ELECTRODYNAMICS

Handouts:
Administration sheet
Subject outline, lecture notes
Homework set 1, text errata

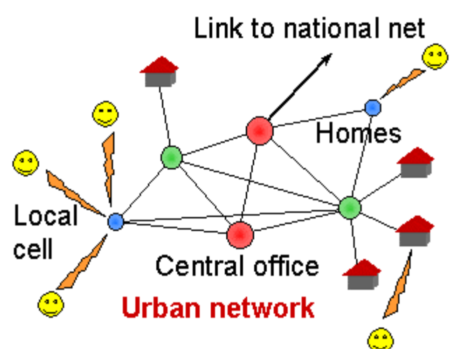
Prerequisites:
6.002, 8.02, 18.02

6.014 Content:
Wireless communications (4.8 weeks)
Circuits (1 week)
Limits to computation speed (1.2 weeks)
Microwave communications and radar (2 weeks)
Optical communications (1 week)
MEMS (1 week)
Power generation and transmission (1 week)

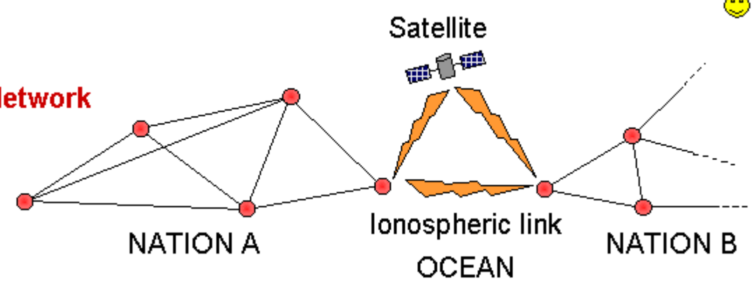
L1-1

WIRELESS COMMUNICATIONS UBIQUITOUS

Phones and Data:
Cell phones (how many have one?)
Wireless phones
Wired phones-microwave links
International satellite links
Transoceanic links, ionosphere
Radio hams (any here? DX record?)
Interplanetary links



National Network



L1-2

Main points of L1: Principal elements of communications links

- Wireless communications are ubiquitous: point-to-point, broadcast, passive sensors
- Receivers need E_b [J/bit] > $\sim 4\times10^{-20}$; received power $P_{rec} \geq M_{bps}E_b$ [W]
- Absent attenuation, total power radiated $P_R = \int_{4\pi} P_r(\theta,\phi,r)r^2\sin\theta\, d\theta\, d\phi$ [W]
- Antenna gain over isotropic $G(\theta,\phi) = P_r(\theta,\phi,r)[Wm^{-2}]/(P_R/4\pi r^2)$, r is range
- Received power P_{rec} = antenna effective area $A_e(\theta,\phi)[m^2]\times$intensity $P_r(\theta,\phi,r)[Wm^{-2}]$
- In general, $A_e(\theta,\phi) = G(\theta,\phi)\lambda^2/4\pi$ [for reciprocal media, not magnetized ferrites]
- With these equations we can design wireless links (choosing G_t, A, P_R for given r, M)
- Antennas have Thevenin equivalents with radiation resistance $R_r = P_R/\langle i^2\rangle$
- Maximum received power = $\langle(V_{Th}(t)/2)^2\rangle/R_r$ when $R_{load} = R_r$

WIRELESS COMMUNICATIONS IS UBIQUITOUS

Other Forms of Wireless Communications:

Broadcast radio, television
Satellite TV (~40,000 km - ~0.3 seconds roundtrip)
Wireless links: computers and peripherals, headend and base stations, hearing aids
Data: remote control (optical and radio); wired home, office, factory
Pills with sensors, radio, and TV (what signals go through body, which don't?)
Passive sensors—IR, microwave

L1-3

COMMUNICATION REQUIRES ENERGY AND POWER

Power Requirements

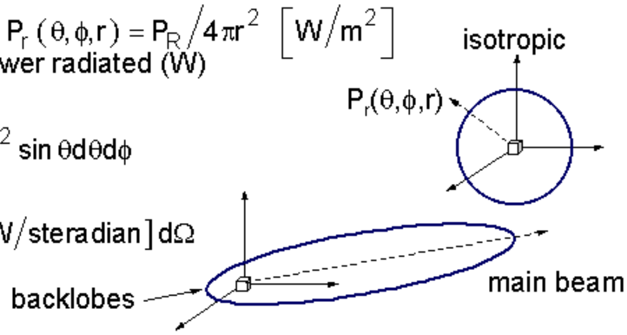
Typical receivers need $E_b > \sim 4 \times 10^{-20}$ Joules/bit
Power received $P = M_{bps}E_b$ (M_{bps} is data rate, bits/sec)
e.g. 10^{-9} Watts permits $M_{bps} = \sim 10^{-9}/4 \times 10^{-20} = 2.5 \times 10^{12}$ bps
This can send $2.5 \times 10^{12}/(8 \times 7 \times 10^{8}$ bits/CD) = 446 CD's/second!)

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

For isotropic radiation: $P_r(\theta,\phi,r) = P_R / 4\pi r^2 \; [\mathrm{W/m^2}]$
where P_R = total power radiated (W)
In general:

$$P_R[\mathrm{W}] = \int_{4\pi} P_r(\theta,\phi,r)\, r^2 \sin\theta\, d\theta\, d\phi$$

$$= \int_{4\pi} P_{r\Omega}(\theta,\phi)\,[\mathrm{W/steradian}]\, d\Omega$$



[Steradian is a unit of solid angle; $d\theta \sin\theta\, d\phi$ is in steradians if $d\theta$ and $d\phi$ are in units of radians]

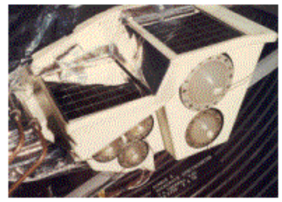
L1-4

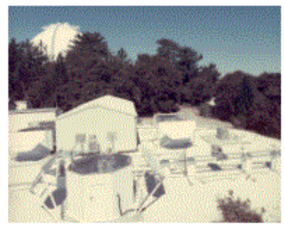
ANTENNA GAIN $G(\theta,\phi)$

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

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

(By definition, P_R is at antenna input; we assume lossless antennas here)



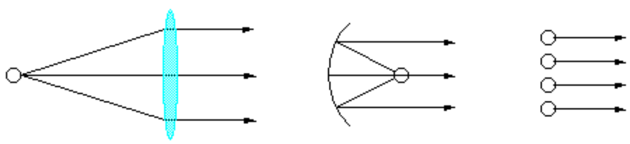


Example – Cellular Phone:

If P_R = 1 Watt, P_r at 10 km = $1/4\pi r^2$
= 8×10^{-14} [W/m^2] for isotropic antenna

How to Increase Gain?

Focus the energy: lenses, mirrors, phasing



L1-5

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

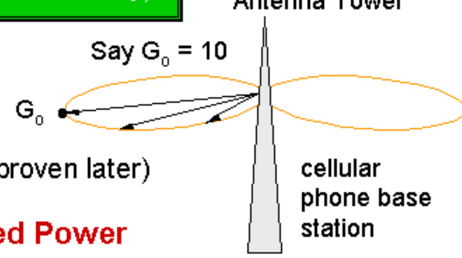
Power Received P_{rec} from a particular direction

$$P_{rec} = A_e\left[m^2\right]P_r\left[W/m^2\right] \quad (\text{by definition of } A_e)$$

Antenna Effective Area and Gain

$$A_e(\theta,\phi) = G(\theta,\phi)\lambda^2/4\pi$$

(to be proven later)



Cellular Phone Example – Received Power

P_R = 1 Watt, $P_r = 1/4\pi r^2$ [W/m^2] for an isotropic antenna (is it isotropic?)
$P_r = 8 \times 10^{-14}$ [W/m^2] at r = 1000 km (or 40-dB margin for r = 10 km)
$P_{rec} = A_e P_r$ (A_e depends on the base station G and λ)
λ=c/f = 3 $\times$ 10^8 [m/s]/900 MHz = 33.3 cm
A_e(base station) = $G\lambda^2/4\pi$ = 10 $\times$ 0.33^2/(4 $\times$ 3.14) = 0.088 m^2
$P_{rec} = A_e P_r$ = 0.088 $\times$ 8 $\times$ 10^{-14} = 7.1 $\times$ 10^{-15} [W]
Data Rate [bps] = P_{rec}[J/s]/E_b[J/b] = 7.1 $\times$ 10^{-15}/(4 $\times$ 10^{-20}) = **176 kbps**
Wishful thinking! Data rate per line limited by bandwidth and frequency reuse

L1-6

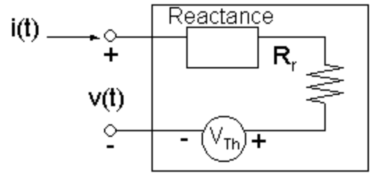
CIRCUIT PROPERTIES OF ANTENNAS

Radiation Resistance R_r

$$P_R = \langle i^2 R_r \rangle$$

$$R_r = P_R / \langle i^2 \rangle$$

Equivalent circuit of antenna



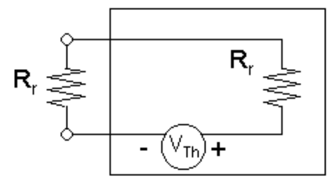
Open-Circuit Voltage (Thevenin voltage)

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



WHAT DO WE NOT YET KNOW?

- What is an electromagnetic wave?
- How does it propagate through air and space, around buildings, around the earth?
- How do we launch and receive them?
- How do we engineer wireless communications systems using waves? Examples.