost in the imperfect conductors as well as in dielectrics
- The gain of an antenna in a given direction is defined as
  - the ratio of the intensity in a given direction
  - to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically

Antenna pattern and parameters

$$G(\theta,\phi)=\frac{4\pi U(\theta,\phi)}{P_{input}}=\frac{4\pi U(\theta,\phi)\mathrm{e}_{\mathrm{rad}}}{P_{rad}}=\mathrm{e}_{\mathrm{rad}}D(\theta,\phi)$$

- *Note that definitions of the antenna directivity and gain are essentially the same*
  - *except for the power terms used in the definitions*
- *Directivity is the ratio of the antenna radiated power density at a distant point to the total antenna radiated power radiated isotropically*
- *Gain is the ratio of the antenna radiated power density at a distant point to the total antenna input power radiated isotropically*

Antenna pattern and parameters

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2$$

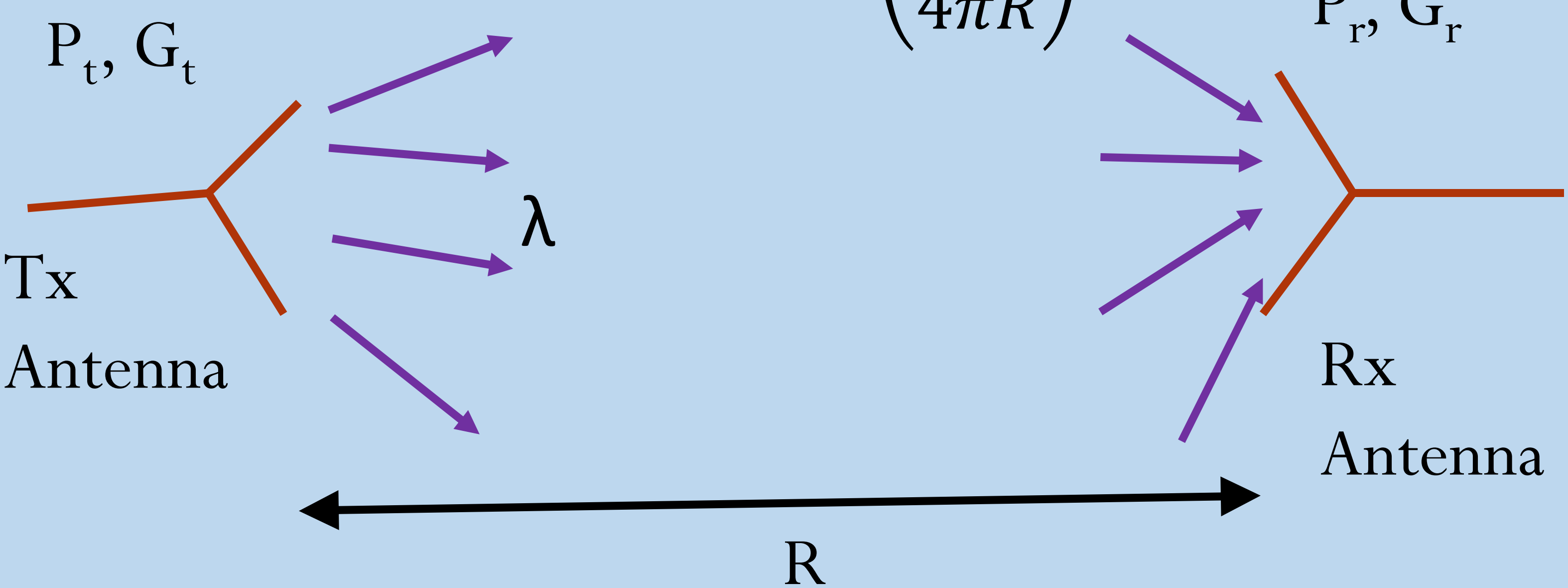


Fig. Friis transmission formula

Antenna pattern and parameters

- Friis transmission equation states that the ratio of the received power at the receiving antenna and transmitted power at the transmitting antenna is:
  - directly proportional to both gains of the transmitting (G_t) and receiving (G_r) antennas
  - inversely proportional to square of the distance between the transmitting and receiving antennas ($1/R^2$) and
  - directly proportional to the square of the wavelength of the signal transmitted (λ^2) (***It means higher frequency, lower is the wavelength, less is the power received***)

Antenna pattern and parameters

- Assumptions made are:
- (a) antennas are placed in the far-field regions
- (b) there is free space direct line of sight propagation between the two antennas
- (c) there are no interferences from other sources and
  - no multipaths between the transmitting and receiving antennas due to
    - reflection,
    - refraction and
    - diffraction

Antenna pattern and parameters

- The antenna gain is usually measured based on Friis transmission formula and it requires two identical antennas
- One of the identical antennas is the radiating antenna, and the other one is the receiving antenna
- Assuming that the antennas are well matched in terms of impedance and polarization,
  - the Friis transmission equation is

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi R}\right)^2 G_t G_r \because G_t = G_r = G \therefore G = \frac{1}{2}\left[20\log_{10}\left(\frac{4\pi R}{\lambda}\right) + 10\log_{10}\left(\frac{P_r}{P_t}\right)\right]$$