ANTENNA FUNDAMENTALS

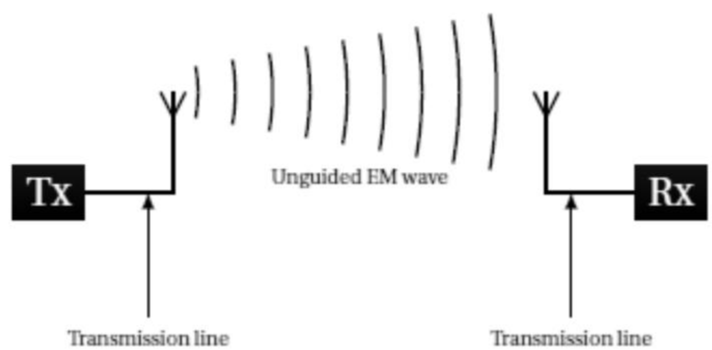
An antenna is a metallic device which is used to transmit or receive electromagnetic energy.

(Or)

According to IEEE standards "An antenna or aerial is a means for radiating or receiving radio waves".

(Or)

An antenna is a transitional structure between free space and guiding device. Usually guiding device may be transmission line or coaxial cable.



WHEN DO ANTENNAS RADIATE? (Fundamental equation of radiation)

Any single wire can be act as an antenna but under specified conditions. It can be explained by following example.

Consider a metallic wire of length 'L' carrying a current 'I' through its length. So we can write from the basic knowledge,

$$\mathbf{i = \frac{q}{t}}$$

Or we can write $\quad \boldsymbol{iL = q\frac{L}{t}}$

$$Li = qv$$

By differentiating the above equation with respect to time we get

$$L\frac{di}{dt} = q\frac{dv}{dt}$$

$$L\dot{I} = q\dot{v}$$

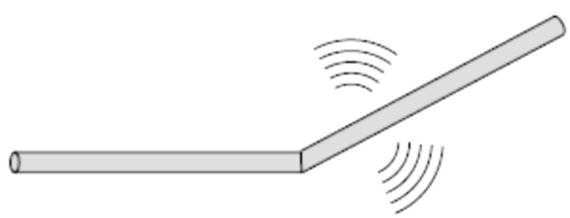
This is the basic relation between charge and current and is known as the fundamental equation of electromagnetic radiation.

Radiation mechanism-Single wire

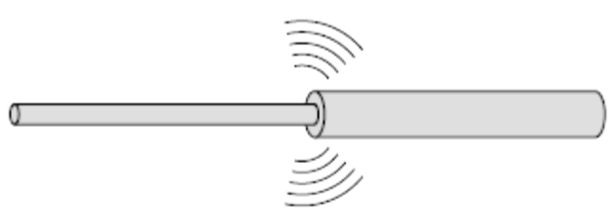
Conducting wires also produce electromagnetic radiation if it satisfies following conditions.

(i) If there is oscillating current in a wire.
(ii) If the wire is curved, bent, discontinuous or terminated as shown in figure.

(a) Curved

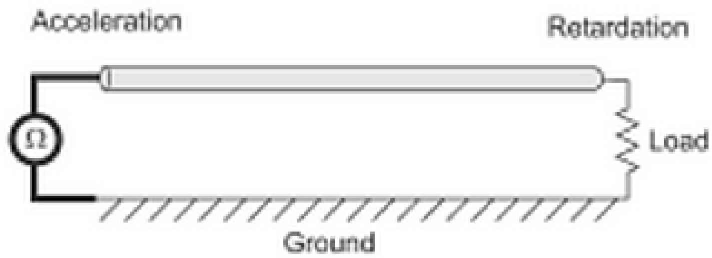


(b) Bent



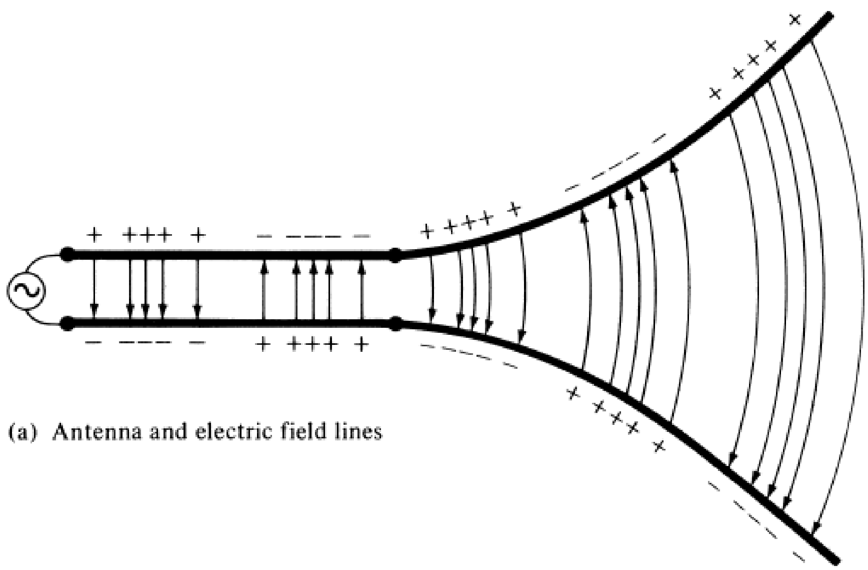
(c) Discontinuous

Consider a pulse source is applied to end of a wire and other end is connected to ground as shown in figure.



The free electrons are accelerated from source and decelerate at the load end due to build up of electrons. The EM radiation produces along the end of the wire since magnitude of acceleration or deceleration is not uniform throughout the wire.

Two wire mechanism



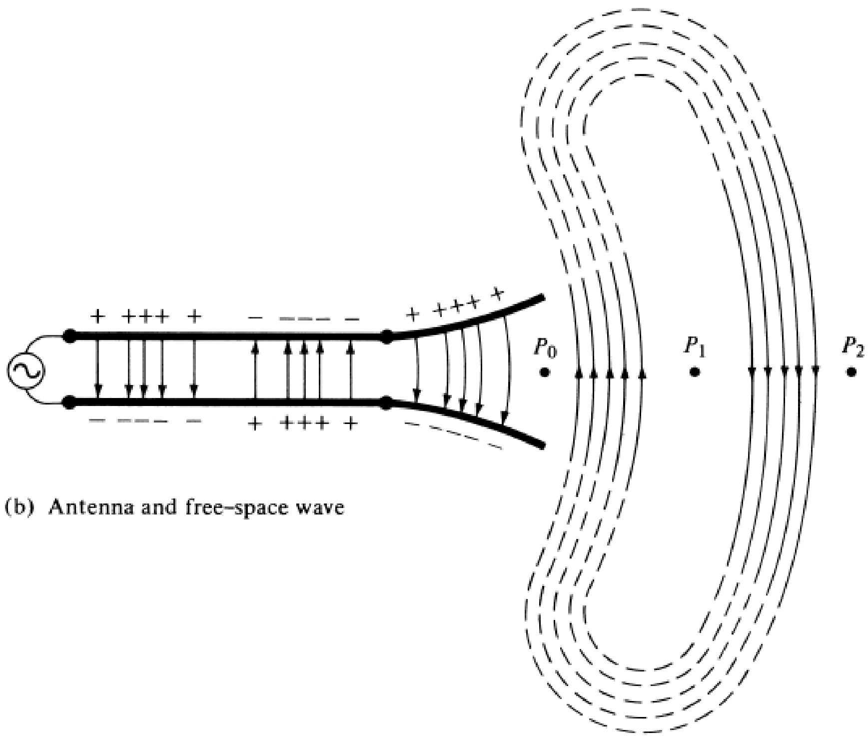
(a) Antenna and electric field lines

In the above figure a voltage source is connected to two wire transmission line which is further connected to antenna. An electric field is created between the conductors, when voltage is applied. The produced electric field of force is tangent to the electric field. Due to this a magnetic field is created by the current.

Since electric field lines, start on positive charge and end on negative charges, they start at infinity and end on negative charge or start at positive end and end at infinity by forming a closed loop.

When sinusoidal voltage is applied EM waves are formed by the time varying electric and magnetic fields between the conductors and which will travel along the transmission line. Then EM waves enter the antenna with electric charges and corresponding currents. When it reaches open ends, free space waves are formed.

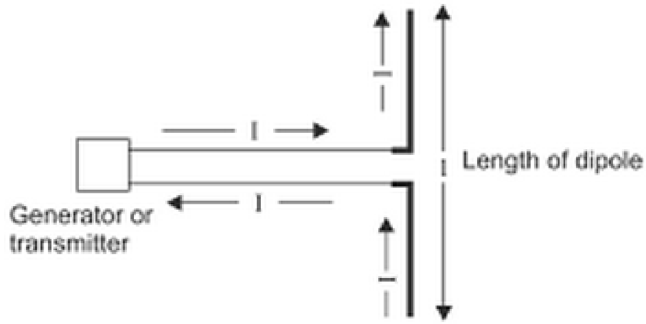
This radiation from the two wire antenna is shown in the following figure below.



(b) Antenna and free-space wave

Radiation from Dipole

If the transition region of the two conductor wire is bent through 90^0 as shown in the figure below, then the two currents become exactly parallel to each other.

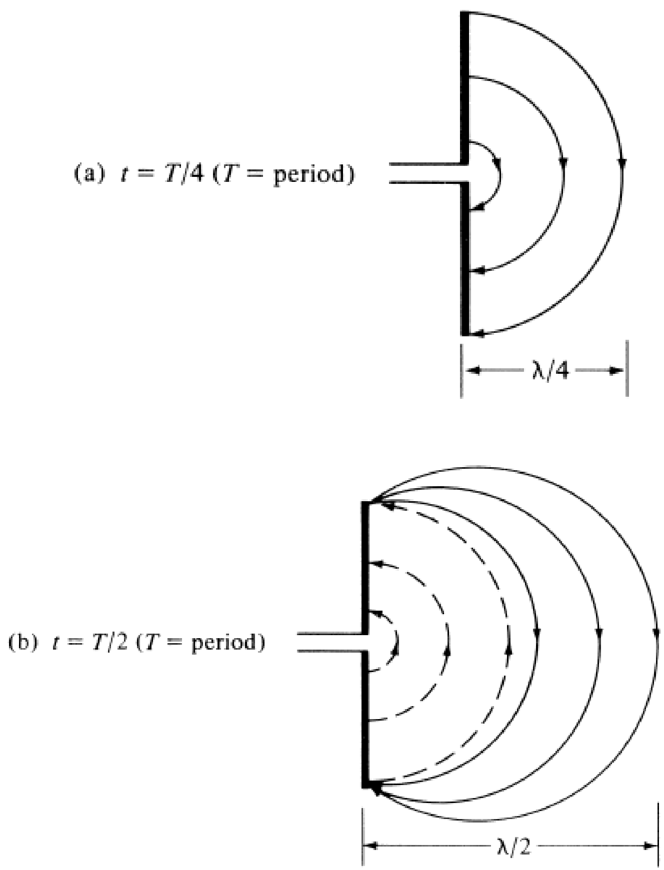


This 90^0 bend provides abrupt change in the impedance at the transition point, where the current is still continuous. This geometry is called as dipole.

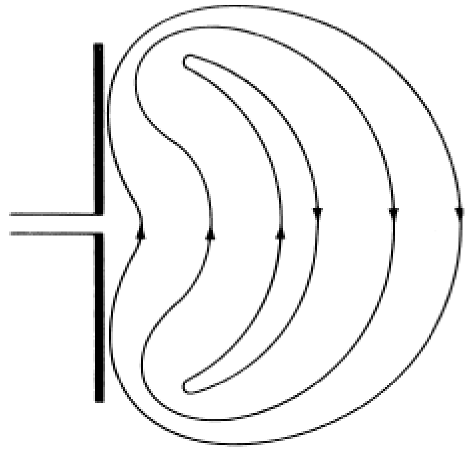
To explain the mechanism in detachment of field lines in to free space. Consider an AC current fed to the dipole. The instantaneous charge on the two arms of the dipole can be written as

$$Q = Q_0 Sin(wt) = Q_0 Sin\frac{2\pi}{T}t$$

The below figure shows how the radiation has been detached from the dipole in step by step.



(c) $t = T/2$ (T = period)



During the fist $T/4$
The charge has reached a maximum. Lines have traveled outwardly a radial distance $\lambda/4$.

During $T/4$ to $T/2$
The original three lines travel an additional $\lambda/4$. The lines created by the opposite charges travel a distance $\lambda/4$. The charge density begins to diminish, leading to neutralization.

At $T/2$
There is no net charge on the antenna. The lines must have been forced to detach themselves from the conductors and to unite together to form closed loops.

Beyond $T/2$
The process repeats.

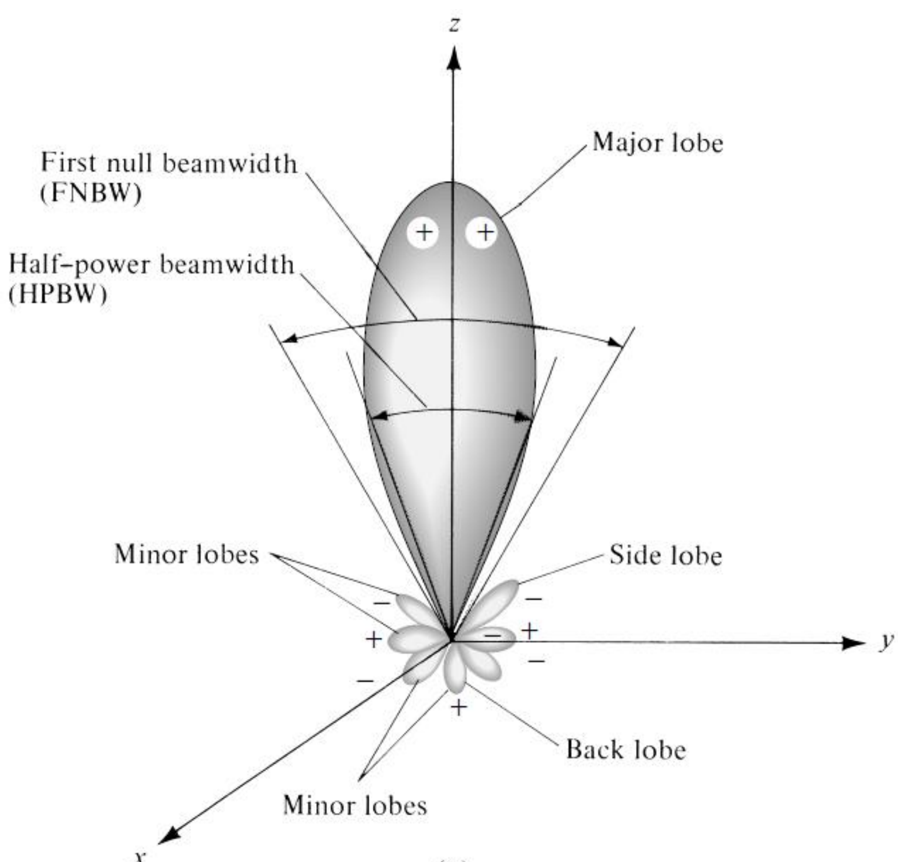
Antenna Parameters

To estimate the performance of the antenna there should be the necessity of studying the different parameters of the antenna. The following parameters are used to characterize any antenna.

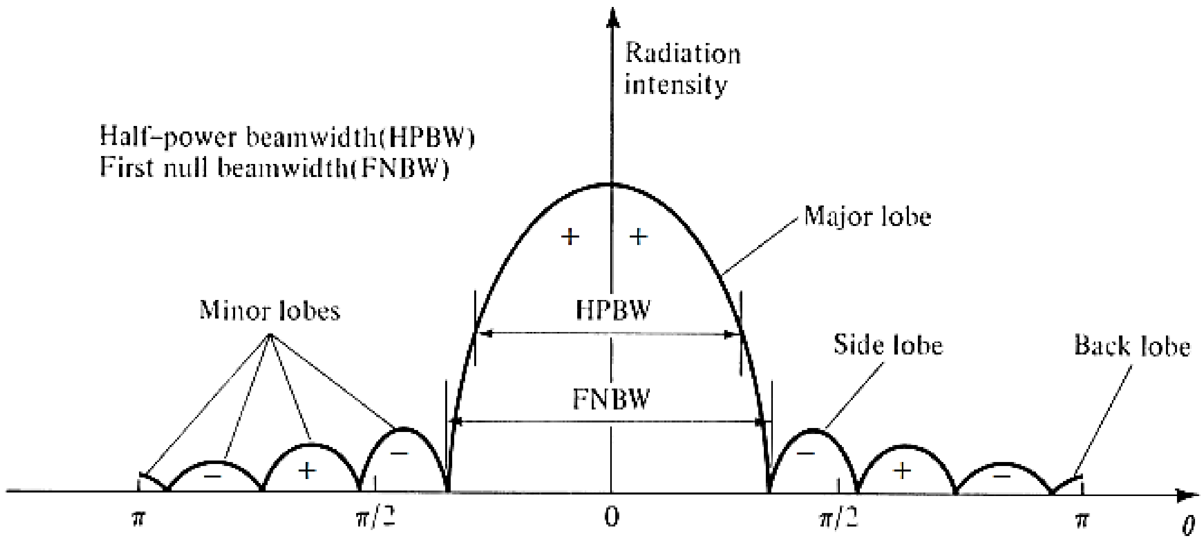
RADIATION PATTERN

An antenna radiation pattern or antenna pattern is defined as "a mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates. Radiation properties include power flux density, radiation intensity, field strength, directivity, phase or polarization."

Various parts of a radiation pattern are referred to as *lobes*, which may be sub classified into *major* or *main, minor, side*, and *back* lobes. A *radiation lobe* is a "portion of the radiation pattern bounded by regions of relatively weak radiation intensity." Figure demonstrates a symmetrical three dimensional polar pattern with a number of radiation lobes.



(a)



(b)

A major lobe (also called main beam) is defined as "the radiation lobe containing the direction of maximum radiation." In Figure the major lobe is pointing in the θ = 0 direction.

A minor lobe is any lobe except a major lobe. In Figures (a) and (b) all the lobes with the exception of the major can be classified as minor lobes.

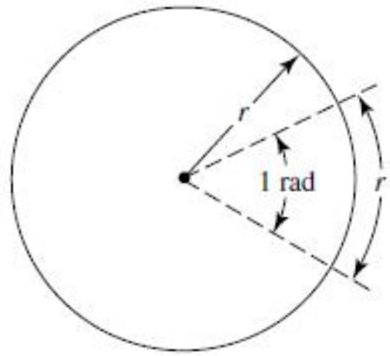
A side lobe is "a radiation lobe in any direction other than the intended lobe".

A back lobe is "a radiation lobe whose axis makes an angle of approximately 180^0 with respect to the beam of an antenna."

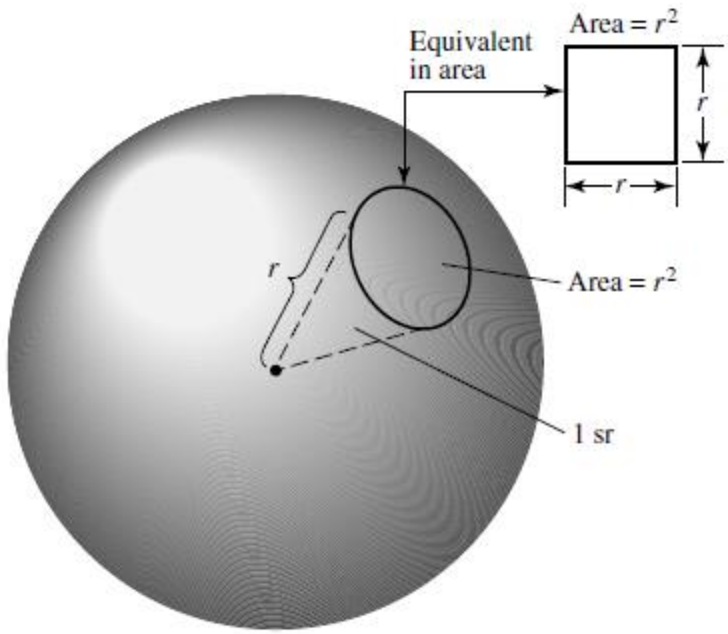
Radian and Steradian

The measure of a plane angle is a radian. One *radian* is defined as the plane angle with its vertex at the center of a circle of radius *r* that is subtended by an arc whose length is *r*. A graphical illustration is shown in Figure. Since the circumference of a circle of radius *r* is $C = 2\pi r$, **there are 2π rad *(2πr/r)* in a full circle.**

The measure of a solid angle is a Steradian. One *Steradian* is defined as the solid angle with its vertex at the center of a sphere of radius *r* that is subtended by a spherical surface area equal to that of a square with each side of length *r*. A graphical illustration is shown in Figure (b). Since the area of a sphere of radius *r* is $A = 4\pi r^2$, **there are 4π sr *($4\pi r^2/r^2$)* in a closed sphere**.



(a) Radian



(b) Steradian

RADIATION POWER DENSITY

This term is used to describe the power associated with the antennas. Radiation power density can be defined as the electromagnetic energy which crosses a unit area in one second. Mathematically it is represented as cross product of electric and magnetic fields. Average power radiated by the antenna is given by

$$\boxed{P_{rad} = P_{av} = \oiint \vec{W}_{av} \cdot d\vec{S} = \frac{1}{2} \oiint \mathrm{Re}\left[\vec{E} \times \vec{H} \right] \cdot d\vec{S} \quad \text{watts}}$$

RADIATION INTENSITY

Radiation intensity in a given direction is defined as "the power radiated from an antenna per unit solid angle." The radiation intensity is a far-field parameter, and it can be obtained by simply multiplying the radiation density by the square of the distance. In mathematical form it is expressed as

$$\boxed{U = r^2 W_{\text{rad}}}$$

where

U = radiation intensity (W/unit solid angle)
W_{rad} = radiation density (W/m^2)

The total power is obtained by integrating the radiation intensity over the entire solid angle of 4π. Thus

$$P_{\text{rad}} = \oint\!\!\oint_{\Omega} U\, d\Omega = \int_0^{2\pi}\int_0^{\pi} U \sin\theta\, d\theta\, d\phi$$

where $d\Omega$ = element of solid angle = $\sin\theta\, d\theta\, d\phi$.

For an isotropic source U will be independent of the angles ϑ and ϕ, as was the case for W_{rad}. Thus can be written as

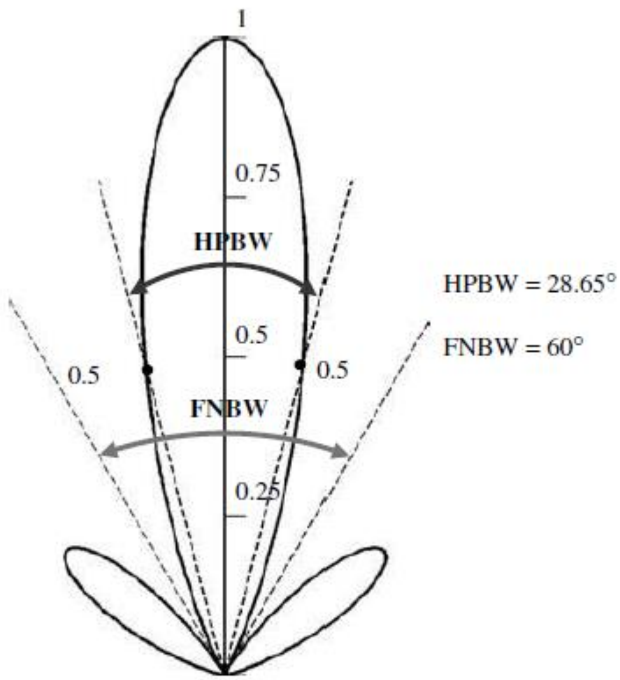
$$P_{\text{rad}} = \oint\!\!\oint_{\Omega} U_0\, d\Omega = U_0 \oint\!\!\oint_{\Omega} d\Omega = 4\pi U_0$$

$$U_0 = \frac{P_{\text{rad}}}{4\pi}$$

BEAMWIDTH

The *beam width* of a pattern is defined as the angular separation between two identical points on opposite side of the pattern maximum. In an antenna pattern, there are a number of beamwidths. One of the most widely used beamwidths is the ***Half-Power Beamwidth*** **(*HPBW)*** which is defined as "In a plane containing the direction of the maximum of a beam, the angle between the two directions in which the radiation intensity is one-half value of the beam."

Another important beamwidth is the angular separation between the first nulls of the pattern, and it is referred to as the ***First-Null Beamwidth* (*FNBW*)**. Both the *HPBW* and *FNBW* are demonstrated for the pattern in Figure.



Beam Efficiency

It is defined as the ratio of Main beam area (Ω_M) to the Total beam area (Ω_A). It is represented by **ε_M** .

$$\in_M = \frac{\Omega_M}{\Omega_A} = \frac{Main\text{ beam area}}{Total\text{ beam area}}$$

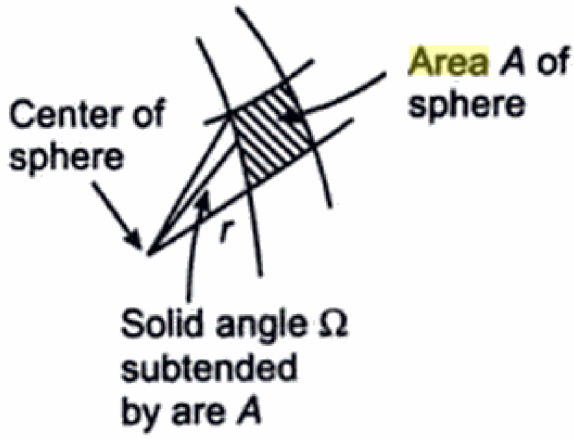
$$Where\ \Omega_A = \Omega_M + \Omega_m$$

$$\in_M + \in_m = 1$$

$$\text{Stray factor} = \in_m = \frac{\Omega_m}{\Omega_A} = \frac{\text{Minor beam area}}{Total\text{ beam area}}$$

Beam Area or Beam solid angle

An area ds of the surface as seen from the center of the sphere subtends a solid angle of Ω. The total solid angle subtended by the sphere is 4π Steradian.



From the above figure incremental area ds is given by

$$ds = r(\sin\theta)\ \mathrm{d}\theta\ \mathrm{d}\phi\ \mathrm{r}$$

$$ds = r^2 \sin\theta \mathrm{d}\theta\ \mathrm{d}\phi$$

$$ds = r^2 d\Omega$$

$d\Omega =$ solid angle subtended by ds

$$d\Omega = \frac{ds}{r^2} = \frac{4\pi r^2}{r^2} = 4\pi \text{ steradian}$$

Thus the beam area of the antenna can be found by integrating the normalized power pattern as follows.

$$\boxed{\begin{aligned} \Omega_A &= \int_0^{\pi}\int_0^{2\pi} P_n(\theta,\phi)\ d\Omega \\ \Omega_A &= \int_0^{\pi}\int_0^{2\pi} P_n(\theta,\phi)\ \sin\theta \mathrm{d}\theta\ \mathrm{d}\phi \end{aligned}}$$

Antenna Efficiency

It is defined as the ratio of power radiated to the total input power supplied to the antenna,

$$\eta = \frac{power\ \text{radiated}}{total\ \text{input power}}$$

$$\eta = \frac{w_r}{w_l} = \frac{I^2 R_r}{I^2 (R_l + R_r)}$$

$$\boxed{\%\eta = \frac{R_r}{(R_l + R_r)} * 100}$$

$where\ R_r = \text{Radiation resistance}$

$R_l = \text{loss resistance}$

Antenna Gain

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. In equation form this can be expressed as

$$\text{Gain} = 4\pi \frac{\text{radiation intensity}}{\text{total input (accepted) power}} = 4\pi \frac{U(\theta, \phi)}{P_{in}} \quad \text{(dimensionless)}$$

For a spherical coordinate system, the total maximum gain for the orthogonal θ and Φ components of an antenna can be written as

$$G_0 = G_\theta + G_\phi$$

while the partial gains G_θ and G_ϕ are expressed as

$$G_\theta = \frac{4\pi U_\theta}{P_{in}}$$

$$G_\phi = \frac{4\pi U_\phi}{P_{in}}$$

where

U_θ = radiation intensity in a given direction contained in E_θ field component
U_ϕ = radiation intensity in a given direction contained in E_ϕ field component
P_{in} = total input (accepted) power

Directivity

The directivity in a given direction can be defined as the ratio of power radiated per unit solid angle to average power radiated.

$$D = \frac{U}{U_{av}}$$

$$U_{av} = \frac{\text{total power radiated}}{\text{total solid angle}} = \frac{P_{rad}}{4\pi}$$

$$\boxed{D = \frac{U}{U_{av}} = 4\pi \frac{U}{P_{rad}} = 4\pi \frac{r^2 W_{rad}}{P_{rad}}}$$

The maximum value of directivity is given by

$$\boxed{D_{max} = \frac{U_{max}}{U_{av}} = 4\pi \frac{U_{max}}{P_{rad}}}$$

Antenna Impedance

Antenna impedance can be defined as ratio of voltage to the current at the input terminals of antenna. This is a complex quantity.

$$Z_A = R_A + jX_A$$

R_A : Antenna resistance. This further consists of two terms

$$R_A = R_L + R_r$$

where R_L : loss resistance of antenna. This represents energy lost as heat in antenna structure

R_r : Radiation resistance. It is fictitious resistance that would dissipate an equivalent amount of power equal to the radiated power

$X_A = \left(\omega L - \dfrac{1}{\omega C}\right)$: Antenna reactance. This is due to the stored energy in the near-field region in the form of electric and magnetic energy. If the two energies become equal, then this term vanishes (antenna resonance).

Effective Area or Effective Aperture

It is defined as the ratio of the power delivered to the receiver and incident radiation power density

$$\boxed{\text{Effective area } (A_e) = \frac{\text{Power delivered to load } (P_R)}{\text{Radiation power density } (W)}}$$

b) Scattering Area (A_S)

It is defined as the ratio of the power scattered (or re-radiated) and incident power density

$$\boxed{\text{Scattering area } (A_S) = \frac{\text{Power re-radiated } (P_r)}{\text{Radiation power density } (W)}}$$

c) Loss Area (A_L)

It is defined as the ratio of power dissipated as heat and incident radiation density

$$\boxed{\text{Loss area } (A_L) = \frac{\text{Power dissipated } (P_L)}{\text{Radiation power density } (W)}}$$

d) Capture Area (A_C)

It is defined as the ratio of total power captured (sum of power delivered to load, scattered power, and power dissipated) by the antenna and incident radiation power density.

$$\boxed{\text{Capture area } (A_C) = \frac{\text{Total power captured } (P_C)}{\text{Radiation power density } (W)}}$$

where $$P_C = P_R + P_r + P_L$$

Capture area is also defined as the sum of the effective, scattering, and loss areas

$$\boxed{A_C = A_e + A_S + A_L}$$

Because on adding equations 3.38, 3.39, and 3.40, we get

$$A_e + A_S + A_L = \frac{P_R + P_r + P_L}{W} = \frac{P_C}{W} = A_C$$

Aperture Efficiency

It is defined as the ratio of Effective area to the physical area. It is given by the following equation. It lies between 0 and ∞.

$$e_{ap} = \frac{A_e}{A_p}$$

Effective Length

The effective is defined as the ability of the antenna to produce a voltage at its terminals from an incident electric field.

$$L_e = \frac{V_A}{E}$$

Since effective length relates to the effective area under perfect matching, so power delivered to the load is given by

Power delivered to load $$P_R = \frac{|V_A|^2}{8R_A}$$

Effective area $$A_e = \frac{P_R}{W} = \frac{|V_A|^2}{8R_A W}$$

Now from equation

$$W = \frac{1}{2}EH \quad = \frac{E^2}{2Z},$$

where $Z = \dfrac{E}{H}$ is the intrinsic impedance

After simplification equation

$$A_e = \frac{L_e^2 Z}{4R_A}$$

If antenna is loss free, then

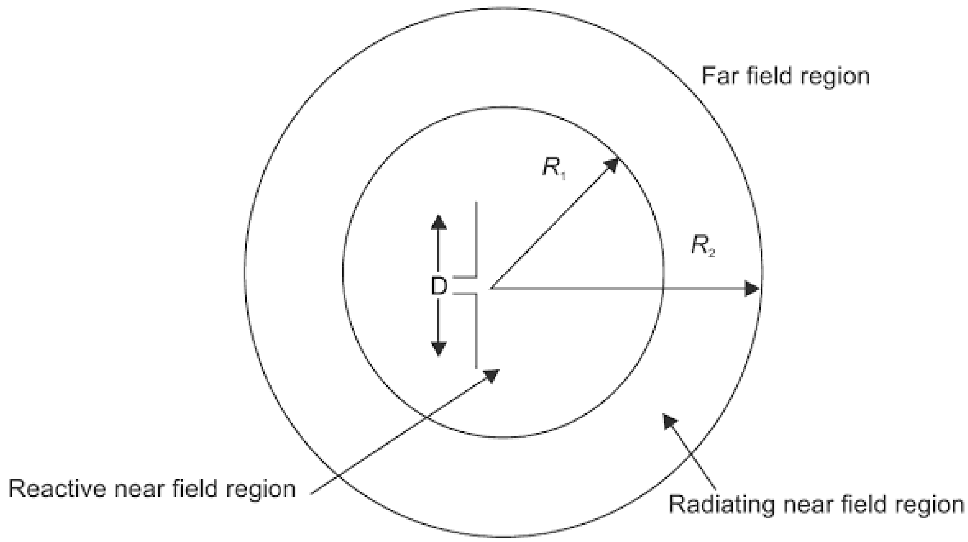
$$R_A = R_r + R_L = R_r \qquad (R_L = 0)$$

Then the above equation becomes

$$\boxed{A_e = \frac{L_e^2 Z}{4R_r}}$$

Field regions of an Antenna

Two types of electromagnetic energies are associated with the antenna; these are the *reactive energy* and *radiant energy*. Because of the presence of these two energies, the region around the antenna can be subdivided into three field regions. These are *reactive near-field region, radiating near- field region, and the far field region.*



a) Reactive Near-field Region

This region is closest to the antenna. In this region electromagnetic energy exists in the stored form and hence there is no energy dissipation. The outermost boundary of this region is at radial distance of about $R_1 = 0.62\sqrt{\frac{D^3}{\lambda}}$ where D is the largest dimension of antenna and λ is the wavelength of electromagnetic waves.

b) Radiating Near-field Region (Fresnel Region)

This is the region which lies in between the reactive near-field region and radiating near-field region. In this region the radiation fields dominate the reactive field, and angular field distribution is function of distance from the antenna. The outermost boundary of this region is at distance $R_2 = \frac{2D^2}{\lambda}$.

c) Far-field Region (Fraunhofer Region)

The region beyond $R_2 = \frac{2D^2}{\lambda}$ is called far-field region. In this region only radiation fields exist. The angular field distribution is distance independent and power density obeys inverse square law of distance from the antenna.