Antennas: From Ham Radio to Modern Communication Systems

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Agenda

1. Antenna Theory
   • Radiation Mechanism
   • Antenna Parameters

2. Antenna Applications
   • Ham Radio
   • Satellite Communication
   • 5G Cellular Communication
   • Antenna Array
Antenna Theory
Antenna Applications

An antenna is an essential element for all wireless communication systems and most of radars and sensors.
How Antennas Radiate*

- Physics behind: Radiation is created by accelerated charges
- Accelerating charges -> changing electric and magnetic fields -> propagating electromagnetic waves.
- \( I = q \cdot v \) (current = charge x velocity)
- \( \frac{dl}{dt} = q \cdot \frac{dv}{dt} \) (time varying current = accelerated charge)
- Time-varying current source (accelerated charges) exposed under an open space creates radiation.

* Referenced Prof. Ethan Wang’s and Prof. Yahya Rahmat-Samii’s classes
How to Get Radiation Characteristic*

Q: Can we find the radiation performance of the antenna with given the distribution of time-varying current?

A: Antenna’s radiation characteristic can be solved by the **vector superposition** of the elementary current elements.

* Referenced Prof. Ethan Wang’s class
How to Solve Electromagnetic (EM) Field of Antenna

1. Find expression of antenna’s current function
2. From the current function, calculate vector potential $A(r)$ ($A(r)$, extracted from Maxwell’s eq.)
3. Find magnetic field $H$ from the vector potential
4. Find electric field $E$ from the magnetic field

Short Dipole Electromagnetic Field

$$E_r = \frac{I_0 l k^2}{2\pi} \eta_0 e^{-jkr} \left[ \frac{1}{kr} - \frac{j}{(kr)^3} \right] \cos \theta$$

$$E_\theta = \frac{I_0 l k^2}{4\pi} \eta_0 e^{-jkr} \left[ \frac{j}{kr} + \frac{1}{(kr)^2} - \frac{j}{(kr)^3} \right] \sin \theta$$

$$H_\phi = \frac{I_0 l k^2}{4\pi} e^{-jkr} \left[ \frac{j}{kr} + \frac{1}{(kr)^2} \right] \sin \theta$$

$k = 2\pi/\lambda$: free space wave number
**Short Dipole**

\[
\begin{align*}
H_\phi &= \frac{I_0 l k^2}{4\pi} e^{-jkr} \left[ \frac{j}{kR} + \frac{1}{(kR)^2} \right] \sin \theta \\
E_R &= \frac{2I_0 l k^2}{4\pi} \eta_0 e^{-jkr} \left[ \frac{1}{(kR)^2} - \frac{j}{(kR)^3} \right] \cos \theta \\
E_\theta &= \frac{I_0 l k^2}{4\pi} \eta_0 e^{-jkr} \left[ \frac{j}{kR} + \frac{1}{(kR)^2} \frac{j}{(kR)^3} \right] \sin \theta
\end{align*}
\]

When \( R >> \lambda \), then \( \frac{1}{R^2} \), \( \frac{1}{R^3} \) terms are gone in the above expressions,

Therefore, we should have,

\[
\begin{align*}
E_\theta &= \frac{jI_0 l k}{4\pi} \eta_0 \left( \frac{e^{-jkr}}{R} \right) \sin \theta \\
H_\phi &= \frac{jI_0 l k}{4\pi} \left( \frac{e^{-jkr}}{R} \right) \sin \theta = \frac{E_\theta}{\eta_0}
\end{align*}
\]

* From Prof. Ethan Wang’s class
Radiation Pattern of Short Dipole

\[
E_\theta = \frac{jI_0 jk}{4\pi} \eta \left( \frac{e^{-jkr}}{r} \right) \sin \theta
\]

\[
H_\phi = \frac{jI_0 jk}{4\pi} \left( \frac{e^{-jkr}}{r} \right) \sin \theta = \frac{E_\theta}{\eta_0}
\]

H plane
E plane
E-plane radiation pattern
H-plane radiation pattern
3-D view - “Donut” shape

* From Prof. Ethan Wang’s class
Antenna Parameter: Pattern*

Normalized field pattern:

$$ F(\theta, \phi) = \frac{E_\theta}{E_\theta(\text{max})} $$

For infinitesimal dipole,

$$ F(\theta) = \frac{(Il / 4\pi) j\omega \mu (e^{-jkr} / r) \sin \theta}{(Il / 4\pi) j\omega \mu (e^{-jkr} / r)} = \sin \theta $$

$$ F(\theta, \phi) = g(\theta, \phi) f(\theta, \phi) $$

- Element factor
- Pattern factor

For z directed current element,

$$ g(\theta) = \sin \theta $$

Uniform line source pattern:

$$ f(\theta) = \frac{\sin[(kL / 2) \cos \theta]}{(kL / 2) \cos \theta} $$

Half-wave dipole pattern:

$$ f(\theta) = \frac{\cos\left(\frac{\pi}{2} \cos \theta\right)}{\sin^2 \theta} $$

* From Prof. Ethan Wang’s class
Antenna Parameter: Pattern*

Side lobe level is defined as:

$$SLL_{dB} = 10 \log \left| \frac{F(SLL)}{F(max)} \right|$$

Half-power beamwidth:

$$HP = \left| \theta_{HPl} - \theta_{HPri} \right|$$

* From Prof. Ethan Wang’s class
Antenna Parameter: Pattern*

* From Prof. Ethan Wang’s class

Two principal planes:
- $\Theta$ plane: elevation plane
- $\phi$ plane: azimuth plane

Beamwidth:
$$\beta = \theta_2 - \theta_1$$

$$F(dB) = 10\log F$$
Antenna Parameter: Directivity & Gain

- Directivity is the ratio of maximum radiation density to the average density.

- Directivity of isotropic antenna: $D_{\text{iso}} = 1$, $D_{\text{iso}} = 0 \text{ dBi}$

- Directivity of half-wave dipole: $D = 1.64$, $D = 2.15 \text{ dBi}$

- Larger directivity means more directional beam pattern. Directivity is solely determined by the radiation pattern.

- Gain: In real systems, antennas have loss. Gain is directivity considering antenna loss.

- With radiation efficiency $e_r = \frac{P_{\text{rad}}}{P_{\text{in}}}$, $G = e_r \cdot D$

- Typical antennas have dielectric loss and conductive loss.
Antenna Parameter: Polarization*

Vertical linear Pol.

Horizontal linear Pol.

Left-handed circular Pol.

Right-handed circular Pol.

Left-handed elliptical Pol.

Right-handed elliptical Pol.

\[ \varphi_x = \varphi_y = \varphi \]

\[ \varphi_y = \varphi_x + \frac{\pi}{2}, \quad |\tilde{E}_x| = |\tilde{E}_y| \]

\[ \varphi_y = \varphi_x - \frac{\pi}{2}, \quad |\tilde{E}_x| = |\tilde{E}_y| \]

* From Prof. Ethan Wang’s class
Antenna Applications
Various Type of Antennas*

(a) Thin dipole  (b) Biconical dipole  (c) Loop  (d) Helix  (e) Log-periodic

(f) Parabolic dish reflector  (g) Horn  (h) Microstrip  (i) Antenna array

* From Prof. Ethan Wang’s class
Various Length of Dipoles

Radiation Patterns of Various Dipoles

Arrows indicate relative current directions for maximum current conditions.

- Larger than one wavelength of dipole produces multiple lobes that are not typically preferred.
- Radiation pattern of longer dipole shows narrower beam-width.

* From “Antenna Theory and Design” book
Typical ham radio transceivers require 50 ohm input impedance of antenna. If your antenna does not provide 50 ohm impedance, additional matching will be required for increasing communication distance.
Ham Radio: Yagi-Uda Antenna*

Yagi-Uda antenna provide more direction beam (higher antenna gain) with simple configuration. Therefore, this type of antenna is commonly used in Ham Radio.

* From “Antenna Theory and Design” book
Satellite Comm.: Reflector Antenna*

Reflector antennas provide very high gain (> 50dBi) and narrow beam. Therefore, it is suitable for satellite communication systems.

* From Wikipedia
Satellite Comm.: Reflector Antenna Feed Horn*

Horn antennas are well established technology and predictable. They are mainly used for feedings of reflector antennas or measurement equipments.

* From Prof. Ethan Wang’s class
Because of the simplicity and conformality, patch antennas are used in various communication systems including airborne, vehicle, cell phone, body-worn, satellite, and etc..
Antenna Array

Phased Antenna Array*

Linear Array Antenna Calculation**

In general, the array factor is

\[
AF = I_0 + I_1 e^{j\beta d \cos \theta} + I_2 e^{j2\beta d \cos \theta} + \cdots = \sum_{n=0}^{N-1} I_n e^{j\beta nd \cos \theta}
\]

For linear phase progression,

\[
I_n = A_n e^{jn\alpha},
\]

\[
AF = \sum_{n=0}^{N-1} A_n e^{jn(\beta d \cos \theta + \alpha)}
\]

Define \( \psi = \beta d \cos \theta + \alpha \)

Then \( AF = \sum_{n=0}^{N-1} A_n e^{jn\psi} \)

Pattern from aperture antennas: Fourier Integration
Pattern from antenna arrays: Fourier series

You can control antenna’s gain and pattern with antenna arrays. Electrically controlled beam scanning and shaping are also available.

* From Wikipedia
** From Prof. Ethan Wang’s class
Q & A