Antenna Basics 1

Presentation Content

Antennas: An Overview

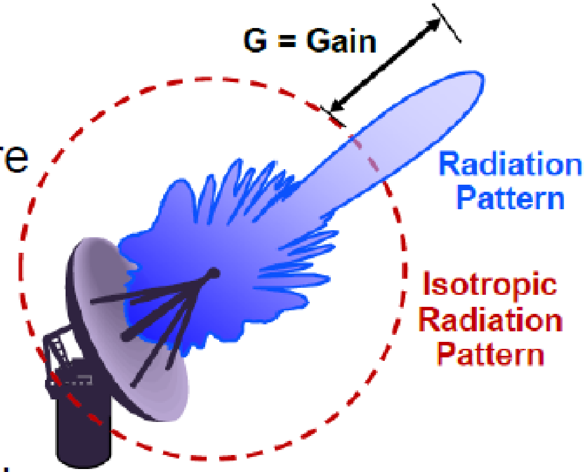
1. What They Do.
2. Where are they used?
3. Antenna Types & Antenna Family.
4. Antenna Selection Trade-offs.
5. Antenna Performance Parameters.
6. Antenna Radiation Pattern.
7. Directional Gain: G.
8. Antenna Efficiency: η_{eff}.
9. Effective Capture Area: A_{eff}.
10. Half-Power Beamwidth: HPBW.

Antennas: What they do

1. Antennas convert a guided electromagnetic (EM) wave that is enclosed inside a transmission line into a propagating wave radiating into free space, with a desired radiation efficiency and directional spatial radiation pattern. The propagating wave radiates from the antenna in straight radial lines.

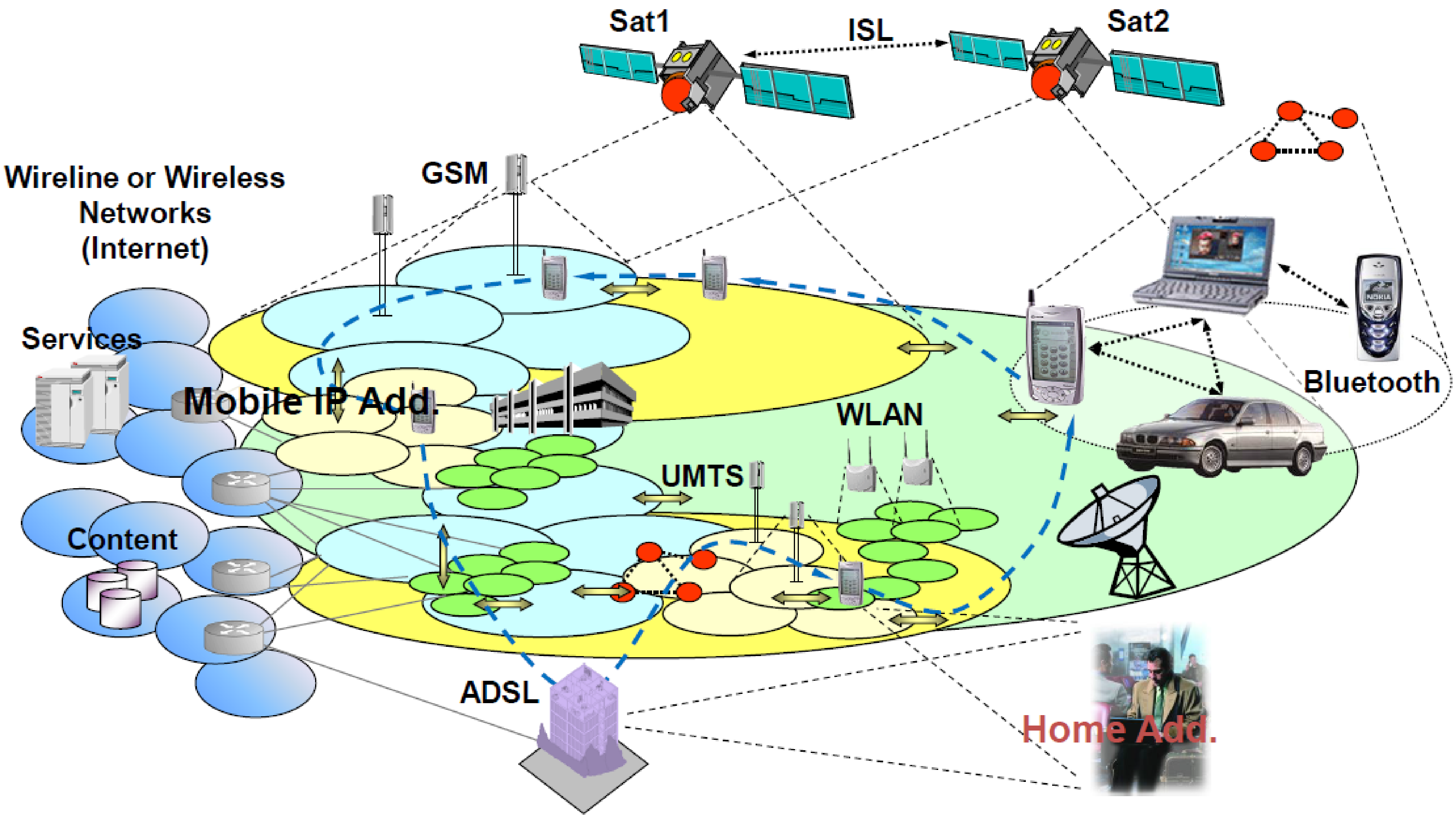
2. The electrical current distributions within the antenna element produce the radiating wave in a specific form and direction (i.e.: spatial radiation pattern) defined by the antenna's structure and its surrounding environment.

3. Since an antenna element is a linear passive reciprocal device, it does not amplify. So "Gain" is a measure of its ability to concentrate RF power in a desired direction, when compared to the spherical radiation from an isotropic antenna. Hence, we use the term: Directional Gain.



4. An antenna's radiation pattern during a transmit period is the same radiation pattern during a receive period. As such, an antenna's performance characteristics do not depend on the direction of energy flow.

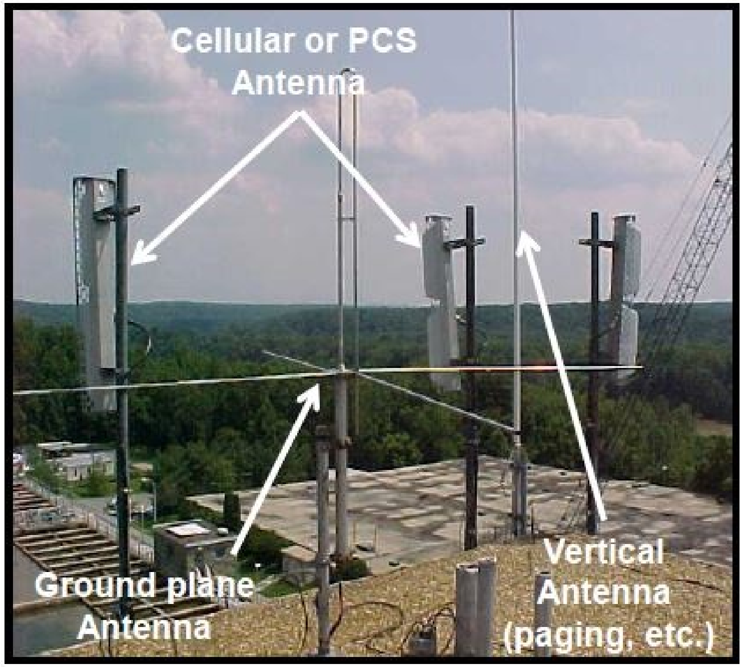
Examples of where Antennas are used



Antennas: Where are they used?

Wireless communications:

1. Personal Communications Systems.
2. Global Positioning Satellite (GPS).
3. Wireless Local Area Networks (WLAN).
4. Direct Broadcast Satellite (DBS) TV.
5. Mobile Communications.
6. Telephone Microwave/Satellite Links.
7. Broadcast Television and Radio, etc.



Remote Sensing:

1. Radar: Active remote sensing (Tx & Rx).
2. Military applications: Target search and tracking radar; Threat avoidance, etc.…
3. Weather radar & Air traffic control.
4. Automobile speed detection.
5. Ground penetrating radar (GPR).
6. Agricultural applications.
7. Radiometry: Passive remote sensing - receive emissions.
8. And many, many more. . . . .

Unwanted Antennas:

1. Any opening/slot in a device/cable carrying a time-varying electrical/RF current.
2. Any discontinuity in a conducting structure irradiated by electromagnetic waves.
   A. Electrical system radiating in vehicles.
   B. Antenna masts or power-line wires.
   C. Windmills or helicopter propellers.

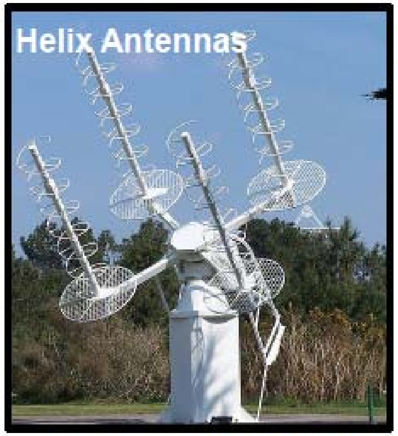
Antenna Types

1. Antenna Shapes:

A. Wire antennas: Dipole, helix, loop, & Yagi antennas.
B. Aperture antennas: Horn & parabolic dish antennas.
C. Printed antennas: Patch, printed dipole, spiral & slot antennas.

2. Antenna Gain Levels:

A. High Gain (> 20 dB): Parabolic dish antenna.
B. Medium Gain (10 to 20 dB): Horn, helix & Yagi antennas.
C. Low Gain (< 10 dB): Dipole, loop, patch, slot & whip antennas.



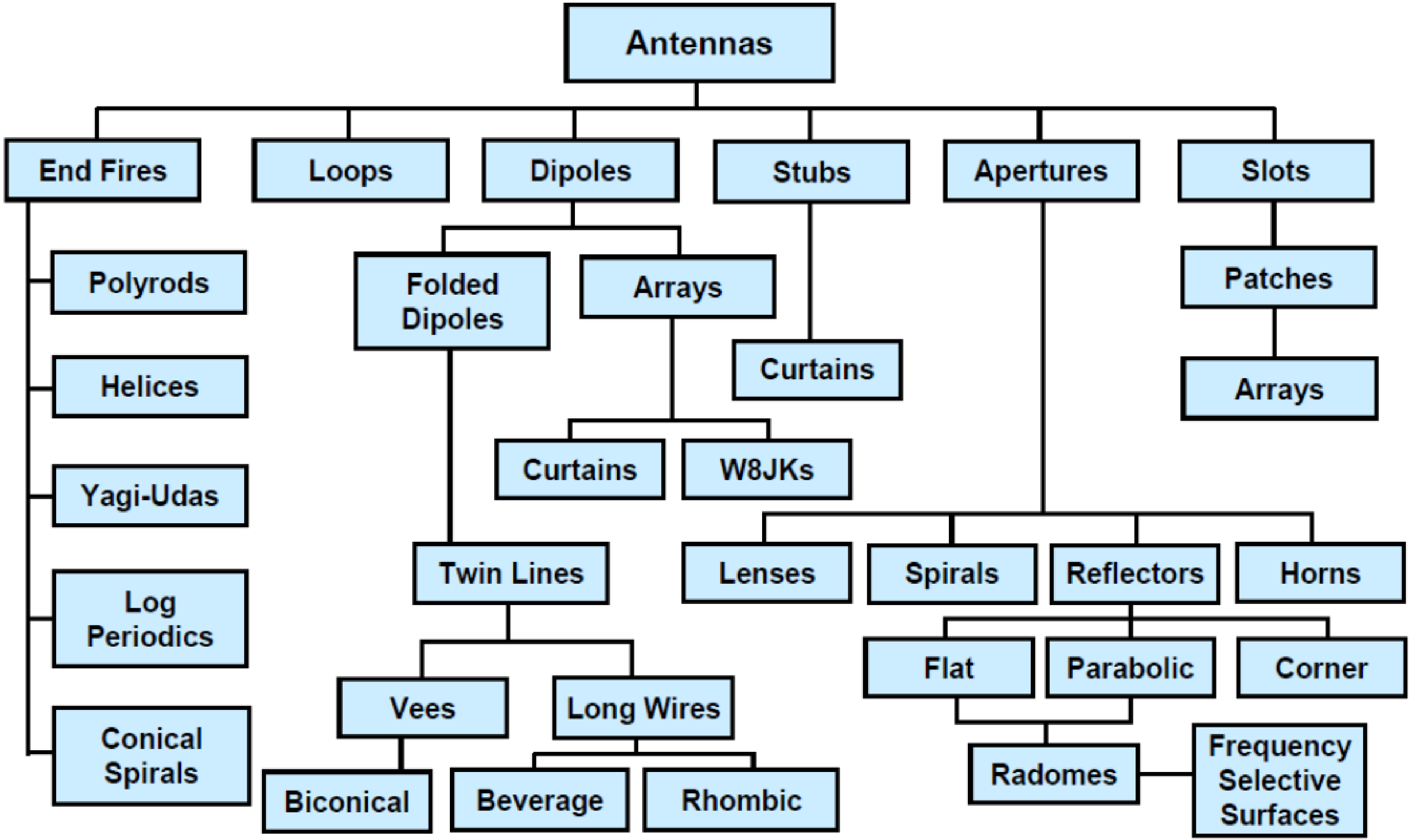
3. Antenna Beam Shapes:

A. Omni-directional in azimuth:
   1) Linear Polarization: Biconical, dipole, loop & whip.
   2) Circular Polarization: Helix & conical spiral.
B. Directional/Pencil beam:
   1) Linear: Parabolic, horn, log periodic & Yagi antenna.
   2) Circular: Parabolic, horn with polarizer, cavity-backed spiral.
C. Fan beam: Antenna array.

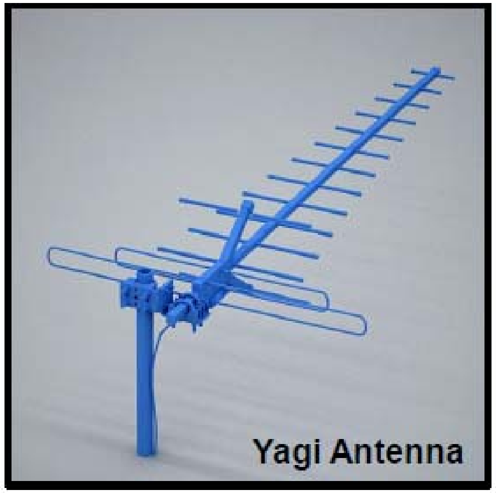
4. Operating Frequency Bandwidth:

A. Wide Bandwidth: Biconical, conical spiral & log periodic antennas.
B. Moderate Bandwidth: Horn & Parabolic dish antennas.
C. Narrow Bandwidth: Dipole, helix, loop, patch, slot, whip & Yagi antennas.

Antenna Family

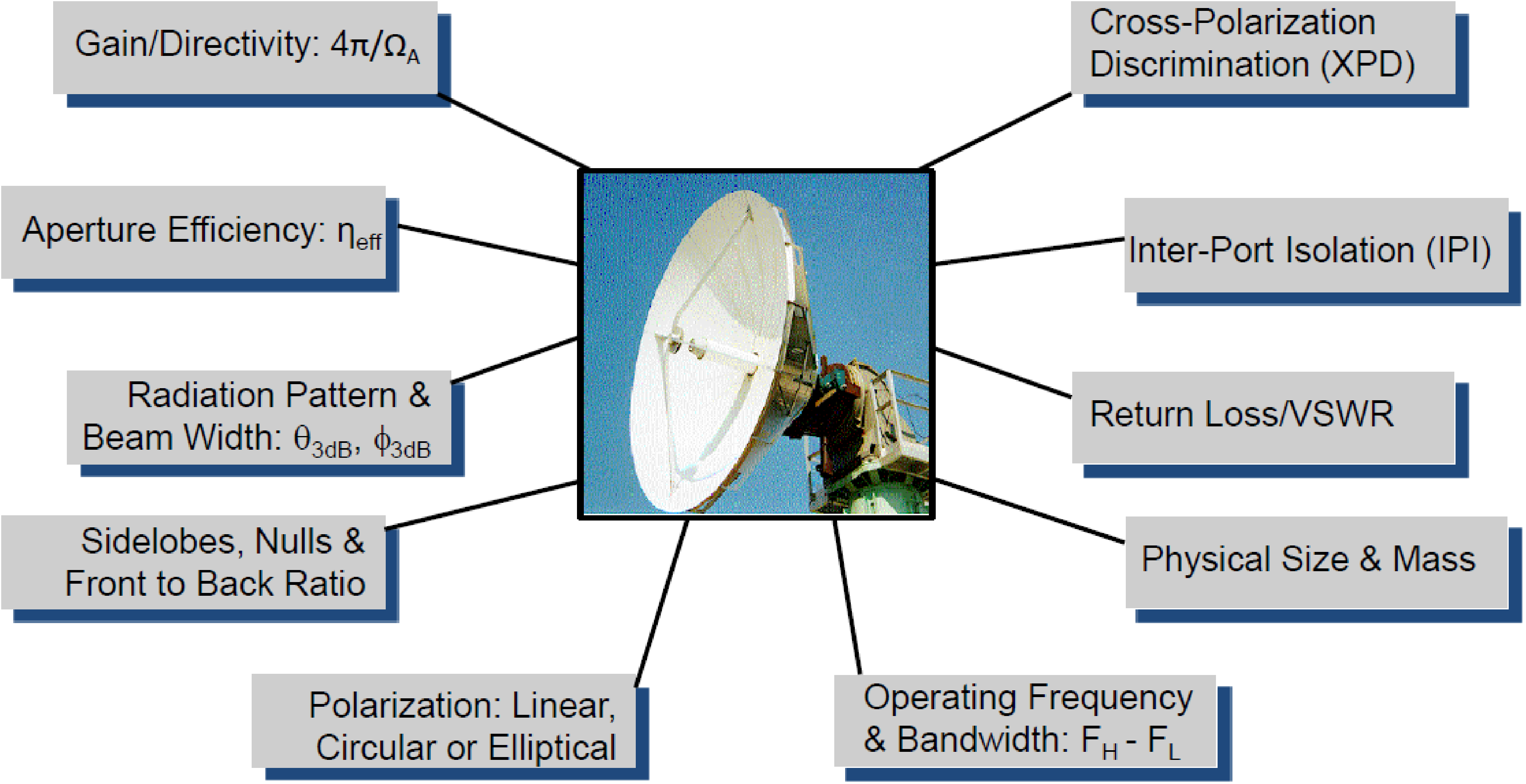


Antenna Selection Trade-offs



1. Selection of the best antenna is highly dependent on its intended use and application in a system or network.
2. Design trade-offs effecting an antenna's selection include:
   - A. Frequency of operation: F_o & frequency bandwidth: BW.
     1) More often: Multiple center frequencies with various bandwidths.
     2) Bandwidth is often defined when VSWR < 2.0:1 versus frequency.
   - B. Angular Coverage (Radiation Pattern)
     1) Half-Power Beamwidth: θ_{3dB} and/or ϕ_{3dB}.
     2) Front-to-Back Ratio: F/B.
     3) Pattern Nulls; First Null Beamwidth (FNBW).
   - C. Directional Gain: $G = \eta_{eff} D_{max}$
   - D. Polarization: Linear, Circular, Elliptical.
   - E. Cross-Polarization rejection (Cross-Pol) or axial ratio.
   - F. RF power handling: CW and/or peak RF power.
   - G. Physical size & weight: Fits inside desired package.
   - H. Vulnerability to weather & physical abuse (i.e.: cell phones).
   - I. Cost: Initial cost & cost of ownership.

Antenna Performance Parameters

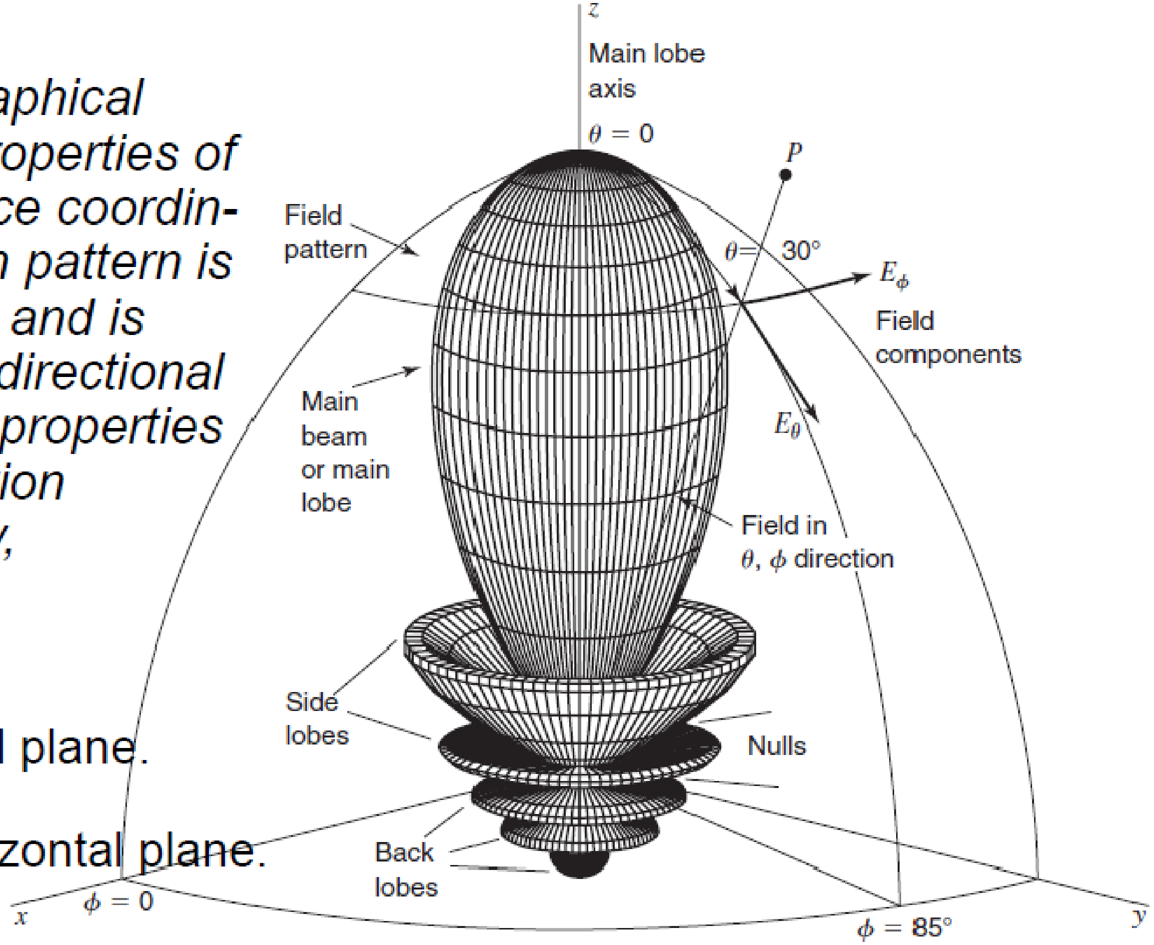


Antenna’s Radiation Pattern: Definition

IEEE Standard Definition:
“A mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates. In most cases, the radiation pattern is determined in the far-field region and is represented as a function of the directional coordinates (ϕ and θ). Radiation properties include power flux density, radiation intensity, field strength, directivity, phase or polarization.”

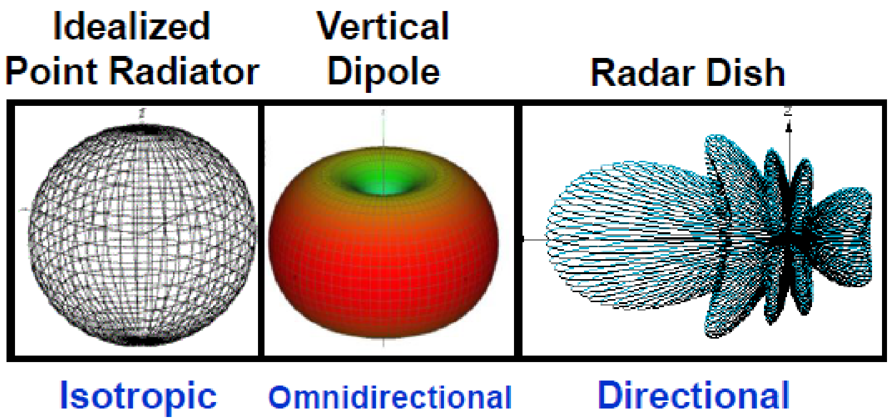
Polar coordinate system:
- ϕ : **Azimuth**: Angle in horizontal plane. (Top down view).
- θ : **Elevation**: Angle above horizontal plane. (Side view).

The angle(s) at which maximum radiation occurs is called “boresight”.



Typical Radiation Pattern: Polar Plot

Types of Radiation Patterns from Antennas



1. **Isotropic Radiation**: Radiation pattern of an antenna having equal radiation in all directions: Spherical radiation pattern. Not physically achievable, but is used to define other antenna's parameters. Represented by a sphere whose center coincides with the location of the isotropic radiator.

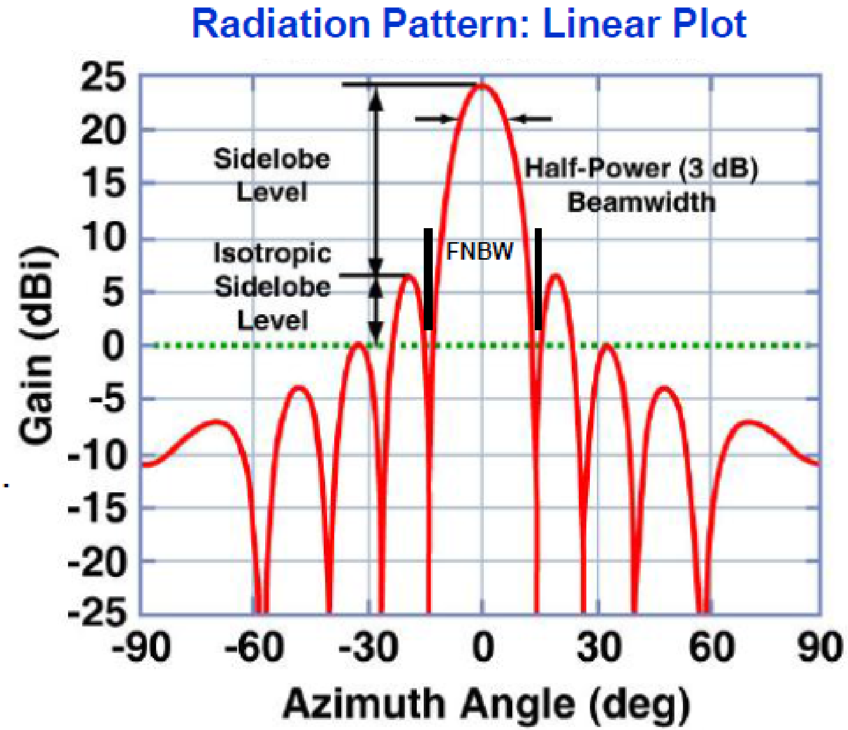
2. **Omnidirectional Radiation**: Radiation pattern provides general coverage in all directions. Usually, wide angular horizontal coverage and limited angular vertical coverage. Donut-shaped radiation pattern. Useful in mobile phone applications.

3. **Directional Radiation**: Radiation pattern characterized by a more efficient radiation in one direction than another. Main beam focused in a desired angular direction. Types: Broadside, Intermediate and Endfire. Spotlight or flashlight-shaped radiation pattern.

4. **Principal Plane Radiation Patterns:** The E-plane and H-plane radiation patterns of a linearly polarized antenna.
   A. E-plane: The plane containing the electric field vector and the direction of maximum radiation.
   B. H-plane: The plane containing the magnetic field vector and the direction of maximum radiation.

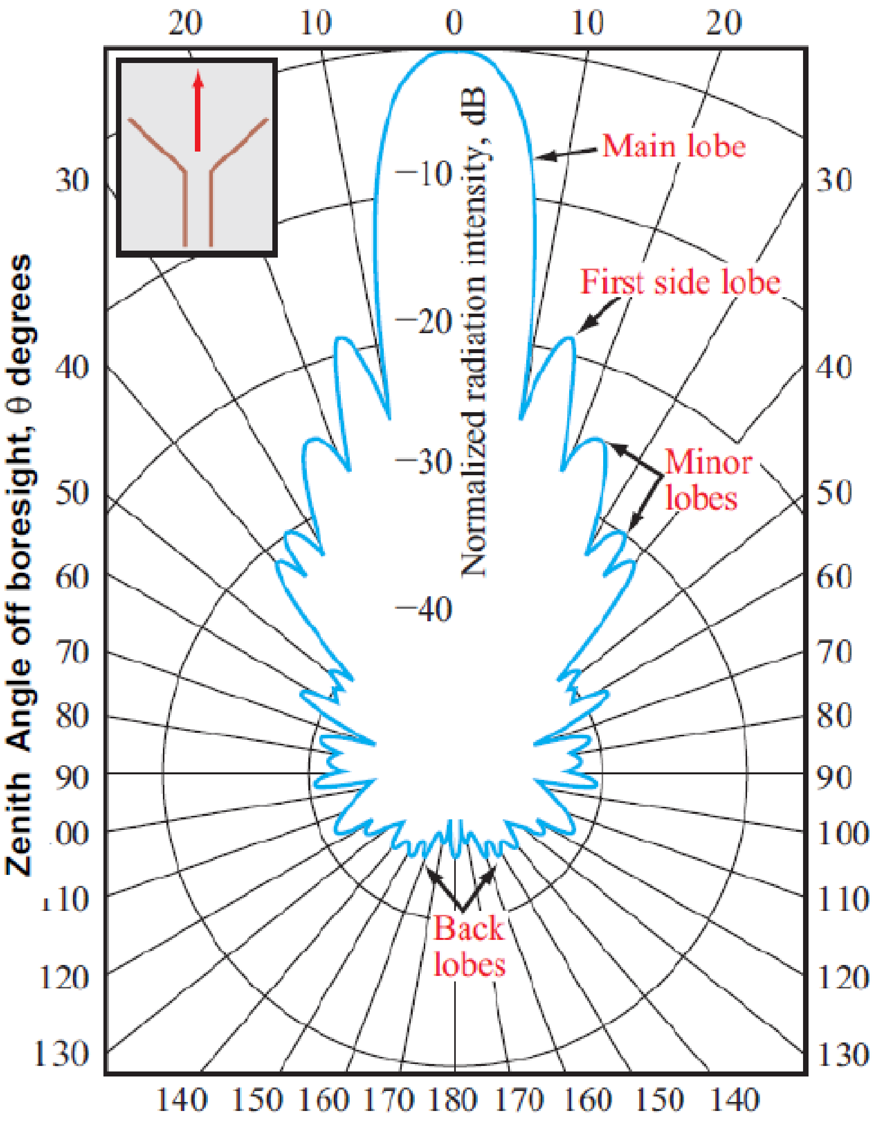
Radiation Pattern Characteristics

1. **Boresight:** Radiation lobe in the direction of maximum radiation.
2. **Gain:** Absolute gain or relative gain, dB.
3. **HPBW:** Half Power Beamwidth, degrees.
   A. A measure of how broad or narrow the focus of radiated power density is.
   B. Measured both horizontally and vertically.
   C. Angle where signal is 3dB below main beam.
4. **FNBW:** First Null Beam Width, degrees.
   A. Angle where destructive interference of radiated energy creates the first null in the radiation pattern.
   B. Often, FNBW = 2 x HPBW, degrees.
5. **Sidelobes:** Direction & depth of sidelobe radiation, dB.
6. **Pattern Nulls:** Direction & depths of no radiation, dB.
7. **F/B:** Front-to-back ratio = Main Lobe (dB) – Back Lobe, dB.
   A. Ratio of the maximum signal radiating from the main/front beam to the maximum signal radiating from the back (180°) of the antenna.

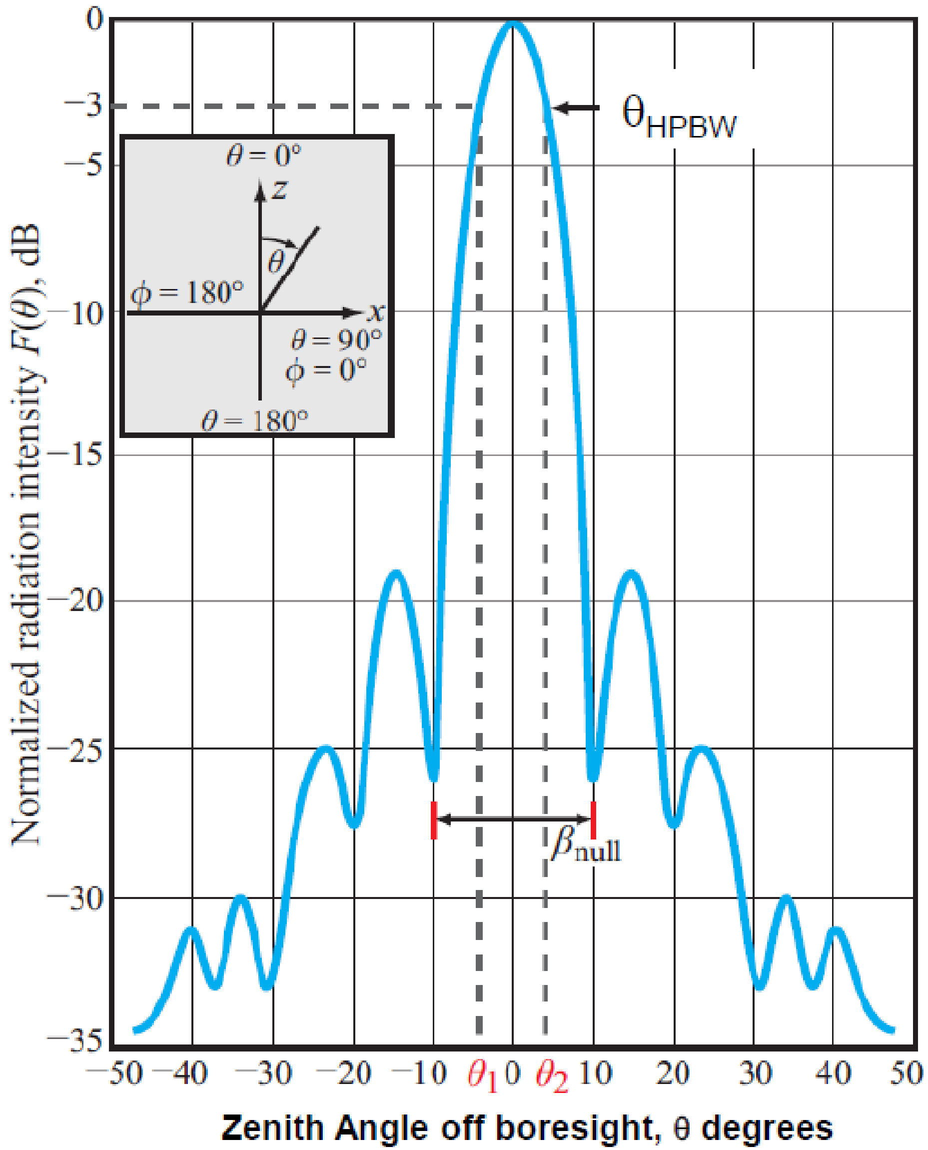


Typical Radiation Pattern Plots

Polar Diagram Plot & Rectangular/Linear Plot

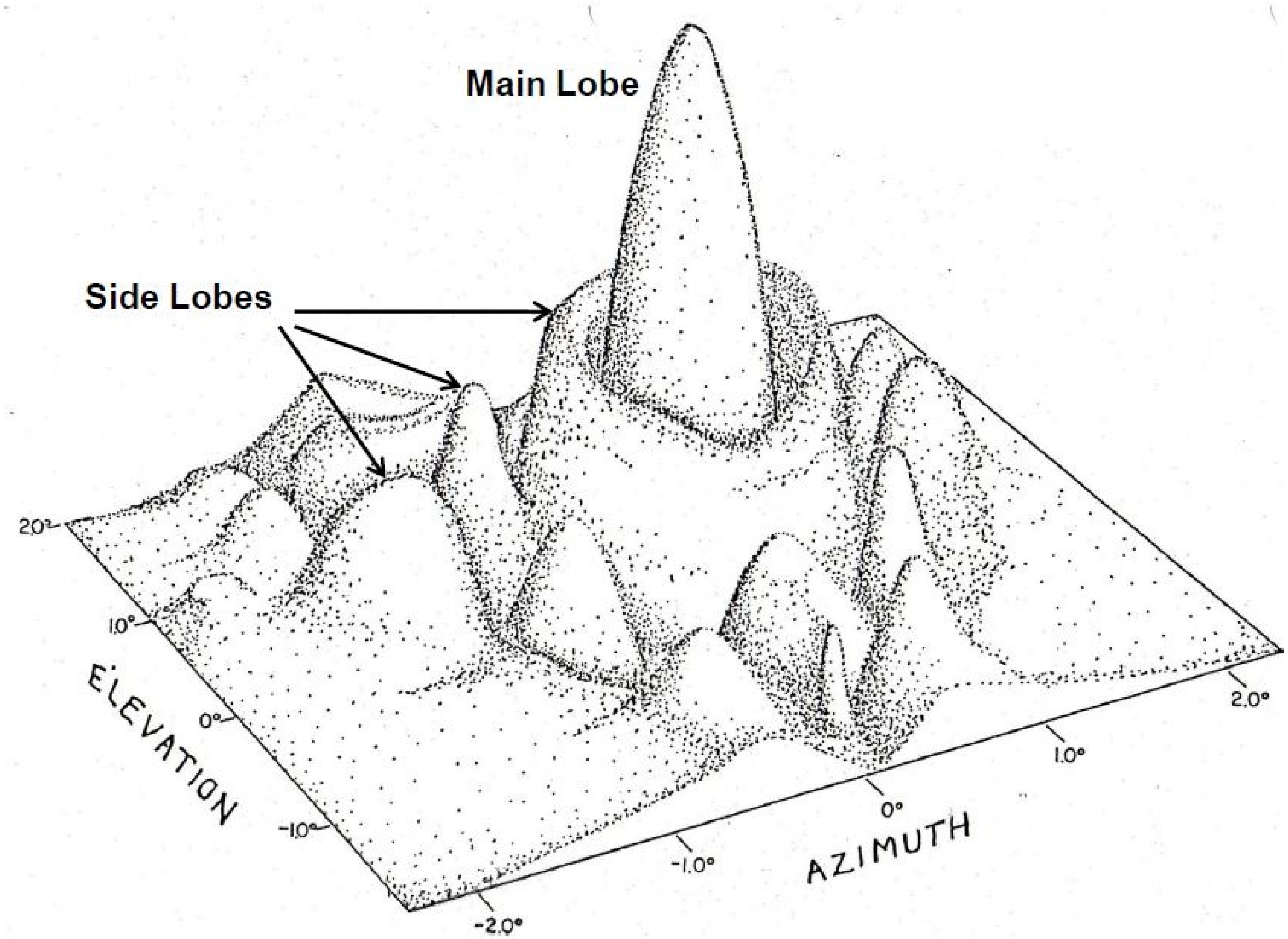


(a) Polar Diagram



(b) Rectangular/Linear Diagram

Depiction: Antenna Gain versus ϕ and θ



ϕ : **Azimuth**: Angle in horizontal plane.

θ : **Elevation**: Angle above horizontal plane.

Antenna Directional Gain: $G = \eta_{eff} D$

1. The directivity, $D(\theta,\phi)$, of an antenna is the ratio of maximum radiation intensity in the main beam direction to the radiation intensity averaged over all directions (sphere). Directivity is a measure of how much radiated power, P_o, is concentrated in a particular spatial direction: ϕ (Az) and θ (EL).
2. The gain, $G(\theta,\phi)$, of an antenna is an actual or realized quantity which is less than the directivity D, due to ohmic and passive losses in the antenna or its radome (if enclosed).
3. The definition of gain does not include impedance mismatch nor polarization mismatch. Those factors are separately accounted for in the link budget.

$$G = \eta_{eff} D = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi f^2 A_e}{c^2}$$

where:

- G = Antenna gain (dimensionless).
- η_{eff} = Radiation efficiency of antenna.
- A_e = Effective aperture area, meter^2.
- f = Signal's frequency, Hertz.
- c = Speed of light (3×10^8 meters/second).
- λ = Signal's wavelength, meters = c/f.

Total power radiated:

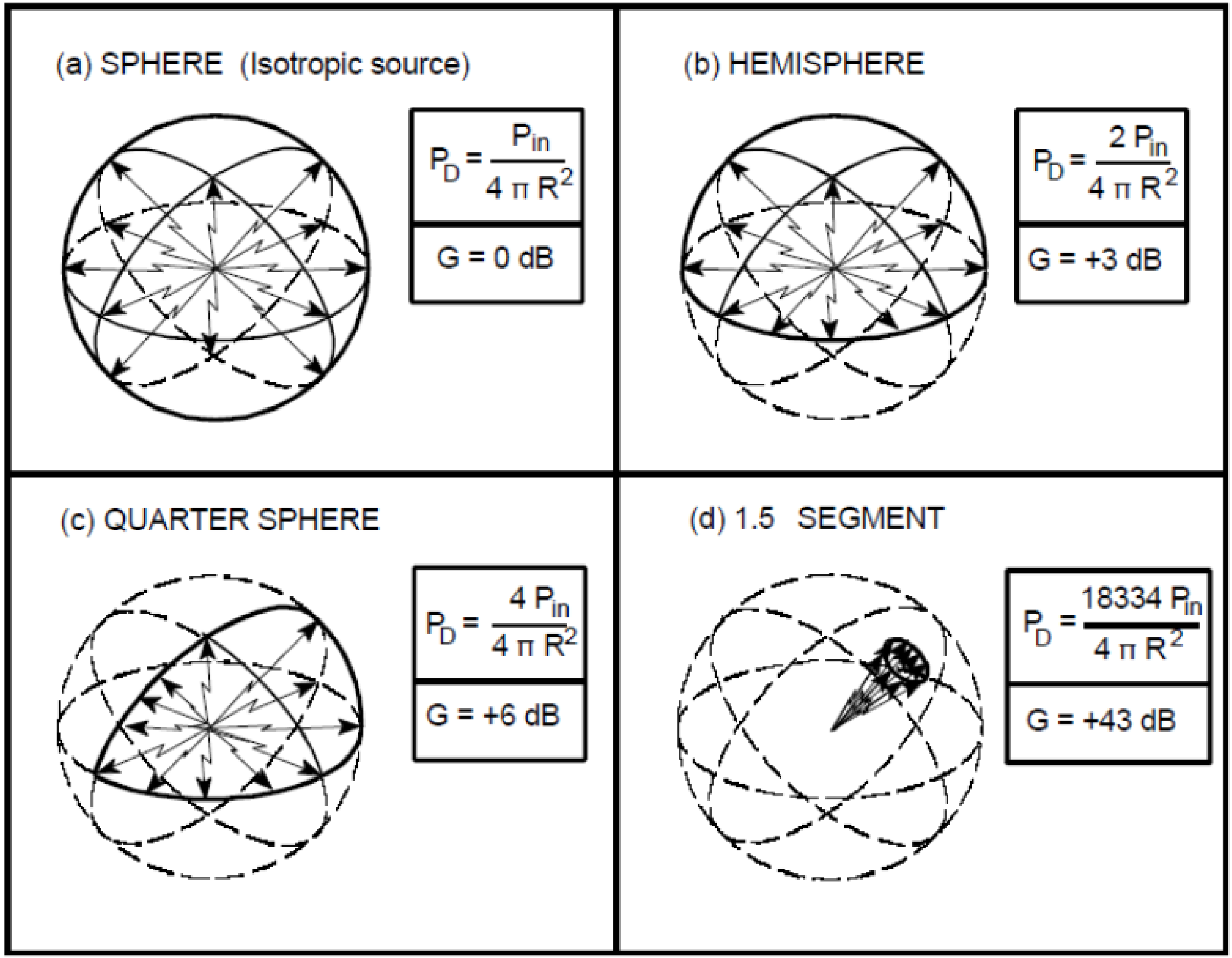
$$P_0 = \int_0^{2\pi} \int_0^{\pi} \Phi(\theta,\phi) \sin d\theta d\phi$$

Average radiation intensity:

$$\Phi_{avg} = \frac{P_0}{4\pi}$$

Antenna Gain

$$Gain = \eta_{eff} D = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi f^2 A_e}{c^2}$$



Gain of an Antenna in a Rectangular sector

1. For an ideal antenna with uniform distribution and no losses, its Gain is equal to the area of an isotropic sphere ($4\pi r^2$) divided by the area of the sector, or cross-sectional area:

$$\text{Gain} = \frac{\text{Area of sphere}}{\text{Area of Antenna pattern}}$$

2. If the antenna pattern has a rectangular area, then the antenna's sector Area = a x b = $r^2 \sin\theta \sin\phi$, where: $a = r\sin\theta$; $b = r\sin\phi$, so:

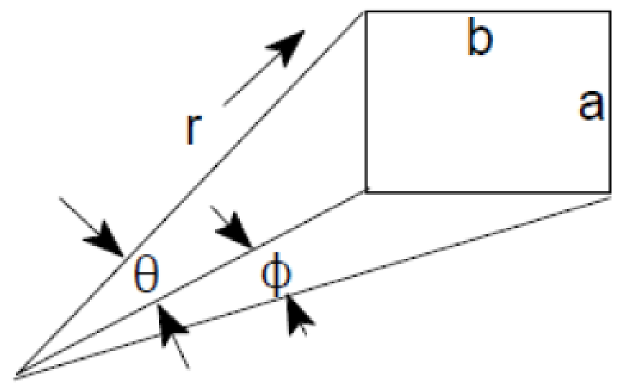
$$\text{Gain} = \frac{4\cdot\pi\cdot r^2}{r^2 \sin\theta \sin\phi} = \frac{4\cdot\pi}{\sin\theta\sin\phi}$$

For small angles, $\sin\phi = \phi$, in radians, then:

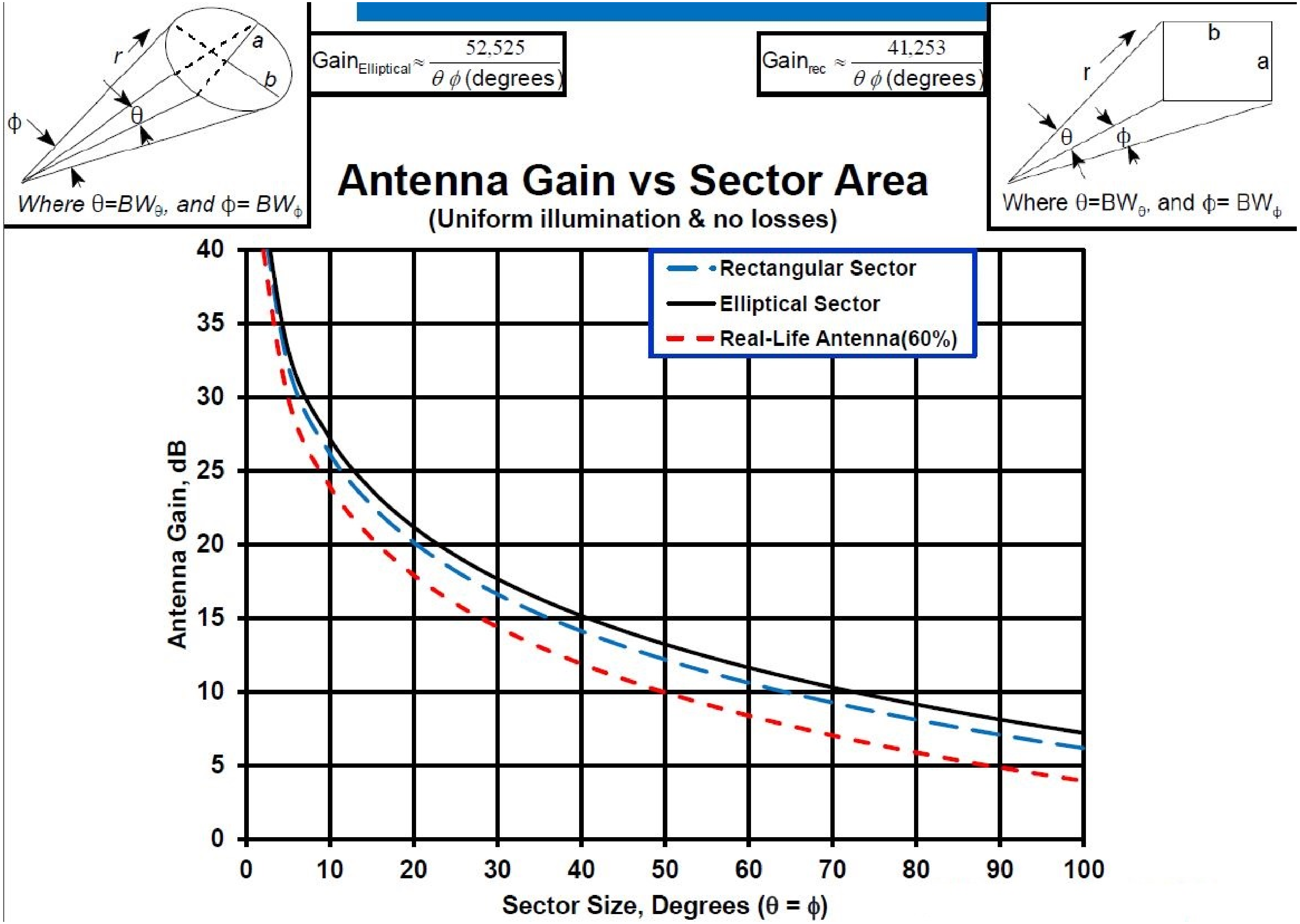
$$\text{Gain} \approx \frac{4\cdot\pi}{\theta\,\phi\,(\text{radians})} = \frac{41{,}253}{\theta\,\phi\,(\text{degrees})}$$

3. For a highly directional antenna with a small beamwidth (~1°) and an average radiation efficiency of η_{eff} = 70%:

$$\text{Gain} \approx \frac{0.70\times 41{,}253}{\theta\,\phi\,(\text{degrees})} = \frac{28{,}877}{\theta\,\phi\,(\text{degrees})} = 44.6dB$$



Where $\theta = BW_\theta$, and $\phi = BW_\phi$


r
a
b
ϕ
θ
Where θ=BW$_\theta$, and ϕ= BW$_\phi$
Gain$_{Elliptical}$ ≈ 52,525 / θ ϕ (degrees)
Gain$_{rec}$ ≈ 41,253 / θ ϕ (degrees)
Antenna Gain vs Sector Area
(Uniform illumination & no losses)
Rectangular Sector
Elliptical Sector
Real-Life Antenna(60%)
Antenna Gain, dB
Sector Size, Degrees (θ = ϕ)
0
5
10
15
20
25
30
35
40
0
10
20
30
40
50
60
70
80
90
100
b
a
r
θ
ϕ
Where θ=BW$_\theta$, and ϕ= BW$_\phi$

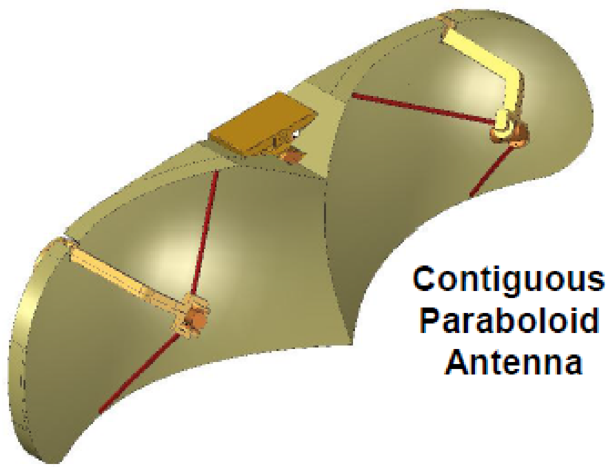
Directive Gain & Beamwidths for Aperture-type Antennas

Aperture-Type	Beamwidth (From Aperture)	Directive gain (From Aperture)	Directive gain (From Beamwidth)	Antenna Efficiency (Aperture Illumination Efficiency)
Uniformly illuminated circular aperture-hypothetical parabola a 18 dB side-lobe level	$\theta = \frac{58\lambda}{a}$ $\theta = \theta_1 = \theta_2$	$g_d = \frac{15\,a^2}{\lambda^2}$ $g_d = \frac{9.87\,a^2}{\lambda^2}$	$g_d = \frac{52{,}525}{\theta^2}$ $\theta = \theta_1 = \theta_2$	100%
Uniformly illuminated rectangular aperture or linear array a, b 13 dB side-lobe level	$\theta_1 = \frac{51\lambda}{a}$ $\theta_2 = \frac{51\lambda}{b}$	$g_d = \frac{1.6\,a\,b}{\lambda^2}$	$g_d = \frac{41{,}253}{\theta_1 \theta_2}$	100%
Rectangular horn a) Polarization plane: E-plane a_E 13 dB side-lobe level b) Orthogonal polarization plane: H-plane a_H 26 dB side-lobe level	$\theta_1 = \frac{56\lambda}{a_E}$ $\theta_2 = \frac{67\lambda}{a_H}$	$g_d = \frac{7.5\,a_E\,a_H}{\lambda}$	$g_d = \frac{31{,}000}{\theta_1 \theta_2}$	60%
Nonuniformly illuminated circular aperture (10 dB taper)–normal parabola a 26 dB side-lobe level	$\theta = \frac{72\lambda}{a}$ $\theta = \theta_1 = \theta_2$	$g_d = \frac{5\,a^2}{\lambda^2}$	$g_d = \frac{27{,}000}{\theta^2}$ $\theta = \theta_1 = \theta_2$	50%
	$a >> \lambda$	$G_d = 10 \log_{10} g_d$ dB	$G_d = 10 \log_{10} g_d$ dB	

Benefits of Directional Antennas

1. Reasons for wanting Directive Antennas:
   A. Lower receive noise when “looking” only at a small sector of free space.
   B. Stronger signal when “looking” in the direction of the transmit power source.
   C. Remote sensing (Radar): When interested in properties of a small section of space.
   D. Can be used to spatially filter-out signals that are unwanted.
   E. Can provide radiation coverage to only desired service region.
2. Typical antenna gain and half-power beamwidths, HPBW:

Type of Antenna	Gain	HPBW
Isotropic	0dBi	360°x360°
Dipole	2dBi	360°x120°
Helix (10 turn)	14dBi	35°x35°
Small parabolic dish	16dBi	30°x30°
Large parabolic dish	45dBi	1°x1°



Contiguous Paraboloid Antenna

Antenna Efficiency: η_{eff}

1. The efficiency to radiate RF power delivered to the antenna accounts for the various losses in the antenna, such as spillover loss, power radiated in the sidelobes, dielectric loss, conduction loss, blockage from any supporting structure, RMS surface deviations, reflection loss and polarization mismatch loss.

$$\eta_{eff} = \frac{\text{Gain}}{\text{Directivity}} = \frac{P_{radiated}}{P_{input}} = \frac{P_{radiated}}{P_{radiated} + P_{loss}}$$

2. Where: $\eta_{eff} = \eta_r \eta_t \eta_s \eta_a$
   A. η_{eff} : Aperture efficiency.
   B. η_r : Radiation efficiency.
   C. η_t : Taper efficiency or utilization factor.
   D. η_s : Spillover loss (reflector antennas) accounts for the RF energy spilling beyond the edge of the reflector into the back lobes of the antenna. Major contributor to the antenna's noise temperature.
   E. $\eta_r \eta_s$ is called η_i : Illumination efficiency, which accounts for the nonuniformity of the illumination, phase distribution across the antenna surface, and power radiated in the sidelobes.
   F. η_{cr} : Cross-polarization efficiency. Due to cross-polarization on-axis.
3. Typical antenna efficiency: η_{eff} = 0.5 to 0.75 (= 50% to 75%).

Typical efficiency for a large Cassegrain Antenna

Efficiency Factor	Efficiency (%)	Loss (dB)
Illumination Efficiency.	98.7	0.06
Subreflector Spill-Over	88.3	0.54
Main Reflector Spill-Over	96.0	0.18
Blockage Losses	92.6	0.33
Manufacturing Losses	92.4	0.34
Feed Ohmic Losses	95.5	0.2
Total Efficiency =	68.4%	1.65dB

Gain at boresight for a 30 meter diameter Cassegrain Antenna at 4 GHz:

- Gain = $10 \log_{10} [0.684(\pi \times 30\text{meter} [4/0.3])^2]$, dBi.
- Gain = 60.3 dBi.

Antenna Effective Capture Area: A_e

1. Antenna Effective Area: A_e is measure of the effective absorption area presented by an antenna to an incident plane wave.
2. Only depends on the antenna's gain, G, and wavelength, λ:

$$A_e = \eta_{eff} A_{physical} = \frac{\lambda^2}{4\pi} D = \eta_{eff} \frac{\lambda^2}{4\pi} G, m^2$$

where:

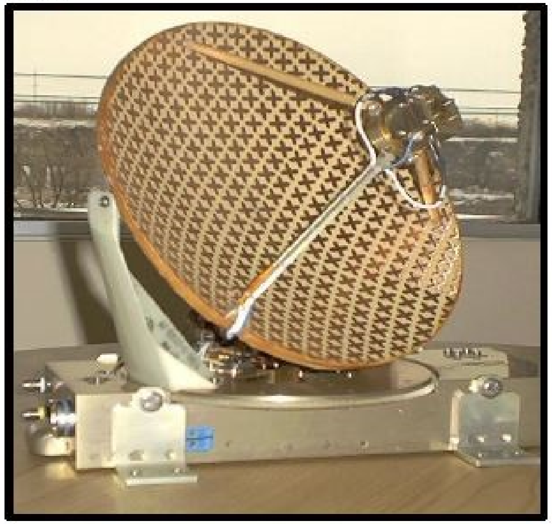
- $\eta_{eff} = A_e / A_{physical}$ = Aperture efficiency.
- $A_{physical}$: Physical area of antenna's aperture, square meters.

3. For a parabolic dish antenna with diameter d and a 65% efficiency:

$$A_e = \eta_{eff} A_{physical} = 0.65 \frac{\pi d^2}{4}, m^2$$

4. Directional Gain for a parabolic dish antenna:

$$Gain = \eta_{eff} \left(\frac{\pi d}{\lambda} \right)^2$$



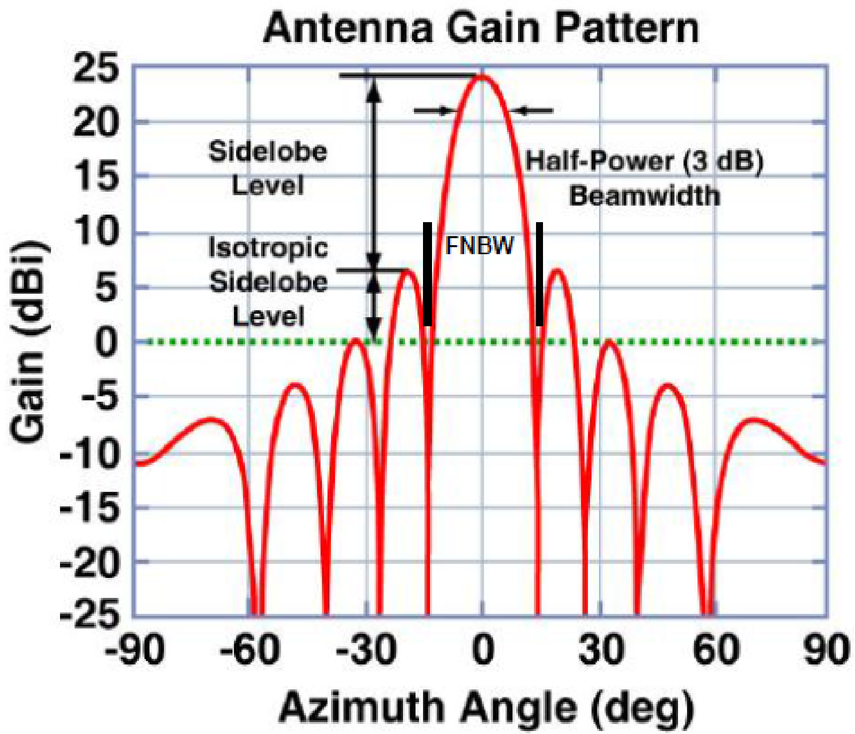
Effective Capture Area of typical Antennas

Type of Antenna	Effective Area A_e , meters^2	Directional $Gain_{max}$
Isotropic	$A_{isotropic} = \frac{\lambda^2}{4\pi}$	1 (0dB)
Infinitesimal Dipole or Loop	$1.5 A_{isotropic}$	$1.5 \sin^2\theta$ (1.76dB)
Half-Wave Dipole	$1.64 A_{isotropic}$	1.64 (2.14dB)
Horn (mouth area: A)	$0.81 \cdot \mathrm{A}$	$10 \cdot \mathrm{A} / \lambda^2$
Parabolic dish (with face area A)	$0.56 \cdot \mathrm{A}$	$7 \cdot \mathrm{A} / \lambda^2$

$$Gain = \eta_{eff} D = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi f^2 A_e}{c^2}$$

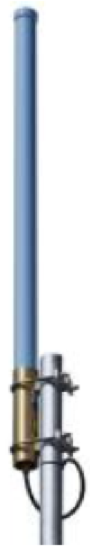
Antenna's Half-Power Beamwidth (HPBW)

1. Beamwidth is associated with the lobes in the antenna's radiation pattern. It is defined as the angular separation between two identical points on the opposite sides of the main lobe.
2. The most common type of beamwidth is the half-power (3 dB) beamwidth (HPBW).
3. Another frequently used measure of beam width is the first-null beamwidth (FNBW), which is the angular separation between the first nulls on either sides of the main lobe. FNBW ~ 2 * HPBW.
4. Beamwidth defines the resolution capability of the antenna: i.e., the ability of the system to separate two adjacent targets.
5. For antennas with rotationally symmetric lobes, the directivity can be approximated:



$$D \approx \frac{4\pi}{\theta_{3dB}\,\phi_{3dB}\ (\text{radians})} = \frac{41{,}253}{\theta^{o}{}_{3dB}\,\phi^{o}{}_{3dB}}$$

Typical Half-Power Beamwidths of Antennas



Omni Antenna

Antenna Type	Horizontal Beamwidth	Vertical Beamwidth
Omnidirectional	360°	7° to 80°
Patch/Panel	30° to 180°	6° to 90°
Yagi	30° to 78°	14° to 64°
Sector	60° to 180°	7° to 17°
Parabolic Dish	<4° to ~25°	<4° to ~21°

Sector Antennas

Patch Antenna

Yagi Antenna

Parabolic Dish Antenna