School on Digital Radio Communications for Research and Training in Developing Countries
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Antenna theory basics

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Note: These are preliminary notes, intended only for distribution among the participants. Beware of misprints!

Purpose

- The purpose of the lecture is to refresh basic concepts related to the antenna physics that are needed to understand better the operation and design of microwave digital radio links
  - Note: Due to time limitations, we will focus here only on these aspects that are critical for microwave LAN/ WAN applications.

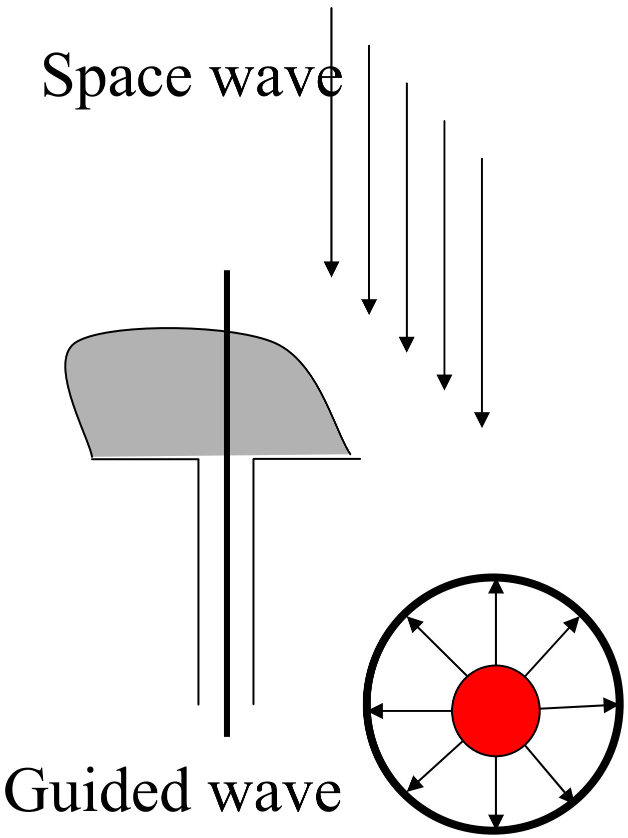
Main topics for discussion

- Antenna concept & Reciprocity Theorem
- Point-antenna, Isotropic antenna
- Antenna impedance, radiation pattern, & gain
- E.I.R.P. and Power Transfer
- Examples

Intended & Unintended Antennas

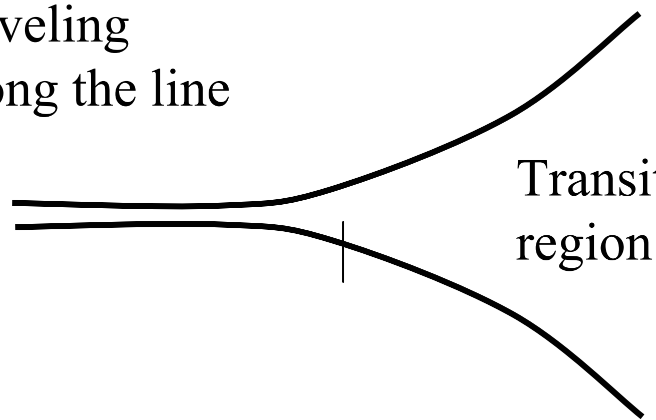
- Intended antennas
  - Radiocommunication antennas
  - Measuring antennas, EM sensors, probes
  - EM applicators (Industrial, Medical)
- Unintended antennas
  - Any conductor/ installation carrying electrical current that vary in time (e.g. electrical installation of vehicles) or any slot/ opening in the device/ cable screen
  - Any conducting structure/ installation irradiated by EM waves
    - Stationary (e.g. antenna masts or power line wires)
    - Time-varying (e.g. windmill or helicopter propellers)
    - Transient (e.g. aeroplanes, missiles)

Antenna function



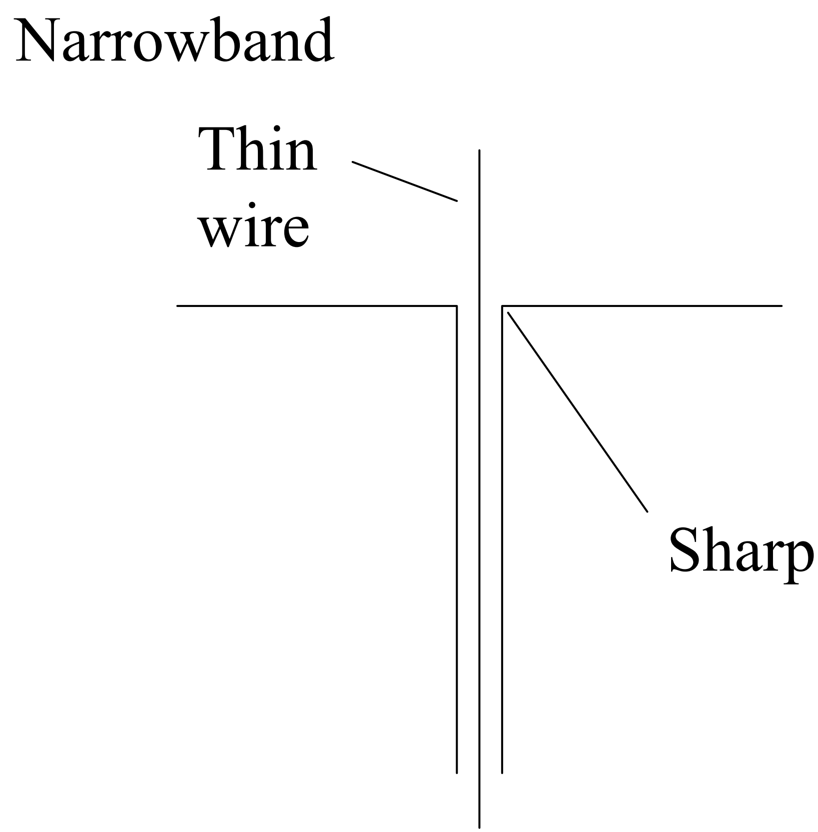
- Transformation of a guided EM wave in transmission line into a freely propagating EM wave in space (or vice versa)
  - From time-function in 1-D geometrical space into time-function in 3-D space (3-D geometrical space, polarization)
- The specific form of the radiated wave is defined by the antenna structure and its closest environment

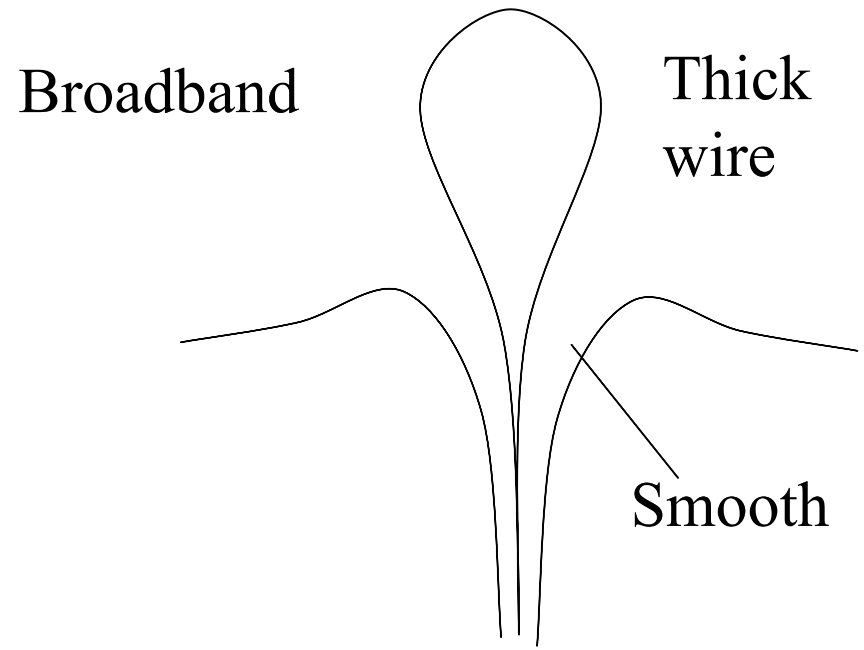
Transition



- If there is an inhomogeneity (obstacle) a reflected wave, standing wave, & higher field modes appear
- With pure standing wave the energy is stored and oscillates from entirely electric to entirely magnetic and back
- Model: a resonator
  - Q = (energy stored) / (energy lost) per cycle, as in LC resonant LC circuits
- Kraus p.2

Dipole over plane

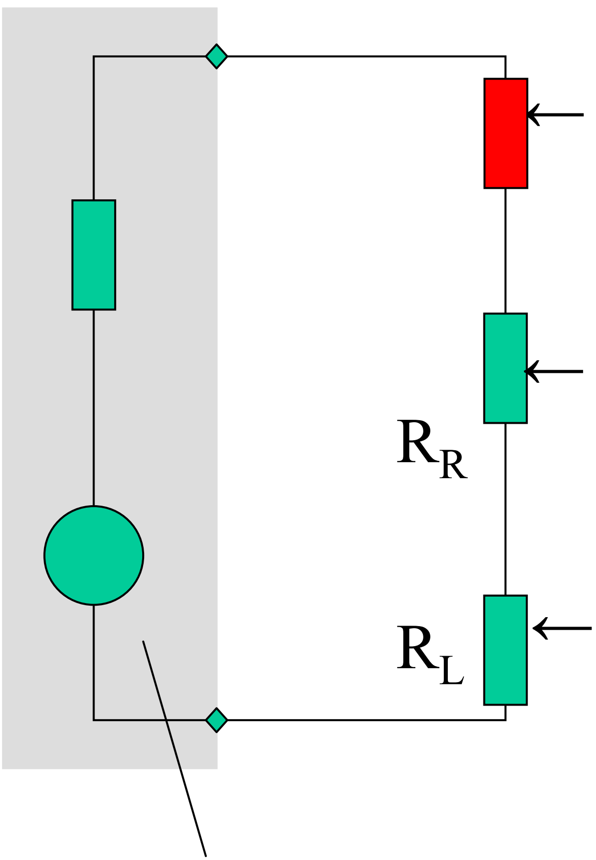




3 functions

- Antenna
  - Must be of a size comparable with the wavelength to be an efficient radiator
- Transmission line
  - Must be homogenous as much as possible to avoid power reflections, otherwise use matching devices
- Resonator
  - For broadband applications resonances must be attenuated

Antenna impedance



jX - Energy stored in H, and E near-field components; must be compensated by matching devices

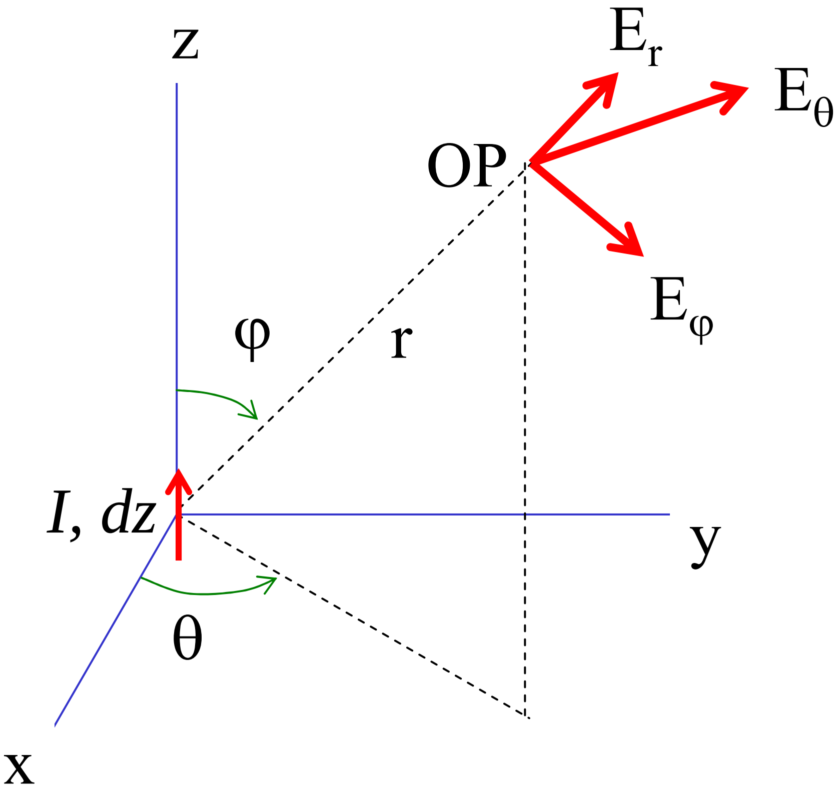
Energy radiated = transformed into heat in space (E & H, far-field components); must be matched to the transmission line

Energy lost = transformed into heat in the antenna structure and nearby; must be minimized

Maxwell's Equations

- EM field interacting with the matter
  - 2 coupled vectors E and H (6 numbers!), varying with time and space and satisfying the boundary conditions
- Reciprocity Theorem
  - Antenna characteristics do not depend on the direction of energy flow. The impedance & radiation pattern are the same when the antenna radiates signal and when it receives it (re-radiates).
  - Note: This theorem is valid only for linear passive antennas (i.e. antennas that do not contain nonlinear and unilateral elements, e.g. amplifiers)

EM Field of Current Element



$$\vec{E} = \vec{E}_r + \vec{E}_\vartheta + \vec{E}_\varphi$$

$$\vec{H} = \vec{H}_r + \vec{H}_\vartheta + \vec{H}_\varphi$$

$$|E| = \sqrt{|E_r|^2 + |E_\vartheta|^2 + |E_\varphi|^2}$$

$$|H| = \sqrt{|H_r|^2 + |H_\vartheta|^2 + |H_\varphi|^2}$$

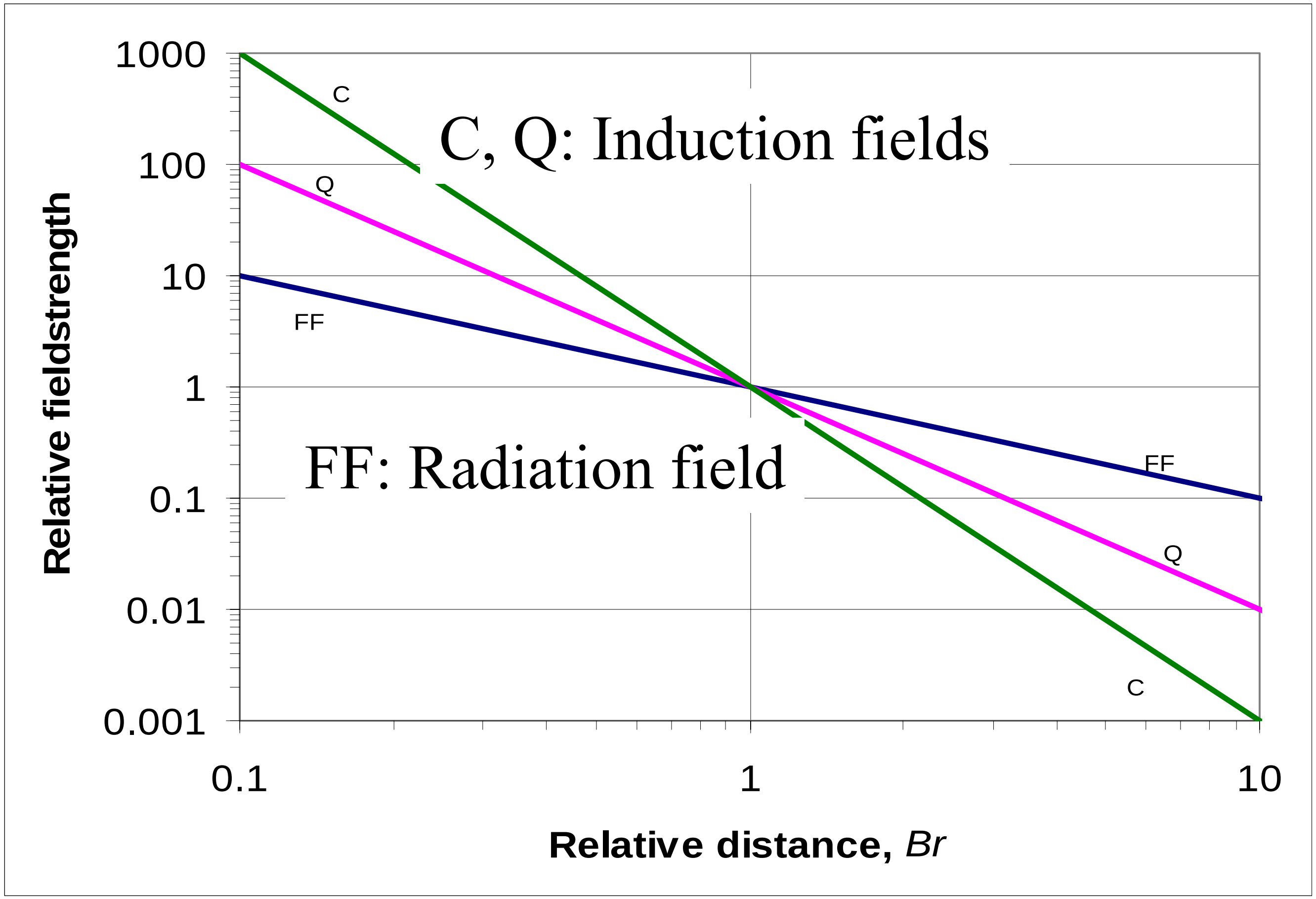
I: current (monochromatic) [A]; *dz*: antenna element (short) [m]

Short dipole antenna: summary

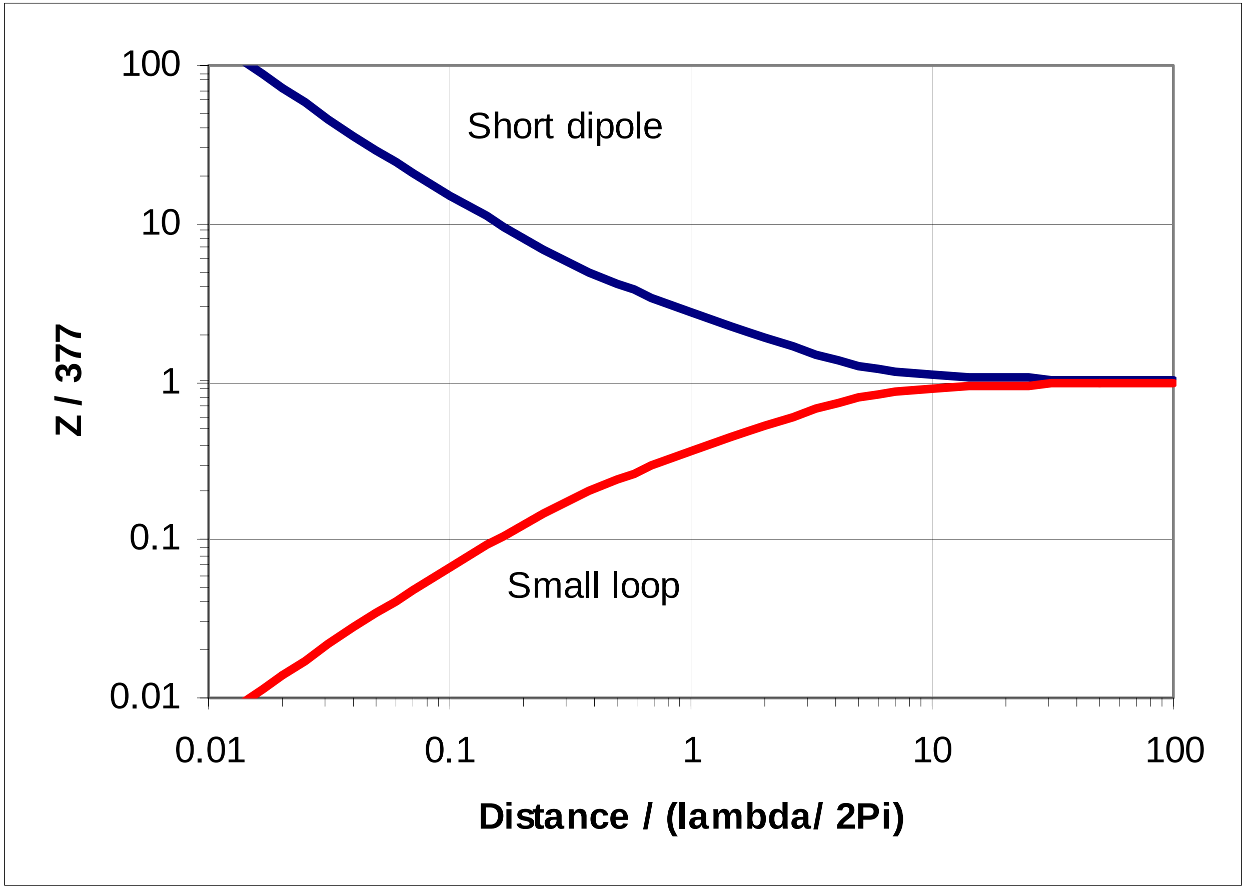
- E_θ & H_θ are maximal in the equatorial plane, zero along the antenna axis
- E_r is maximal along the antenna axis *dz*, zero in the equatorial plane
- All show axial symmetry
- All are proportional to the current moment *Idz*
- Have 3 components that decrease with the distance-to-wavelength ratio as
  - $(r/\lambda)^{-2}$ & $(r/\lambda)^{-3}$: near-field, or induction field. The energy oscillates from entirely electric to entirely magnetic and back, twice per cycle. Modeled as a resonant LC circuit or resonator;
  - $(r/\lambda)^{-1}$: far-field or radiation field
  - These 3 component are all equal at $(r/\lambda) = 1/(2\pi)$

β

Field components



Field impedance



Field impedance

Z = E/H

depends

on the antenna type and on distance

Far-Field, Near-Field

- Near-field region:
  - Angular distribution of energy depends on distance from the antenna;
  - Reactive field components dominate (L, C)
- Far-field region:
  - Angular distribution of energy is independent on distance;
  - Radiating field component dominates (R)
  - The resultant EM field can locally be treated as uniform (TEM)

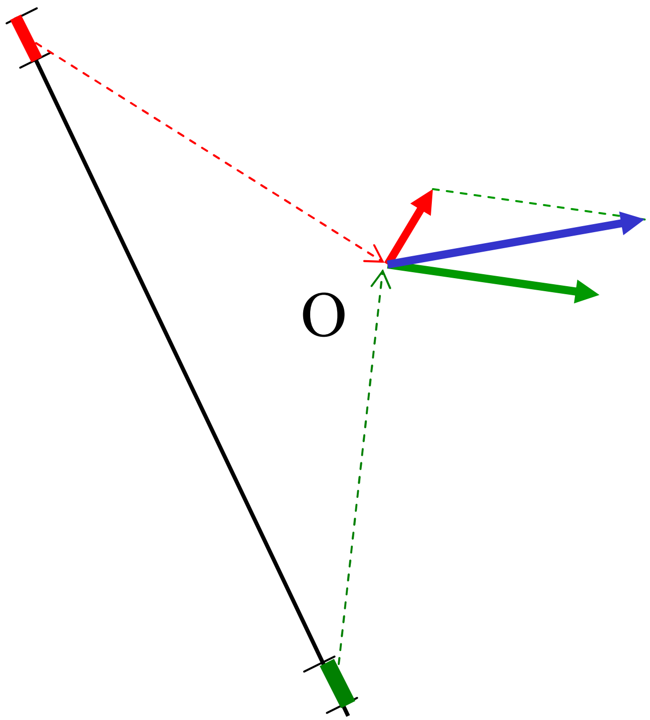
Poynting vector

- The time-rate of EM energy flow per unit area in free space is the *Poynting vector*.
- It is the cross-product (vector product, right-hand screw direction) of the electric field vector (E) and the magnetic field vector (H): P = E x H.
- For the elementary dipole $E_\theta \perp H_\theta$ and only E_θxH_θ carry energy into space with the speed of light.

Power Flow

- In free space and at large distances, the radiated energy streams from the antenna in radial lines, i.e. the Poynting vector has only the radial component in spherical coordinates.
- A source that radiates uniformly in all directions is an *isotropic source (radiator, antenna)*.
  For such a source the radial component of the Poynting vector is independent of θ and φ.

Linear Antennas



- Summation of all vector components E (or H) produced by each antenna element

$$\vec{E} = \vec{E}_1 + \vec{E}_2 + \vec{E}_3 + \ldots$$

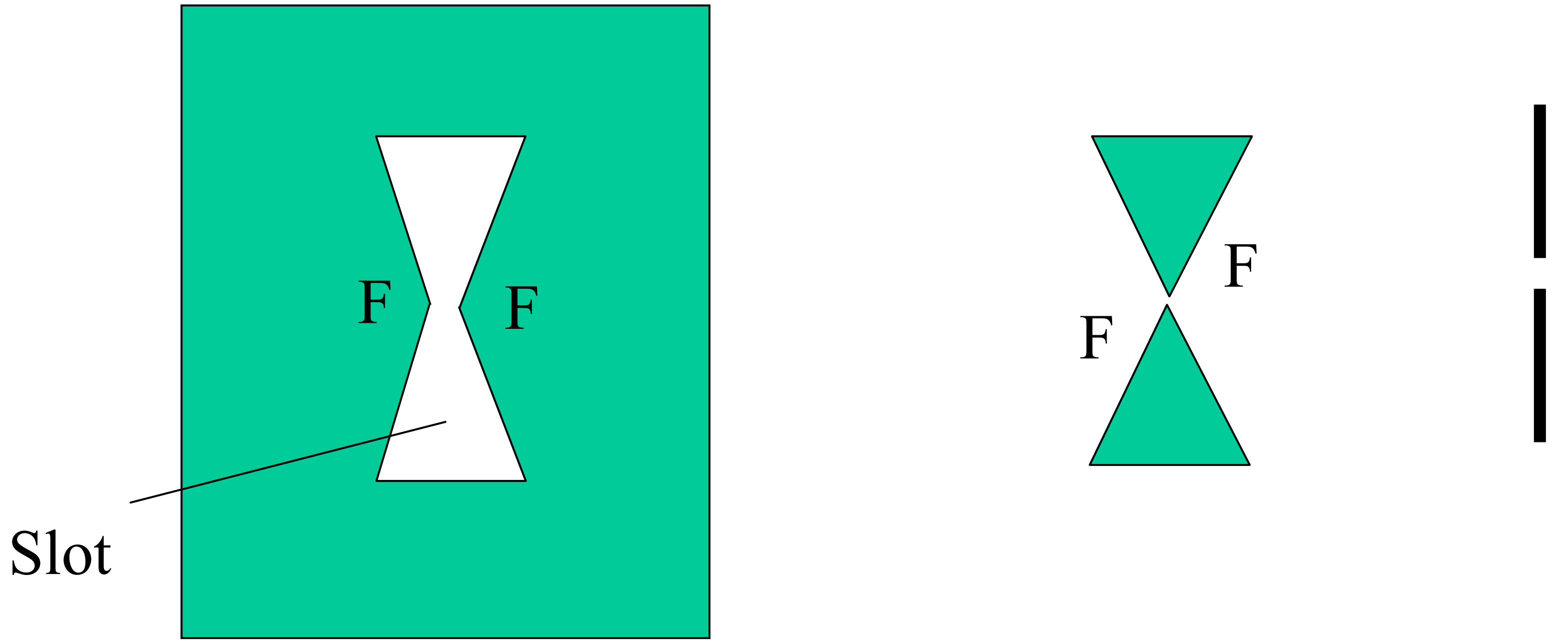
$$\vec{H} = \vec{H}_1 + \vec{H}_2 + \vec{H}_3 + \ldots$$

- In the far-field region, the vector components are parallel to each other
- Method of moments

Simulated experiment

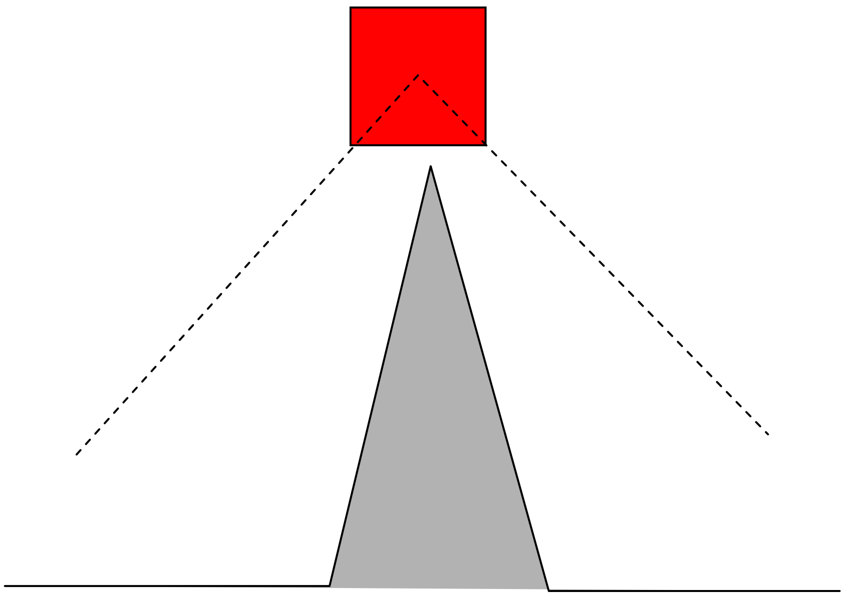
- http://www.amanogawa.com
  - Linear dipole antenna java applet – change the dipole length

Planar (printed) antennas



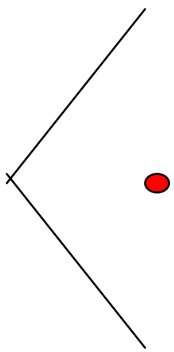
- Slot & complementary antennas

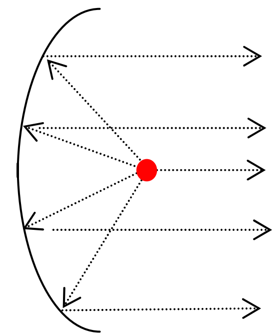
Reflector antenna



- Intended reflector antenna allows maintaining radio link in non-LOS conditions (avoiding propagation obstacles)
- Unintended antenna create interference

Reflector-type antennas



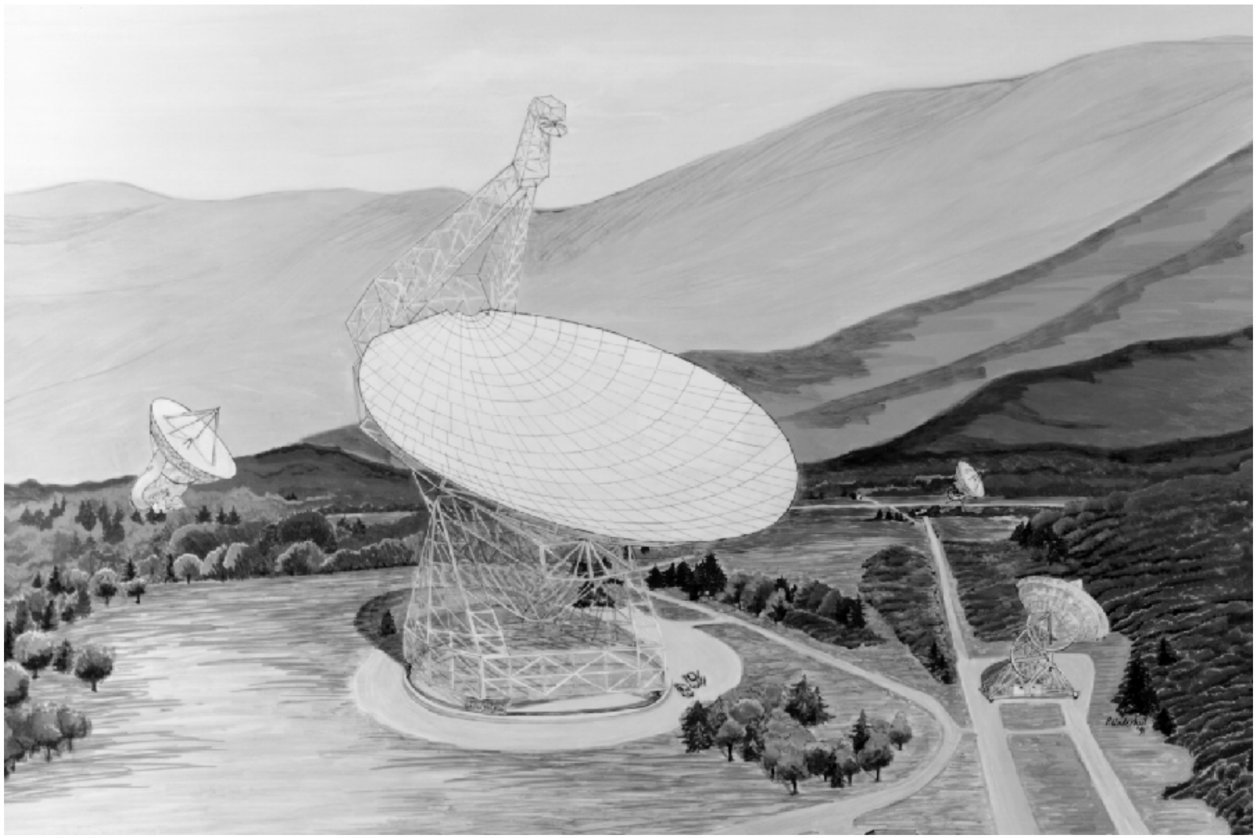


- Reflector concentrates energy radiated

  - Kraus p.324

Laboratory!

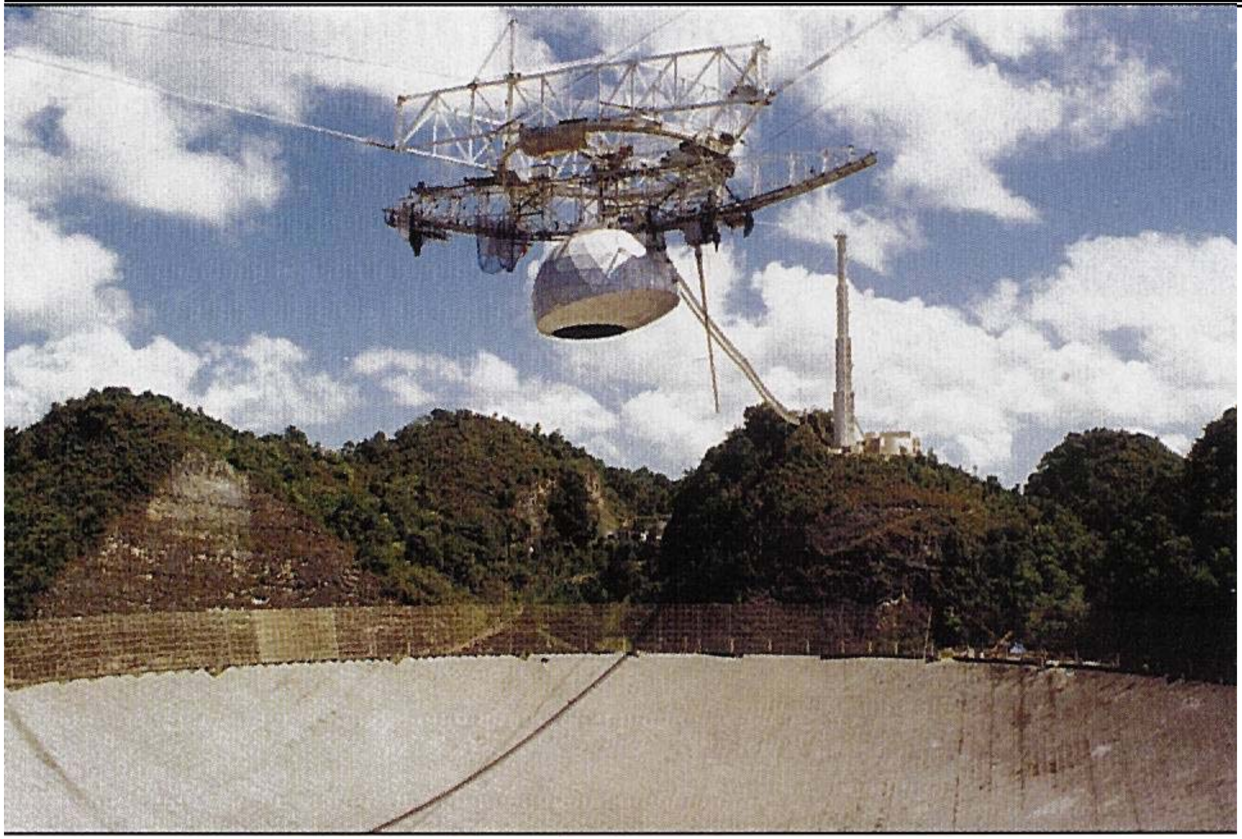
The Green Bank Telescope



The largest (140m), fully steerable telescope in the world (Green Bank W. Virginia). Its 8000 ton surface points to targets with arcsecond precision. (1998)

[Sky & Telescope, Feb. 1997 p.28]

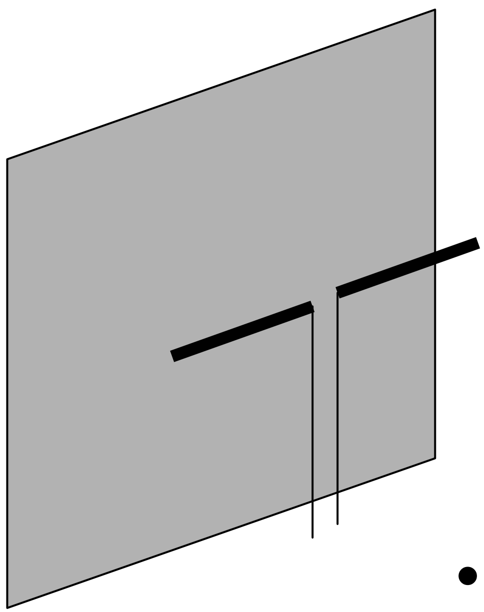
The Arecibo Radio Telescope

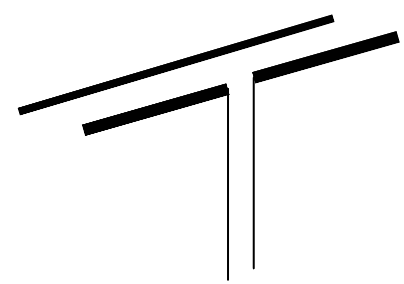


The world's largest (1000-foot) single "dish".

[Sky & Telescope Feb 1997 p. 29]

Simple reflector antennas

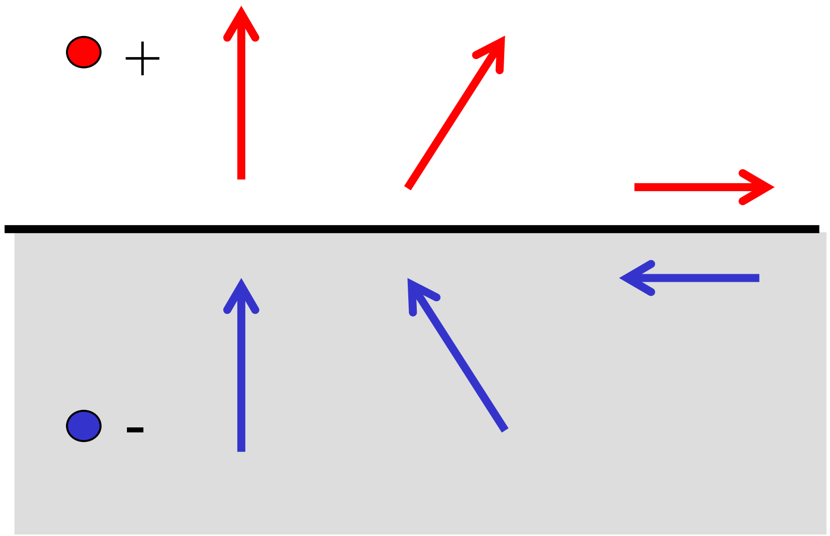




- Uda-Yagi, Log-periodic antennas

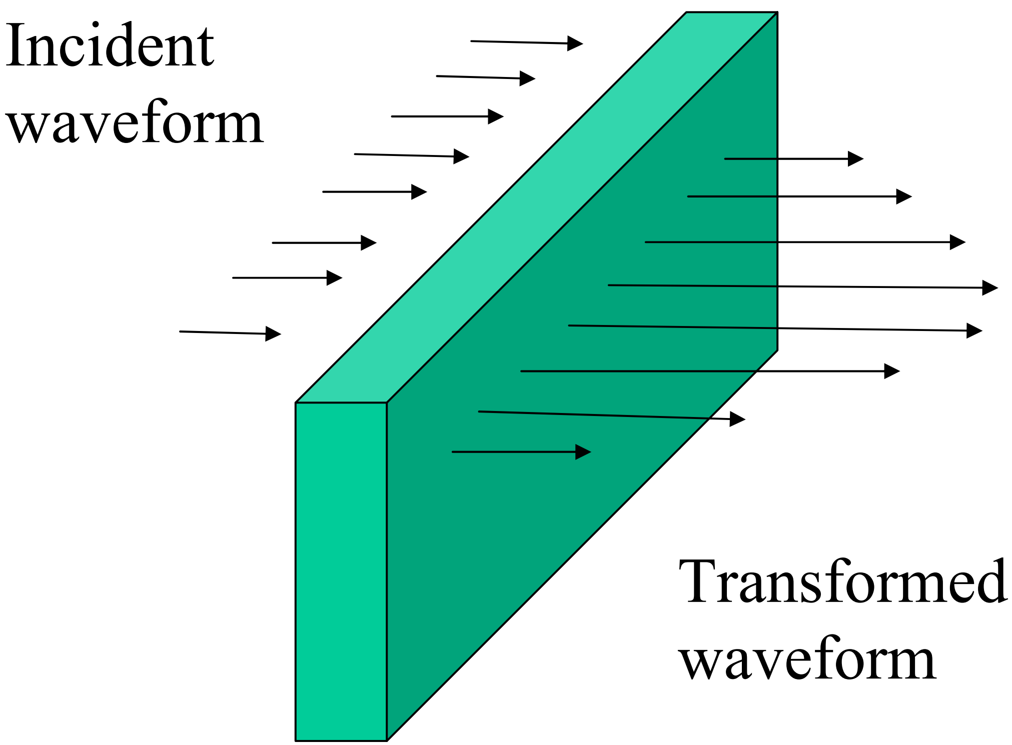
Reflection & Image Theory

- Antenna above perfectly conducting plane surface
- Tangential electrical field component = 0
  – vertical components: the same direction
  – horizontal components: opposite directions
- The field (above the ground) is the same as if the ground is replaced by the antenna image



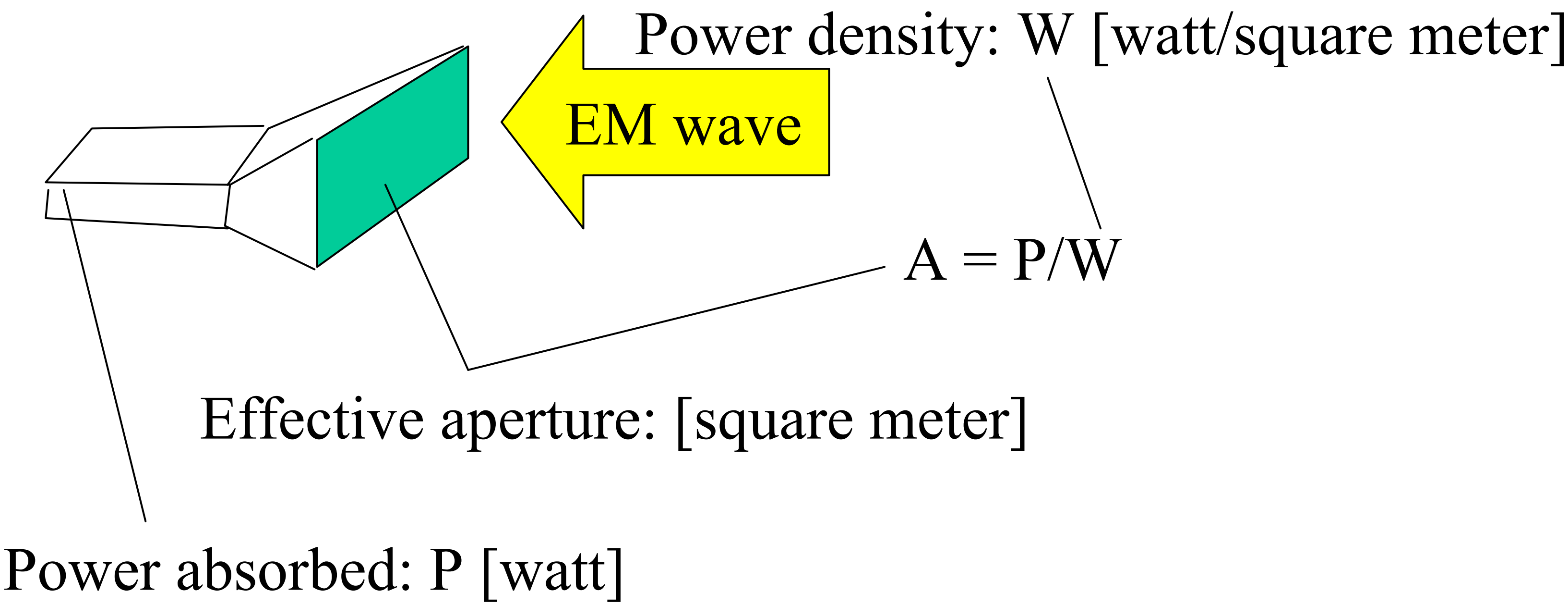
Elliptical polarization:
change of the rotation sense!

Lens-type antennas



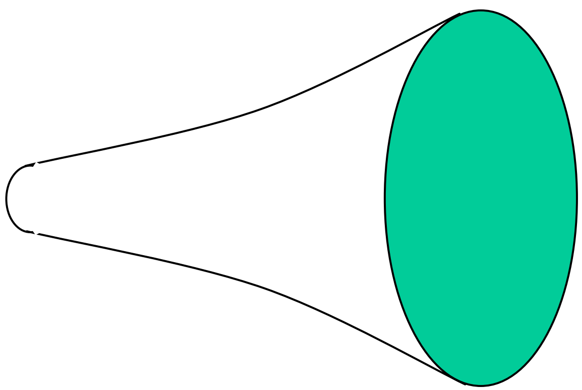
- Retardation of the wave in dielectric lens
  - Natural dielectric
  - Artificial dielectric
- Acceleration of the wave in the metal-plate waveguide-type lens
- Kraus p.382

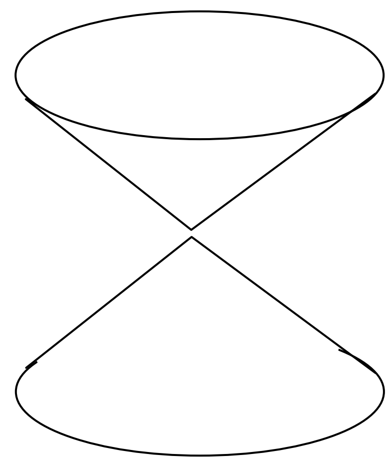
Aperture-antenna



- Note: The max effective aperture of linear $\lambda/2$ wavelength dipole antenna is $\lambda^2/8$

Horn antennas





<u>Laboratory!</u>

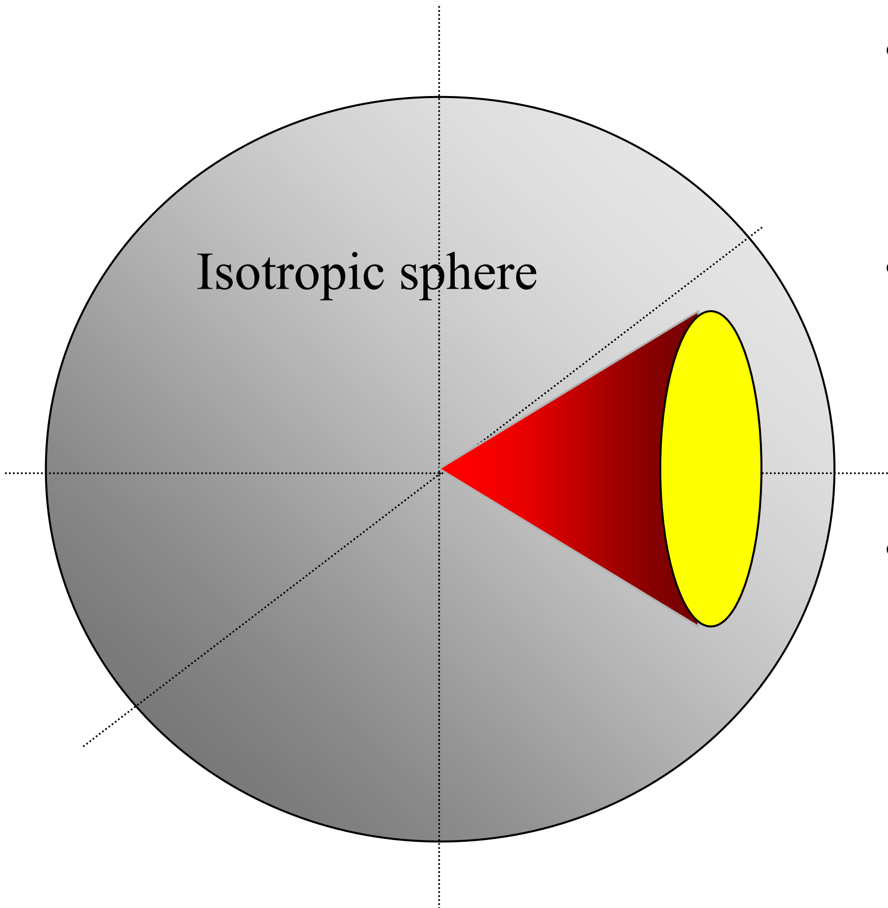
Point Source

- For many purposes, it is sufficient to know the direction (angle) variation of the power radiated by antenna at large distances.
- For that purpose, any practical antenna, regardless of its size and complexity, can be represented as a point-source.
- The actual field near the antenna is then disregarded.

Point Source 2

- The EM field at large distances from an antenna can be treated as originated at a point source - fictitious volume-less emitter.
- The EM field in a homogenous unlimited medium at large distances from an antenna can be approximated by an uniform plane TEM wave

Anisotropic sources

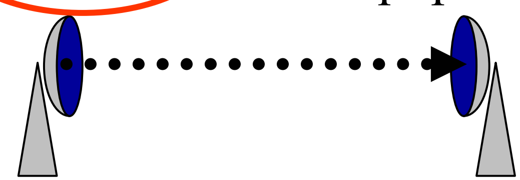


- Every antenna has directional properties (radiates more energy in some directions than in others).
- Idealized example of directional antenna: the radiated energy is concentrated in the yellow region (cone).
- The power flux density gains: it is increased by (roughly) the inverse ratio of the yellow area and the total surface of the isotropic sphere.

Antenna gain

Actual antenna

Measuring equipment



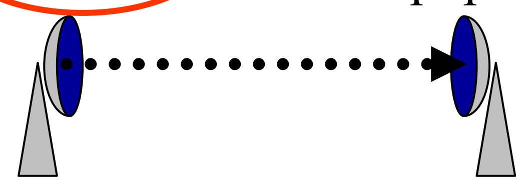
P = Power delivered to the actual antenna

S = Power received (the same in both steps)

Step 1

Reference antenna

Measuring equipment



P_o = Power delivered to the reference antenna

S_0 = Power received (the same in both steps)

Step 2

$$\text{Antenna Gain} = (P/P_o)_{S=S0}$$

Antenna Gains G_i, G_d, G_r

- G_i “Isotropic Power Gain” – theoretical concept, the reference antenna is isotropic
- G_d - the reference antenna is a half-wave dipole

Antenna Gain: Comments

- Unless otherwise specified, the gain refers to the direction of maximum radiation.
- Gain is a dimension-less factor related to power and usually expressed in decibels

Power vs. fieldstrength

$$P_r = \frac{E^2}{Z_0} \rightarrow E = \sqrt{P_r Z_0}$$

$$E = \sqrt{E_\theta^2 + E_\varphi^2}$$

$$Z_0 = 377 \text{ ohms}$$

for plane wave

in free space

- Gain in the field intensity may also be considered - it is equal to the square root of the power gain.

e.i.r.p.

- Equivalent Isotropically Radiated Power (in a given direction):

$$e.i.r.p. = PG_i$$

- The product of the power supplied to the antenna and the antenna gain (relative to an isotropic antenna) in a given direction

Antenna gain and effective area

- Measure of the effective absorption area presented by an antenna to an incident plane wave.
- Depends on the antenna gain and wavelength

$$A_e = \eta \frac{\lambda^2}{4\pi} G(\theta, \varphi) \ \ [\mathrm{m}^2]$$

Aperture efficiency: $\eta_a = A_e / A$
A: physical area of antenna's aperture, square meters

Power Transfer in Free Space

$$P_R = PFD \cdot A_e$$

$$= \left(\frac{G_T P_T}{4\pi r^2}\right)\left(\frac{\lambda^2 G_R}{4\pi}\right)$$

$$= P_T G_T G_R \left(\frac{\lambda}{4\pi r}\right)^2$$

- λ: wavelength [m]
- P_R: power available at the receiving antenna
- P_T: power delivered to the transmitting antenna
- G_R: gain of the transmitting antenna in the direction of the receiving antenna
- G_T: gain of the receiving antenna in the direction of the transmitting antenna
- Matched polarizations

Gain, Directivity, Radiation Efficiency

- The radiation intensity, directivity and gain are measures of the ability of an antenna to concentrate power in a particular direction.
- Directivity relates to the power radiated by antenna (P_0)
- Gain relates to the power delivered to antenna (P_T)

$$G(\vartheta,\varphi) = \eta D(\vartheta,\varphi)$$

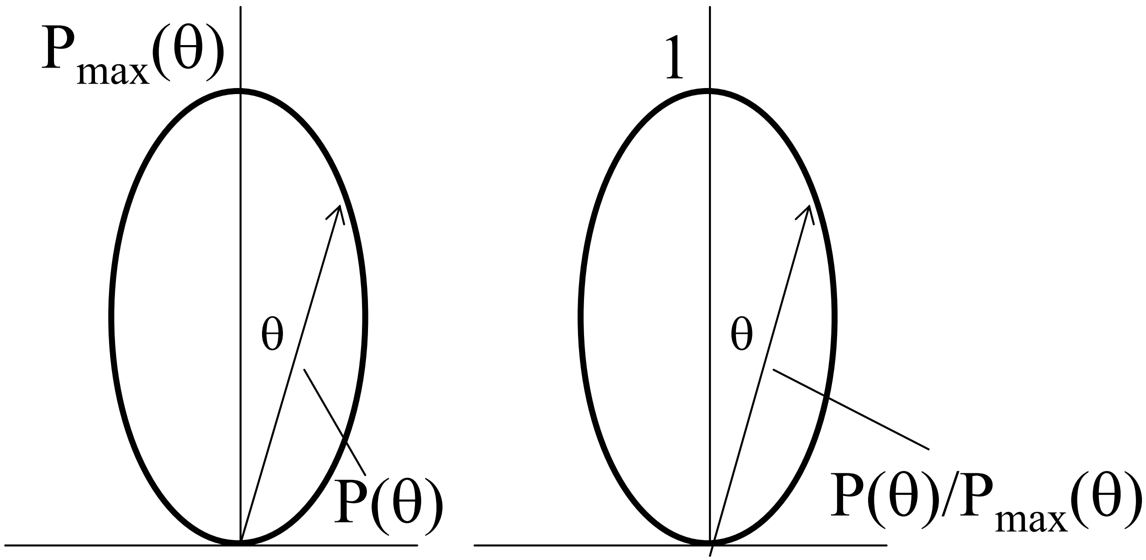
$$\eta = \frac{P_T}{P_0}$$

- η: radiation efficiency (0.5 - 0.75)

Directivity Pattern

- The variation of the field intensity of an antenna as an angular function with respect to the axis.
- Usually represented graphically for the far-field conditions.
- May be considered for a specified polarization and/or plane (horizontal, vertical).
- Depends on the polarization and the reference plane for which it is defined/measured
- *Synonym:* Radiation pattern**.**

Antenna patterns

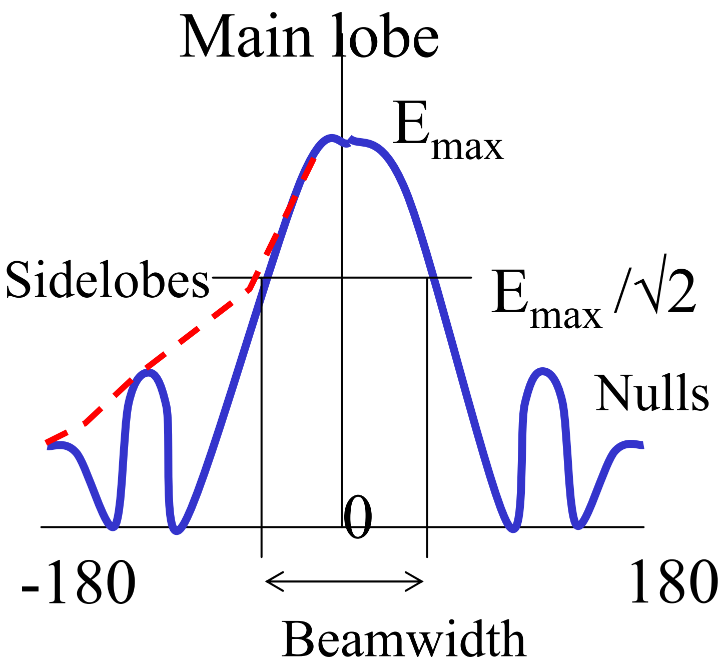


Power pattern

Relative (normalized) power pattern

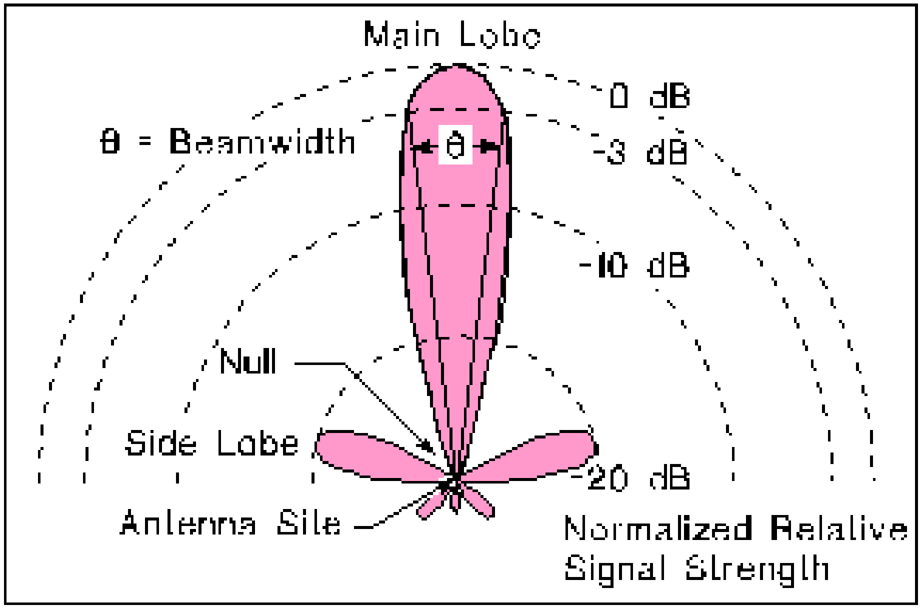
- Usually represented in 2 reference planes φ=const. and θ=const.
- E & PDF relate to the equivalent uniform plane wave
- Note: Peak value = $\sqrt{2}$ x Effective value for sinusoidal quantities

Elements of Radiation Pattern



- Gain
- Beam width
- Nulls (positions)
- Side-lobe levels (envelope)
- Front-to-back ratio

Beam width



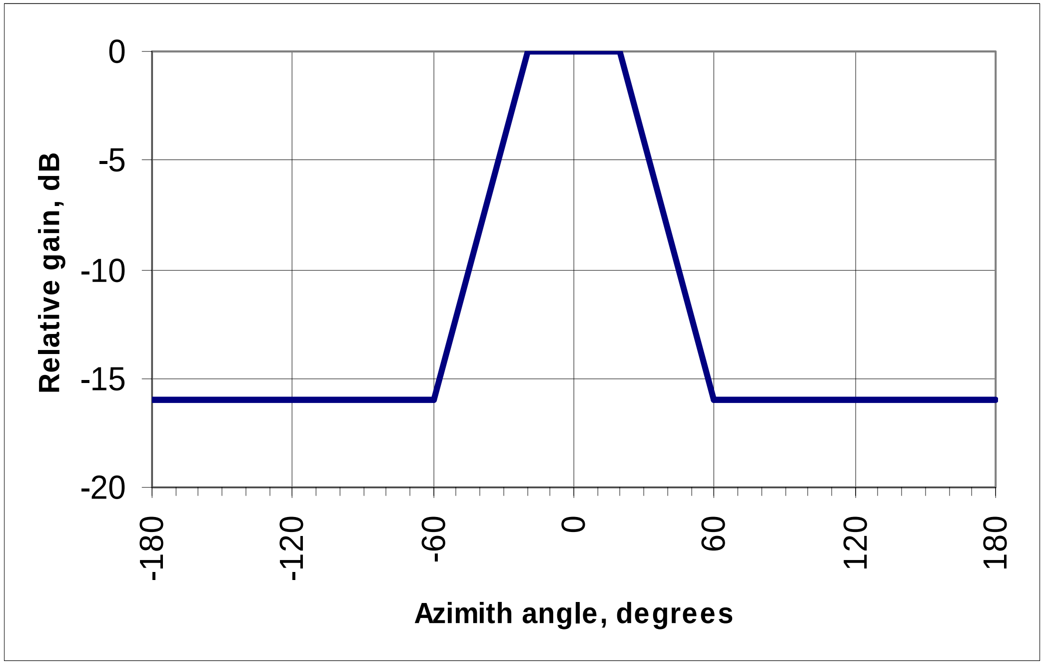
beamwidth

- **Beamwidth** of an antenna pattern: the angle between the half-power points of the main lobe.
- Defined separately for the horizontal plane and for the vertical plane.
- Usually expressed in degrees.

Typical Gain and Beamwidth

Type of antenna	G_i [dB]	BeamW.
Isotropic	0	360^0x360^0
Half-wave Dipole	2	360^0x120^0
Helix (10 turn)	14	35^0x35^0
Small dish	16	30^0x30^0
Large dish	45	1^0x1^0

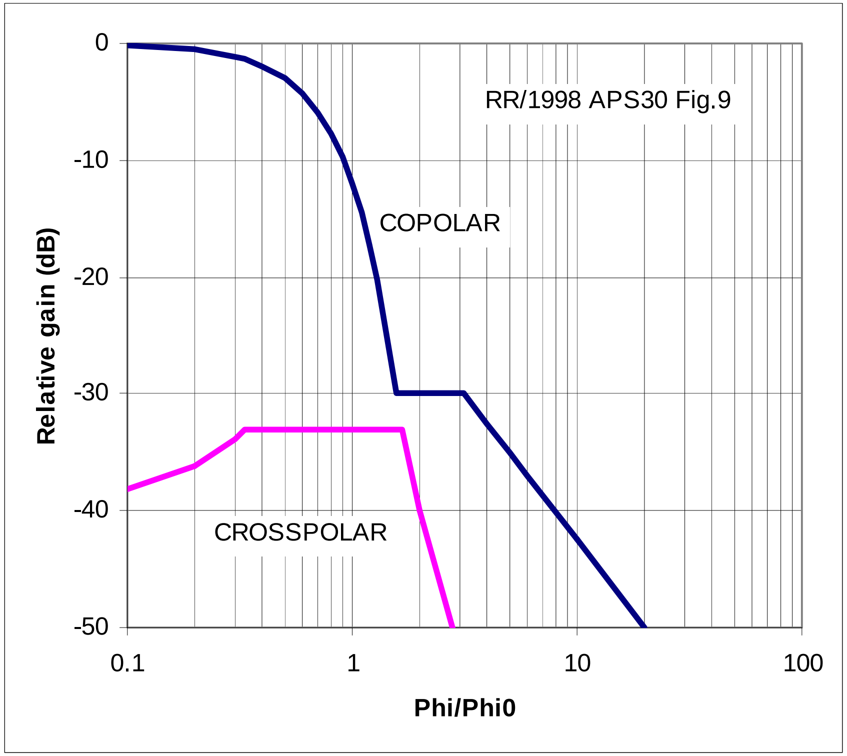
Antenna Mask (Example 1)

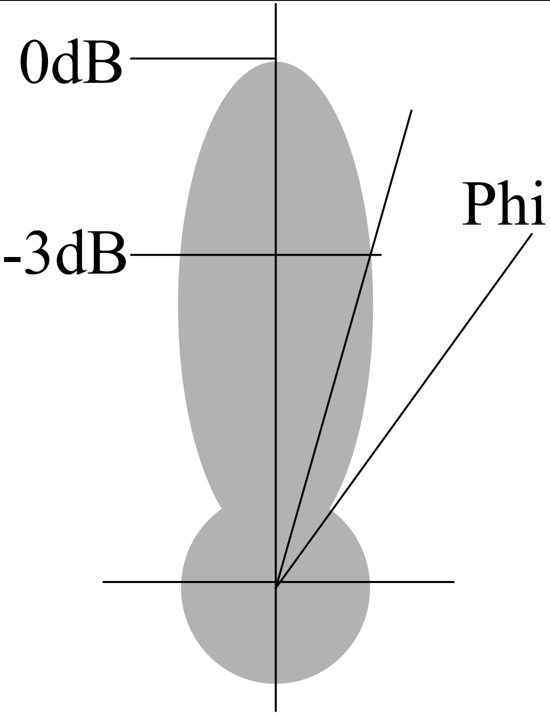


Typical relative directivity- mask of receiving antenna (Yagi ant., TV dcm waves)

[CCIR doc. 11/645, 17-Oct 1989)

Antenna Mask (Example 2)

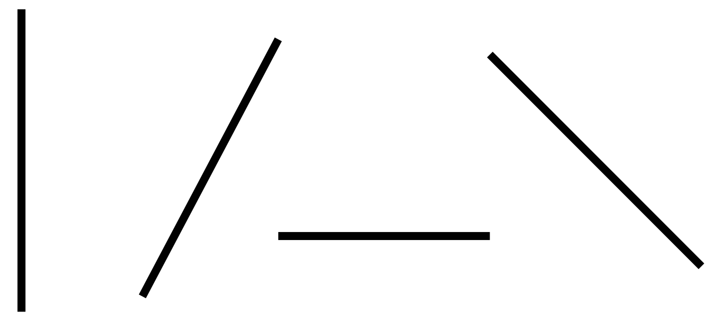




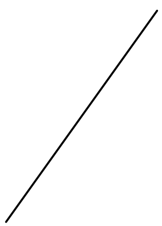
Reference pattern for co-polar and cross-polar components for satellite transmitting antennas in Regions 1 and 3 (Broadcasting ~12 GHz)

Linear Polarization

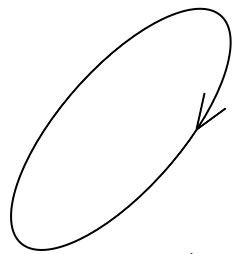
- In a linearly polarized plane wave the direction of the E (or H) vector is constant.



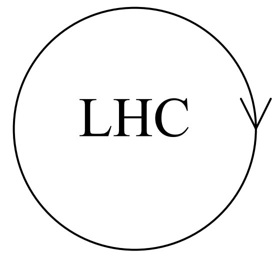
Elliptical Polarization



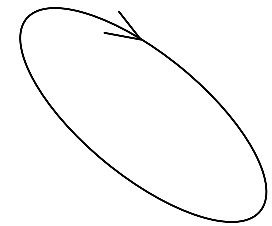
Ex = cos (wt)
Ey = cos (wt)



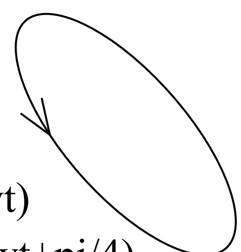
Ex = cos (wt)
Ey = cos (wt+pi/4)



Ex = cos (wt)
Ey = -sin (wt)



Ex = cos (wt)
Ey = cos (wt+3pi/4)



Ex = cos (wt)
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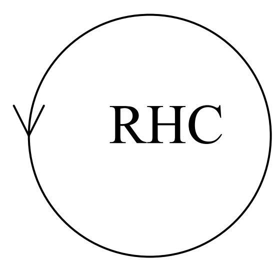
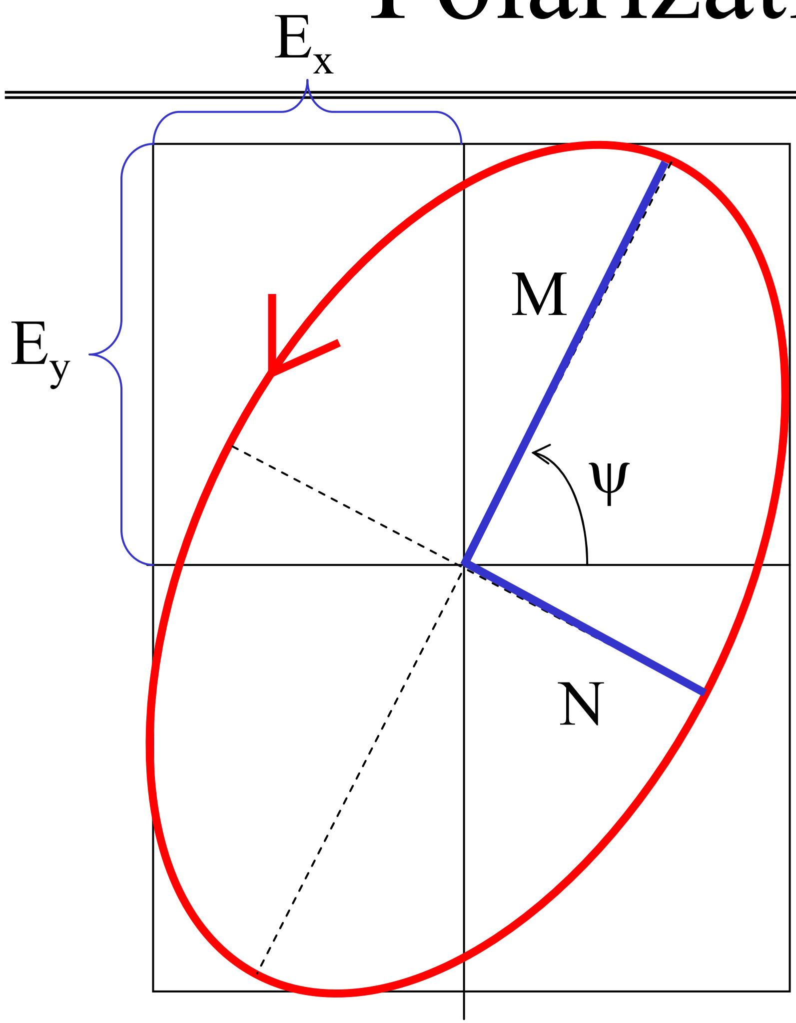


Ex = cos (wt)
Ey = sin (wt)

Polarization ellipse



- The superposition of two plane-wave components results in an elliptically polarized wave
- The polarization ellipse is defined by its axial ratio N/M (ellipticity), tilt angle ψ and sense of rotation

Polarization states

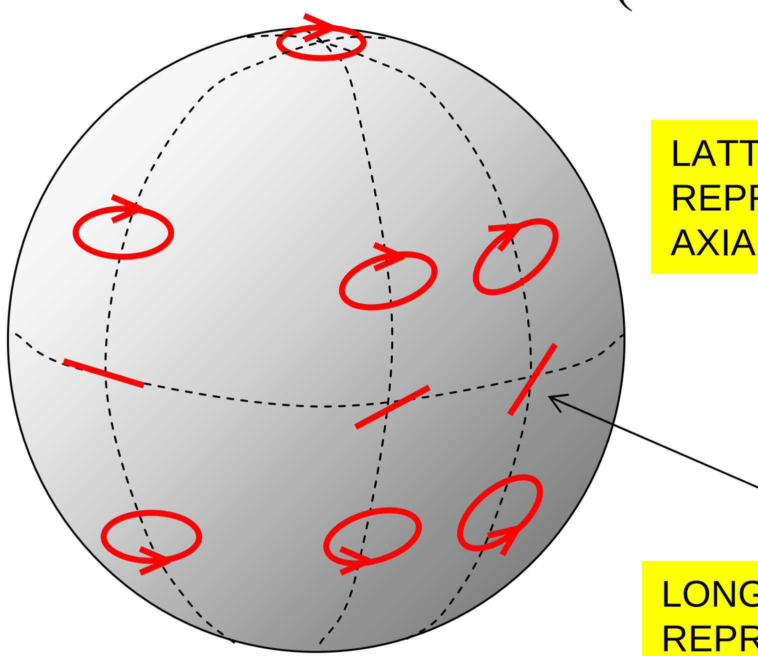
(Poincaré sphere)

UPPER HEMISPHERE:
ELLIPTIC POLARIZATION
LEFT_HANDED SENSE

EQUATOR:
LINEAR POLARIZATION

LOWER HEMISPHERE:
ELLIPTIC POLARIZATION
RIGHT_HANDED SENSE

LHC



RHC

45^0 LINEAR

LATTITUDE:
REPRESENTS
AXIAL RATIO

LONGITUDE:
REPRESENTS
TILT ANGLE

POLES REPRESENT
CIRCULAR POLARIZATIONS

Comments on Polarization

- At any moment in a chosen reference point in space, there is actually a single electric vector E (and associated magnetic vector H).
- This is the result of superposition (addition) of the instantaneous fields E (and H) produced by all radiation sources active at the moment.
- The separation of fields by their wavelength, polarization, or direction is the result of ‘filtration’.

Antenna Polarization

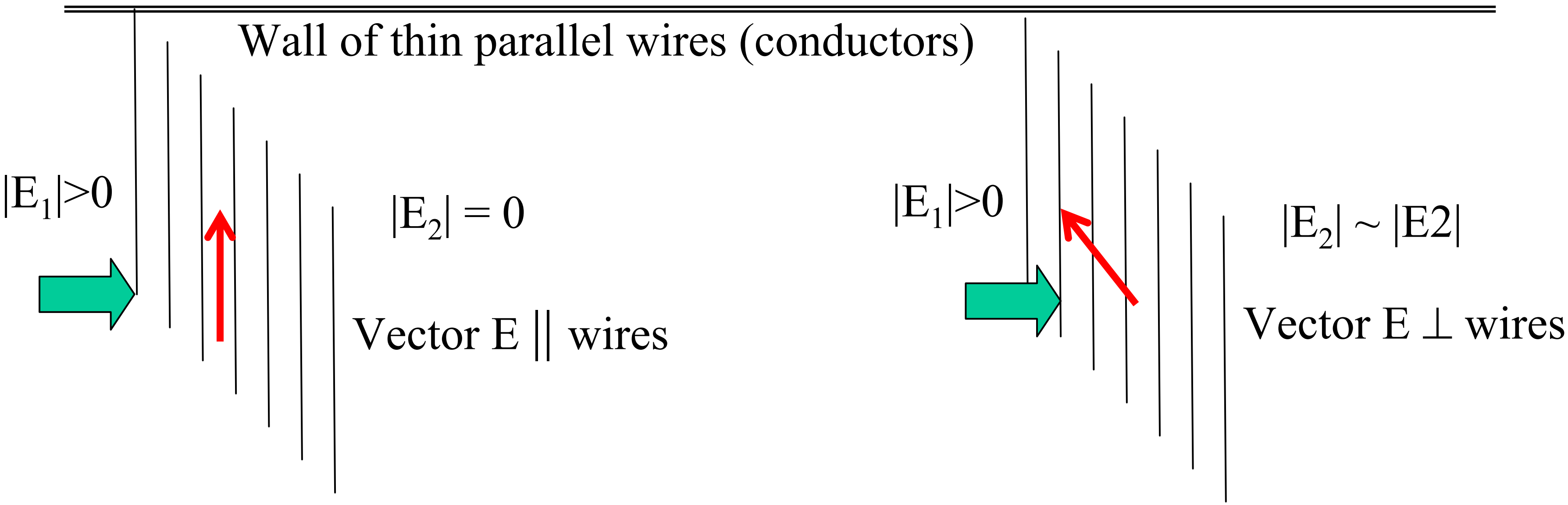
- The polarization of an antenna in a specific direction is defined to be the polarization of the wave produced by the antenna at a great distance at this direction

Polarization Efficiency

- The power received by an antenna from a particular direction is maximal if the polarization of the incident wave and the polarization of the antenna in the wave arrival direction have:
  - the same axial ratio
  - the same sense of polarization
  - the same spatial orientation

.

Polarization filters/ reflectors



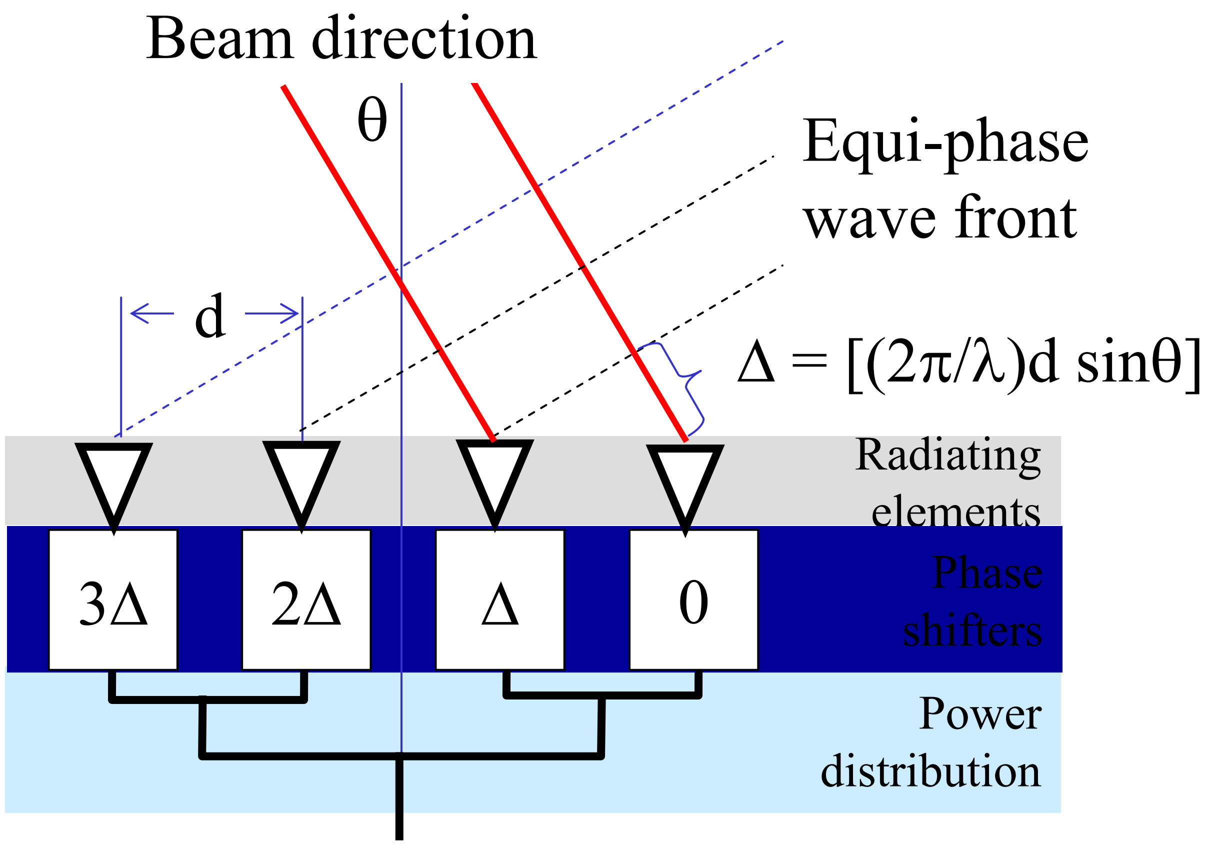
Wire distance ~ 0.1λ

- At the surface of ideal conductor the tangential electrical field component = 0

Phased Arrays

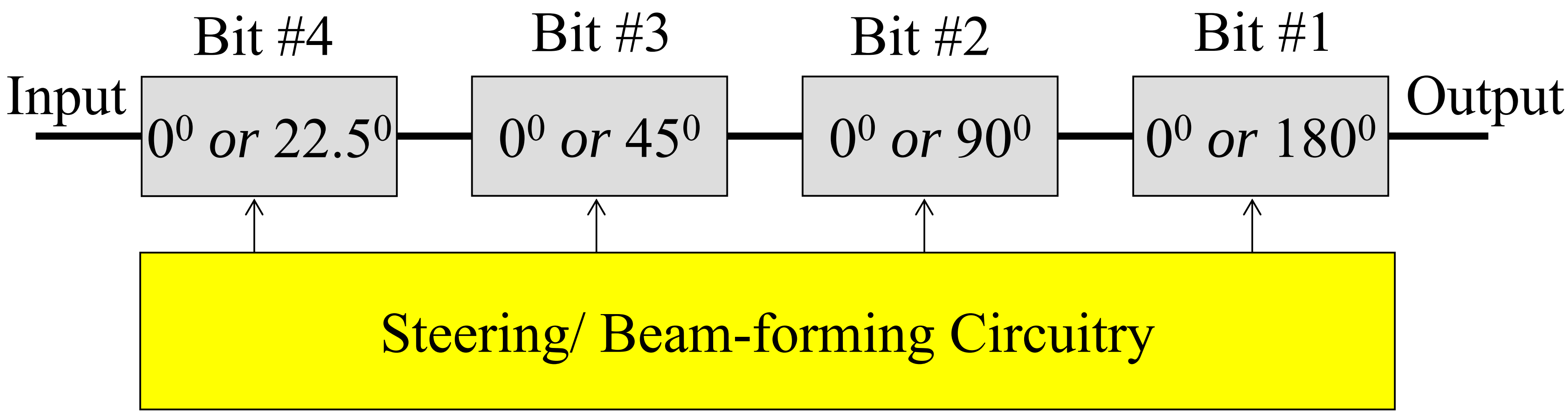
- Array of N antennas in a linear or spatial configuration
- The amplitude and phase excitation of each individual antenna controlled electronically ("software-defined")
  - Diode phase shifters
  - Ferrite phase shifters
- Inertia-less beam-forming and scanning (μsec) with fixed physical structure

Beam Steering

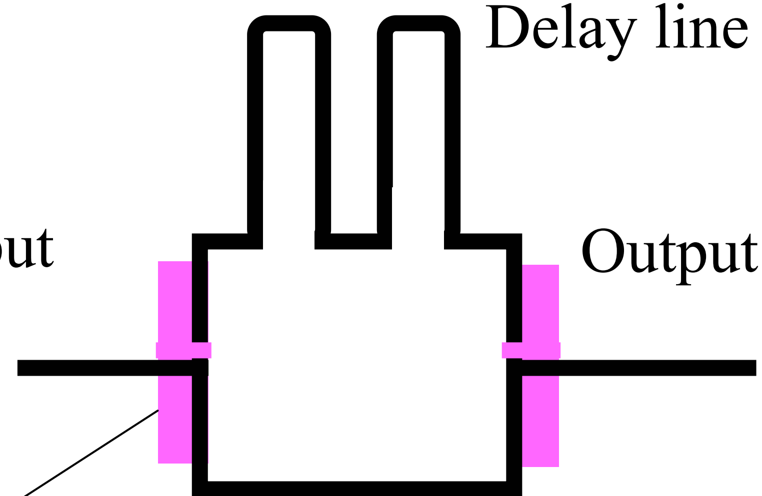


- Beam-steering using phase shifters at each radiating element

4-Bit Phase-Shifter (Example)

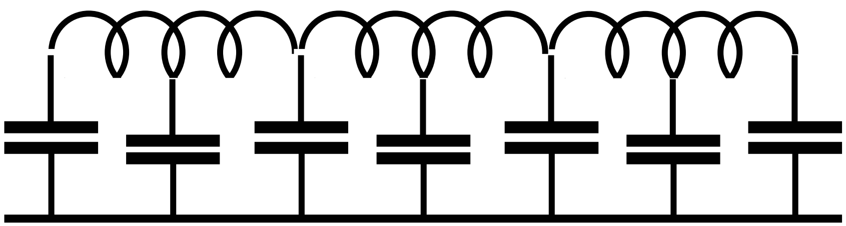


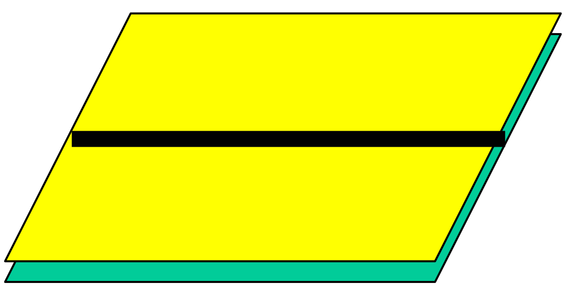
Switched-Line Phase Bit



Phase bit = delay difference

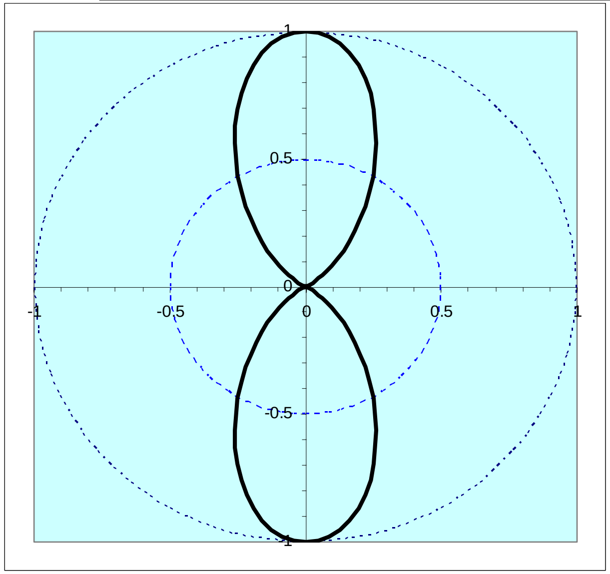
Delay line w. nonlinear dielectric



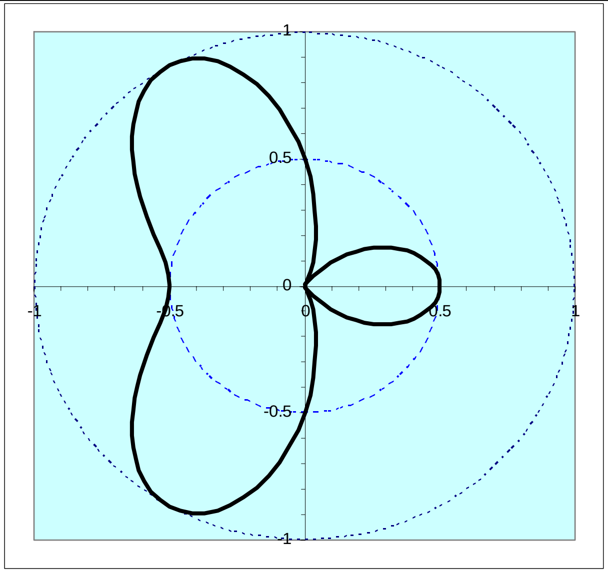


$$Z = \sqrt{\frac{\Delta L}{\Delta C}}$$

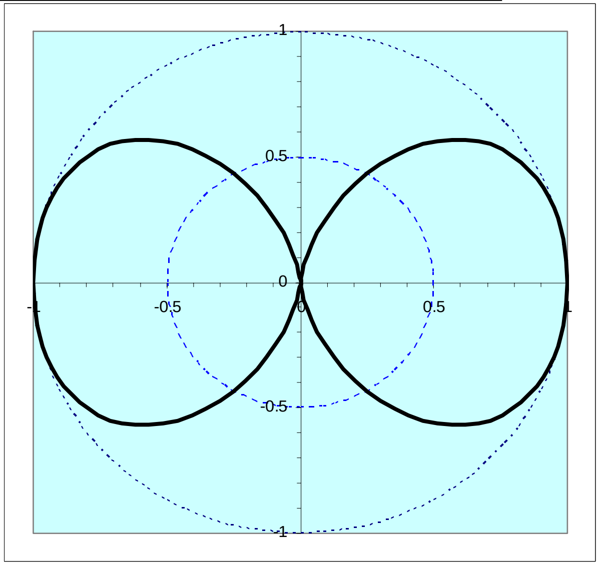
2 omnidirectional antennas



$D = 0.5\lambda, \theta = 0^0$

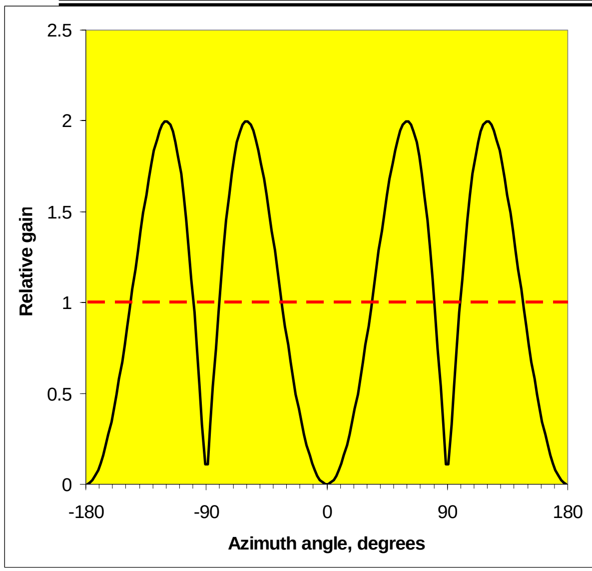


$D = 0.5\lambda, \theta = 90^0$

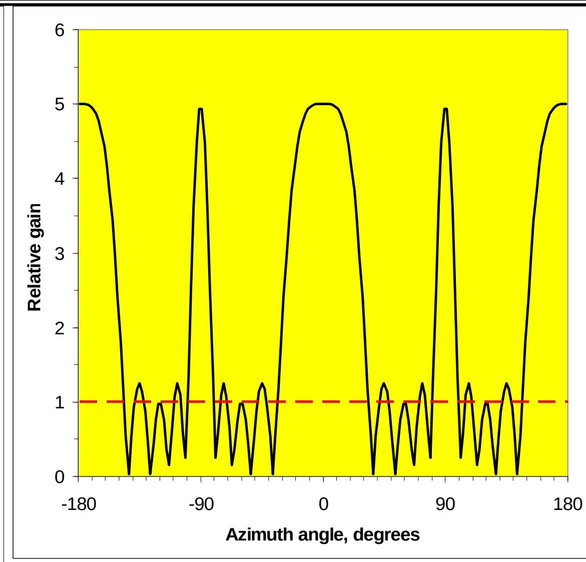


$D = 0.5\lambda, \theta = 180^0$

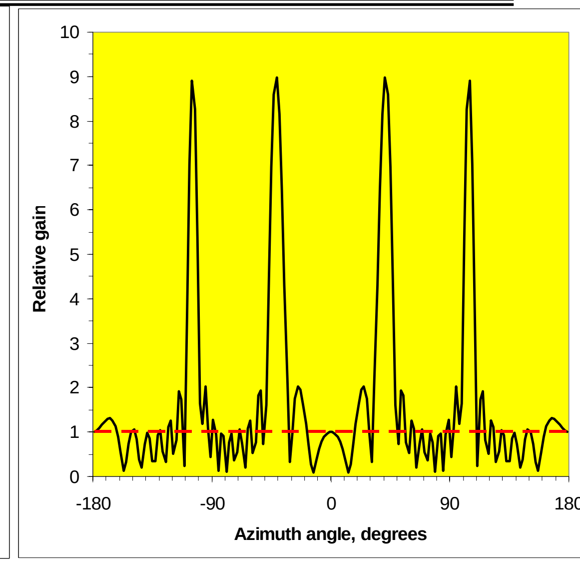
N omnidirectional antennas



$N = 2, \theta = 90^0$



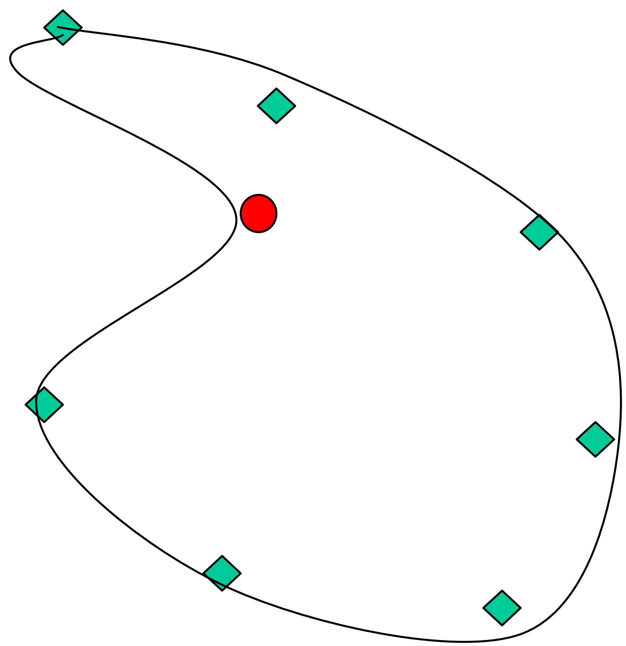
$N = 5, \theta = 180^0$



$N = 9, \theta = 45^0$

- Array gain (line, uniform, identical power)

Antenna synthesis objective



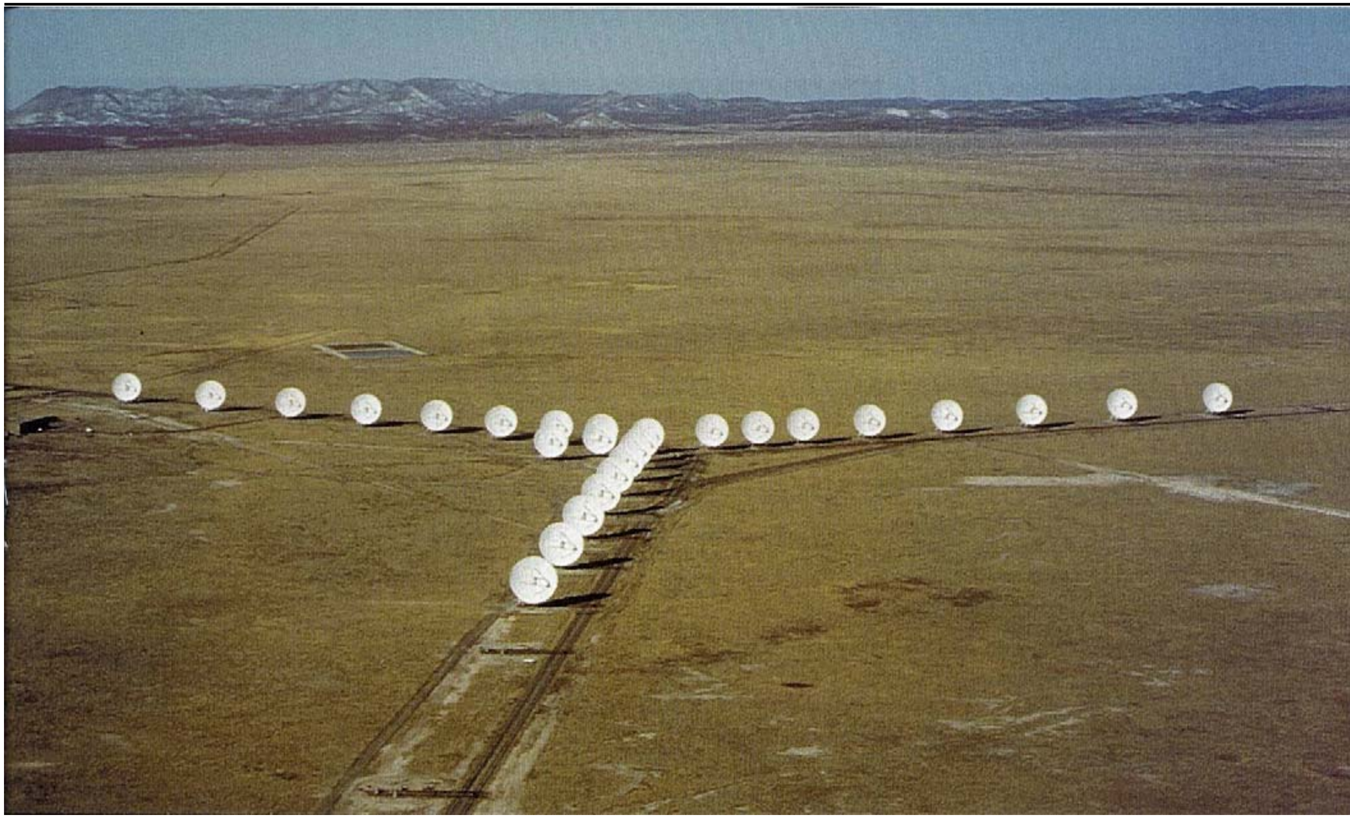
- Main lobe ‘looks’ in the required direction
- The signal delivered to N fixed points is above the required minimal level
- The signal delivered to N fixed points is zero, or below the required maximal level

Owens Valley Radio Observatory

The Earth's atmosphere is transparent in the narrow visible-light window (4000-7000 angstroms) and the radio band between 1 mm and 10 m.

[Sky & Telescope Feb 1997 p.26]

The New Mexico Very Large Array



[Sky & Telescope
Feb 1997 p. 30]

27 antennas along 3 railroad tracks provide baselines up to 35 km. Radio images are formed by correlating the signals garnered by each antenna.

Circular antenna arrays

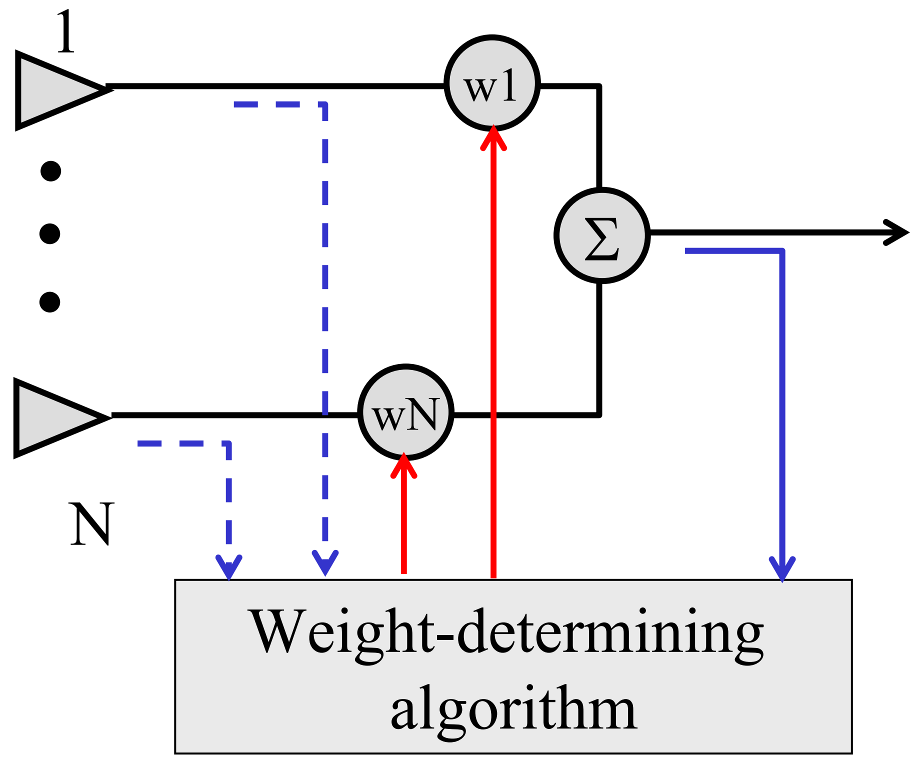
Antenna Arrays: Benefits

- Possibilities to control electronically
  - Direction of maximum radiation
  - Directions (positions) of nulls
  - Beam-width
  - Directivity
  - Levels of sidelobes

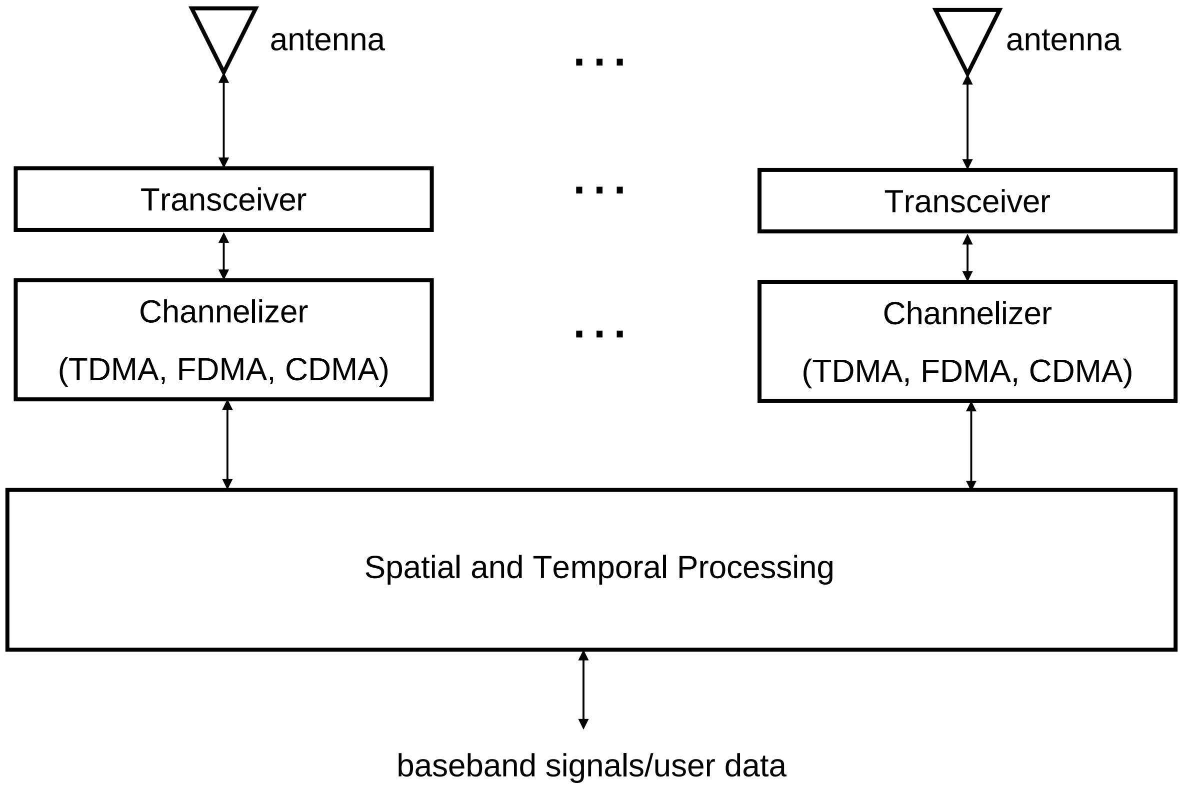
  using standard antennas (or antenna collections) independently of their radiation patterns
- Antenna elements can be distributed along straight lines, arcs, squares, circles, etc.

Adaptive (“Intelligent”)Antennas

- Array of N antennas in a linear or spatial configuration
- Used for selection receiving signals from desired sources and suppress incident signals from undesired sources
- The amplitude and phase excitation of each individual antenna controlled electronically (“software-defined”)
- The weight-determining algorithm uses a-priori and/ or measured information
- The weight and summing circuits can operate at the RF or at an intermediate frequency



Protocol independence



2 GHz adaptive antenna

- A set of 48 2GHz antennas
  - Source: Arraycomm

Simulated experiments

- 2 omnidirectional antennas (equal amplitudes)
- N omnidirectional antennas (arranged along a line, with equal amplitudes)
- Variables (In both cases):
  - distance increment
  - phase increment

What we have learned

- Antenna: substantial element of radio link
- We have just reviewed
  - Basic concepts
  - Radio wave radiation physics
  - Elementary radiators
  - Selected issues relevant to antennas

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Any questions?

Thank you for your attention

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