6.013 Electromagnetics and Applications
Spring 2009

WIRELESS COMMUNICATIONS

RANGE	ACTIVE	PASSIVE
Arm's Length	Pills, hearing aids, computer peripherals	Faucets, CD's, thermometers,
<100 m	Wireless phones, remote controllers, computer links	Cameras, doors
<100 km	Radio, television, cell phones, UWB, 802.11	Multispectral remote sensing
Global	Ham radio, communications satellites, radar, lidar	Weather satellites
Cosmic	Radio & optical interplanetary communications, radar, lidar	Radio & optical astronomy

COMMUNICATION REQUIRES ENERGY AND POWER

Typical receivers need: $E_b > \sim 10^{-20}$ Joules/bit

Received power required: $P_{rec} = M_{bps} E_b$ [Watts]

(M_{bps} is data rate, bits/sec)

RADIATED POWER

Transmitted Intensity: $I(\theta,\phi,r)$ [W/m^2]

For isotropic radiation: $I(\theta,\phi,r) = \mathbf{P_R}/4\pi r^2$ [Wm^{-2}]

↑ Total power radiated [W]

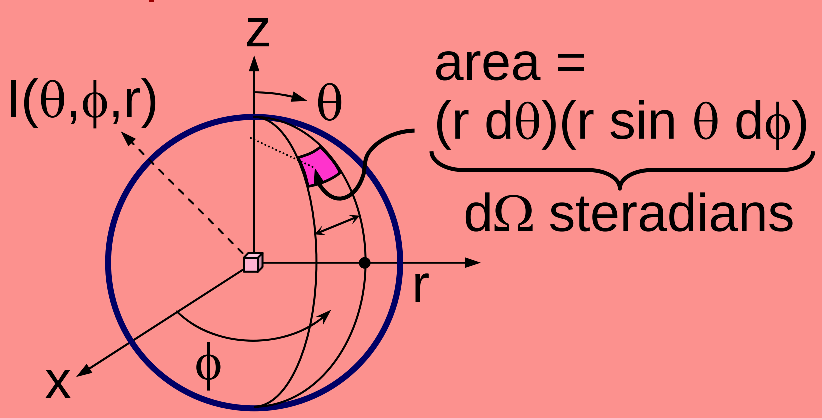
$$P_R = \int_0^{2\pi}\int_0^{\pi} I(\theta,\phi,r)\, r^2 \underbrace{\sin\theta\, d\theta\, d\phi}_{d\Omega \text{ (steradians)}}$$

Steradian: unit of solid angle

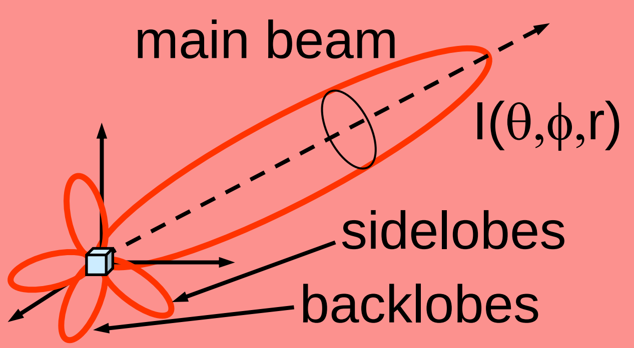
$d\theta$, $d\phi$: units of radians.

Spheres: span 4π steradians

Isotropic:



Antenna pattern:



ANTENNA GAIN $G(\theta,\phi)$

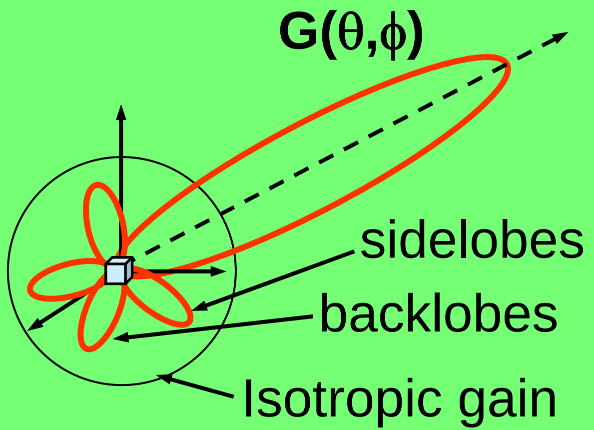
Gain over Isotropic, $G(\theta,\phi)$:

$$G(\theta,\phi) = \frac{I(\theta,\phi,r)}{(P_R/4\pi r^2)}$$

- $I(\theta,\phi,r)$ ← Intensity actually radiated [Wm^{-2}]
- $(P_R/4\pi r^2)$ ← Intensity if P_R were radiated isotropically

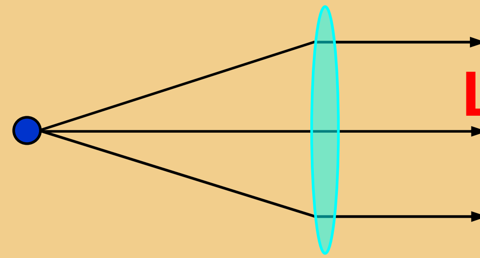
Intensity at receiver:

$$I(\theta,\phi,r) = G(\theta,\phi)\,(P_R/4\pi r^2) \quad [Wm^{-2}]$$



HOW TO INCREASE ANTENNA GAIN G(θ,ϕ)?

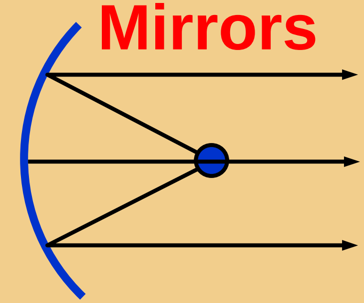
Focus the energy

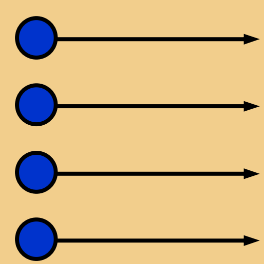


Lenses

Photographs illustrating lenses, mirrors, and phasing removed due to copyright restrictions.

Mirrors





Phasing

ANTENNA EFFECTIVE AREA $A_e(\theta,\phi)[m^2]$

Intensity radiated in a particular direction

$I(\theta,\phi,r) = G_t(\theta,\phi)\,(P_R/4\pi r^2)$ [W/m^2]

Power Received from a particular direction

$P_{rec} = I(\theta,\phi)\,A(\theta,\phi)$ [W]

Antenna Effective Area and Gain

$A(\theta,\phi) = G(\theta,\phi)\,(\lambda^2/4\pi)$ [m^2]

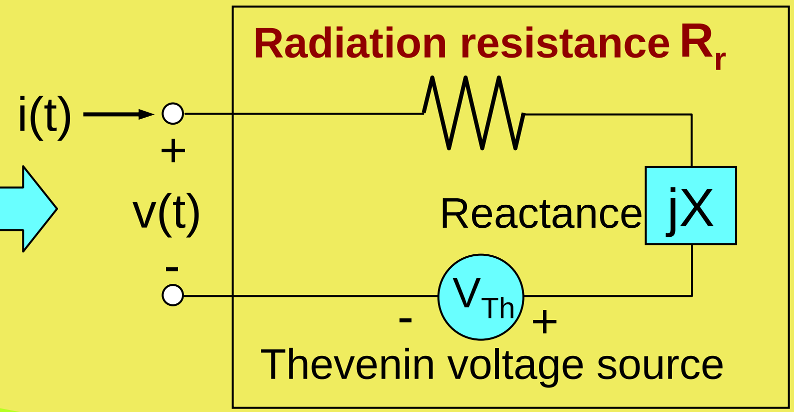
Power Received from a particular direction

$P_{rec} = P_t G_t G_r (\lambda/4\pi r)^2$ [W] $\Rightarrow$ "reciprocity"

CIRCUIT PROPERTIES OF ANTENNAS

When transmitting:

Equivalent circuit of antenna



Power radiated = P_R

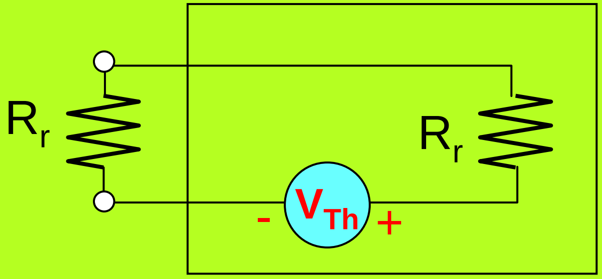
$P_R = \langle i^2(t) \rangle R_r$ [W]

When receiving:

Thevenin voltage V_{Th} is induced by incoming waves

Maximum power extractable from the antenna:

$P_{rec} = \langle (V_{Th}(t)/2)^2 \rangle / R_r$



Reactive elements are tuned out

SUMMARY

Wireless communications are ubiquitous

$G(\theta,\phi) = I(\theta,\phi,r) / (P_t/4\pi r^2)$ = Antenna gain over isotropic

Boost antenna gain using lenses, mirrors, or phasing

$A_r = G_r (\lambda^2/4\pi)$ = Antenna effective area [m^2]

M [bps] = $P_{rec}/E_b = IA_e/E_b = P_tG_tG_r(\lambda/4\pi r)^2/E_b$ = data rate

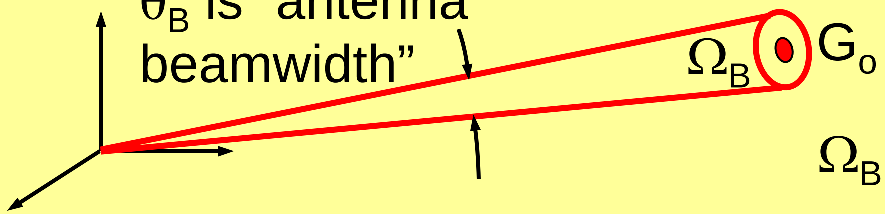
$E_b > \sim 10^{-20}$ [J] at the receiver (see footnote 39 on p360)

Antennas have Thevenin equivalent circuits, radiation resistance

EXAMPLE – INTERSTELLAR COMM.

$$P_{Rad} = \int_0^{2\pi}\int_0^{\pi} G(\theta,\phi)\frac{P_{Rad}}{4\pi r^2}\, r^2 \underbrace{\sin\theta\, d\theta\, d\phi}_{d\Omega \text{ steradians}} \Rightarrow \int_{4\pi} G(\theta,\phi)\, d\Omega = 4\pi$$

θ_B is "antenna beamwidth"



$G_o\Omega_B = 4\pi \Rightarrow G_o = 4\pi/\Omega_B$

Ω_B is the "beam solid angle"

Best microwave antennas: $\theta_B \cong$ 1 arc min = $(1/60)^o(1/57)$ radians $\cong 2^{-12}$ rad

$G_o = 4\pi/\Omega_B \cong 2^3/2^{-24} \cong 2^{27} \cong 10^8$ (or 80 dB)

Strongest transmitters ~ 10^6 Watts

Nearest stars ~1 light year = 3×10^7 sec $\times$ 3×10^8 m/s $\cong 10^{16}$ m

$$P_{rec} = \frac{P_{rad}}{4\pi r^2} G_t G_r \frac{\lambda^2}{4\pi} \cong \frac{10^6\ 10^8\ 10^8\ 0.03^2}{10\ 10^{32}\ 10} \cong 10^{-15} \text{ [W] [J/s]}$$

Data rate R $\cong P_{rec}$[J/s] / 10^{-20}[J/bit] = $10^{-15}/10^{-20}$ = 10^5 bits/sec