Antennas and Wave Propagation

Short notes for B.Tech ECE · GATE EC

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I. Antenna Basics

- **Antenna** = a device that changes guided waves (on a line) into free-space waves and back. It is reciprocal: same pattern for transmit and receive.
- Radiation happens when charges accelerate (time-varying current).
- Field regions: **reactive near field** (very close), **radiating near field (Fresnel)**, **far field (Fraunhofer)** beyond $R = 2D^2 / \lambda$.

➤ Antenna parameters

Parameter	Meaning
Radiation pattern	Plot of field or power vs direction (E-plane, H-plane)
HPBW	Angle between the half-power (−3 dB) points of the main lobe
FNBW	Angle between the first nulls of the main lobe
Directivity D	Max radiation intensity / average radiation intensity
Gain G	$G = \eta D$ (η = radiation efficiency)
Radiation resistance Rr	Resistance that would use the same power as is radiated: $Prad = I^2 Rr / 2$ (I = peak)
Effective aperture Ae	Area that collects power: Pr = Ae x power density
Polarisation	Direction of the E field (linear, circular, elliptical)
Bandwidth	Frequency range where performance is acceptable
Front-to-back ratio	Power in main direction / power in opposite direction

FORMULA Directivity $D = 4\pi U(max) / Prad$. Approx $D \approx 41{,}253 / (\theta E \times \phi H)$ with beamwidths in degrees.

FORMULA Effective aperture Ae = λ^2 G / (4π). Radiation efficiency η = Rr / (Rr + Rloss).

FORMULA EIRP = Pt Gt. dBi = gain over isotropic. dBi = dBd + 2.15.

➤ Friis transmission equation

FORMULA Pr = Pt Gt Gr (λ / 4πR)^2. Free-space path loss FSPL (dB) = 20 log10(4πR / λ).

➤ Solved example (Friis link)

- Pt = 10 W, Gt = Gr = 20 dB (100 each), f = 3 GHz, R = 10 km.
  - λ = 3 x 10^8 / 3 x 10^9 = 0.1 m
  - λ / 4πR = 0.1 / (4π x 10^4) = 7.96 x 10^-7, squared = 6.33 x 10^-13
  - Pr = 10 x 100 x 100 x 6.33 x 10^-13 = 6.33 x 10^-8 W (about 63 nW)
  - Check in dB: FSPL = 20 log(1.257 x 10^6) ≈ 122 dB. Pr = 40 dBm + 20 + 20 − 122 = −42 dBm (about 63 nW).

2. Wire Antennas

➤ Hertzian (short) dipole

- Length dl << λ, uniform current. Pattern ∝ sin θ (doughnut shape, null along the axis).

FORMULA Hertzian dipole: Rr = 80 π^2 (dl / λ)^2, D = 1.5 (1.76 dBi), HPBW = 90°.

- **Short dipole** (triangular current, l < λ/10): Rr = 20 π^2 (l / λ)^2 (one quarter of the Hertzian value for the same length).

➤ Half-wave dipole and monopole

Antenna	Rr	Directivity	HPBW
Hertzian dipole	80π^2 (dl/λ)^2	1.5 (1.76 dBi)	90°
Half-wave dipole	73 Ω	1.64 (2.15 dBi)	78°
Quarter-wave monopole (on ground plane)	36.5 Ω	3.28 (5.15 dBi)	Half space only
Small loop (area A)	320 π^4 (A / λ^2)^2	1.5	90°

- Monopole uses an image in the ground plane, so it acts like a dipole of twice its length, radiating only into the upper half.
- **Folded dipole**: Rr ≈ 4 x 73 = 292 Ω (about 300 Ω), wider bandwidth. Used as the driven element of Yagi antennas.

EXAMPLE Half-wave dipole at 300 MHz (λ = 1 m): Ae = λ^2 D / 4π = 1 x 1.64 / 12.57 ≈ 0.13 m^2 (lossless).

3. Antenna Arrays

- Several antennas fed together to get high directivity and steerable beams.
- **Pattern multiplication**: total pattern = element pattern x array factor (AF).

FORMULA Uniform linear array of N elements: AF = sin(Nψ/2) / (N sin(ψ/2)), ψ = k d cos θ + β, k = 2π / λ.

Type	Progressive phase β	Main beam direction
Broadside	0	Perpendicular to array axis (θ = 90°)
End-fire	−k d (or +k d)	Along the array axis (θ = 0° or 180°)
Phased (scanning)	Changed electronically	Any chosen angle θ0: β = −k d cos θ0

- Spacing d < λ avoids grating lobes for broadside (d < λ/2 for end-fire and wide scanning).
- **Binomial array**: amplitudes follow binomial coefficients (1, 2, 1 ...). No side lobes, but wide beam.

- **Dolph–Chebyshev array**: all side lobes at an equal chosen level; narrowest beam for that level.
- **Uniform array**: narrowest beam, but first side lobe ≈ −13.5 dB.

EXAMPLE Two isotropic elements, $d = \lambda/2$, $\beta = 0$ (broadside). $\psi = \pi \cos\theta$. $AF \propto \cos((\pi/2)\cos\theta)$: maximum at $\theta = 90°$, nulls at $\theta = 0°$ and $180°$.

4. Practical Antennas

Antenna	Frequency band	Key feature
Yagi–Uda	HF to UHF	Driven dipole + reflector (longer) + directors (shorter); TV reception
Log-periodic	HF to UHF	Very wide bandwidth (frequency independent)
Helical (axial mode)	VHF / UHF	Circular polarisation, circumference ≈ λ; satellite links
Horn	Microwave	Flared waveguide, good gain, used as feed and gain standard
Parabolic reflector	Microwave	Very high gain, narrow beam; feed at the focus
Microstrip patch	Microwave	Low profile, cheap, narrow bandwidth; mobile phones, GPS
Rhombic	HF	Large, travelling wave, high gain for long links
Loop	LF / MF	Direction finding (null along the axis of small loop)

FORMULA Parabolic dish: $G = \eta (\pi D / \lambda)^2$, $HPBW \approx 70\lambda / D$ degrees ($\eta \approx 0.55$ typical).

FORMULA Rectangular patch length $L \approx \lambda 0 / (2\sqrt{\varepsilon eff})$ (a little less due to fringing).

- **Babinet's principle**: slot antenna and its complementary dipole: $Zslot \times Zdipole = \eta 0^2 / 4$.

5. Antenna Measurements (short)

- Far-field condition for test range: $R >= 2D^2 / \lambda$.

- **Gain**: by comparison with a standard horn, or the two-antenna / three-antenna method.
- **Pattern**: rotate the test antenna and record received power. **Impedance / VSWR**: with a network analyser.
- **Polarisation mismatch**: received power falls by cos^2 ψ, where ψ = angle between the wave and antenna polarisations.
- A linearly polarised antenna receiving a circularly polarised wave loses half the power (3 dB).

REMEMBER Gain includes losses ($G = \eta D$); directivity does not. For a lossless antenna, $G = D$.

6. Wave Propagation

Mode	Frequency range	How it travels	Range
Ground (surface) wave	Up to about 2 MHz (LF, MF)	Follows the earth's surface, vertical polarisation	Hundreds of km
Sky (ionospheric) wave	About 2 to 30 MHz (HF)	Reflected (bent) by the ionosphere	Thousands of km (with hops)
Space (LOS) wave	Above 30 MHz (VHF and up)	Direct + ground-reflected ray	Limited by horizon
Troposcatter	UHF / microwave	Scattered by the troposphere	Few hundred km
Satellite	Microwave	Passes through the ionosphere	Global

➤ Ionosphere layers

Layer	Approx height	Note
D	50–90 km	Daytime only, absorbs MF/HF
E	90–140 km	Mainly daytime
F1	about 150–250 km	Daytime; merges with F2 at night
F2	about 250–400 km	Main HF reflecting layer, present day and night

FORMULA Critical frequency $f_c = 9 \sqrt{N_{max}}$ Hz (N_{max} in electrons per m^3). MUF = $f_c / \cos \theta_i = f_c \sec \theta_i$ (θ_i from the vertical).

FORMULA Refractive index of ionosphere $n = \sqrt{(1 - 81\,N / f^2)}$.

- **Skip distance**: shortest ground distance where the sky wave returns, for a given frequency.
- **Virtual height**: height from which the wave seems to be reflected (higher than the actual height).
- **Fading**: changing signal strength due to multipath and changes in the ionosphere.
- **OWF** (optimum working frequency) ≈ 0.85 MUF.

➤ Solved example (sky wave)

- f_c = 8 MHz, wave hits the layer at $\theta_i = 60°$ from the vertical.
  - MUF = 8 / cos 60° = 8 / 0.5 = 16 MHz
  - OWF ≈ 0.85 x 16 = 13.6 MHz
  - Electron density: $N_{max} = (f_c / 9)^2 = (8 \times 10^6 / 9)^2 \approx 7.9 \times 10^{11}$ per m^3

➤ Space wave (line of sight)

FORMULA LOS range d (km) = 4.12 (sqrt(ht) + sqrt(hr)), heights in metres (includes standard refraction, k = 4/3). Without refraction: 3.57 (sqrt(ht) + sqrt(hr)).

EXAMPLE ht = 100 m, hr = 16 m: d = 4.12 (10 + 4) = 57.7 km.

- **Duct propagation**: temperature inversion traps the wave in a layer near the earth → very long range at VHF/UHF.
- **Effective earth radius** = k x actual radius, k = 4/3 for a standard atmosphere.
- Ground wave attenuation rises with frequency; sea water (high conductivity) is better than dry land.

7. Most Asked Questions (practice)

1. Define directivity, gain, HPBW, effective aperture and radiation resistance.
2. Derive the radiation resistance of a Hertzian dipole.
3. Find the fields and radiation resistance of a half-wave dipole (73 Ω).
4. State the Friis equation and solve a link budget numerical.
5. Explain pattern multiplication with a 4-element array example.

6. Compare broadside and end-fire arrays; explain binomial arrays.
7. Explain Yagi–Uda, helical, horn and parabolic antennas.
8. Describe the ionosphere layers and define critical frequency, MUF and skip distance.
9. Find the LOS distance for given antenna heights.
10. Explain ground wave, sky wave and duct propagation.

TIP For GATE EC, focus on Friis, dipole values (73 Ω, 1.64), $A_e = \lambda^2 G / 4\pi$, array factor and MUF. Many questions are direct substitutions.