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] > $4 \times 10^{-20}$; 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 $G(\theta,\phi) = P_r(\theta,\phi,r) \frac{\lambda^2}{4\pi} \sin \theta \, d\theta \, d\phi$ [W]
- Received power $P_{rec} = A_e(\theta,\phi)[\text{m}^2] \times \text{intensity } P_r(\theta,\phi,r) [\text{W} \cdot \text{m}^{-2}]$
- In general, $A_e(\theta,\phi) = G(\theta,\phi)\frac{\lambda^2}{4\pi}$ [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 $R_r = P_R/e^2$
- Maximum received power $= <(V_{Th}(t)/2)^2>/R_r$ 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

COMMUNICATION REQUIRES ENERGY AND POWER

Power Requirements

Typical receivers need $E_R > 4 \times 10^{20}$ Joules/bit
Power received $P = M_{bps}E_R$ ($M_{bps}$ is data rate, bits/sec)
    e.g. $10^8$ Watts permits $M_{bps} = \approx 10^8/4 \times 10^{20} = 2.5 \times 10^{12}$ bps
This can send $2.5 \times 10^{12}/(8 \times 7 \times 10^3 \text{ bits/CD}) = 446 \text{ CD's/second!}$

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

For isotropic radiation: $P_r(\theta, \phi, r) = P_R/4\pi r^2 \left[ \text{W/m}^2 \right]$

where $P_R = \text{total power radiated (W)}$

In general:

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

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

[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]
ANTENNA GAIN \( G(\theta, \phi) \)

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

\[
G(\theta, \phi) = \frac{P_r(\theta, \phi, r)}{P_{r0}/4\pi r^2}
\]

(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 = \( 1/4\pi r^2 \)

\[ = 8 \times 10^{-14} \text{ [W/m}^2\text{]} \]

for isotropic antenna

**How to Increase Gain?**

Focus the energy: lenses, mirrors, phasing

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ANTENNA EFFECTIVE AREA \( A_e(\theta, \phi) \) \([\text{m}^2]\)

**Power Received \( P_{\text{rec}} \) from a particular direction**

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

(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, \( P_r \) = \( 1/4\pi r^2 \) \([\text{W/m}^2]\) for an isotropic antenna (is it isotropic?)

\( P_r = 8 \times 10^{-14} \) \([\text{W/m}^2]\) at \( r = 1000 \) km (or 40-dB margin for \( r = 10 \) km)

\( P_{\text{rec}} = A_e P_r (A_e \text{ depends on the base station } G \text{ and } \lambda) \)

\( \lambda = \text{c}/f = 3 \times 10^9 \) [m/s] 900 MHz = 33.3 cm

\( A_e(\text{base station}) = G\lambda^2/4\pi = 10 \times 0.33^2/(4 \times 3.14) = 0.088 \text{ m}^2 \)

\( P_{\text{rec}} = A_e P_r = 0.088 \times 8 \times 10^{-14} = 7.1 \times 10^{-15} \) [W]

Data Rate \([\text{bps}] = P_{\text{rec}} [\text{W}] [E_{\text{b}}/N_0] = 7.1 \times 10^{-15}/(4 \times 10^{-20}) = 176 \text{ kbps} \)

Wishful thinking! Data rate per line limited by bandwidth and frequency reuse
CIRCUIT PROPERTIES OF ANTENNAS

Radiation Resistance $R_r$

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

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

Open-Circuit Voltage (Thevenin voltage)

Induced by incoming waves
Maximum power extractable from the antenna:

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

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.