Antennas

Lecture Notes

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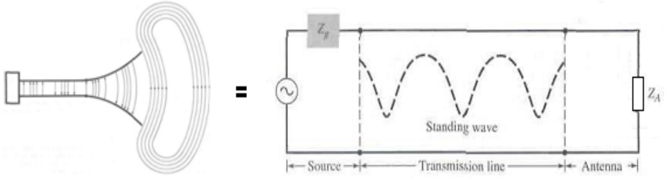
These lecture notes are heavily based on the book of *Antenna Theory and Design* by W.L. Stutzman and G. A. Thilie. For future version or any proposals, please contact with *Dr. Serkan Aksoy* (saksoy@gyte.edu.tr).

Content

1. INTRODUCTION

A device for radiating and receiving of EM waves.



1.1. Historical Advancement

- 1842, First radiation experiment, J. Henry
- 1872, Improvement in telegraphing (patent), M. Loomis
- 1873, Maxwell's equations
- 1875, Communication system (patent), T. Edison
- 1886, Hertz's experiment ($\lambda/2$ dipole)
- 1901, Marconi's success
- 1940, UHF antennas
- 1960, Modern antennas

Before WW II : Wire types
During WW II : Aperture types
Before 1950 : BW – Z , 2 : 1
In the 1950 : BW – Z , 40 : 1 (Frequency Independent)
In the 1970 : Microstrip (or Patch antennas)
: MM wave antennas (Monolithic forms)
Later : Arrays

1.2. Antenna Types

- Electrically Small (Dipole, Loop)
- Resonant (HW Dipole, Patch, Yagi)
- Broadband (Spiral, Log Periodic)
- Aperture (Horn, Waveguide)
- Reflector and Lens

- *Standing Wave (Resonant) Antenna:* SWR pattern of v and i is formed by the reflection from open end of the wire.
- *Travelling Wave (Non-Resonant) Antenna:* The proper termination of the antenna so that Γ is minimized. It has uniform pattern (surface wave (slow wave) and leaky wave (fast wave) antennas).

Standing Wave Antennas may be analyzed as Travelling Wave Antennas by thinking inverse individual currents.

1.3. Method of Analysis

To obtain a closed form solution, antenna geometry must be described by an orthogonal curvilinear system. If not possible, the following methods are applied:

- *Geometrical Theory of Diffraction (GTD):* Antenna system is many wavelengths. GO's disadvantage is overcome by including diffraction mechanism (high frequency).
- *Integral Equations (IE):* Unknown induced currents (explained by magnetic field) are solved by IE (Numerically MoM). EFIE (for all regions) and MFIE (for closed region) are based on the boundary conditions.
- *FDTD, FEM and Hybrid* methods.

1.4. Radiation Mechnasim

$$i(t) = qv(t) \quad \Rightarrow \quad \frac{di(t)}{dt} = q\frac{dv(t)}{dt} = qa$$

where a is acceleration (m/s^2). For radiation *Time Varying Current* (or *Accelerated Charge*) is necessary. The electrical charges are required to excite electromagnetic waves, but not necessary to propagate them.

1.1. Fundamental Parameters

1.1.1. Radiation Pattern & Radiation Power

Normalized Field Pattern

$$F(\theta,\phi) = \frac{E_\theta(\theta,\phi)}{E_\theta^{max}(\theta,\phi)} = g(\theta,\phi)f(\theta,\phi)$$

where $g(\theta,\phi)$ is *Element Factor*, $f(\theta,\phi)$ is *Pattern Factor*. *Radiation Power*, P_{rad} is calculated by *Radiation Power Density* for isotropic source is

$$P_{rad} = \iint_S \mathbf{P}_{rad}^{density}\,\mathbf{ds} = \frac{P_{rad}^{density}}{(4\pi r^2)^{-1}} \Rightarrow P_{rad}^{density} = \frac{P_{rad}}{4\pi r^2} \quad [W/m^2]$$

In far field region, P_{rad} is real valued. Power pattern

$$P_{rad}(\theta,\phi) = P_{in}G = |F(\theta,\phi)|^2$$

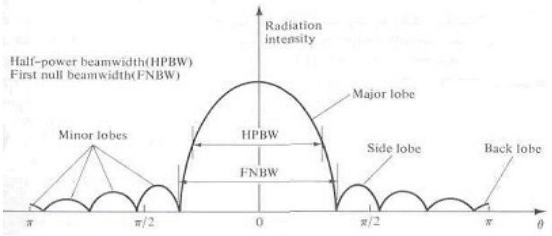
Since the magnitude variation of the power is $1/r^2$, *Radiation Intensity* is defined as the power radiated in a given direction per unit solid angle (far field region) is given

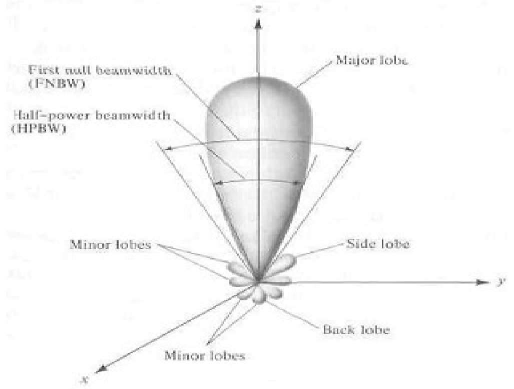
$$P_{rad} = 4\pi I_{rad}^{avg} \quad \Rightarrow I_{rad}^{avg} = \frac{P_{rad}}{4\pi} = r^2 P_{rad}^{density}(\theta,\phi) \quad [W/Sr]$$

Radiation Pattern is a function of coordinates given at constant radius in 2D or 3D forms. Reciprocal antennas have identical radiation patterns as transmitter & receiver antennas.

- *Isotropic:* A hypothetical, lossless antenna has equal radiation in all direction. Not realized, but used as a reference.
- *Directional:* Radiating or Receiving of electromagnetic waves more efficiently in some directions than in others.
- *Omnidirectional:* Having non-directional pattern in a given direction, a directional pattern in any orthogonal system. A special type of the directional antenna.

The values of ***E*** or ***H*** field with maximum direction of radiation is known *Principal Patterns*. The parts of the Radiation Pattern are lobes (major, minor, side and back).





- Major Lobe (Main Beam): contains direction of maximum radiation (maybe more than one as in split beam antenna).
- Minor Lobe: any lobe except a major lobe.
- Side Lobe: other than intended lobe.
- Back Lobe: 180° angle with respect to antenna beam.

Minor lobes are undesired. Side lobes are the largest lobes of minor lobes. *Side Lobe Level, SLL*

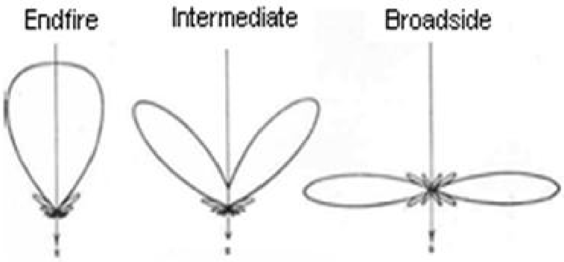
$$SLL = \frac{Side\ Lobe\ Level}{Major\ Lobe\ Level}$$

$SSL \cong -\ 20\ dB$, not desirable
$SSL \cong -320\ dB$, desirable but difficult.

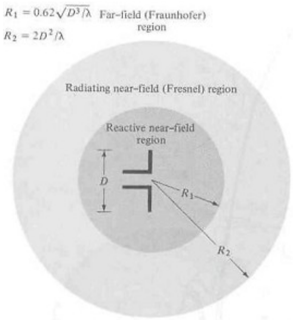
Half Power Beam Width (HPBW): The angular separation of the points where the main beam of the power pattern equals to one half of the maximum value.

$$HP = |\theta_{HPleft} - \theta_{HPright}|$$

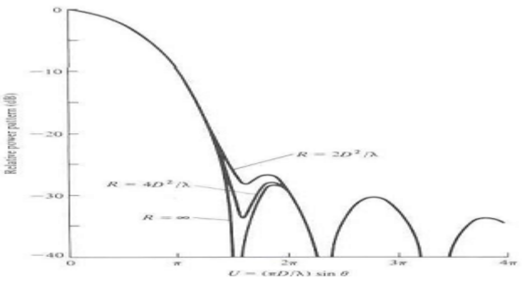
Beam Width between First Nulls (BWFN): A measure of the main beam for arrays.



1.1.2. Field Region



Rayleigh region: The reactive field region (dominant).
Fresnel region: Angular distribution depends on range.
Fraunhoufer region: Angular distribution is independent on range.



If $l \ll \lambda$, Fresnel region may not be exist. Some antennas such as multibeam reflector $2L^2/\lambda$ is not enough to determine borders. Plane angle is Radian (2π) and Solid angle is Steradian (4π).

1.1.3. Antenna Impedance & Efficiency

$Z_A = R_A + jX_A = R_{rad} + R_{loss} + jX_A$: Antenna impedance

R_{rad}: *Radiation resistance*-Power lead from antenna not return
R_{loss}: *Conduction and dielectric losses* (Ohmic losses converted to heat)
X_A: *Power stored in the near field* region of antenna

Z_A is affected by nearby object but assumed that isolated. Due to reciprocity, Z_A is same in reception and transmission antennas. Radiation resistance may be defined as

$$P_{input} = P_{rad} + P_{loss} \implies \frac{1}{2}R_A|I_A|^2 = \frac{1}{2}(R_{rad} + R_{loss})|I_A|^2$$

$$P_{rad} = \frac{1}{2}R_{rad}|I_A|^2 \implies R_{rad} = 2\frac{P_{rad}}{|I_A|^2} = 2\frac{P_{input} - P_{loss}}{|I_A|^2}$$

$$\eta = \frac{P_{rad}}{P_{input}} = \frac{P_{rad}}{P_{rad} + P_{loss}} = \frac{R_{rad}}{R_{rad} + R_{loss}} = \frac{R_{rad}}{R_A}$$

If assumed that $R_{loss} = R_{ohmic}$, then

$$R_{ohmic} \cong \frac{L}{2\pi a}R_S$$

where $R_S = \sqrt{\omega\mu/2\sigma}$ is surface resistance. For many antennas $\eta \longrightarrow \%\ 100$, but for all electrically small antennas η is lower.

1.1.4. Directivity and Gain

Directivity is ratio of radiation power in a given direction to the ratio of radiation power averaged overall direction.

$$D(\theta,\phi) = \frac{P_{rad}}{P_{rad}^{avg}} = \frac{4\pi}{\Lambda_{solid}}|F(\theta,\phi)|^2$$

where $\Lambda_{solid} = \iint_{\Lambda} |F(\theta,\phi)|^2 d\Lambda$. When $D(\theta,\phi)$ is quoted as a single number, the maximum directivity can be considered

$$D = \frac{P_{rad}^{max}}{P_{rad}^{avg}} = \frac{I_{rad}^{max}}{I_{rad}^{avg}} = \frac{4\pi I_{rad}^{max}}{P_{rad}} = \frac{4\pi I_{rad}^{max}}{I_{rad}^{max}\Lambda_{solid}} = \frac{4\pi}{\Lambda_{solid}}$$

Then $D(\theta,\phi) = D|F(\theta,\phi)|^2$. If no direction is specified, the direction of maximum radiation is taken into account (For isotropic source $I_{rad} = I_{rad}^{max}$). For partial directivities

$$D_\theta = 4\pi \frac{I_{rad}^{\theta}}{P_{rad}^{\theta} + P_{rad}^{\phi}} \quad , \quad D_\phi = 4\pi \frac{I_{rad}^{\phi}}{P_{rad}^{\theta} + P_{rad}^{\phi}}$$

- *Gain* is ratio measure of input & output power of antenna.

$$G(\theta,\phi) = \eta D(\theta,\phi) = \frac{P_{rad}}{P_{input}} = 4\pi \frac{I_{rad}(\theta,\emptyset)}{P_{input}} = \eta \frac{P_{rad}}{P_{rad}^{avg}}$$

where $\eta = P_{rad}^{avg}/P_{input}$ is *Antenna Efficiency* and $I_{rad}(\theta,\emptyset)$ is the radiation intensity. Gain can be given as $20log(V/V_{dipole})$ where V is induced voltage at the input of antenna. (dBd: reference is a half wave dipole, dBi: reference is an isotropic antenna ($D_{ideal\ dipole} = D_{isotropic} = 1$).

1.1.5. Antenna Polarization

The main beam determines antenna polarization having the types of *Linearly, Circularly (RHS and LHS)* and *Elliptical*. Side lobes can differ in polarizations. EM waves can have a nonperiodical behavior, but antennas can not generate them (randomly polarized waves).

1.1.6. Antenna Effective Length and Aperture

Antenna Effective Length, l_e is the ratio of the open circuit voltage at the terminals to the magnitude of the electric field strength in the direction of polarization

$$l_e = \frac{V_{open}}{|\vec{E}|} \quad [m]$$

Antenna Effective Aperture, A_e can be defined by using *Antenna Efficiency,* η as $A_e = \eta\, A_{em}$ due to antenna losses where the maximum antenna effective aperture, A_{em} (conjugate matching case) is the ratio between the power dissipated in the receiver resistance (W) and the power density (W/m^2) of incident field as

$$A_{em} = \frac{P_{receiver}}{P_{incident}^{density}} \quad [m^2]$$

It can be proved that the relation between the directivity of an antenna and A_{em} $[m^2]$ can be written as

$$A_{em} = \frac{\lambda^2}{4\pi} D \;\Rightarrow\; G = \eta D = \eta \frac{4\pi}{\lambda^2} A_{em} = \frac{4\pi}{\lambda^2} A_e$$

1.1.7. Antenna Factor and Calibration

Antennas are affected by mutual coupling to their environment. Different types of antennas can give different answers for electric field strength for certain geometries. These are uncertainties in electric field strength that should be taken into account. The output voltage of an antenna is converted to electric field strength via its *Antenna Factor* by which the output voltage of a receiving antenna would be multiplied to recover the incident electric or magnetic field as

$$Antenna\ Factor = \frac{|\vec{E}|}{V} \quad [1/m]$$

Different types of antennas overlap in frequency; they must all give same electric field result at a given frequency within the antenna factor uncertainties for each type. The antenna factor needs to be taken into account when calibrating antenna.

1.1.8. Beam Efficiency

The ratio between the solid angle extend to the main beam Λ_{main} relative to the entire pattern solid angle as

$$\eta_{beam} = \frac{\iint_{main} |F(\theta,\phi)|^2 d\Lambda}{\iint_{4\pi} |F(\theta,\phi)|^2 d\Lambda}$$

1.2. Antennas in Communication

Using *Friss transmission formula*, the received power

$$P^r = P^t \frac{G^r G^t}{(4\pi r)^2} \lambda^2 = P^t \frac{A_e^t A_e^r}{(r\lambda)^2}.$$

The relation for physical dimension of aperture is $A_e = \eta_e A_{physical}$ where η_e *Aperture Efficiency*. In practice, often polarization and impedance mismatches affect the delivered power be modeled as

$$P_{delivered} = \eta_{total} P_{input}$$

where $\eta_{total} = \eta_{polarization}\eta_{impedance}$ show the polarization and impedance match efficiency. EIRP (*Effective Isotropically Radiated Power*) is defined as multiplication of gain and input power of a transmitting antenna as

$$EIRP = P_{input}^t G^t = 4\pi I_{max}$$

EIRP (dBi) is given for a reference of the isotropic antenna, but ERP (dBd) for a half-wave dipole. Balun (*Balanced-Unbalanced*) is used to stop for the connection to the ground of one end of the antenna.

2. SIMPLE RADIATING SYSTEM

These are generally electrically small systems whose dimensions are small compared to wavelength (VLF or AM antennas). A radiation resistance of electrically small antennas is much less than reactance (input reactance of the short dipole is capacitive). The far-field pattern and directivity are independent of the antenna size, but radiation resistance and reactance not (It makes difficult the power transfer for different frequencies). Loading coil is used to tune the input impedance. The larger radiation resistance can be obtained by *Capacitor Plate antenna*. Another small antenna is TL loaded antenna and monopole form of it inverted L (or inverted F).

- Q of an Electrically Small Antenna

$$Q = \omega \frac{Stored\ Energy}{Radiated\ Power}$$

The impedance bandwidth of electrically small antennas is $\approx 1/Q$. The high Q (means Z_{input} is very sensitive to frequency) and small bandwidth are the limitations of electrically small antennas. Electrically small antennas tend to be *Superdirective* means that a directivity that is greater than normal for an antenna of a given electrical size. Superdirectivity is measured by superdirectivity, SD ratio

$$SD = \frac{P_{radiated} + P_{reactive}}{P_{radiated}} = 1 + Q$$

Antennas greater in size than a wavelength, the directivity is proportional to L/λ (or A_e^2/λ^2).

2.1. Monopoles

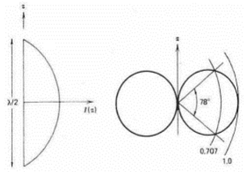
A monopole is a dipole divided in half at its center feed point against a ground plane.

$$Z_A^{monopole} = 0.5 \times Z_A^{dipole} \ , \ R_{rad}^{monopole} = 0.5 \times R_{rad}^{dipole}$$

$$D^{monopole} = 2 \times D^{dipole}$$

The directivity will increased due to decrease in average radiation intensity, not increasing the radiation intensity (the shorter monopole, the more directivity). The guy wires with insulators are used for longer monopoles. The radiation pattern of a monopole above a perfect ground plane is the same as a dipole for only over half space.

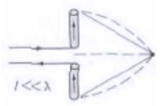
2.2. Electrically Small Dipoles



The radiation pattern of all form of the electrically small antennas can be evaluated as $sin(\theta)$. Because dipoles are resonate ($X_A = 0$) type antennas, the bandwidth is low. Bandwitdh is directly proportional to the thickness of the wire (construction from flat metallic strip also causes large bandwith). Dipoles can be form of *Open, Closed Loops, Collinear, Log Periodic* etc. The current distribution may be assumed as sinusoidal, but the current must be zero at the ends. The dipoles can be classified as given at below.

2.2.1. Ideal (or Short) Dipoles

$L \ll \lambda$, the current distribution must be zero at then ends.



The vector potential of a z directed current density is

$$\vec{A}_z = \mu \frac{e^{-jkr}}{4\pi r} \iiint_v \vec{J}_z e^{jk|z-z\prime|}\, dv' = \mu \frac{e^{-jkr}}{4\pi r} \int_{z\prime} \vec{J}_z e^{jkz\prime cos\theta}\, dz'$$

Then, the electric field in the far-field region is

$$\vec{E}_\theta = +j\omega sin\theta A_z \vec{e}_\theta$$

The current of short (or ideal) dipole may be approximated *triangle* (or *constant*). For uniform line source current

$$I(z) = \begin{Bmatrix} I_0 \ , & |z'| \le \frac{L}{2} \\ 0 \ , & elsewhere \end{Bmatrix}$$

The vector potential A_z may be calculated as

$$A_z = \frac{\mu I_0 L}{4\pi} \frac{e^{-jkr}}{r} \frac{sin\left(\frac{kl}{2} cos\theta\right)}{\frac{kl}{2} cos\theta}$$

where $\lim_{kl \to 0} sin\left(\frac{kl}{2} cos\theta\right) \cong \frac{kl}{2} cos\theta$, then the potential is

$$A_z = \frac{\mu I_0 L}{4\pi} \frac{e^{-jkr}}{r} \quad \Rightarrow \quad \vec{E}_\theta = -\frac{j\omega\mu I_0 L}{4\pi} \frac{e^{-jkr}}{r} sin\theta \vec{e}_\theta \, .$$

The normalized field pattern of ideal/short dipole

$$\vec{E}_\theta = -\frac{j\omega\mu I_0 L}{4\pi} \frac{e^{-jkr}}{r} F(\theta) \vec{e}_\theta \quad \Rightarrow \quad F(\theta) = sin\theta$$

The directivity of ideal/short dipole is 1.5 (1.76 dB) and % 50 bigger than isotropic source. HPBW of ideal/short dipole is 90°.

	Ideal dipole	Short dipole
R_{rad}	$80\pi^2(\Delta z/\lambda)^2$	$20\pi^2(\Delta z/\lambda)^2$
R_{ohmic}	$(R_s/2\pi a) \times L$	$(R_s/2\pi a) \times (L/3)$

In ideal dipole, all charges are accumulated at ends of antenna (means 4 times more radiation resistance than short dipole). Therefore electric dipole is used to represent it ($R_s = \sqrt{\omega\mu/2\sigma}$).

2.2.2. Half Wave Dipole

The advantage of it is to resonate and present a zero input reactance eliminating the tuning of input impedance. The normalized field pattern of the Half Wave (HW) dipole

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

The directivity of HW dipole $D = 1.64\,(2.15\,dB)$. The HPBW of the HW dipole is 78°. The radiation resistance is $R_{rad}{\sim}70\,\Omega$ and the ohmic loss resistance is $R_{ohmic} = (R_s/2\pi a) \times (\lambda/4)$. As L/λ becomes small, HW dipole approaches to short dipole.

2.3. Small Loop Antennas

A closed loop having the maximum dimensions is less than about a tenth of a wavelength is called a *Small Loop Antenna* used as a receiving antenna at low frequencies in AM receivers. It is a dual of an ideal dipole. The horizontal small loop and short vertical dipole have uniform pattern in horizontal plane, but loop provides horizontal $(E_{\emptyset})$ polarization, short dipole provides vertical (E_{θ}) polarization. Although the ideal dipole is *capacitive*, the small loop is *inductive*. The radiation resistance of the small loop can be increased by multiple turns (but losses are also increased by multiple turns) and ferrite core (loop-stick antenna). When frequency decreases its radiation resistance decreases much faster (f^{-4}) than a short dipole (f^{-2}).

3. ARRAYS

First proposed in 1889, but appeared in 1906. High directivities, sharp (desired) or scanned radiation pattern. The large directivities can be achieved by increasing the antenna size without arrays.

Advantages:

- Desired directional patterns,
- Scanned radiation pattern (no movement of the antenna with no mechanical difficulties),
- Track multiple targets.

Disadvantages:

- Bandwidth limitations,
- Mutual coupling between elements,
- Complexity network to feed elements.

Types of arrays: *Linear, Planar, Conformal*

Collinear Array: Elements of an array are placed along a line and the currents in each element also flow in the direction of that line. Collinear arrays are in widespread use in base stations. Lengthening the array by adding elements causes

- Narrows the beamwidth
- Increase the directivity
- Extending the range.

Array (or a simple antenna having same features) can be chosen in the applications according to following criteria:

- Available space
- Power handling
- Cost
- Scanning requirements.

Array factor (AF) can give chance to calculate the array field by using the single element antenna.

Array Pattern = AF x Single Element Pattern

Array factor depends on the relative location of elements and relative excitation of the elements

$$AF = \sum_{n=0}^{N-1} I_n e^{jn\psi} = I_0 + I_1 e^{jkd\vec{e}_d\vec{e}_r} + I_2 e^{jk2d\vec{e}_d\vec{e}_r} + \cdots$$

where $\vec{e}_d\vec{e}_r = cos\theta$ for collinear array, $\vec{e}_d\vec{e}_r = sin\theta cos\emptyset$ for others. $e^{jkRsin\theta cos(\emptyset-\emptyset_n)}$ for cylindrical array. AF of a discrete array has form of Fourier series whenever pattern factor for a continuous current distribution has form of Fourier transform.

3.1. Uniform Excited & Equally Spaced One

Consider only element phasing of a linear form for AF as

$$AF = A_0 \sum_{n=0}^{N-1} e^{jn\psi}$$

This relation can be modified as

$$AF = A_0 \frac{1-e^{jN\psi}}{1-e^{j\psi}} = A_0 e^{j(N-1)\frac{\psi}{2}} \frac{sin\left(N\frac{\psi}{2}\right)}{sin\left(\frac{\psi}{2}\right)}$$

The maximum value is $AF(\psi = 0) = A_0 N$. If the current has a linear phase progression as

$$I_n = A_n e^{jn\alpha}$$

then, the maximum value for AF occurs at the angle θ_0

$$\psi|_{AF\to max} = \alpha + kdcos\theta_0 = 0 \quad \Rightarrow \quad \alpha = -kdcos\theta_0$$

In that case $\psi = kd(cos\theta - cos\theta_0)$. Sometimes, a single pencil beam is required. The proper selection of array antenna elements or proper design of end fire antennas may yield a single pencil beam. To make main beam narrower (increasing directivity), inter-element phase-shifting should be increased.

3.1.1. Pattern Multiplication

N short dipoles are equally spaced a distance d apart and have currents $I_0, I_1, \dots, I_{N-1}$. In the far field condition

$$E_\theta = \overbrace{j\omega\mu \frac{e^{-jkr}}{4\pi r} sin\theta}^{Single\ element} \overbrace{A_0 \sum_{n=0}^{N-1} I_n e^{jkndcos\theta}}^{AF}$$

where the field pattern can be rearranged as

$$F(\theta,\emptyset) = g_{single}(\theta,\emptyset) \times AF$$

The process of factoring the pattern of an array into an element pattern and array factor is referred to as *Pattern Multiplication*.

3.1.2. Array Directivity

Directivity is determined entirely from the radiation pattern. Array directivity represents the increase in the radiation intensity in the direction of maximum radiation over a single element. The directivity of a broadside array of isotropic elements

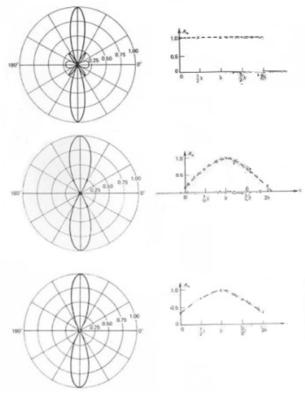
$$D = 2\frac{Nd}{\lambda}$$

3.2. Nonuniform Excited & Equal Spaced One

Although the main beam of the end wire antenna can be narrowed by chancing of phase as in previous chapter, shaping the beam and controlling the side lobes are also possible with array current amplitudes.

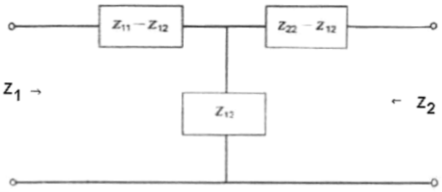
$$AF = \sum_{n=0}^{N-1} A_n e^{jn\psi} = \sum_{n=0}^{N-1} A_n Z^n$$

where A_n can be different for each element. If A_n's are equal to the coefficients of binominal series, all side lobes can be eliminated such as *Dolph-Chebyshev polynomials*. As the current amplitude is tapered more toward the edges of the array, the side lobes tend to decrease and the beamwidth increases. The following example is given for different current distributions of different patterns.



3.3. Mutual Coupling & Scan Blindness

In reality, array elements interact with each other and alter the currents (impedances) and known as *Mutual Coupling* changes the current magnitude and phase and distribution on each element. This will be clear in total array pattern in different frequency and scan directions relating to no-coupling case. Network representation of coupling is shown as below.



One of the important effects due to mutual coupling is *Scan Blindness* manifested by a dramatic reduction of radiated power for certain blind scan angles. In that case, generator power is reflected rather than radiated (no radiation), which can damage the electronics parts. It may be considered for different reflection of angles because of matching is confirmed at a single angle ($\Gamma(0,0) = 0$). To avoid it, use spacing of a half wavelength or less (no grating lobes).

3.3.1. Impedance Effects of Mutual Coupling

Three mechanisms are responsible for mutual coupling as *Direct Space Coupling* between array elements, *Indirect Coupling* can occur by scattering from nearby objects and *Feed Networks* (can be minimized with impedance matching) interconnects element can provide a path. In the case of coupling, the input impedance of m'th element (*Active Impedance* or *Driving Point Impedance*) is given as

$$\left.\begin{array}{l} V_1 = Z_{11}I_1 + \cdots + Z_{1n}I_n \\ \quad \cdots \\ V_n = Z_{n1}I_1 + \cdots + Z_{nn}I_n \end{array}\right\} \Rightarrow Z_m = Z_{m1}\frac{I_1}{I_m} + \cdots + Z_{mn}\frac{I_n}{I_m}$$

As general rules of the mutual coupling

- The coupling strength decreases as spacing increases ($1/d^2$).
- The far field pattern of each element gives information about coupling strength. When elements are oriented such that illuminated by a pattern maximum, then coupling will be appreciable. If individual patterns exhibit null in the direction of the coupled antennas, the coupling will be small.
- Elements with electric field orientations (i.e. polarizations) that are parallel will couple more than when collinear.
- Larger antenna elements with broadside patterns have lower coupling to neighboring elements.

3.3.2. Pattern Effects of Mutual Coupling

Gain, polarization and far field pattern are also affected from the mutual coupling. To analyze the effect of far field pattern, two ways are proposed as

- *Isolated Element Pattern Approach*: All coupling effects in array pattern are accounted in the excitations.
- *Active Element Pattern Approach*: All coupling effects are accounted for through the active element.

3.4. Multidimensional Array

Linear arrays have the following limitations:

- Phase scanned in only a plane containing line of elements.
- Beamwidth in a plane perpendicular to the line of element centers is determined by the element beamwidth in that plane (limitation of realizable gain).

Requiring a pencil beam, high gain or beam scanning in any direction, multidimensional arrays are used with classification

- The geometric shape of surface on element centers located
- The perimeter of the array
- The grid geometry of the element centers

The pattern multiplication and array factors are used for analysis of multidimensional array. The array factor of an arbitrary three dimensional array is given as below

$$AF = \sum_{n=1}^{N}\sum_{m=1}^{M} I_{mn} e^{j(\mathbf{kr}_{mn} - \alpha_{mn})}$$

3.4.1. Phased Arrays and Scanning

The scanning of main beam pointing direction is an important request from arrays. *A Phased Array* is an array whose main beam maximum direction is controlled by varying the phase or time delay to the elements. The term *Smart Antennas* have been coined that includes control functions such as beam scanning. For a linear array with unequally spaced elements

$$AF = \sum_{n=0}^{N-1} I_n e^{j\xi_n} = \sum_{n=0}^{N-1} A_n e^{j(\alpha_n + j\delta_n)} e^{j\xi_n}$$

where element spatial phase $\xi_n = kz_n cos\theta$. The portion of the phase $\alpha_n = -kz_n cos\theta_0$ varies linearly (*Linear Phase*) and responsible for *steering* the main beam peak. The remaining part of the phase δ_n is nonlinear and responsible for *beam shaping*. When spacing of several wavelengths is used, many grating lobes are visible and the array is called an *Interferometer*. To avoid grating lobes, the condition $d < \lambda/(1 + |cos\theta_{0max}|)$ must be satisfied.

The hardware connecting elements of an array are called *Feed Network*. To feed networks for beam scanning, *Parallel*, *Series* and *Space networks* are used. Especially for multidimensional arrays hybrid-feed is used and recently *Optical Feed* is also issued. The construction of feed networks can be in the form of *Brick* and *Tile*. Another feed configuration is *Sum Feed* for course angular tracking and *Difference Feed* for fine angle tracking. The feed network combines the left or right halves of an array both in phase and out of phase creating these patterns.
Electronic scanning can be constructed with

- Frequency scanning
- Phase scanning
- Time-delay scanning (overcomes instantaneous bandwidth limitation of phase shifters)
- Beam switching (avoids use of variable shifters)

Analog or digital phase shifters (ferrite or semiconductor diode) are also used for beam scanning.

These lecture notes are heavily based on the book of *Antenna Theory and Design* by W.L. Stutzman and G. A. Thilie. For future version or any proposals, please contact with *Dr. Serkan Aksoy* (saksoy@gyte.edu.tr).

4. LINE SOURCES

Many antennas can be modeled as a line source (or its combinations). A line source along z axis has the far zone electric field as

$$\vec{E} = j\omega\mu \frac{e^{-jkr}}{4\pi r} sin\theta \int_{-L/2}^{L/2} I(z')e^{-jkz'cos\theta} dz'$$

This is similar to an array's far zone electric field means that a line source is a continuous array. For the far field pattern of arrays, a link may be found with Fourier transform. Because $I(z') = 0$ except $-L/2 < z < L/2$, the field pattern $F(\theta)$ can be viewed as a Fourier transform of $I(z')$ as

$$F(\theta) = \int_{-\infty}^{\infty} I(z')e^{-jkz'cos\theta} dz'$$

According to that, the field pattern $F(\theta)$ and spatial current distribution $I(z')$n can be related as a Fourier and Inverse Fourier transform of each other. This means that to obtain narrow field pattern (like narrow pulse), wide band of spatial frequencies must pass from antenna related to $I(z')$. This needs electrically large antennas. In this sense, the antenna can be viewed as a spatial filter. Line sources can also show super-directivity by controlling the variation of phases.

4.1. Uniform Line Source

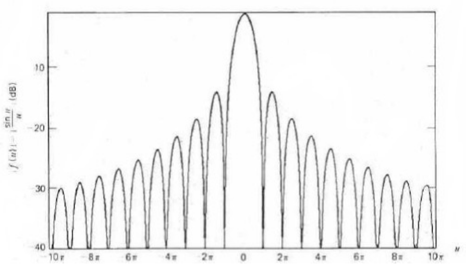
The current

$$I(z) = \begin{Bmatrix} I_0 e^{-jk_0 z} \ , & -\frac{L}{2}<z<\frac{L}{2} \\ 0 \quad , & elsewhere \end{Bmatrix}$$

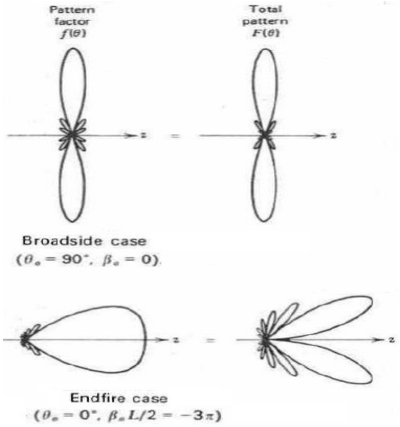
The normalized pattern factor

$$f(u) = \frac{sin\left(\frac{kl}{2}(cos\theta - cos\theta_0)\right)}{\frac{kl}{2}(cos\theta - cos\theta_0)}$$

The HPBW can be found by the solution of the equation $sin(u)/u = 1/\sqrt{2}$. Depending on the broadside or endfire uniform line source, HP can be calculated, exactly. The largest side lobe is the first one (closest to main beam). The pattern of the line source is given below.



The broadside and endfire line sources patterns are evaluated in the sense of pattern factor and total pattern as follow.



The directivity of the uniform line source can be calculated if the element factor is assumed to have negligible effect on the pattern as

$$D^{broadside} = 2\frac{L}{\lambda} \ , \ D^{endfire} = 4\frac{L}{\lambda}$$

The uniform line source has the most directivity in the case of a linear phase source of fixed length. The length increases, the beamwidth decreases and the directivity increases. The SLL remains constant with length variation.

4.2. Tapered Line Source

Many antennas can be modeled by line sources designed to have tapered current distributions. As an example, cosine taper current

$$I(z) = \begin{Bmatrix} I_0 cos\left(\frac{\pi}{L}z\right) e^{-jk_0 z} \ , & -\frac{L}{2}<z<\frac{L}{2} \\ 0 \quad , & elsewhere \end{Bmatrix}$$

with actual directivity

$$D^{broadside} = 1.620\frac{L}{\lambda}$$

Whenever current amplitude taper is increased (more severe), the sidelobes are reduced even more and beamwidth is further widened. In many applications, low side lobes (wider main beam) are necessary.

5. RESONANT ANTENNAS

A resonant antenna is a Standing Wave Antenna with zero input reactance at resonance and they have small bandwidths as % 8 or % 16.

5.1. Dipole Antenna

- <u>Straight Wire Dipole:</u> The assumed current distribution

$$I(z) = I_m sin\left[k\left(\frac{L}{2} - |z|\right)\right] \ , \quad -\frac{L}{2} < z < \frac{L}{2}$$

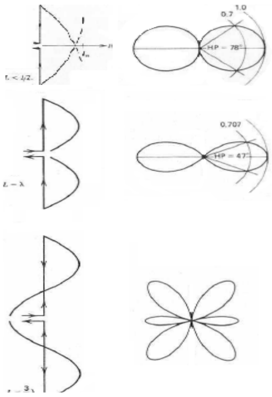
Then, $F(\theta)$for a straight wire dipole is

$$F(\theta) = \frac{cos\left(\frac{kl}{2}cos\theta\right) - cos\left(\frac{kl}{2}\right)}{sin\theta}$$

In case of a half wave straight wiredipole, $L = \lambda/2$:

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

Different lengths of dipole produce different $F(\theta)$ means different radiation patterns as below:



We can see that the dipoles longer than one wavelength, the currents on the antenna are not all in the same direction. Over a half wave section, the current is in phase and adjacent half wave sections are of opposite phase will lead large canceling effects in radiation pattern.

- $L = m\lambda/2 \quad \Rightarrow \ X_A \cong 0$, Resonate (m odd number)
- $L < \lambda/2 \quad \Rightarrow \ X_A < 0$, Capacitive
- $\lambda/2 < L < \lambda \quad \Rightarrow \ X_A > 0$, Inductive

- *Vee Dipole:* Whenever the directivity is bigger than straight dipole, input impedance is smaller than straight one.

- *Folded Dipole:* The folded dipoles (FM receiving antenna) are two parallel dipoles connected at the ends forming a half narrow loop with ease of rigidity reconstruction, impedance properties and wider bandwidth than ordinary HW dipole. The feed point is at the center of one side. It is an unbalanced transmission line with unequal currents (two closely spaced equal in one) and can be analyzed as transmission line (the currents cancel each other) and antenna mode (current reinforce each other).

$$Z_{HW\ folded} = 4Z_{dipole}^{\lambda/2}$$

5.2. Yagi-Uda Antenna

Yagi-Uda antenna is used for HF, VHF, UHF bands with the advantages of high gain, simplicity, low weight, low cost, relatively narrow bandwidth. Using folded dipole, Yagi-Uda will show higher input impedance. The gain may be increased by stacking. It is a *Parasitic Array* means that a few elements are fed directly, the other elements receive their excitation by near field coupling. The longer parasitic element behaves as a reflector and changes the pattern through feed. The shorter parasitic element behaves as a director and changes the pattern through the parasitic element. Metal boom is used at the center in which the currents are zero. It is Travelling Wave Antenna supporting the surface wave of slow type.

5.3. Corner Reflector Antenna

A practical gain standard antenna at HF band having a gain of 10 to 12 dB over a HW dipole. Method of Images and AF are used to analyze it. The finite extend of plates result broader pattern and feed driving impedance is negligible.

5.4. Large Loop Antenna

The large loop antennas have the loop's perimeter are sizable fraction of a wavelength or greater means that the current and phase of the loop are vary with position around the loop chancing the antenna performance. This also shows the similar effect whenever different frequencies are applied to the same loop antenna.

5.5. Microstrip Antenna

Microstrip antennas can be produced as a kind of printed antennas (patches) and were conceived in the 1950's. These are popular because of low profile, low cost, specialized geometries. The main challenge in microstrip patch antenna is to achieve adequate bandwidth in which conventional one has as low as a few percent. Because of resonance behavior of microstrip patches, they become excessively large below UHF and typically used from 1 to 100 GHz. They have loosely bound fields extending into space, but the fields tightly bound to the feeding circuitry. The patches geometry are generally rectangular but square and pentagonal patches are also possible for circular polarizations. Microstrip arrays can also be constructed for using advantages of printed circuit feed network with microstrip on the same single layer.

5.6. Wire Antennas above a Ground Plane

- <u>Imperfect Real Ground Plane:</u> Especially in low frequencies, electric field of an antenna penetrates into the earth causing the conductivity current due to the low conductivities. This gives rise of ohmic losses means increasing of input ohmic resistance lowering the radiation efficiency. Approximate pattern can be obtained using Method of Images combining the reflection coefficients. The pattern is different from free space antenna pattern.

6. BROADBAND ANTENNAS

A broadband antenna can be defined as its impedance and pattern do not change significantly over about an octave or more. The bandwidths of the narrow and wideband broadband antenna are generally calculated as

$$BW_{narrow} = \frac{f_{upper} - f_{lower}}{f_{center}} \times 100\ \%$$

$$BW_{wide} = \frac{f_{upper}}{f_{center}}$$

The wire antennas are broadband, such as Traveling-Wave antennas, Helix and Log-Periodic.

6.1. Traveling Wave Antenna, TWA

The reflected wave is not a strongly present with guiding EM waves. TWA can be created using very long antennas (or matched loads at the ends). Their bandwidth is broader than Standing Wave Antennas (SWA) and distinguishing with no second major lobe in reverse direction like SWA. Longer than one-half wavelength wire antenna is one of the *Travelling Wave Long Wire* antennas. Using some assumptions, the current of TWA

$$I(z) = I_m e^{ikz}.$$

TWA has real valued input resistance. Some types of TWA

- Travelling Wave Vee Antenna,
- Rhombic Antenna,
- Beverage Antenna: On the imperfect ground plane.

6.2. Helical Antenna

It has a helical shape as an uncoiled form. As two limit case, it reduces to loop or a linear antenna. Two forms of its operation are possible as

- *Normal Mode:* The radiated field is maximum in a direction normal to the helix axis. Because the dimension of the helix must be small compared to wavelength (electrically small antenna) for this mode, the efficiency is low (low radiation resistance) with emitting circularly polarized waves. The analysis may be done by using a small loop model with constant amplitude and phase variation. The depending on its orientation (such as quarter wave length with higher radiation resistance), vertical polarization may be dominant.

- *Axial Mode:* This mode is used when a moderate gain up to about 15 dB and circular polarization is required. Assuming the helix carries pure travelling wave, an approximate model can be used for analysis. The amplitude and phase of the antenna are not uniform.

6.3. Biconical Antenna

The conductors of the wire antenna can be flared to form biconical structure. This extends to increase bandwidth. The types are

- *Infinite Biconical Antenna:* The biconical structure is infinite and can be analyzed by Transmission Line Method.
- *Finite Biconical Antenna:* Practical one with less weight, less cost. Bow-Tie antenna is a favor example.
- *Discone Antenna:* One of the finite biconical antenna is replaced with a discone. Omnidirectional pattern is obtained.

6.4. Sleeve Antenna

The addition of a sleeve to a dipole or monopole antenna can increase bandwidth more than one octave and the frequency sensitivity is decreased. Types are

- *Sleeve Monopoles*: VSWR may be high and requires matching network feed.
- *Sleeve Dipoles*: VSWR is low over a wide bandwidth.

6.5. Frequency Independent Antenna

A bandwidth of an antenna about 10:1 or more is referred to as a *Frequency Independent Antenna*. The impedance, pattern and polarization should nearly remain constant over a broad frequency range. The following properties yield broadband behavior

- Emphasis on angles rather than lengths,
- Self complementary structures,
- Thick metal.

6.5.1. Spiral Antenna

Either exactly or nearly self-complementary with a bandwidth of 40:1. Types are

- *Equiangular Spiral:* It has a bidirectional pattern with two wide beams broadside to the plane of the spiral.
- *Archimedean Spiral:* It has a broad main beam perpendicular to the plane of spiral. Unidirectional beam can also be created by a cavity backed feeding.
- *Conical Equiangular Spiral:* It has a single main beam is directed of the cone tip.

Spiral antennas can also have different configurations such as Sinuous Antenna offering flexible polarizations.

6.5.2. Log-Periodic Antenna

Log-Periodic antenna has a structural geometry such that its impedance and radiation characteristics repeat periodically as the logarithm of frequency. Because of this variability is minor, it is considered as a frequency independent antenna. Using parallel wire segments, Log-Periodic Dipole Arrays can also be constructed of different types are

- Log-Periodic Toothed Planar Antenna
- Log-Periodic Toothed Wedge Antenna
- Log-Periodic Toothed Trapezoid Antenna
- Log-Periodic Toothed Trapezoid Wedge Antenna
- Log-Periodic Toothed Trapezoid Wire Antenna
- Log-Periodic Toothed Trapezoid Wedge Wire Antenna
- Log-Periodic Zigzag Antenna.

7. APERTURE ANTENNAS

These (Horns, Reflectors etc.) are in common use at UHF and higher frequencies. These have very high gain increasing of f^2 and nearly real valued input impedance.

7.1. Rectangular Aperture

Many horn antennas and slots have rectangular apertures. If the aperture fields are uniform in phase and amplitude across the physical aperture, it is referred as a *Uniform Rectangular Aperture* having effective aperture equal to its physical aperture. Uniform excitation amplitude for an aperture gives the highest directivity. To reduce low side lobes, tapering the excitation of amplitude toward the edges of a line source (*Tapered Rectangular Apertures*) is a good way.

7.2. Circular Aperture

An antenna having a physical aperture opening with a circular shape is known as *a Circular Aperture*. If the aperture distribution amplitude is constant, it is referred to *Uniform Circiular Aperture*. To reduce low side lobes at the expense of wider bandwidth and reduced directivity, *Tapered Circular Apertures* such as parabolic taper (tapering the excitation of amplitude) is a good way.

7.3. Horn Antenna

They are popular at the frequencies above about 1 GHz having high gain, low VSWR, relatively wide bandwidth, low weight and easy to construct with theoretical analysis achieving to closing the experimental results. Types of the horn antennas as

- E Plane Sectoral Horn
- H Plane Sectoral Horn
- Pyramidal and Conical Horn

These horns are fed by a rectangular waveguide oriented its broad wall horizontal. Horn antenna emphasizes traveling waves leads to wide bandwidth and low VSWR. Because of longer path length from connecting waveguide to horn edge, phase delay across aperture causes phase error. Dielectric or metallic plate lens in the aperture are used to correct phase error. Those with metallic ridges increase the bandwidth. Horns are also used for a feed of reflector antennas.

7.4. Reflector Antenna

High gain for long distance radio communication and high resolution for radar applications need the reflector antenna. *A Parabolic Reflector Antenna* is a widely used one having a reflecting surface large relative to the wavelength with a smaller fed antenna. One of the fundamental problems is to match the feed antenna to the pattern of the parabolic reflector. GO/Aperture Distribution Method or PO/Surface Current Method are used to analyze the antenna with the principles of

- All reflected rays are colliminated at the focal point,
- All path lengths are the same. Phase of the waves at the focal point is constant means constant phase center.

It is inherently a very wide band antenna. Bandwidth is limited to the size of the reflector (low frequency limit) or smoothness of the reflector surface (high frequency limit). The bandwidth of the feed antenna is also another limit for overall system. Types:

- *Axisymmetric Parabolic Reflector:* Feed is located at the focal point. The main peak is directed toward reflector center.

- *Offset Parabolic Reflector:* It avoids blockage caused by the hardware in feed region created by a cluster of the feed horn.

- *Dual Parabolic Reflector:* Using a hyperbolic sub-reflector with parabolic main reflector (Gregorian or Cassegrain), the aperture amplitude and phase can be controlled by design. The advantages of this antenna

- Reduced support problem for feed hardware
- Avoids long transmission line currents and losses
- Fed radiation is directed toward the low noise sky region rather than more noisy ground region.

The other types of the reflector antenna are

- Parabolic Cylinder,
- Parabolic Torus,
- Non-Circular Parabolic,
- Spherical Reflector at all.