ECE 516E – ANTENNA & RADIOWAVE PROPAGATION

STUDY GUIDE: INTRODUCTION TO DIPOLE ANTENNA

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1. OBJECTIVE

The objective of this study guide is to provide undergraduate electrical engineering students with a foundational understanding of dipole antennas, starting from the basic electrostatic dipole model and progressing to the practical half-wave dipole, by explaining their operational principles, key characteristics like radiation patterns and impedance, and the critical distinction between near and far fields, thereby equipping students with the necessary knowledge to analyse basic antenna performance and serve as a stepping stone for more advanced electromagnetic and antenna theory courses.

1. WHAT IS A DIPOLE?

At its most fundamental, a **dipole** is a system of two equal but opposite charges (or poles) separated by a finite distance. The concept is ubiquitous in electrical engineering, appearing in:

- **Electrostatics:** A fundamental charge configuration.
- **Circuit Theory:** A model for polarized components.
- **Electromagnetics & Antenna Theory:** The foundation of radiation and antenna design.

The most important quantity defining a dipole is its ** dipole moment**.

2. THE ELECTROSTATIC DIPOLE (THE FOUNDATION)

This is the simplest form, consisting of two point charges, +*q* and –*q*, separated by a distance *d*.

- **Electric Dipole Moment (p):** A *vector* quantity that measures the strength and orientation of the dipole.
  - **Formula:** $p = q \cdot d$
    - q: magnitude of one of the charges (in Coulombs, C)
    - d: displacement vector *pointing from the negative charge to the positive charge* (in meters, m)
  - **Units:** Coulomb-meters (C·m)
- **Key Idea:** The dipole moment characterizes the dipole's behavior in an external electric field. It is a property of the system as a whole.

- **Torque in an External Field:** A dipole experiences a torque (a rotating force) when placed in a uniform external electric field **E**.
    - **Formula: $\tau = \mathbf{p} \times \mathbf{E}$**
    - **Effect:** The torque aligns the dipole moment vector **p** with the external field vector **E**. (Think of a compass needle aligning with a magnetic field).
- **Potential and Field:** The electric potential and field around a dipole decay faster than those of a single point charge.
    - For a single charge: *$V \propto 1/r$* and *$E \propto 1/r^2$*
    - For a dipole: *$V \propto 1/r^2$* and *$E \propto 1/r^3$*
    - This is because the fields of the two opposite charges partially cancel each other out at large distances.

3. THE IDEAL DIPOLE (THE HERTZIAN DIPOLE)

Also known as an **infinitesimal dipole** or **point dipole**, this is a fundamental concept in antenna theory and electromagnetics. It is a theoretical construct consisting of a very short, thin conductor of length dl (where $dl \ll \lambda$, the wavelength) with a uniform alternating current I.

- **Current Moment:** The source of radiation is the time-varying current. The equivalent dipole moment for a Hertzian dipole is related to the current.
    - For a sinusoidal current, $I = I_0 \cos(\omega t)$, the dipole moment is $p = (I_0 \cdot dl / \omega) \sin(\omega t)$.
- **Radiation Mechanism:** The oscillating current accelerates charges, which, according to Maxwell's equations, produces electromagnetic waves that *radiate away* from the antenna.
- **Radiation Pattern:** The Hertzian dipole has a specific **doughnut-shaped (toroidal)** radiation pattern.
    - **Maximum radiation:** Perpendicular to the axis of the dipole.
    - **No radiation:** Along the axis of the dipole.
- **Why it's Important:** It is the simplest solution to the wave equation for a radiating element. The analysis of all complex antennas begins by modeling them as a collection of Hertzian dipoles.

4. THE HALF-WAVE DIPOLE

This is the most common and practical type of dipole antenna. Its length is approximately half the wavelength of the frequency it's designed to operate at (*$L \approx \lambda/2$*).

- **Current Distribution:** The current is *not* uniform along the length. It is approximately sinusoidal, with maximum current at the center (feed point) and zero current at the ends.

    - **Formula (for a center-fed dipole):** $I(z) = I_0 \cos(kz)$, where *k* is the wave number and *z* is the distance from the center.
- **Advantages over Hertzian Dipole:**
    - Much more efficient radiator.
    - Reasonable input impedance (~73 Ω) close to standard coaxial cable impedance (50 Ω or 75 Ω), which simplifies impedance matching and reduces reflected power.
    - Directional radiation pattern with higher gain than a Hertzian dipole.
- **Radiation Pattern:** Similar to the Hertzian dipole but slightly more directional.
- **Application:** The half-wave dipole is the workhorse of antenna design. It's used as a standalone antenna (e.g., for FM radio, TV reception) and as the driven element in more complex arrays like the Yagi-Uda antenna.

5. NEAR FIELD VS. FAR FIELD

This is a critical distinction for any radiating dipole.

- **Near Field (Reactive Field):** Region close to the antenna (distance $r \ll \lambda$).
    - The field structure is complex and stores energy.
    - Dominated by reactive components (capacitive and inductive fields that oscillate energy back to the antenna).
    - The field strength decays very rapidly ($E \propto 1/r^3$).
- **Far Field (Radiative Field):** Region far from the antenna (distance $r \gg \lambda$).
    - The electromagnetic wave has formed and propagates outward independently.
    - The wave is *transverse electromagnetic (TEM)*, meaning the E and H fields are perpendicular to each other and to the direction of propagation.
    - The field strength decays as $1/r$.
    - The radiation pattern is well-defined and stable. This is the region where communication happens.

The boundary is typically defined as $r = 2D^2/\lambda$, where *D* is the largest dimension of the antenna.

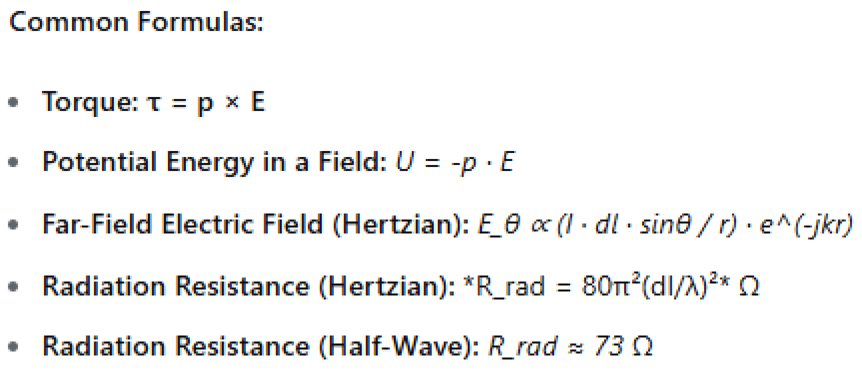
6. SUMMARY & KEY FORMULAS

Dipole Type	**Key Feature**	**Dipole Moment / Key Parameter**	**Primary Use**

Electrostatic	Static +/- charges	**p = q · d**	Understanding polarization, torque
Hertzian	Length *dl* << λ, uniform current *I*	**I · dl** (Current Moment)	Theoretical model for radiation
Half-Wave	Length L ≈ λ/2, sinusoidal current	**I_0** (Peak current)	Practical antenna design

Common Formulas:

- **Torque: $\tau = p \times E$**
- **Potential Energy in a Field:** $U = -p \cdot E$
- **Far-Field Electric Field (Hertzian):** $E_\theta \propto (I \cdot dl \cdot \sin\theta / r) \cdot e^{(-jkr)}$
- **Radiation Resistance (Hertzian):** $R_{rad} = 80\pi^2(dl/\lambda)^2$ Ω
- **Radiation Resistance (Half-Wave):** $R_{rad} \approx 73$ Ω



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7. STUDY TIPS & COMMON PITFALLS

- **Vector vs. Scalar:** The dipole moment **p** is a vector. Always remember its direction (from -q to +q).
- **Field Regions:** Don't confuse the behaviour of fields in the near zone (reactive, complex) with the far zone (radiative, simple *1/r* decay).
- **Current Assumption:** The assumption of sinusoidal current distribution is crucial for analyzing the half-wave dipole and is derived from transmission line theory.
- **Think in 3D:** Dipole radiation patterns are three-dimensional. Sketching the E-plane and H-plane patterns is essential for understanding their directivity.
- **Connect to Maxwell's Equations:** The radiation from a dipole is a direct consequence of Maxwell's Equations, specifically the solution to the wave equation with a current source. Understanding this link is key for advanced electromagnetics.