Antennas for Wireless Communications: Basic Principles and System Applications

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antenna.ece.vt.edu
OUTLINE

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1. INTRODUCTION

- The Speakers
- Self Introductions of Class
- Wireless versus Wireline
- History of Communications
- The Spectrum
- Antenna Performance Parameters
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- Fellow of the IEEE
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- Incoming Commission Chair – International URSI Commission A
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- Vice Chair 2005 IEEE APS/URSI Symposium
Wireless versus Wireline

• **Fields of Application**
  – **Communications**
  – **Sensing and Imaging**
    • Active – Radar
    • Passive – Radiometry
  – **Industrial**
    • Control Ex.: garage door opener
    • Medical Ex.: pace maker interaction
    • Heating, cooking, drying, ...

• **Communications**
  – **Antennas must be used for:**
    • Mobile communications
    • Very long distances
      – Space
      – Remote terrestrial locations
– Antennas are preferred for
  • Broadcast and point-to-multipoint comm.
  • Long distance communications
  • Thin routes
  • Portable and personal communications

– The physics of wireless vs. wireline
  • Loss in wireline is $e^{-2\pi r}$
  • Loss in wireless is $1/r^2$

References
The History of Communications

Pre-modern civilization
   Optical communications: Smoke signals, flags, ....
   Acoustical communications: Drums
   [note – all are forms of wireless ndigital communications]

1844
   Telegraph (Morse) – digital wireline comm.

1864
   Maxwell’s equations – principles of radio waves

1876
   Telephone (Bell) – analog wireline comm.

1887
   First antenna (Hertz)

1897
   First radio systems (Marconi, Popov)
1901
First transatlantic radio (Marconi)

1907
Lee de Forest invented triode tube

1920
KDKA, 1st modern radio station (Pittsburgh)

World War II
Development of radar & Magnetron

1960
Fiber optics

1980s
Wireless reinvented
The Spectrum

- **Wavelength** \( \lambda (m) = \frac{300}{f(MHz)} \)  \( \lambda (cm) = \frac{30}{f(GHz)} \)

- **Frequency bands**

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Antenna Performance Parameters

- **Radiation pattern** $F(\theta, \phi)$
  The angular variation of radiation around an antenna

**Pattern types:**
- Directive (narrow main beam)
- Omnidirectional
- Shaped beam
- Low side lobe

- **Directivity D**
  Ratio of power density in the direction of pattern maximum to the average power density at the same distance from the antenna; i.e. how much more focused the power is than if isotropically distributed.

- **Gain G**
  Directivity reduced by losses on the antenna
• **Polarization**
  The figure traced out with time by the instantaneous electric field vector.
  Types:
  Linear, circular, elliptical, dual (for diversity and reuse)

• **Impedance**
  Input impedance at the antenna terminals

• **Bandwidth**
  Range of operating frequencies for which performance parameters are acceptable.

• **Scanning**
  Movement of the radiation pattern in angular space
  Types: electronic, mechanical, hybrid

• **Mechanical**
  Size, weight, RCS, aerodynamics

• **Cost**
2. ANTENNA FUNDAMENTALS

• What is an antenna?
• Connecting to the antenna
• Basic properties
  – Impedance
  – Gain
  – Pattern
  – Polarization
• Fundamental Limits
What is an antenna?

• Collection of metal/material objects
  – Wire
  – Plates (reflector, dish)
  – EM Bandgap Materials …

• Absence of metal
  – Slots
  – Waveguide apertures

Transformation from Electronics to Space
Determining the Radiation

- Start with the current (assume)
  - Wire: Approximate sinusoid/traveling wave
  - Plate: Physical Optics approximation or image current
- Giving for example (dipole):

\[
\vec{J}(\vec{r}, \omega) = \hat{z}I \cos(\beta z) \delta(x) \delta(y)
\]
To the Fields

Current

\[ \vec{A}(\vec{r}) = \mu \frac{e^{-j\beta r}}{4\pi r} \int_{V} \vec{J}(\vec{r}') e^{j\beta \vec{r} \cdot \vec{r}'} d\vec{r}' \]

\[ \vec{E}, \vec{H} \]
The Fields (far field)

- Magnetic Field
  \[ \vec{H} = \frac{1}{\mu} (-j \beta \hat{r} \times \vec{A}) \]

- Electric Field
  \[ \vec{E} = -\eta \hat{r} \times \vec{H} = -j \omega (\vec{A} - \hat{r}A_r) \]
Far Field

Linear E-field

Decibel E-field
Far-Field Conditions

- Wavelength
  \[ r \gg \lambda \]

- Distance
  \[ r \gg \max(r') = D \]

- Size
  \[ r > \frac{2D^2}{\lambda} \implies \text{phase} < \frac{\lambda}{16} \]
Far Field

Antenna

Projection \sim \text{replace distance}

Diameter D

Distance

Observation
Example – Short Dipole

- **Current**
  \[ \mathbf{J} \sim \hat{z} I \Delta_z \delta(\mathbf{r}) \]

- **Vector Potential**
  \[ \mathbf{A} = \mu \frac{e^{-j\beta r}}{4\pi r} \hat{z} I \Delta_z \]

- **Magnetic Field**
  \[ \mathbf{H} = j \beta \frac{e^{-j\beta r}}{4\pi r} I \Delta_z \sin \theta \phi \]

- **Electric Field**
  \[ \mathbf{E} = j \beta \frac{e^{-j\beta r}}{4\pi r} \eta I \Delta_z \sin \theta \hat{\theta} \]

- **Poynting Vector**
  \[ \mathbf{S} = \frac{1}{2} \mathbf{E} \times \mathbf{H}^* = \frac{1}{2} \hat{r} \eta \beta^2 \frac{|I|^2 \Delta_z^2}{16\pi^2 r^2} \sin^2 \theta \]
  \[ P = \eta \beta^2 \frac{|I|^2 \Delta_z^2}{12\pi} \]
Radiation Resistance

Short Dipole

- **EQUATE**
  - Input Power & Radiation Power

\[
R_{rad} = \frac{P_{rad}}{\frac{1}{2}|I|^2} \Rightarrow \frac{2\eta\pi}{3} \left| \frac{\Delta_z}{\lambda} \right|^2 \approx 80\pi^2 \left| \frac{\Delta_z}{\lambda} \right|^2
\]

\[
\Delta_z \approx \frac{L}{2}, \text{ For practical dipole}
\]
Radiation Pattern

• Variation of Fields with Elevation ($\theta$) and Azimuth ($\phi$)

\[ F(\theta, \phi) = \frac{|E(\theta, \phi)|}{\text{max}_\theta,\phi|E|} = \sin \theta, \text{ for short dipole} \]

• Variations:
  – Spherical
  – E-plane & H-plane (or Elevation & Azimuth)
  – Conical
Patterns

3-D Pattern Plot, $|F|

Linear, Principal-Plane Cuts

$y = 0$ or $\phi = 0^\circ$ Cut

$x = 0$ or $\phi = 90^\circ$ Cut

$z = 0$ or $\theta = 90^\circ$ Cut
Half-Power Beamwidth

Main lobe maximum direction

Main lobe

Half-power point (left)

1.0

Half-power point (right)

0.5

Half-power beamwidth (HP)

Beamwidth between first nulls (BWFN)

Minor lobes
Efficiency

- **Loss**
  \[ e = \frac{\text{Power Radiated}}{\text{Power Input}} = \frac{R_{\text{rad}}}{R_{\text{rad}} + R_{\text{loss}}} \]

  - Radiation Resistance
  \[ R_{\text{loss}} = \frac{1}{|I|^2} \int_S \left| \mathbf{j}_S \right|^2 R_{\text{surface}} \, ds \]

- **Mismatch**
  \[ q = 1 - |\Gamma|^2 = \frac{4Z_o R_{\text{Ant}}}{\left| Z_{\text{Ant}} + Z_o \right|^2}, \quad Z_o \text{ Real} \]

- **Total**
  \[ Efficiency = q e \]
Example: Approximate $\lambda/4$ dipole

- $f = 150$ MHz
- $L = 0.5$ m
- $Dia. = 0.01$ m

\[ R_s = \sqrt{\frac{\omega \mu}{2\sigma}} = 3.2 \text{ m}\Omega \]
\[ |R_{loss} = \sqrt{\frac{\omega \mu}{2\sigma} \frac{h}{3\pi a}} = 17 \text{ m}\Omega \]

\[ e = \frac{3.09}{3.09 + .017} = 99.5\% \]
\[ q_{tuned} = \frac{4 \times 3.09 \times 50}{|3.09 + 50|^2} = 22\% \]

**Efficiency** $\equiv q e = 21.9\%$
Directivity & Directive Gain

$$D(\theta, \phi) = \frac{F^2}{\text{Average}(F^2)} = \frac{4\pi F^2}{\int F^2(\theta, \phi)d\Omega}$$

$$D = \max[D(\theta, \phi)]$$

$$D = \frac{4\pi}{\Omega_A}$$

$$\Omega_A = \int F^2 d\Omega = \text{Beam Solid Angle}$$
Directivity

\[ d\Omega = \sin \theta \, d\theta \, d\phi \]

Figure 1-17
Element of solid angle \( d\Omega \).

Figure 1-18
Antenna beam solid angle \( \Omega_A \).

(a) Actual pattern
(b)
Open Circuit Voltage & Effective Length

- **Open Circuit Voltage**

\[ V_{OC} = -\hat{h}^* \cdot \vec{E} \]

- **Effective Length**

\[
\hat{h}^* (\theta, \phi) = -\hat{r} \times \hat{r} \times \frac{1}{I} \int_{\text{Ant}} \vec{J}(\vec{r}') e^{j\beta \hat{r} \cdot \vec{r}'} d\nu'
\]

\[
= - \frac{\vec{E}_{rad}}{j\omega \mu (e^{-j\beta r} / 4\pi r) I}
\]
Short Dipole

\[ \vec{E}_{rad} = j \beta \frac{e^{-j \beta r}}{4\pi r} \eta I \Delta_z \sin \theta \hat{\theta} \]

\[ \vec{h}^* (\theta, \phi) = -\Delta_z \sin \theta \ \hat{\theta} \]
Polarization

- Linear, Circular, Elliptical

\[ E = \hat{x}E_1 \cos \omega t + \hat{y}E_2 \cos(\omega t + \delta) \]
Polarization Factor

\[ p = \left| \frac{\hat{h}^2 |\vec{E}|^2}{|\hat{h} \cdot \vec{E}|^2} \right|^2 \]

p=1  for matched wave and antenna
p= ½  for CP ant. and LP wave
p=0  for orthogonal ant. and wave
\[ E = \hat{x} E_x + \hat{y} E_y = \hat{x} E_1 e^{j\omega t} + \hat{y} E_2 e^{j(\omega t + \delta)} \]

**Figure 2-37**  Polarization ellipses as a function of the ratio \( \frac{E_2}{E_1} \) and phase angle \( \delta \) with wave approaching. Clockwise rotation of the resultant \( E \) corresponds to left-handed polarization (IEEE definition) while counterclockwise corresponds to right-handed polarization.
Gain & Realized Gain

- Gain
  \[ G = eD \]

- Realized Gain
  \[ G_R = qeD \]

- Partial Realized Gain
  \[ g_R = pG_R = pqeD \]
A Communication Link

- Friis’ Trans. Formula

\[ P_{Rcv} = \frac{P_{Xmit} G_T G_R \lambda^2}{(4\pi R)^2} \]
Effective Area

\[ A_R(\theta, \phi) = \frac{\lambda^2}{4\pi} G_R(\theta, \phi) \]

To Give

\[ P_{Rcv} = \frac{P_{Xmit} G_T A_R}{4\pi R^2} \]
Transient Link

\[ v_{OC} = \hat{h}_r(t) \star \left( \frac{\mu}{4\pi R} \right) \hat{h}_t \left( t - \frac{R}{c} \right) \star \frac{\partial i(t)}{\partial t} \]
Connections

• Connectors (coax, twin-lead)
• Balanced vs Unbalanced
  – Balun
• Feed Network (Arrays)
  – Phased
  – True Time-Delay
• Filtering & Impedance Transformation
  – Circuit & loading
  – Tapering
Properties

• Impedance
  – Treat as a circuit element
  – By Reciprocity:

\[ Z_{Rcv} = Z_{Xmit} \]

– Induced EMF \( Z \)

\[ Z = \frac{1}{I^2} \int_{\text{Ant}} \vec{J} \cdot \vec{E}(\vec{J}) d\Omega \]
Properties

• Patterns

\[ F_{Rcv} = F_{Xmit} \]
Pattern Reciprocity

\[(a)\] The transmitting pattern of antenna \(a\) is \(Z_{pa}(\theta, \phi) = V_p^a(\theta, \phi)/I_a.\)

\[(b)\] The receiving pattern of antenna \(a\) is \(Z_{ab}(\theta, \phi) = V_a^b(\theta, \phi)/I_b.\)
Fundamental Limits

• A bit of Controversy
  – Chu (1948)
  \[ Q = \frac{2\beta^2 a^2 + 1}{\beta^3 a^3 (\beta^2 a^2 + 1)} \]
  – McLean
  \[ Q = \frac{1}{\beta^3 a^3} + \frac{1}{\beta a} \]
New Pub. on Fund. Limits

\[ Q = \frac{1}{\beta^3 a^3} \]

- Previous error: Assumed radiation fields travel RADIALLTY at speed of light.
3. ANTENNA ELEMENTS

• The Four Antenna Types
  – Electrically Small Antennas
  – Resonant Antennas
  – Broadband Antennas
    • Frequency Independent
    • Ultra Wideband
  – Aperture Antennas
The Four Antenna Types

• Electrically Small Antennas

Examples

- Short dipole
- Small loop

Properties
- Low directivity
- Low input resistance
- Low efficiency and gain
• Resonant Antennas

Examples

Dipole  Microstrip antenna  Yagi

Properties
Low to moderate gain
Real input impedance
Low efficiency and gain
Monopoles and Images

(a) Monopole antenna

(b) Capacitor plate monopole

(c) Transmission line monopole

ILA
• Broadband Antennas
  Examples (Frequency Independent)

  Spiral  Log Periodic Dipole Array

There are two types of broadband antennas, ones that have frequency independent performance and ones that preserve signal properties in the time domain (UWB).

Properties
  Low to moderate gain
  Real input impedance
  Low efficiency and gain
• Aperture Antennas

Examples

Horn antenna

Parabolic reflector antenna

Properties
Low to moderate gain
Real input impedance
Low efficiency and gain
4. ARRAY ANTENNAS

A. Array Basics
B. Arrays of Isotropic Elements
C. Inclusion of Element Effects
D. Mutual Coupling
E. Phased Arrays
A. Array Basics

Def.: Array Antenna. An antenna comprised of a number of identical radiating elements in a regular arrangement and excited to obtain a prescribed radiation pattern.

Advantages of arrays:

- Many small antenna elements instead of one large mechanical structure
- Scanning at electronic speeds is possible
- Multiple user (target) tracking is possible
- Many geometries, including conformal, are possible

Problems:

- A feed network is required with its losses and bandwidth limitations
- Mutual coupling between elements affects performance and complicates design
- Computer control may be necessary

General array configuration with feed network

Figure 3-1 A typical linear array. The symbols $\phi$ and $\psi$ indicate variable phase shifters and attenuators. The output currents are summed before entering the receiver.
B. Linear Arrays of Isotropic Elements

- General array configuration of isotropic elements

Figure 3-2 Equivalent configuration of the array in Fig. 3-1 for determining the array factor. The elements of the array are replaced by isotropic point sources.

\[
\text{Array factor} \quad \text{AF} = I_0 e^{j\xi_0} + I_1 e^{j\xi_1} + I_2 e^{j\xi_2} + \ldots \tag{3-3}
\]

\[\xi_n = \text{phases at element } n \text{ due to incoming wave}\]

\[I_n = \text{complex current representing the feed network amplitude and phase at element } n\]
Two element arrays of isotropic elements of various spacings and phasings.

\[
\begin{align*}
\delta & \quad 0^\circ & 45^\circ & 90^\circ & 135^\circ & 180^\circ \\
\frac{d}{\lambda} & = \frac{1}{8} & & & & \\
\frac{d}{\lambda} & = \frac{1}{4} & & & & \\
\frac{d}{\lambda} & = \frac{3}{8} & & & & \\
\frac{d}{\lambda} & = \frac{1}{2} & & & & \\
\frac{d}{\lambda} & = \frac{5}{8} & & & & \\
\frac{d}{\lambda} & = 1 & & & &
\end{align*}
\]

From [Kraus]
• General uniformly excited, equally spaced linear array (UE,ESLA)

![Equally spaced linear array of isotropic point sources.](image)

**Figure 3-7** Equally spaced linear array of isotropic point sources.

\[
AF = I_0 + I_1 e^{j\beta d \cos \theta} + I_2 e^{j\beta 2d \cos \theta} + \cdots = \sum_{n=0}^{N-1} I_n e^{j\beta nd \cos \theta} \tag{3-14}
\]

Now consider the array to be transmitting. If the current has a linear phase progression (i.e., relative phase between adjacent elements is the same), we can separate the phase explicitly as

\[
I_n = A_n e^{jna} \tag{3-15}
\]

where the \(n + 1\)th element leads the \(n\)th element in phase by \(a\). Then (3-14) becomes

\[
AF = \sum_{n=0}^{N-1} A_n e^{jn(\beta d \cos \theta + a)} \tag{3-16}
\]

Define

\[
\psi = \beta d \cos \theta + a \tag{3-17}
\]

Then

\[
AF = \sum_{n=0}^{N-1} A_n e^{jn\psi} \tag{3-18}
\]

Universal array factor
Properties of the universal array factor

- The array factor is periodic in $2\pi$
  
  Proof: \( AF(\psi + 2\pi) = \sum A_n e^{jn(\psi + 2\pi)} \)  
  \[ \begin{align*}  
  &= \sum A_n e^{jn\psi} e^{jn2\pi} \\
  &= \sum A_n e^{jn\psi} \\
  &= AF(\psi)  
  \end{align*} \]

- Visible region extent:
  
  \[ 180^\circ \geq \theta \geq 0^\circ \]  
  \[-1 < \cos \theta < 1 \]  
  \[-\beta d < \beta d \cos \theta < \beta d \]  
  \[\alpha - \beta d < \psi < \alpha + \beta d\]

- Exactly one period of the array factor appears in the visible region when the element space is $\lambda/2$.
  
  Proof: Width of the visible region = $2\beta d$  
  AF period = $2\pi$  
  For one period visible:  
  \[ 2\pi = 2\beta d = 2(2\pi/\lambda)d \]  
  \[ d = \lambda/2 \]

  For $d > \lambda/2$, grating lobes may appear in the visible region depending on $\alpha$.

  For $d \geq \lambda$, grating lobes will appear in the visible region.
The general array factor expression for a UE, ESLA

\[ A_0 = A_1 = A_2 = \cdots \]

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

\[ = A_0 e^{j(N-1)\psi/2} \frac{\sin(N\psi/2)}{\sin(\psi/2)} \]

The expression is maximum for \( \psi = 0 \)

\[ AF(\psi = 0) = A_0 (1+1+\cdots+1) = A_0 N \]

\[ f(\psi) \frac{\sin(N\psi/2)}{N \sin(\psi/2)} \quad UE, ESLA \quad (3-33) \]

This is the normalized array factor for an \( N \) element UE, ESLA that is centered about the coordinate origin.
Universal array factors for \( N = 3, 5, 10 \)

Figure 3-11 Array factor of an equally spaced, uniformly excited linear array for a few array numbers. (a) Three elements. (b) Five elements. (c) Ten elements.
Example 3-5  Four-element array steered to 120°

(a)

\[ f(\psi) = \left| \frac{\sin 2\psi}{4 \sin \frac{\psi}{2}} \right| \]

(b)

Figure 3-12  Array factor for a four-element, uniformly excited, equally spaced phased array (Examples 3-5). (a) The array excitations. (b) Universal pattern for \( N = 4 \). (c) Polar plot for \( d = \lambda/2 \) and \( \alpha = \pi/2 \).
• Scanning the pattern of a linear array in space

The main beam maximum occurs for $\psi = 0$. Let $\theta_o$ be the value of $\theta$ in the direction of the beam maximum. Then

$$\psi = 0 = \beta d \cos \theta_o + \alpha$$

$$\alpha = \beta d \cos \theta_o$$  \hspace{1cm} (3-36)

This element-to-element phase shift will scan the main beam peak to $\theta = \theta_o$. Often, we express $\psi$ as

$$\psi = \beta d \left( \cos \theta - \cos \theta_o \right)$$  \hspace{1cm} (3-38)

• Beamwidth of the main beam

For \( Nd >> \lambda \) \hspace{1cm} (Nd = L = \text{length of the array})

$$\text{HP} \approx 0.886(\lambda/Nd) \csc \theta_o \quad \text{near broadside}$$  \hspace{1cm} (3-45)

$$\text{HP} \approx 2 \left[ 0.886(\lambda/Nd) \right]^{1/2} \quad \text{at endfire}$$  \hspace{1cm} (3-46)

**Example** \( N = 20 \quad d = \lambda/2 \)

$$0.886(\lambda/Nd) = 0.886 \left[ \lambda / (20\lambda/2) \right] = 0.0886 \text{ radians}$$

$\theta_o = 90^\circ$ \hspace{1cm} $\text{HP} = 0.0886 \Rightarrow 0.0886 \left( 180/\pi \right) = 5.1^\circ$

$\theta_o = 0^\circ$ \hspace{1cm} $\text{HP} = 2 \left[ 0.0886 \right]^{1/2} = 0.595 \left( 180/\pi \right) = 34.1^\circ$
• Directivity of Uniformly Excited, Equally Spaced Linear Arrays

\[
D = \frac{4\pi}{\Omega_4^2} = \frac{\sin(N\delta/2)}{N\sin(\delta/2)} + \frac{1}{N} + \frac{2}{N^2} \sum_{m=1}^{N-1} \frac{N-m}{m} \sin m\beta d \cos m\alpha
\]

\[
= \sum_{m=1}^{N-1} \frac{N-m}{m} \sin m\beta d \cos m\alpha
\]

(3-78)

If \( d = n\frac{\lambda}{2} \), \( \alpha = 0 \)

Then \( D = N \)

Figure 3-20  Directivity as a function of element spacing for a broadside array of isotropic elements for several element numbers \( N \).

The directivity of a broadside array of isotropic elements is approximated by

\[
D \approx 2 \frac{L}{\lambda} = 2 \frac{Nd}{\lambda} \quad \text{broadside}
\]

(3-80)

where \( L = Nd \) is the array length. This is a straight-line approximation to the curves
• Nonuniformly excited, ESLA

\[ AF = \sum_{n=0}^{N-1} A_n e^{in\psi} \quad \psi = \beta d \cos \theta + \alpha \]

- Uniform
  \[ 1:1:1:1:1 \]
- Triangular
  \[ 1:2:3:2:1 \]
- Binomial
  \[ 1:4:6:4:1 \]
- Dolph-Chebyshev for a side lobe level of -20dB
  \[ 1:1.61:1.94:1.61:1 \]
- Dolph-Chebyshev for a side lobe level of -30dB
  \[ 1:2.41:3.14:2.41:1 \]

**Figure 3-24** Current distributions corresponding to the patterns of Fig. 3-23. The current phases are zero (\(\alpha = 0\)). Currents are normalized to unity at the array center.

- (a) Uniform.
- (b) Triangular.
- (c) Binomial.
- (d) Dolph-Chebyshev (SLL = -20 dB).
- (e) Dolph-Chebyshev.
Figure 3-23  Patterns of several uniform phase ($\theta_0 = 90^\circ$), equally spaced ($d = \lambda/2$) linear arrays with various amplitude distributions. The currents are plotted in Fig. 3-24.
(d) Dolph-Chebyshev

Current amplitude distribution, \(1 : 1.61 : 1.94 : 1.61 : 1\)
for a side lobe level of -20 dB.

(e) Dolph-Chebyshev

Current amplitude distribution,
\(1 : 2.41 : 3.14 : 2.41 : 1\), with a side lobe level of -30 dB.

Fig. 3-23 (continued)
We can draw a general conclusion from the foregoing examples that applies to antennas in general:

As amplitude taper increases:

- Beamwidth increases
- Directivity decreases (as a consequence of beamwidth increasing)
- Sidelobes decrease
Directivity of nonuniformly excited, isotropic element arrays

General case of unequally spacings and nonuniform phasings

\[
D = \frac{\left(\sum_{k=0}^{N-1} A_k\right)^2}{\sum_{m=0}^{N-1} \sum_{p=0}^{N-1} A_m A_p e^{j(\alpha_m - \alpha_p)} \frac{\sin[\beta (z_m - z_p)]}{\beta (z_m - z_p)}} \tag{3-91}
\]

Equal spacings and broadside operation

\[
D = \frac{\left(\sum_{k=0}^{N-1} A_k\right)^2}{\sum_{m=0}^{N-1} \sum_{p=0}^{N-1} A_m A_p \frac{\sin[(m-p)\beta d]}{(m-p)\beta d}} \quad \alpha_n = 0, \quad z_n = nd \tag{3-92}
\]

Spacings a multiple of a half-wavelength and broadside

\[
D = \frac{\left(\sum_{n=0}^{N-1} A_n\right)^2}{\sum_{n=0}^{N-1} (A_n)^2} \quad d = \frac{\lambda}{2}, \frac{\lambda}{\lambda}, \ldots \tag{3-93}
\]
C. Inclusion of Element Effects

**Principle of Pattern Multiplication:** The pattern of an array (array pattern, F) consisting of similar elements is the product of the pattern of one of the elements (the element pattern, $g_a$) and the pattern of the array of isotropic elements with the same locations, relative amplitudes and phases as the original array (the array factor, $f$).

\[ F(\theta, \phi) = g_a(\theta, \phi) \cdot f(\theta, \phi) \]  \hspace{1cm} (3-36)
Collinear elements

Example: Two collinear short dipoles

\[ \frac{\lambda}{2}, \frac{\lambda}{2} \]
\[ I_o = 1, I_1 = 1 \]

(a) The array.

\[ \begin{align*}
\sin \theta & \quad \cos \left( \frac{\pi}{2} \cos \theta \right) \\
\sin \theta \cos \left( \frac{\pi}{2} \cos \theta \right) &
\end{align*} \]

(b) The pattern.

Parallel elements

Figure 3-17 Array of two half-wavelength spaced, equal amplitude, equal phase, collinear short dipoles (Example 3-8).
Parallel half-wave dipoles

For a half-wave dipole along z-axis

\[
\cos \left[ \left( \frac{\pi}{2} \right) \cos \theta \right] \over \sin \theta \quad \text{half-wave dipole} \quad (2-8)
\]

For an array of parallel half-wave dipoles it is best to orient the elements along the x-axis. Then the element pattern is expressed as

\[
g_a(\gamma) = \frac{\cos \left[ \left( \frac{\pi}{2} \right) \cos \gamma \right]}{\sin \gamma} \quad (3-68)
\]

\[
cos \gamma = \sin \theta \cos \phi \quad \sin \gamma = \sqrt{1 - \sin^2 \theta \cos^2 \phi}
\]

\[
g_a(\theta, \phi) = \frac{\cos \left[ \left( \frac{\pi}{2} \right) \sin \theta \cos \phi \right]}{\sqrt{1 - \sin^2 \theta \cos^2 \phi}} \quad (3-69)
\]
Prob. 3.3-2

From (2-7) \( g_a(\theta) = \frac{\cos\left(\frac{\pi}{2} \cos \theta\right)}{\sin \theta} \)

From (3-13) \( f(\theta) = \cos(\pi \cos \theta) \)

So \( F(\theta) = g_a(\theta) f(\theta) = \frac{\cos\left(\frac{\pi}{2} \cos \theta\right)}{\sin \theta} \cos(\pi \cos \theta) \)

(Fig. 2-5b) (Fig. 3-6c)
- Method used in practice to produce a single endfire beam

**Image theory solution**

The array factor is that of Example 3-2

Problem 3.7-7 uses array theory to find the patterns
• Directivity of arrays of real elements

There is no general exact formula for the directivity of arrays including the element pattern. The following often-quoted approximate directivity formula must be used with caution

\[ D \approx D_e D_i \]

- \( D_e \) = directivity of a single element
- \( D_i \) = directivity of the array with isotropic elements

Example: 4-element, broadside array of collinear short dipoles with spacing \( d = \lambda/2 \)

(3-83) gives \( D = 5.6 \), an exact answer

\[ D \approx D_e D_i = (1.5)(4) = 6 \]
• Base Station Collinear Arrays

From code

\[ D = 7.75 \text{ dBi} \quad (d = 0.72\lambda) \]
\[ = 5.6 \text{ dBi} \]

Approximate directivity

\[ D \approx D_0 D_1 = 1.64(5.4) = 8.9, \text{ using Fig. 3-20} \]
\[ = 9.5 \text{ dB} = 7.3 \text{ dBi} \]

The tower enhances the gain by making pattern more directive
Base station with elements in opposing pairs and clocked 90 degrees around the tower to produce nearly an omnidirectional pattern.
D. Mutual Coupling

There are three mechanisms responsible for mutual coupling:

- Direct free space coupling between elements
- Indirect coupling due to scattering by nearby objects
- Coupling through the feed network

In many arrays the elements are impedance matched to the feed network and feed coupling can be ignored. Then the array can be modeled with independent generators, leading to the conventional circuit N port representation.

\[ V_1 = Z_{11} I_1 + Z_{12} I_2 + \ldots + Z_{1N} I_N \]
\[ V_2 = Z_{12} I_1 + Z_{22} I_2 + \ldots + Z_{2N} I_N \]
\[ \quad \quad \quad \vdots \]
\[ V_N = Z_{1N} I_1 + Z_{1N} I_2 + \ldots + Z_{NN} I_N \]

where the mutual impedance is

\[ Z_{mn} = \frac{V_m}{I_m} \quad \text{with} \quad I_i = 0 \quad \text{for all} \quad i \quad \text{except} \quad i = n \]

and reciprocity has been assumed through \( Z_{mn} = Z_{nm} \)
The input impedance of the mth element in an array with all elements active and mutual coupling included is

\[ Z_m = \frac{V_m}{I_m} = Z_{m1} \frac{I_1}{I_m} + Z_{m2} \frac{I_2}{I_m} + \ldots + Z_{mN} \frac{I_N}{I_m} \quad (3-103) \]

This is often called active impedance or driving point impedance.

Note that active impedance depends on mutual impedances between elements as well as the excitations of all elements. This dependence includes the current phases and thus scan angle in phased arrays.

The effects of mutual coupling include:

- The impedance of an element in an array differs from its free space value and depends on that array scan angle (element phases) and the element location.

- The pattern of an element is changed from its isolated pattern and depends on array position.

- Polarization characteristics deteriorate.
Example: Mutual coupling effect on a 12-element, half-wave spaced linear array

Figure 10-27  Linear array pattern with main beam steered to $\phi_o = 45^\circ$ and ideal current generators (solid curve) compared to patterns from an array with voltage generators for 72-$\Omega$ loaded voltage generator excitations (dashed curve).

E. Phased Arrays

Figure 3-32 Example of phase-scanned patterns for a five-element linear array along the z-axis with elements equally spaced at $d = 0.4\lambda$ and with uniform current magnitudes for various main beam pointing angles $\theta_o$. 
Important point to remember:
The array factor scans inside the envelope of the fixed element pattern

Example: Linear array of four broadside elements spaced $0.7\lambda$ apart. The element pattern is $g(\theta) = (\cos \theta)^2$.

Broadside operation

Scanned 30° off broadside
• Basic Feed Types

(a) Parallel, or corporate, feed.

(b) Series feed.

(c) Space feed.

(d) Parallel-series feed.

Figure 3-33 Types of array feed networks.
Phased array example: AWACS (Airborne Warning and Control System)

Mounted on top of aircraft such as E-3A, E-2C for aerial surveillance and detection of bombers and low flying fighters coming in over north pole
First operational radar antenna with very low sidelobes: -40 dB
Slotted waveguide array with 4000 slots
Scanned in vertical plane using ferrite phase shifters
Rotated for azimuth coverage
Next generation: phased array conforming to the aircraft
• Beam switched scanning

Switched antenna system vs linear array configurations: (a) switched antennas; (b) multiple-beam array; (c) steered-beam array.

[Microwave Journal, January 1987]
• Digital Beam Forming
• Scanning arrays of wideband elements
  [Stutzman and Buxton, Microwave Journal, Feb. 2000.]
The future for phased arrays
- Wideband, multifunctional arrays will be used
- Intelligence will be integrated with arrays, creating “smart arrays” that can adapt to changing conditions and faults
- Radiating elements will be printed, giving low cost and uniform geometrical construction (see figure)
- Feed networks will make use of integrated fabrication techniques such as MMIC.
- Elements and feeds will be integrated together
- Beam steering:
  - Low cost phase shifters: MEMS, Ferroelectric, ...
  - Photonic feeds
  - Digital beam forming will be very popular as RF and DSP module performance and cost improve

2x2 array of Foursquare elements
Fourpoint element
capable of 2:1 bandwidth and dual polarization
5. SYSTEM CONSIDERATIONS

- Friis Transmission Equation
- Propagation in real links
- Factors in selecting an operating frequency
Friis Transmission (review)

Basic Single Path

\[ P_{Rcv} = \frac{P_{Xmit} G_T G_R \lambda^2}{(4\pi R)^2} \rho \]

Multipath link

\[ P_{Rcv} = \int_{\Omega_T} \int_{\Omega_R} G_R(\theta_R, \phi_R) p_R(C(\theta_R, \phi_R; \theta_T, \phi_T)) \]

\[ \star G_T(\theta_T, \phi_T) p_T d\Omega_R d\Omega_T \frac{\lambda^2}{4\pi} P_{Xmit} \]
Basic Propagation

- Two main factors affecting signal at receiver
  - Distance (or delay) $\Rightarrow$ Path attenuation
  - Multipath $\Rightarrow$ Phase differences

Green signal travels $1/2\lambda$ farther than Yellow to reach receiver, who sees Red. For 2.4 GHz, $\lambda$ (wavelength) = 12.5 cm.

Ref: UCLA, CSCI 694, 24 September 1999, Lewis Girod
Basic Issues

- Outdoor
  - Free Space Loss
  - Ground Bounce
  - Atmospheric Absorption
  - Building/Mountain reflection/diffraction

- Indoor
  - Doors
  - Walls
  - Waveguide effects (maybe use – ducting)
Transient links

**Basic Single Path**

\[ v_{OC} = \vec{h}_r(t) \ast \left( \frac{\mu}{4\pi R} \right) \vec{h}_t \left( t - \frac{R}{c} \right) \ast \frac{\partial i(t)}{\partial t} \]

**Multipath link**

\[ v_{OC} = \int_{\Omega_T} \int_{\Omega_R} \vec{h}_r(t) \ast \mu \left( \vec{C}(\theta_R, \phi_R; \theta_T, \phi_T; t) \right) \vec{h}_t \left( t - \frac{R}{c} \right) \ast \frac{\partial i(t)}{\partial t} \, d\Omega_R \, d\Omega_T \]
Frequency Tradeoff

• Lower Frequency ⇒
  – Higher signal vs \( \lambda \)
  – Scale antenna size
  – Higher noise

• Higher Frequency ⇒
  – Smaller Antenna
  – Lower Q for same size
  – Higher Gain for same size
Factors in operating frequency selection

- Propagation and link budget considerations
  - VHF and below for long distance, narrow bandwidth
  - UHF and above for wide bandwidth
  - Above 10 GHz, atmospheric losses are high

- Antenna considerations
  - Very long distance point-to-point communications require high frequencies to enable large antenna gains

- Regulatory issues
  - Must use allocated bands
  - Licensed vs. unlicensed bands
6. WIRELESS APPLICATIONS

- Base Station Antennas for Land Mobile
- Antennas for Satellite Communications
- Vehicle Antennas
- Antennas for Personal Communications
- UWB
  - Some Concepts
- Radiation Safety
Base Station Antennas for Land Mobile Radio

- **Cell Coverage Types**

  - Omnidirectional
  - Sectorized

  Smart antenna that forms beams on users
- Omnidirectional pattern base station antennas
  - Pattern is constant in azimuth and narrow in elevation
  - Usually realized with collinear array of dipoles

Exam

Transmit -
  1 active
  1 spare

Transmit Antennas

Transmit setup

Receive -
Diversity; select strongest signal

Receive Antennas
Antel Cellular
Base Station Antenna
870-970 MHz
Collinear dipoles
136 in long
10 dBi gain
1.25 deg downtilt
• Sector base station antennas

Typical
120 deg sectors, VP

Polarization diversity
120 deg sectors, dual slant 45 deg LP

Wind Area = 95ft²

Panels mounted in compact configuration
Wind Area = 10ft²
• **Sector (“panel”) antennas**
  – **Elements**
    • Dipoles in front of a ground plane
    • Log periodic dipole (LPDA) and LPDA vees
    • Patches
    • Fourpoint antenna (VT) covers both cellular and PCS with dual polarization
  – **Considerations**
    • Bandwidth (VSWR<2)
    • Power handling
    • Intermodulation products
DB Products LPDA

vee antenna

ideal for cellular and trunking/ESMR applications, these high-quality log periodic antennas are now available from DB Products in four new models with 80 or 90 degree horizontal apertures. They're compact, lightweight, and provide an unmatched front-to-back ratio of 40 dB.

- **1 ft Wind Loading** — They measure only 31 or 48 inches (810 or 1219 mm) tall, 0.3 inches deep (76 mm), and 8 inches wide (152 mm). They weigh only 5 or 10 pounds (2.3 or 4.6 kg).
- **Null-Fill** — Four-foot models provide null-fill and upper lobe suppression.
- **Most Stringent IM Test** — Each antenna is tested for the absence of IM with 16 carriers at 500 watts of power.
- **Sturdy Construction** — Made in the U.S. of high-strength anodized aluminum alloy tubes, brass elements and UV-resistant ABS plastic radomes. No nuts are used!
- **Lightning Resistant** — All metal parts are grounded.
- **Terminations and Mounts** — All models are available with N-Female or 7/16 DIN connectors. DB380 clamps are included, or, for downtilt applications order DB5081.

### Ordering Information
See table for models to fit your requirements.

<table>
<thead>
<tr>
<th>Models Available</th>
<th>DB842H80-XY</th>
<th>DB844H80-XY</th>
<th>DB842H90-XY</th>
<th>DB844H90-XY</th>
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<tbody>
<tr>
<td><strong>Gain — dBi</strong></td>
<td>10</td>
<td>13</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td><strong>P/B Ratio — dB</strong></td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td><strong>Horizontal Beamwidth</strong></td>
<td>80°</td>
<td>80°</td>
<td>90°</td>
<td>90°</td>
</tr>
<tr>
<td><strong>Vertical Beamwidth</strong></td>
<td>30°</td>
<td>15°</td>
<td>30°</td>
<td>15°</td>
</tr>
<tr>
<td><strong>Height — in. (mm)</strong></td>
<td>24 (610)</td>
<td>48 (1219)</td>
<td>24 (610)</td>
<td>48 (1219)</td>
</tr>
<tr>
<td><strong>Weight — lbs. (kg)</strong></td>
<td>5 (2.3)</td>
<td>10 (4.6)</td>
<td>5 (2.3)</td>
<td>10 (4.3)</td>
</tr>
<tr>
<td><strong>Shipping weight — lbs. (kg)</strong></td>
<td>8 (3.6)</td>
<td>13 (5.9)</td>
<td>8 (3.6)</td>
<td>13 (5.9)</td>
</tr>
</tbody>
</table>

* For 7/16 DIN connectors add “E” to model numbers. Example: DB842H80E-XY.
* *3 dB from maximum.

**DB380 mounting clamps are included. For downtilt applications order DB5081.**

### Electrical Data

- **Frequency Range — MHz**: 800-960
- **Gain — dBi**: See table above
- **Front-to-back ratio — dB**: 40
- **Beamwidths**: See table above
- **VSWR**: <1.5:1
- **Null-fill and secondary**: On 48° (1219 mm) low-suppression models only
- **Maximum power input — watts**: 500
- **Nominal impedance — ohms**: 59
- **Lightning protection**: All metal parts grounded
- **Termination**: N-Female or 7/16 DIN

### Mechanical Data

- **Width — in. (mm)**: 8 (152)
- **Depth — in. (mm)**: 8.3 (211)
- **Height**: See table above
- **Maximum wind speed — mph (km/hr)**: 100 (161)
- **Wind area — ft² (m²)**: 1 (0.09)
- **Wind load (at 100 mph/161 km/hr)**:
  - lbs (kg): 40 (18)
- **Radiator**: Gray ABS
- **Backplate**: Anodized aluminum
- **Radiators**: Brass
- **Mounting hardware**: Galvanized steel
- **Weight**: See table above

**UPS Shippable**
• A new wideband base station antenna developed at VTAG:
  – Minimum number of antennas on tower
  – Dual-polarized for diversity
  – Multi-functional capability (800 ~ 2200 MHz)
  – Low profile and compact
  – Printed antenna on a PCB

Front view Tuning plate on back
Fourpoint Antenna Data

![Graph showing VSWR vs Frequency for AMPS, GSM, DCS, PCS, etc.]

**Graph Details:**
- **Y-axis:** VSWR
- **X-axis:** Frequency, MHz
- Comparison between Simulation and Measurement data points
- Frequencies: 700 MHz to 2300 MHz
- Bands: AMPS, GSM, DCS, PCS, etc.
Measured Radiation Patterns

900 MHz
- HPBW: 60° ~ 80°
- Low cross-pol, less than -30 dB

1800 MHz
• Satellite communications antennas

Satellite services

FSS – Fixed Satellite Service
[gateways, VSATs]
BSS – Broadcast Satellite Service
(DBS, DTH)
Mobile (Iridium, Orbcom, Inmarsat)

Gain of spacecraft antenna

Global coverage  19 dB
US coverage  34 dB

Ground station antennas

Reflectors are used above a few GHz
Small offset reflectors for VSAT
Large, dual reflectors for gateways
Direct Broadcast system from DirecTV manual

12.2 -12.7 GHz downlink to user
17.3-17.8 GHz uplink from gateway
Dual circularly polarized
Vehicular Antennas

- Broadcast reception
  Traditional 31” (0.003 λ at AM) fender mount whip antenna is vanishing.
  New cars have mostly on-glass antennas

Example of a Ford rear window glass antenna
• Two-way land mobile vehicle antennas
  VHF and below
  Short monopole
  Quarter-wave monopole

Example quarter-wave monopole
UHF
Quarter-wave monopole
5/8 over ¼ wavelength

Example 5/8 over ¼ wavelength
• Aircraft antennas

Example: Commercial MD-80 airplane

Source: McDonnell Douglas
• Antennas for fixed wireless
  – Access points and terminals

Omnidirectional antennas
  Collinears for access points
  Stubby or planar antennas for terminals
High gain (20 dB or more) – reflectors
Moderate gain
  Yagi
  Stub loaded helix antenna
    75% volume reduction
    Circularly polarized

Example; Stub loaded helix antenna
  www.frc-corp.com
• Antennas for personal communications
  VHF
  Short monopole
  Loops, small and/or loaded
  Normal mode helix
  UHF
  Monopole
  Normal mode helix
  Patch
  Inverted-L
  Planar inverted-L
  Embedded
Perhaps the most popular antenna for cell phones is the stubby antenna with an extendable wire antenna.

Nokia Patent 5,612,704
• Inverted-L family of antennas
Wideband Compact PIFA

VT patent 6,795,028

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Bandwidth (%)</th>
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<tbody>
<tr>
<td>Patch</td>
<td>1</td>
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<tr>
<td>IFA</td>
<td>2</td>
</tr>
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<td>DIFA</td>
<td>4</td>
</tr>
<tr>
<td>PIFA</td>
<td>8</td>
</tr>
<tr>
<td>Dipole</td>
<td>12</td>
</tr>
<tr>
<td>WC PIFA</td>
<td>43</td>
</tr>
</tbody>
</table>
UWB Antennas

TEM Horn  
Ridged Horn  
BiCone

Tapered Slot (Vivaldi)  
Impulse Radiating Antenna (IRA)
Half-Disk

$\varepsilon_r = 2.33$
Size: 1" x 1" x 31mil
PICA & VSWR

Simulation
Measurement
Typical Responses – TEM Horn

**Reflection**

- **Return Loss**
  - Amplitude (dB) vs. Frequency (GHz)
  - Frequency Response $s_{21}$
  - Phase - Delay Phase
  - Frequency (GHz)
  - Phase (degrees)

**Transmission Link**

- **Frequency Response $s_{21}$**
  - Amplitude (dB) vs. Frequency (GHz)
  - Frequency (GHz)
  - $s_{21}$ (dB)

**Phase**

- Amplitude ($s^{-1}$) vs. Time (nsec)

**Transient Transmission**

- Amplitude ($s^{-1}$) vs. Time (nsec)
The Monster Antenna

- At least 10:1 “instantaneous” Gain Bandwidth with 0.1 $\lambda$ Size
- Relatively-constant Monopole-like Radiation Pattern
- Size & Performance $\rightarrow$ Close to Theoretical Limits
- Light, Aerodynamic, and Inexpensive Design

Picture of Prototype  Realized Gain v.s. Frequency  Comparison to Limit
The Monster Antenna

Measured and Simulated VSWRs

Radiated Pulse

Measured Patterns @ Selected Freqs

Printed Version: 450 MHz–10 GHz
Radiation Safety & Interference

- **SAR** – Specific Absorption Rate
  - Power per area absorption

- **HAC** – Hearing Aid Compatibility
  - Buzzing and related noise in Hearing Aid

- System Interference and Cross-Modulation
Facilities

INSTRUMENTATION

• ANTCOM 7+1 axis near field – far field scanner
• Agilent 8510, 8511, 8530 Network Analyzer
Next:

Pictorial Presentation on Antennas