# The Wireless Channel

Ermanno Pietrosemoli

ICTP

The Abdus Salam International Centre for Theoretical Physics

UNESCO
United Nations Educational, Scientific and Cultural Organization

# Objective

To present the basics concepts of telecommunication systems with focus on digital and wireless

# Agenda

- Signals
- Bandwidth
- Spectrum
- Ideal channel, attenuation, delay
- Channel capacity, Noise, Interference,
- Modulation, Multiplexing, Duplexing
- Transmission impairments: Attenuation, Delay, Distortion.
- Propagation of Radio Waves
- Free Space Loss

# Signals

Signals are variation over ***time*** of voltages, currents or light levels that carry information.

The output of sensors are often ***analog*** signals, directly proportional to some physical variable like sound, light, temperature, wind speed, etc.

The information can also be transmitted by digital binary signals, that will have only two values, a digital ***one*** and a digital ***zero***.

Some sensors output ***digital*** signals.

# Signals

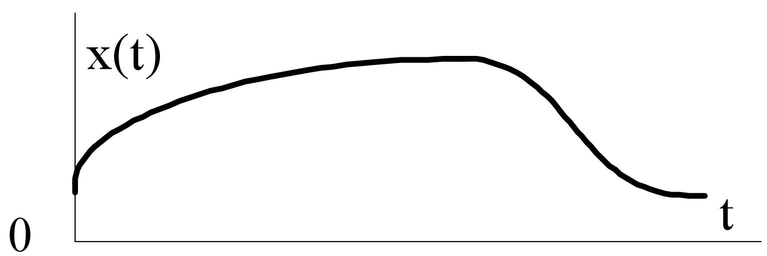
Any analog signal can be converted into a digital signal by appropriately ***sampling*** it.

The sampling frequency must be ***at least twice*** the maximum frequency present in the signal in order to carry ***all*** the information contained in it.

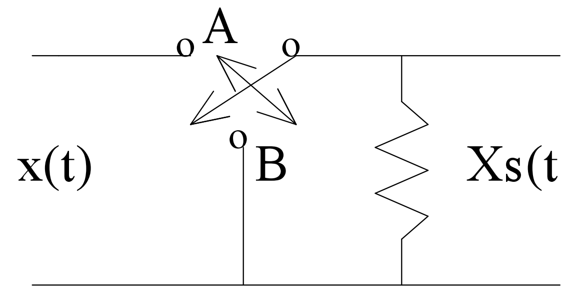
Random signal are the ones that are unpredictable and can be described only by statistical means.

Noise is a typical random signal, described by its mean power and frequency distribution.

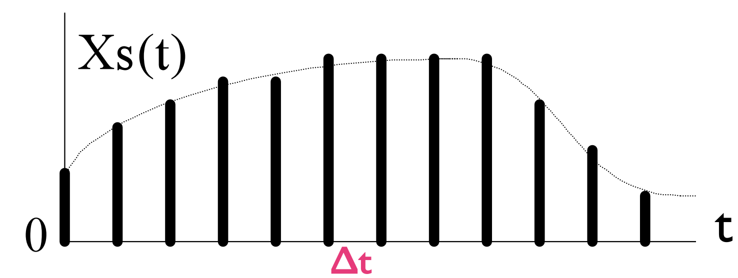
# Sampling




Analog Signal




Sampling Circuit



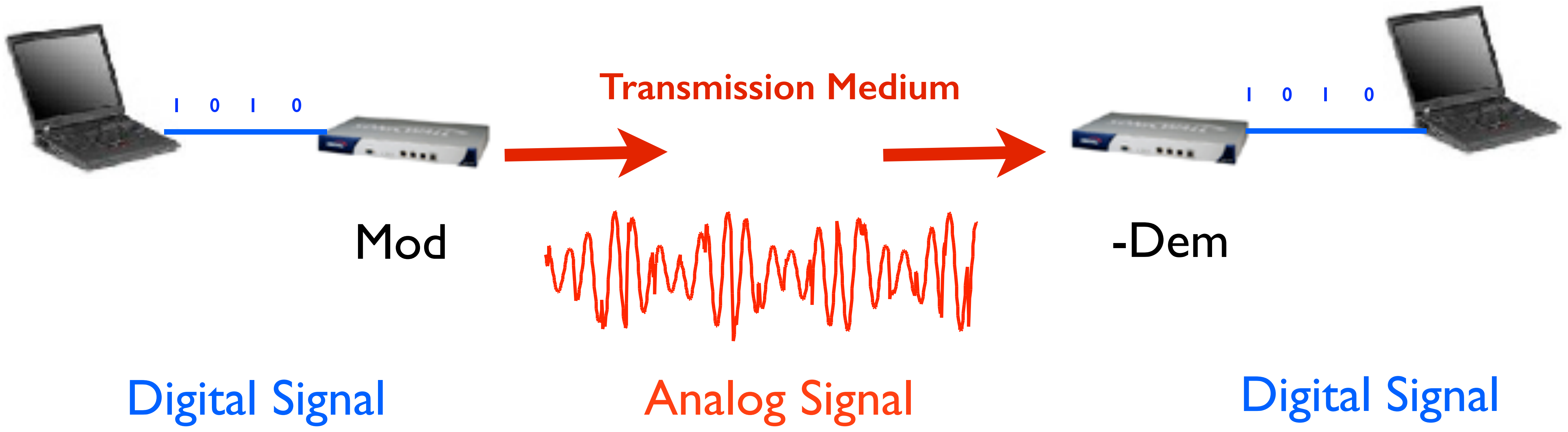

Sampled Signal

The sampling frequency $f_s$ must be at least twice the highest frequency $f_h$ present in the analog signal.

The original signal can be recovered from its samples by means of a low pass filter with cutoff frequency $f_h$. This is called an interpolation filter.

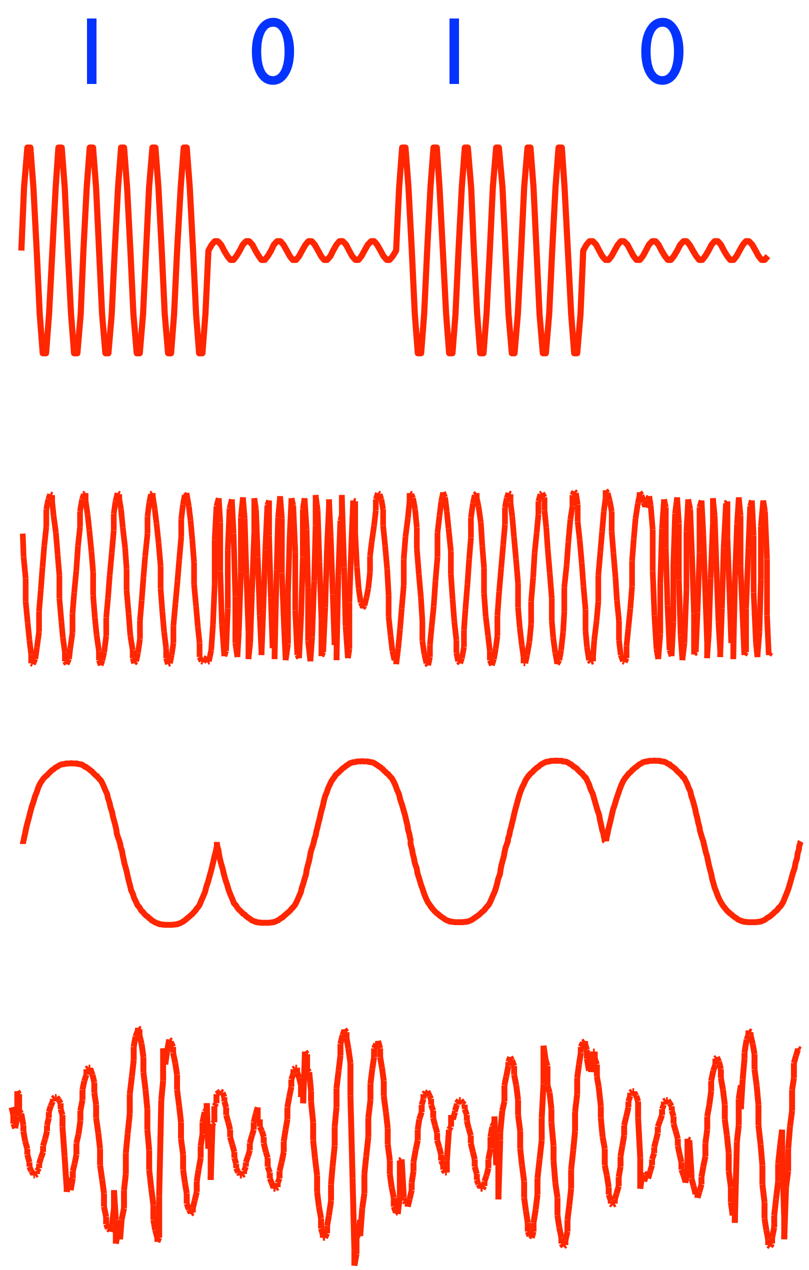
Sampling implies multiplication of the signal by a train of impulses equally spaced every $\Delta t = 1/f_s$

# MODEM



I 0 I 0
Transmission Medium
I 0 I 0
Mod
-Dem
Digital Signal
Analog Signal
Digital Signal

# Modulated Signals




Digital Sequence

ASK modulation

FSK modulation

PSK modulation

QAM modulation, changes both amplitude and phase

Throughput and Signal to Noise for different modulation schemes

| Mod. Type | Bits/Symbol | Required $E_b/N_o$ |
|---|---|---|
| 16 PSK | 4 | 18 dB |
| 16 QAM | 4 | 15 dB |
| 8 PSK | 3 | 14.5 dB |
| 4 PSK | 2 | 10.1 dB |
| 4 QAM | 2 | 10.1 dB |
| BFSK | 1 | 13.5 dB |
| BPSK | 1 | 10.5 dB |

# Electrical Noise

- Noise poses the ultimate limit to the range of a communications system
- Every component of the system introduces noise
- There are also external sources of noise, like atmospheric noise and man made noise
- Thermal noise power (always present) is frequency independent and is given (in watts) by k*T*B, where:

k is Boltzmann constant, $1.38 \times 10^{-23}$ J/K
T is absolute temperature in kelvins (K)
B is bandwidth in Hz
At 26 °C (T= 273.4+26) the noise power in dBm in 1 MHz is:
$-174 + 10 * \log_{10}(B) = -144$ dBm

# Duplexing

**Simplex**:

one way only, example: TV Broadcasting

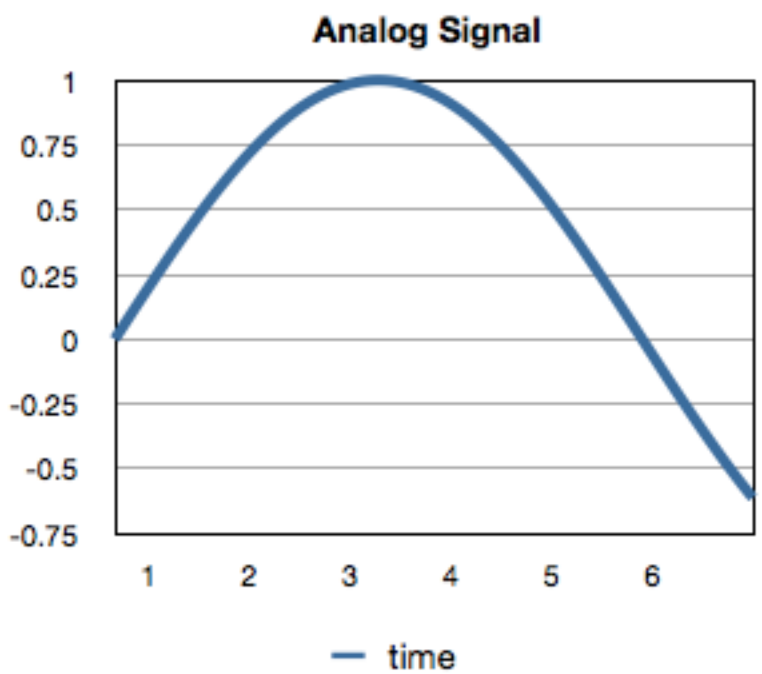
**Half-duplex:**

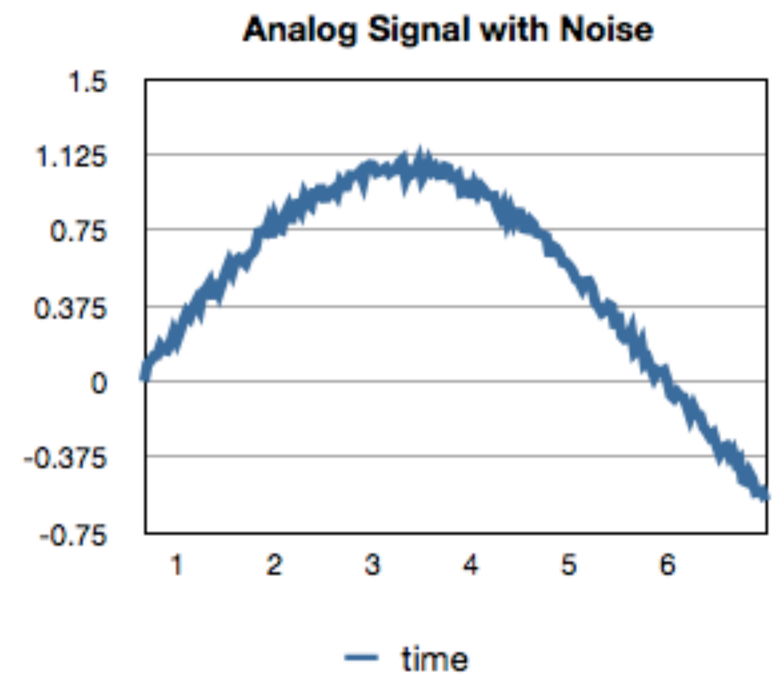
the corresponding stations have to take turns to access the medium, example: walkie-talkie. Requires hand-shaking to coordinate access. This technique is called **TDD** (Time Division Duplexing)

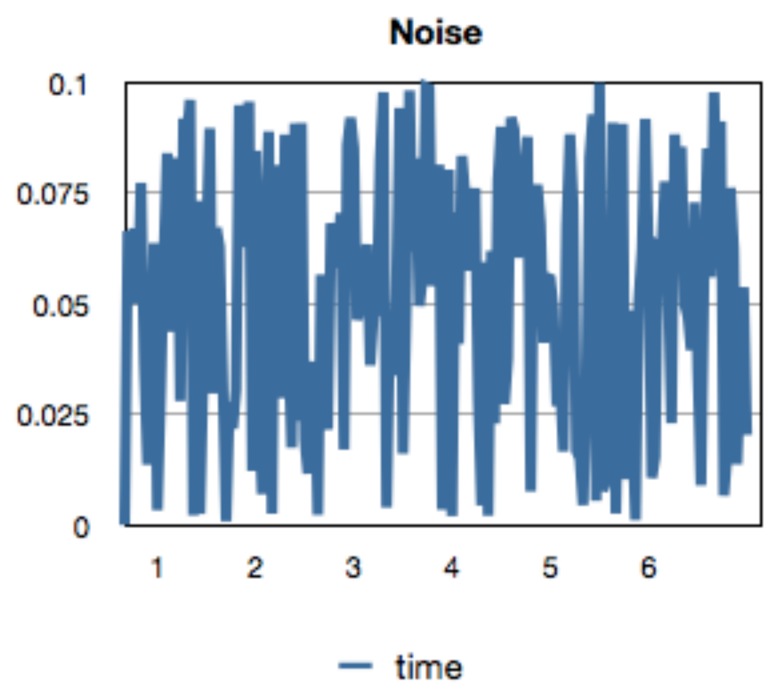
**Full-duplex:**

the two corresponding stations can transmit simultaneously, employing different frequencies. This technique is called **FDD** (Frequency Division Duplexing). A guard band must be allowed between the two frequencies in use.

# Signal and Noise



# Telecommunication Channel


$$C = B \log_2 \{1 + S/(N_o B)\}$$

Capacity, bit/s

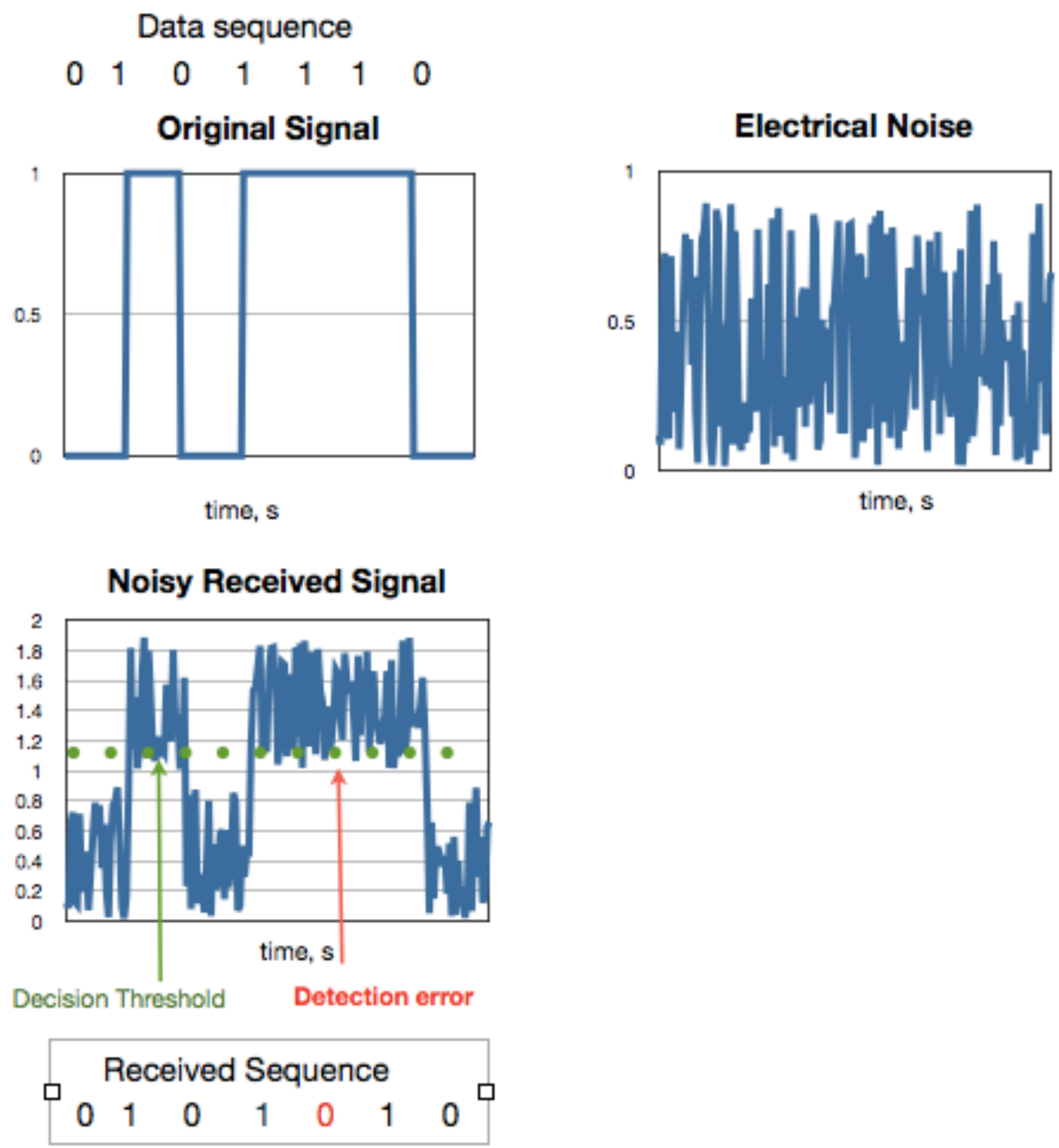
B, bandwidth = $(F_M - F_m)$, Hz

Signal power, W

Noise Power density, W/Hz

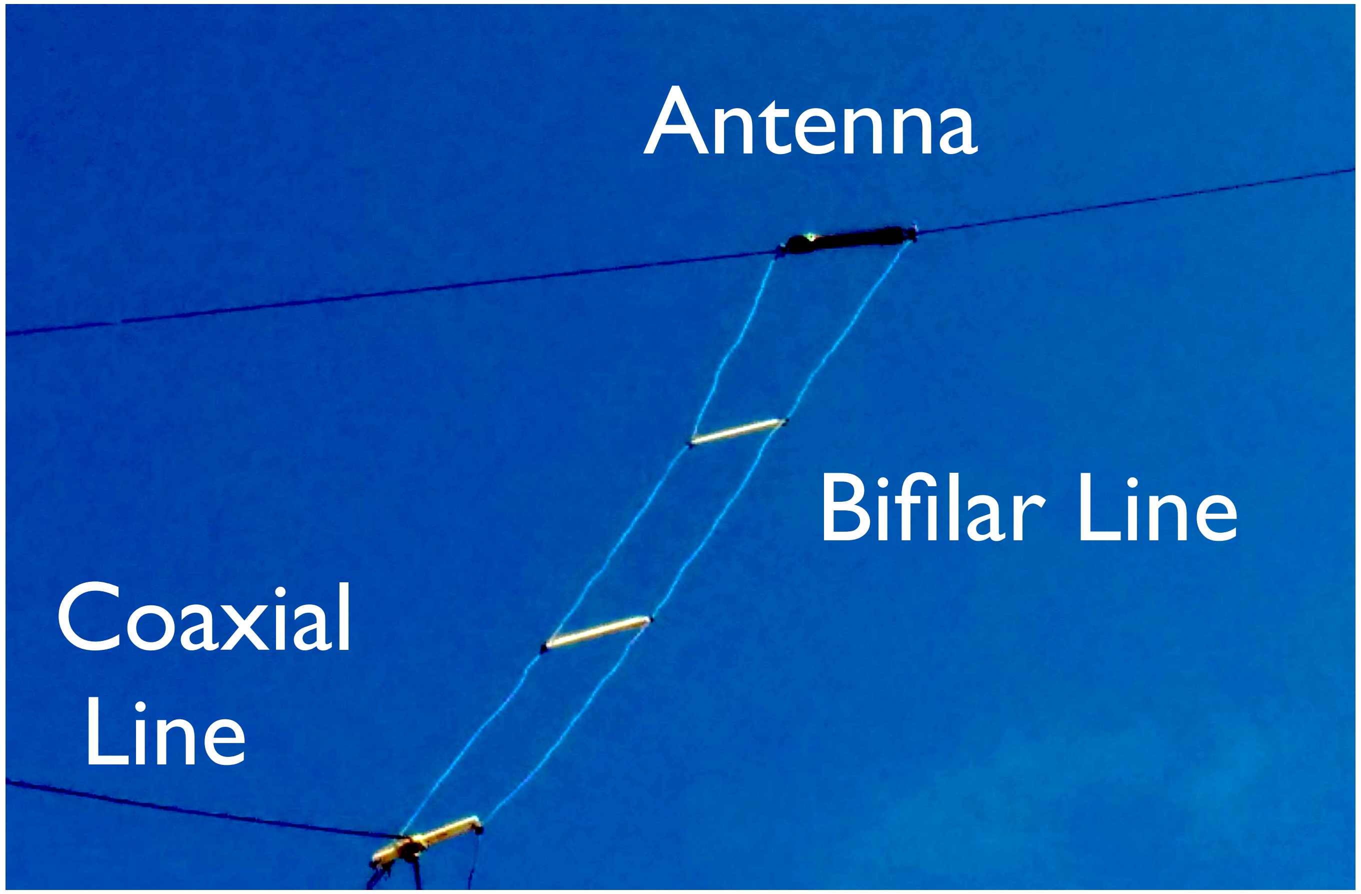
The capacity, also called throughput is the number of bits transmitted in one second.
The received signal will always be attenuated, delayed, and distorted by the effect of noise.

# Detection of a noisy signal

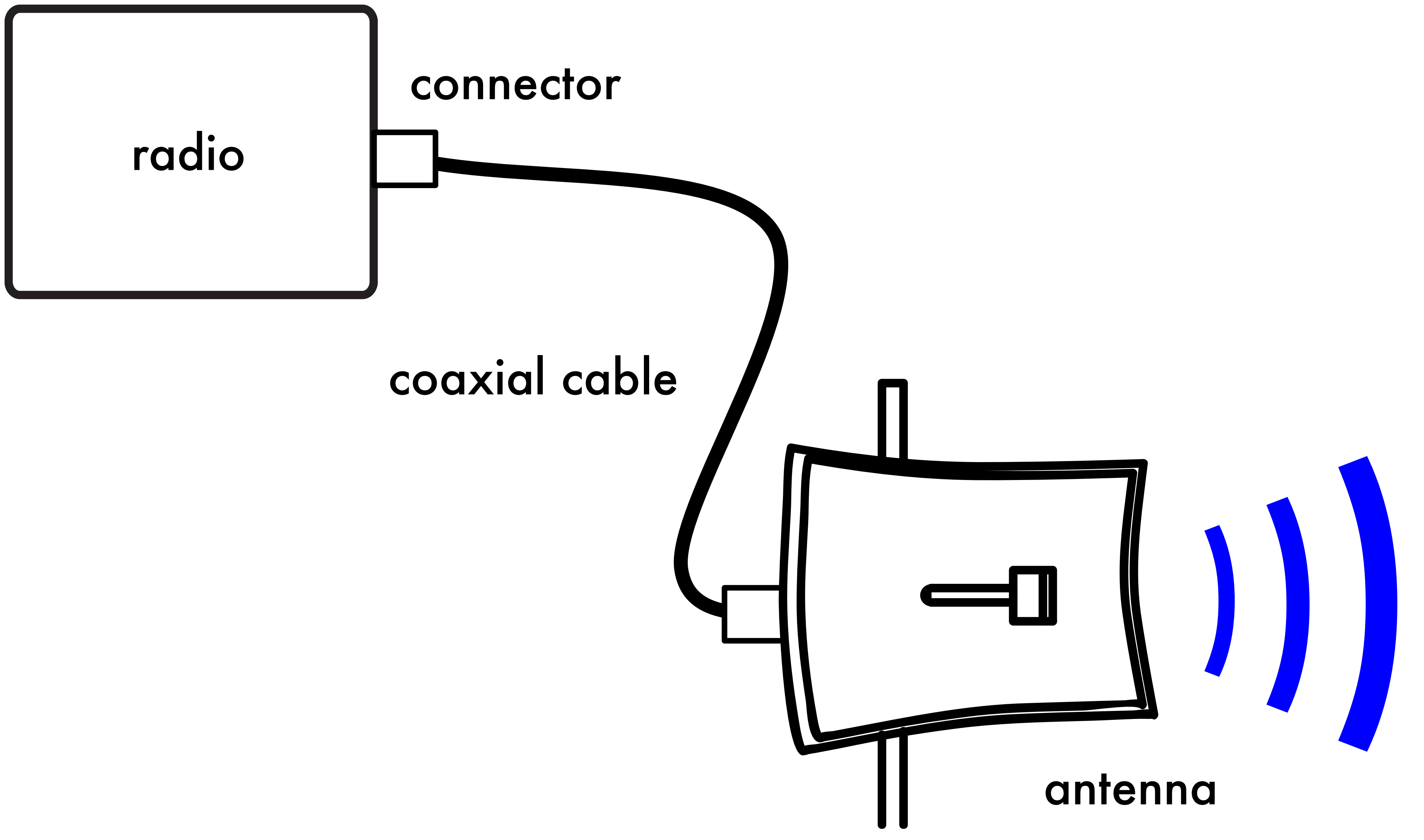


# Transmission lines and antennas

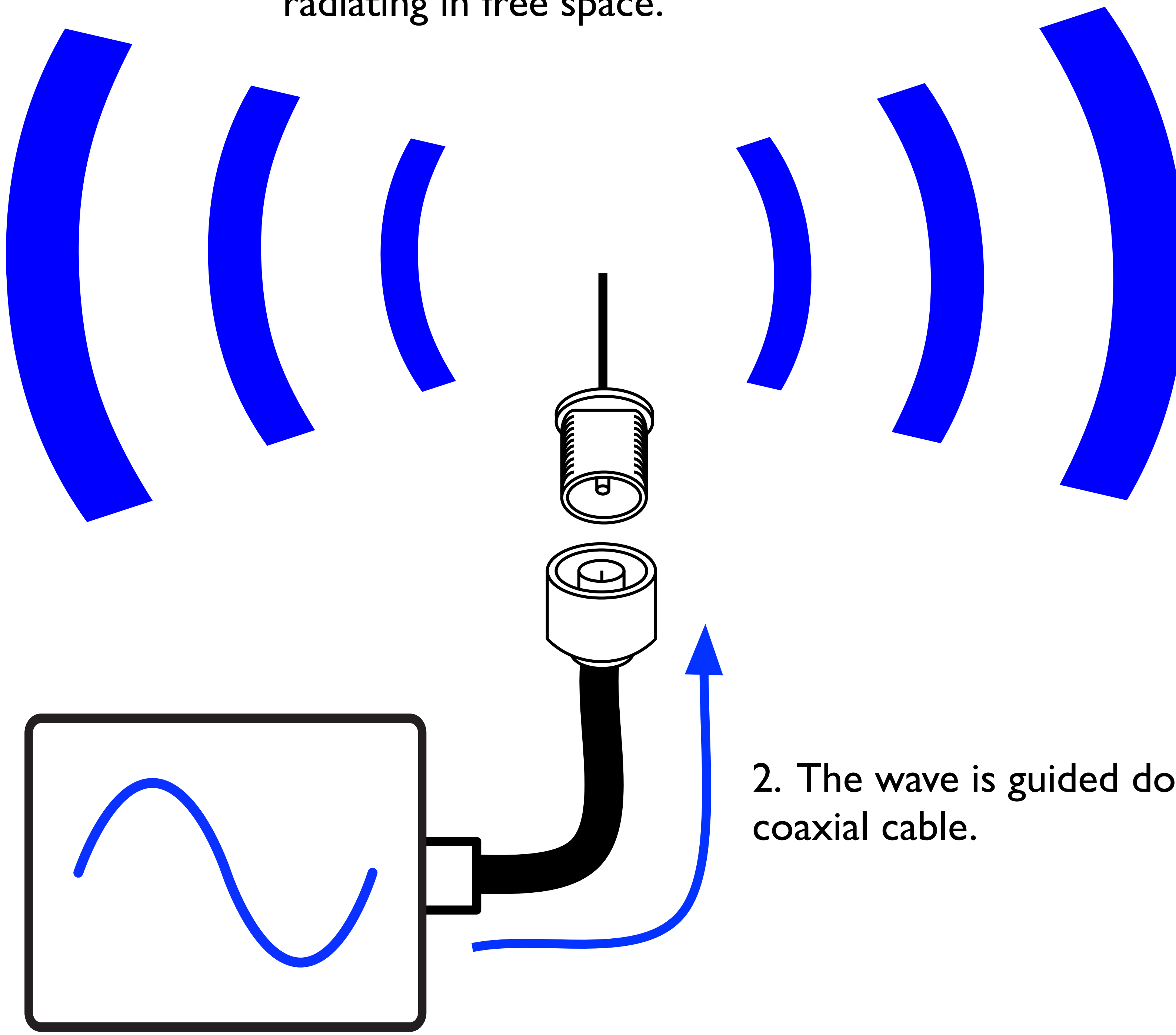
- An ***antenna*** is the structure associated with the region of transition from a guided wave to a free space wave, radiating RF energy.
- A ***transmission line*** is a metallic device used to guide radio frequency (RF) energy from one point to another (for example a *coaxial* cable or *bifilar* line).



# Wireless system connections



3. The wave arrives at a bare wire, and induces an electromagnetic wave radiating in free space.



2. The wave is guided down a coaxial cable.

1. The radio creates an electrical current oscillating at high frequency.

# Connectors

Connectors come in a huge variety of shapes and sizes. In addition to standard types, connectors may be ***reverse polarity*** (genders swapped) or ***reverse threaded***.

# Adapters & Pigtails

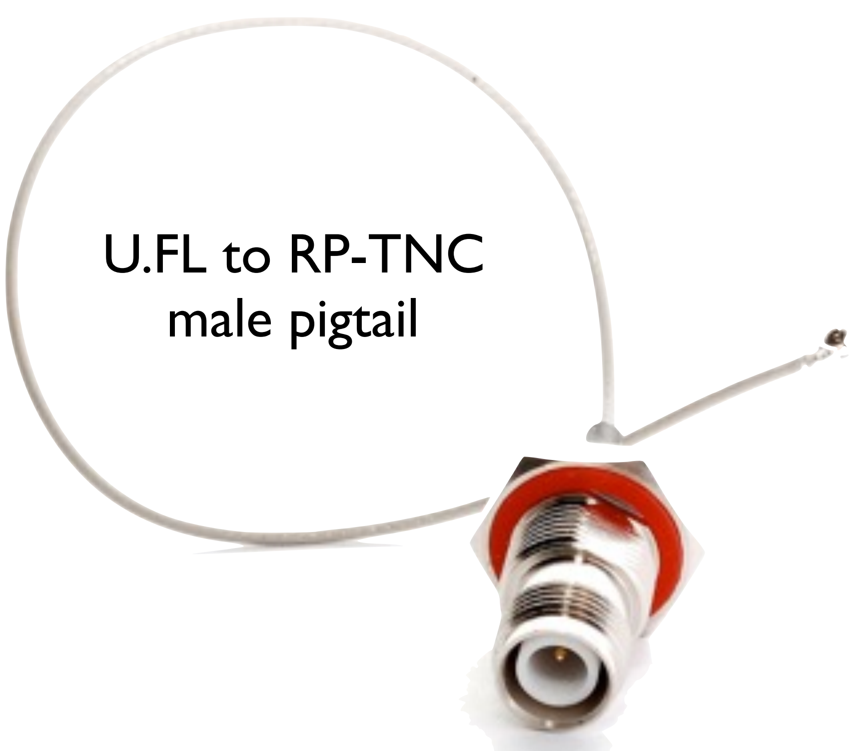
Adapters and pigtails are used to interconnect different kinds of cable or devices.

SMA female to N male

N male to N male

N female to N female

SMA male to TNC male



U.FL to RP-TNC male pigtail

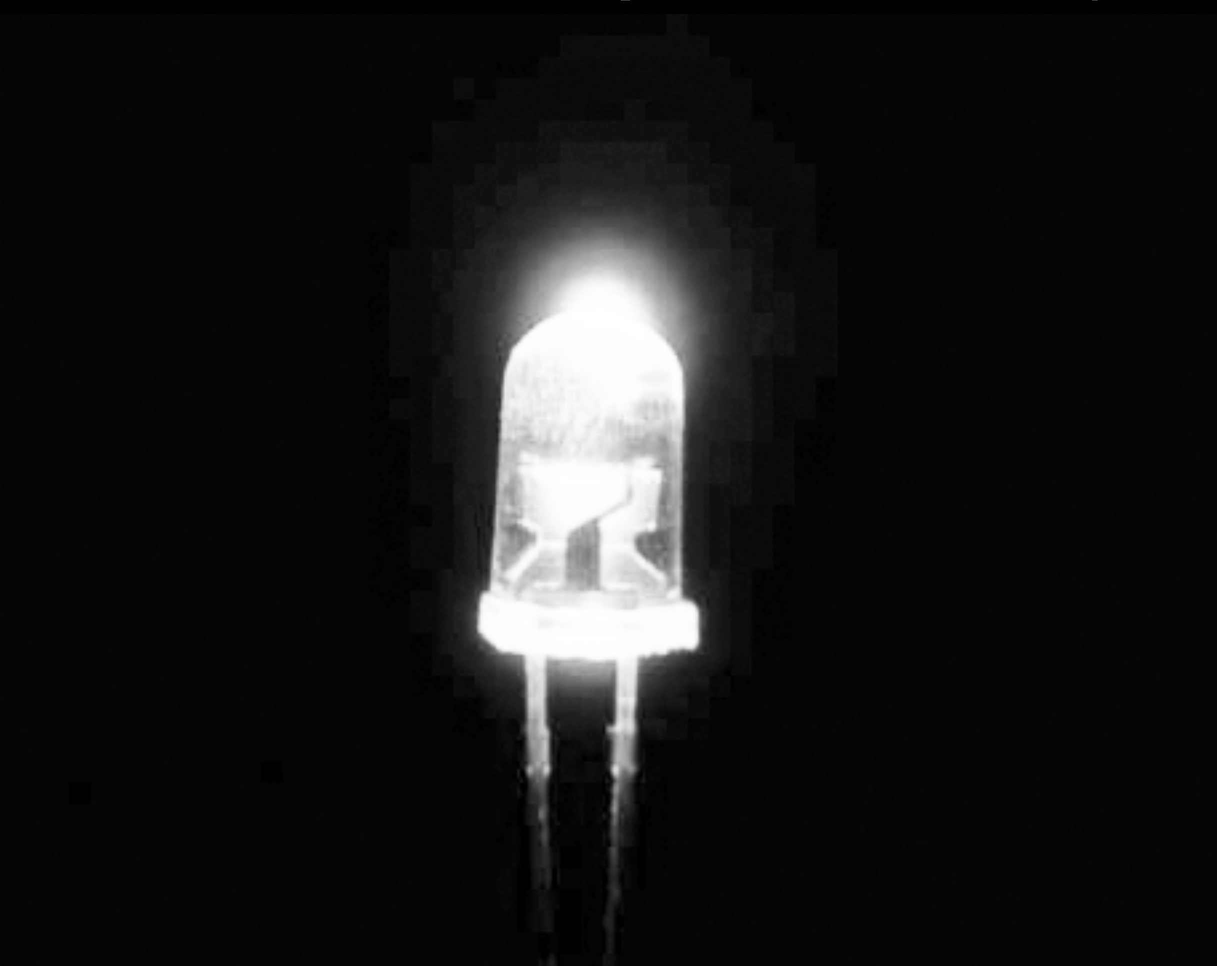
U.FL to N male pigtail

SMA male to N female

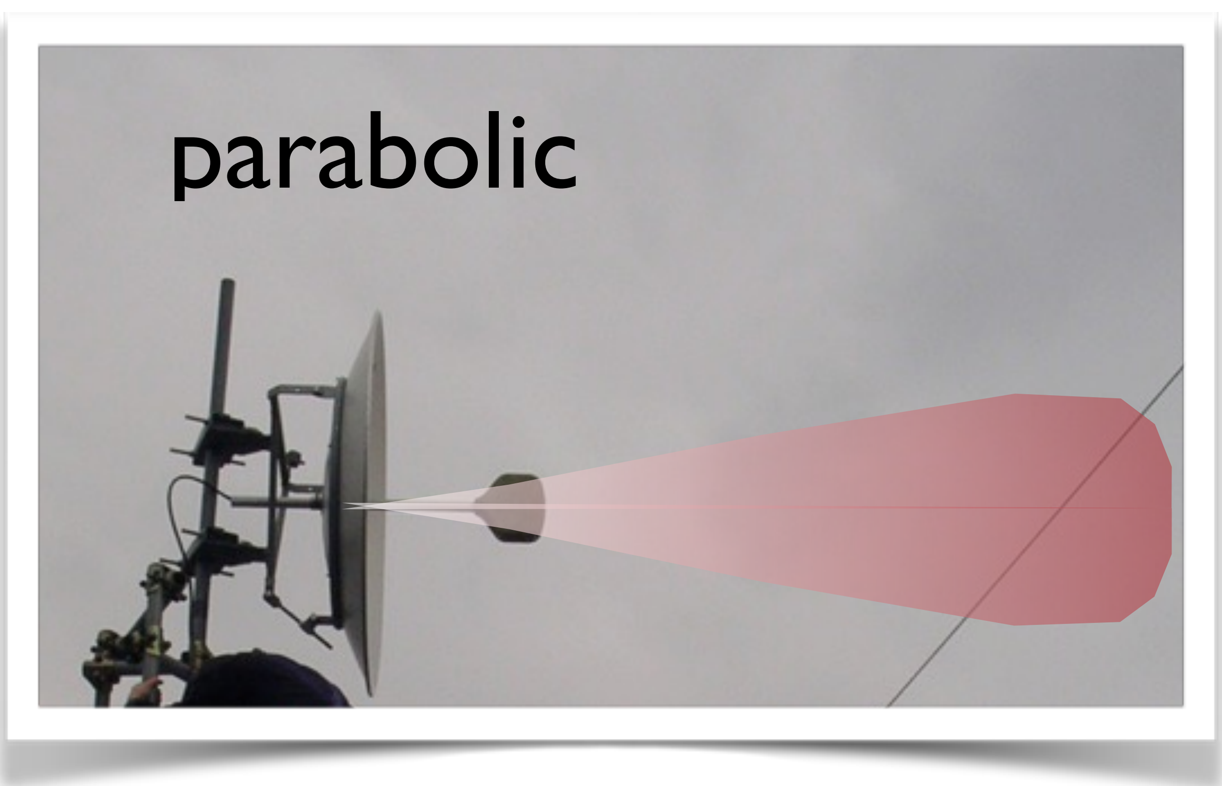
# dBi

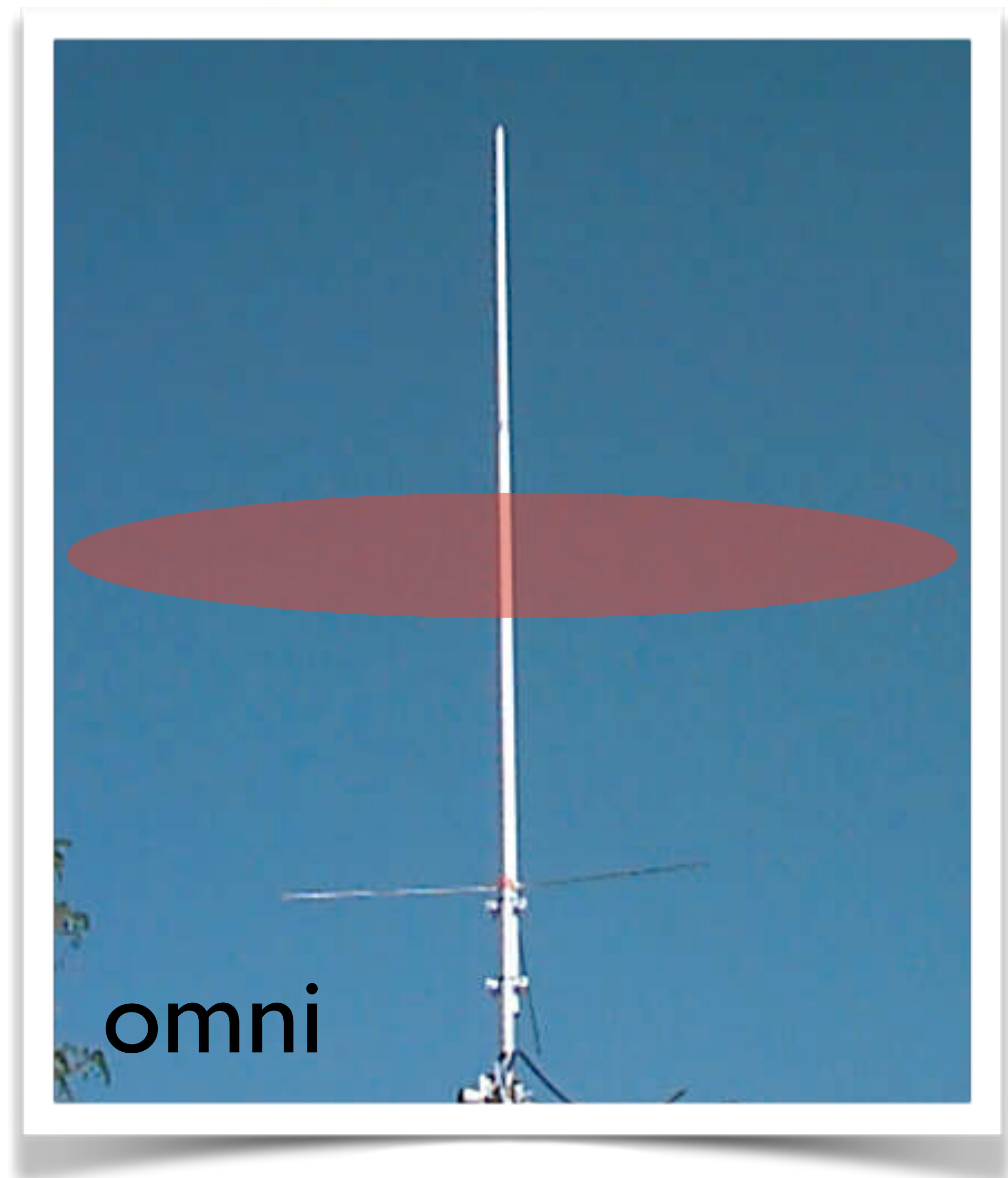
Antennas do not add power. They direct available power in a particular direction.

The gain of an antenna is measured in ***dBi*** (decibels relative to an isotropic radiator).



# Directional vs. Omnidirectional



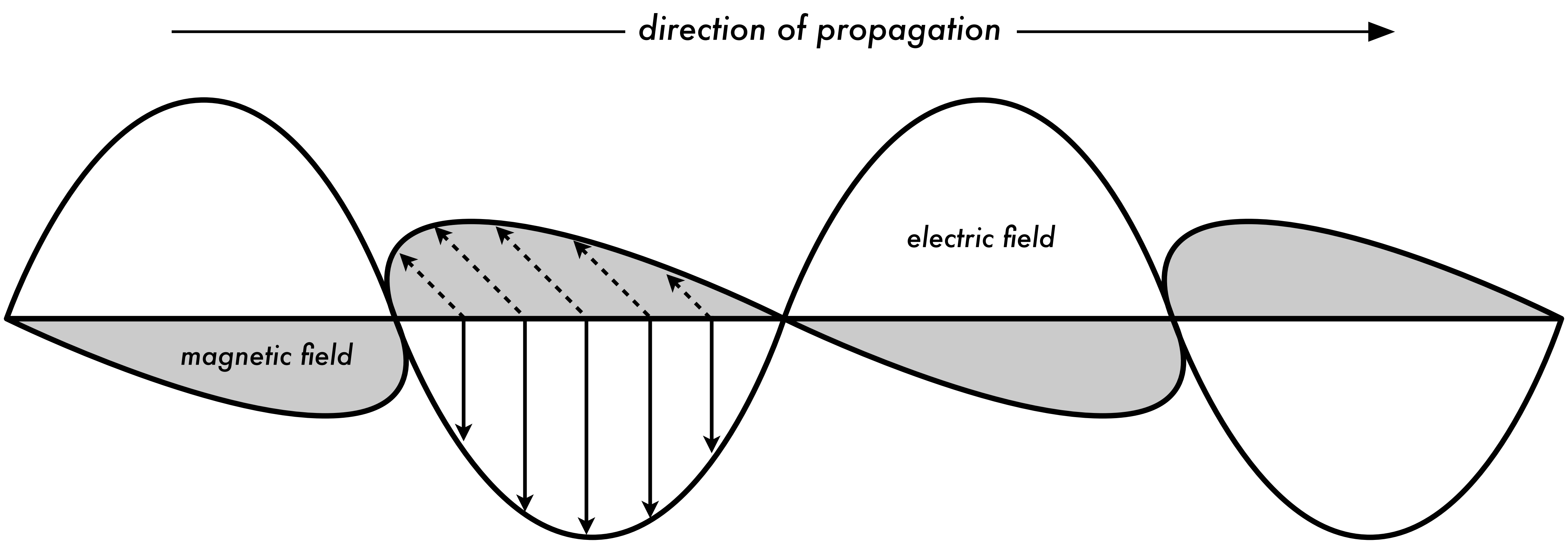
# Antenna features

When choosing an antenna, what features must be considered?

- Frequencies of operation
- Input impedance (50 or 75 ohm)
- Physical size
- Gain
- Radiation pattern (beamwidth, sidelobes,)
- Cost

# Polarization

- Electromagnetic waves have electrical and magnetic components. The direction of the electrical field defines the polarization of the wave.
- The polarization of transmitting and receiving antennas **MUST MATCH** or significant losses may occur.



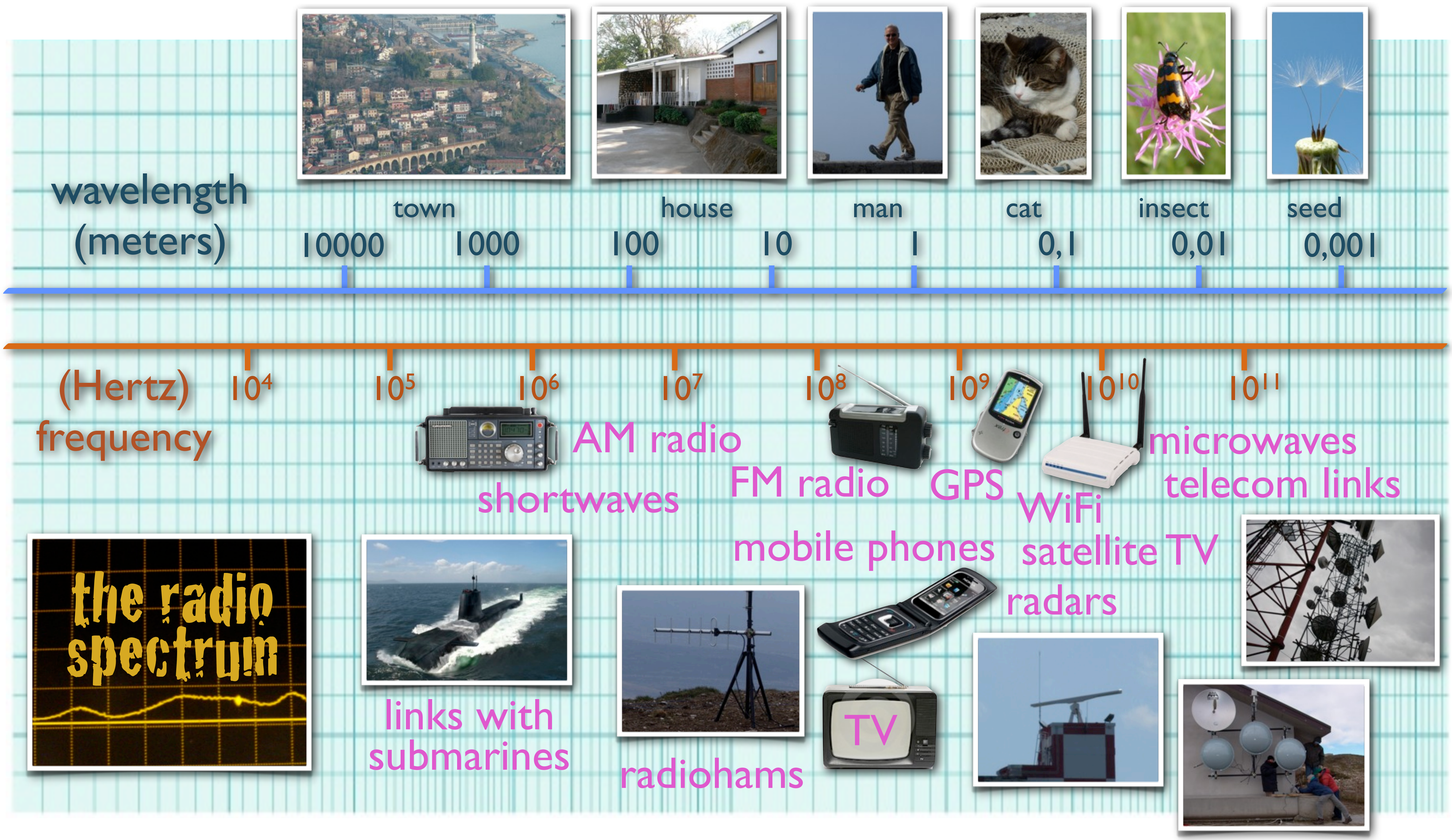
# Frequency and Wavelength

$$\lambda = c / f$$

$\lambda$ = wavelength in m (meters)
c = speed of light, approximately $3*10^8$ m/s
f = frequency in Hz (cycles per second)

Example: for f = 100 MHz, $\lambda$ = 3 m
for f = 2400 MHz, $\lambda$ = 0.125 m

# Electromagnetic Spectrum



# Electromagnetic Spectrum

- The Spectrum is regulated in each country by a national regulatory body, following the recommendations of the ITU (International Telecommunications Union), a UN agency.
- The regulations specify the allowed power in each frequency range, and the services to be offered.
- In general, one must obtain a license from the national regulator to use a radio transmitting device, which often entails the payment of yearly fees.

# Unlicensed bands

- There are some frequency bands that can be used without the need for the end user to apply for the license, these are the so called “unlicensed bands”, although often the license has been awarded to the manufacturer of the equipment.
- ISM (Industrial, Scientific and Medical) bands are meant to be used for purposes other than telecommunications, but they are also been used nowadays for WiFi and many other devices.
- WiFi success has prompted the designation of other “lightly licensed” bands for telecommunications applications.
- SRDs (Short Range Devices) are very low power radios that can be operated without a licence in ISM and other special bands.

# ISM bands

- **6 765-6 795 kHz**
- **13 553-13 567 kHz**
- **26 957-27 283 kHz**
- **40.66-40.70 MHz**
- **433.05-434.79 MHz   Only in Region 1 (Europe and Africa)**
- **902-928 MHz   Only in Region 2 (America)**
- **2 400-2 500 MHz**
- **5 725-5 875 MHz**
- **24-24.25 GHz**
- **61-61.5 GHz**
- **122-123 GHz**
- **244-246 GHz**

# Non ISM bands available for SRDs

- 9-148.5 kHz
- 3 155-3 400 kHz
- 72-72.25 MHz
- 315 MHz
- 402-405 MHz
- 862-875 MHz, only in Europe, part of this range
- 5470-5725 MHz

# Propagation of radio waves

Radio waves do not move in a strictly straight line. On their way from “point A” to “point B”, waves may be subject to:

- Absorption
- Reflection
- Diffraction
- Refraction

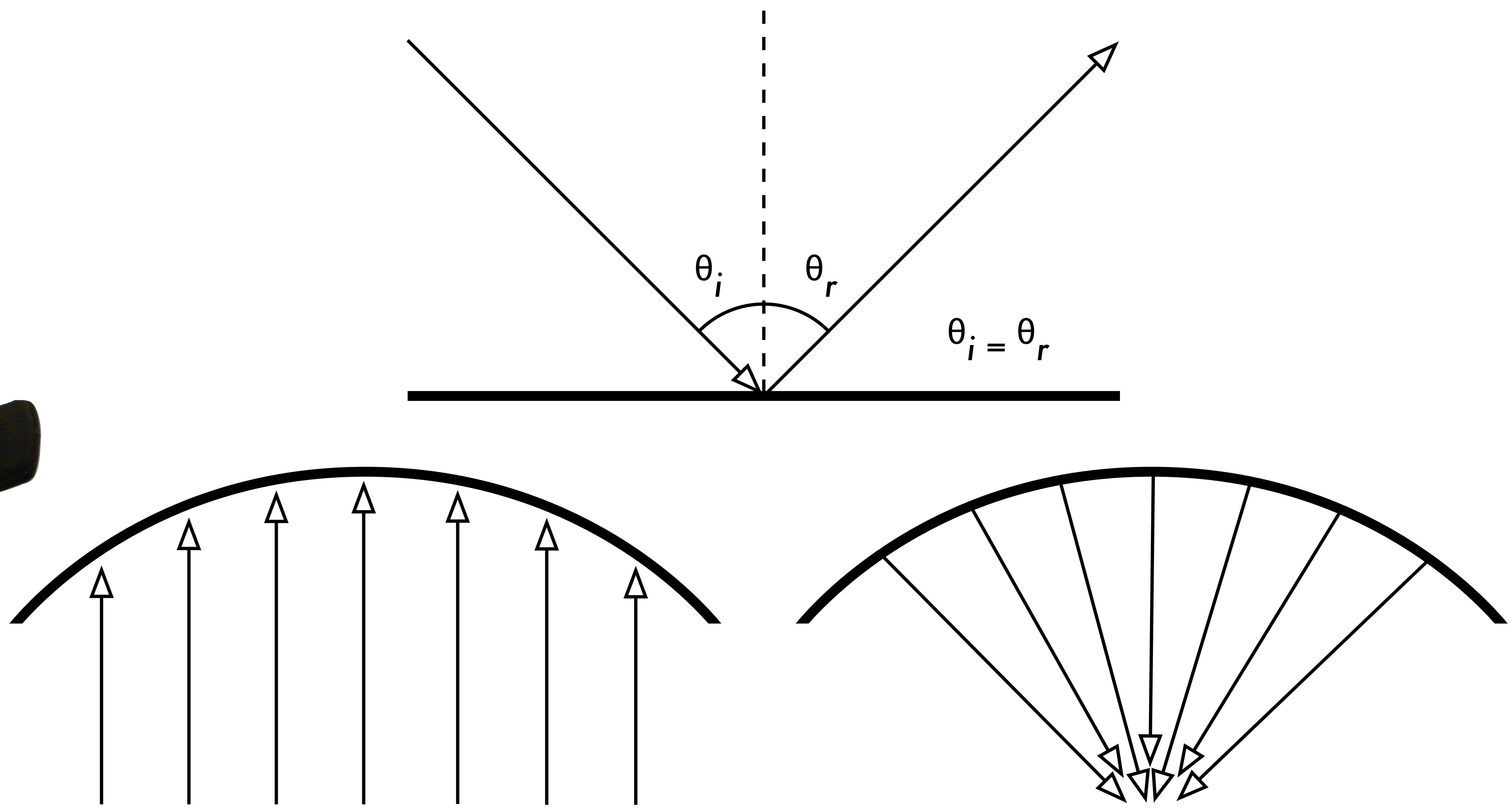
# Absorption

When electromagnetic waves go through some material, their strength diminishes because of the absorption.

- *Metal*. Electrons can move freely in metals, and are readily able to swing and thus absorb the energy of a passing wave.
- *Water* molecules jostle around in the presence of radio waves, thus absorbing some energy.
- *Trees* and ***wood*** absorb radio energy proportionally to the amount of water contained in them.
- ***Humans*** are mostly water: we absorb radio energy quite well!
- *Walls* absorb waves **increasingly** with the frequency.

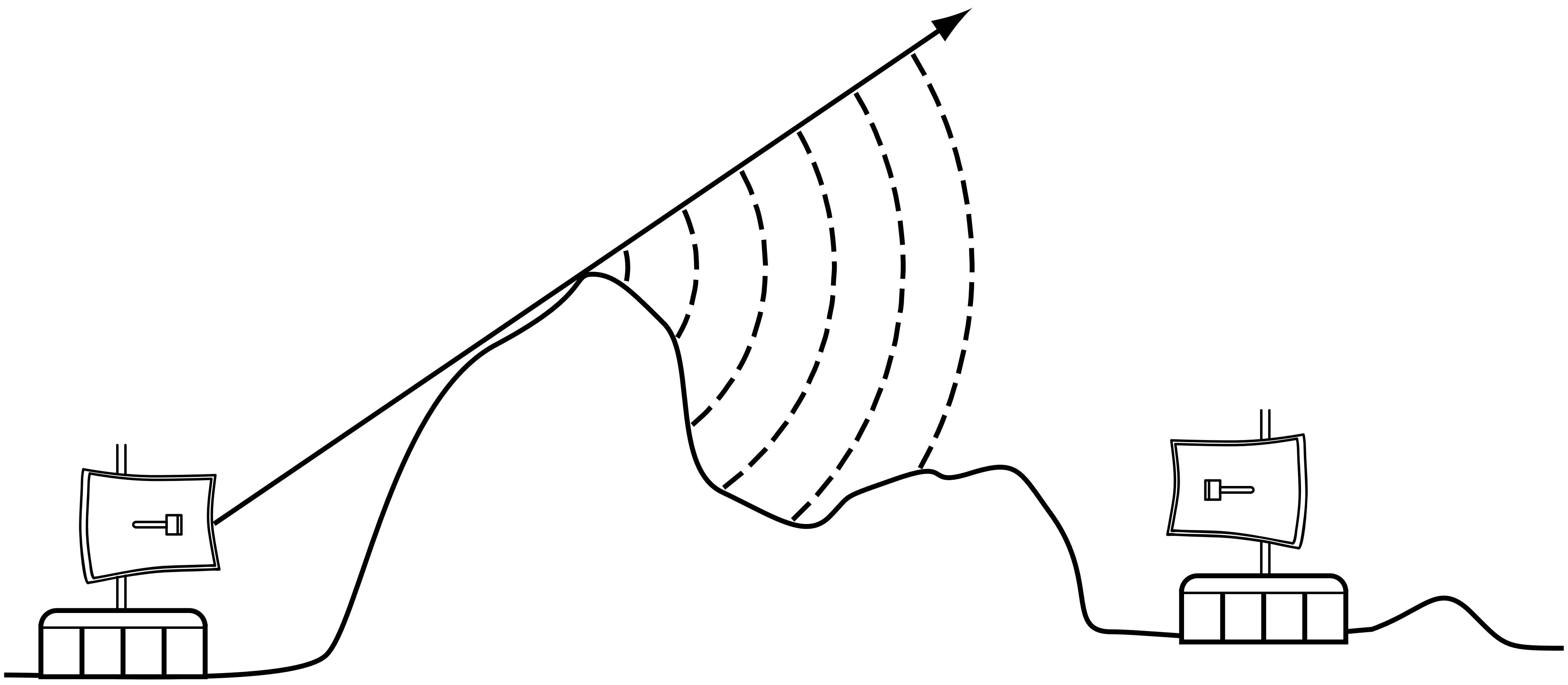
# Reflection

The rules for reflection are quite simple: the angle at which a wave hits a surface is the same angle at which it gets deflected. **Metal** and **water** are excellent reflectors of radio waves.




# Diffraction

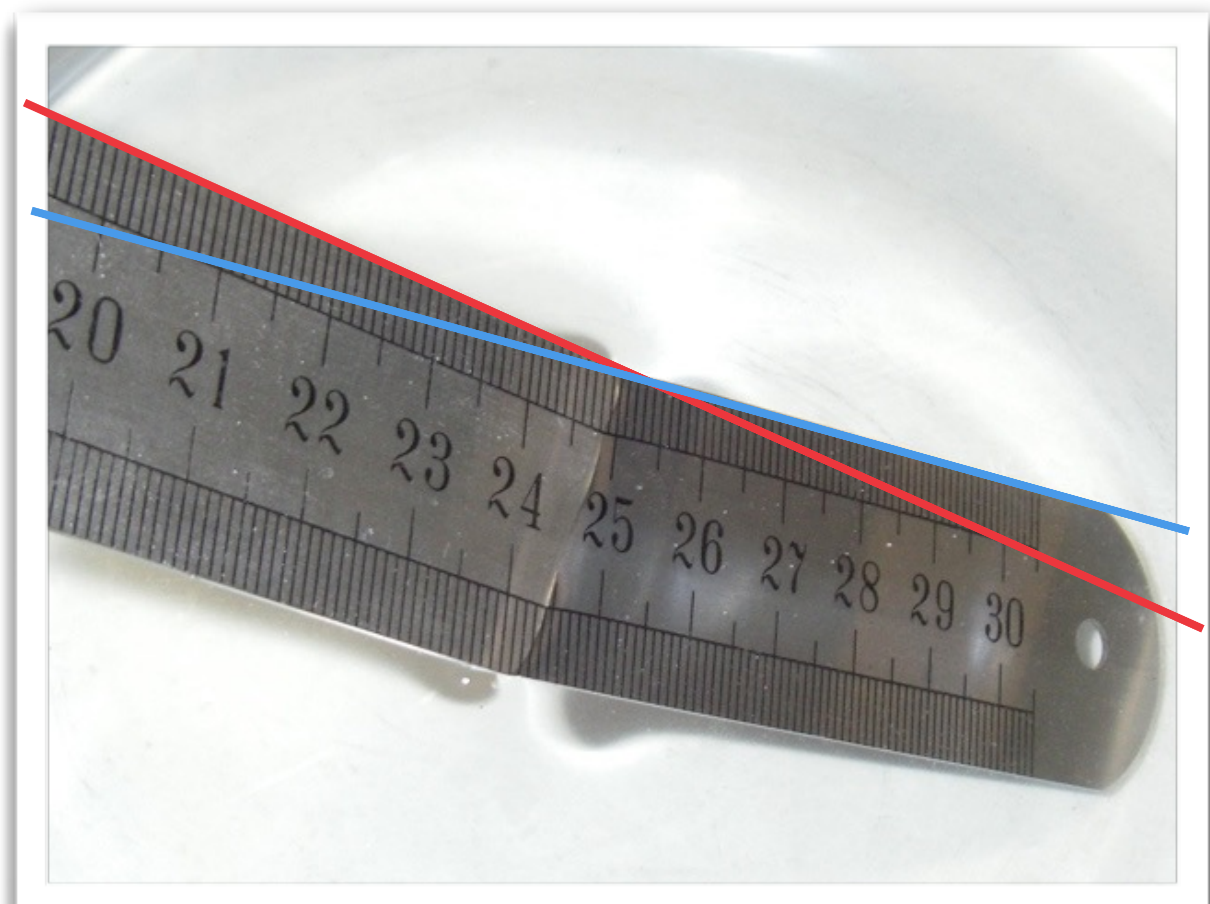
Because of the effect of diffraction, waves will "reach" around corners or through an opening in a barrier. This effect is much more stronger at lower frequencies.



# Refraction

Refraction is the apparent "bending" of waves when they meet a material with different characteristics.

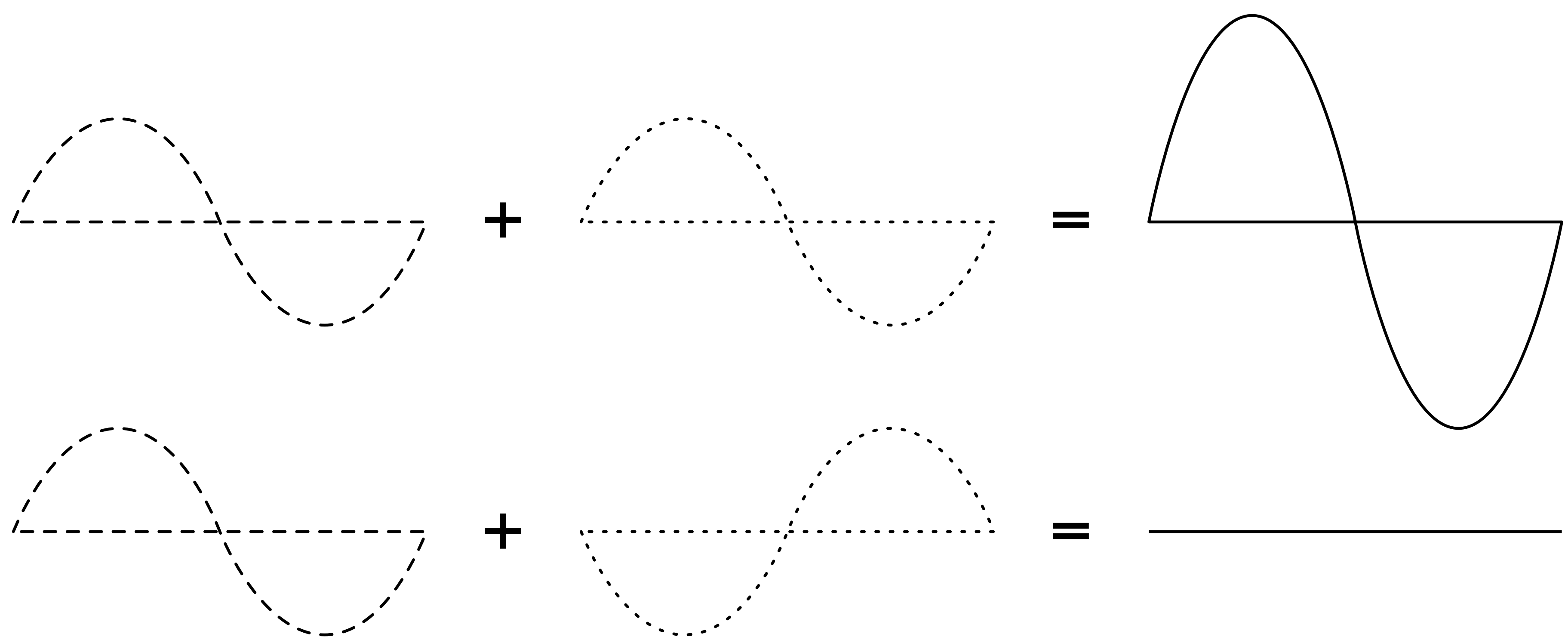
When a wave moves from one medium to another, it changes speed and direction upon entering the new medium.

# Interference

When two waves of the same frequency and **phase** meet, the result is ***constructive interference***: the amplitude increases.

When two waves of the same frequency and amplitude and **opposite phase** meet, the result is ***destructive interference***: the wave is annihilated.



# Free space loss

- Signal power is diminished by geometric spreading of the wavefront, commonly known as ***Free Space Loss***.
  - The power of the signal is spread over a wave front, the area of which increases as the distance from the transmitter increases. Therefore, the power density diminishes.

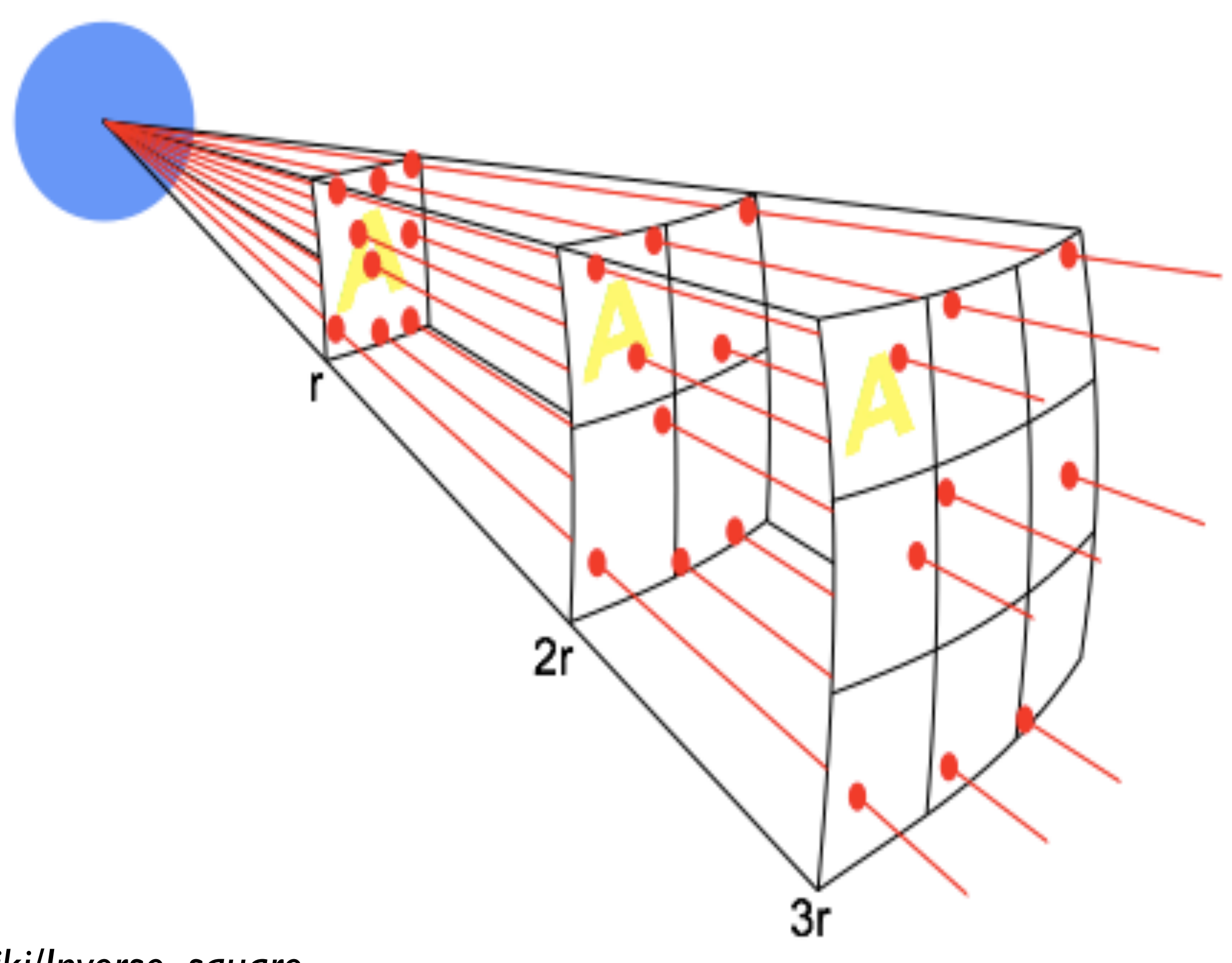



Figure from *http://en.wikipedia.org/wiki/Inverse_square*

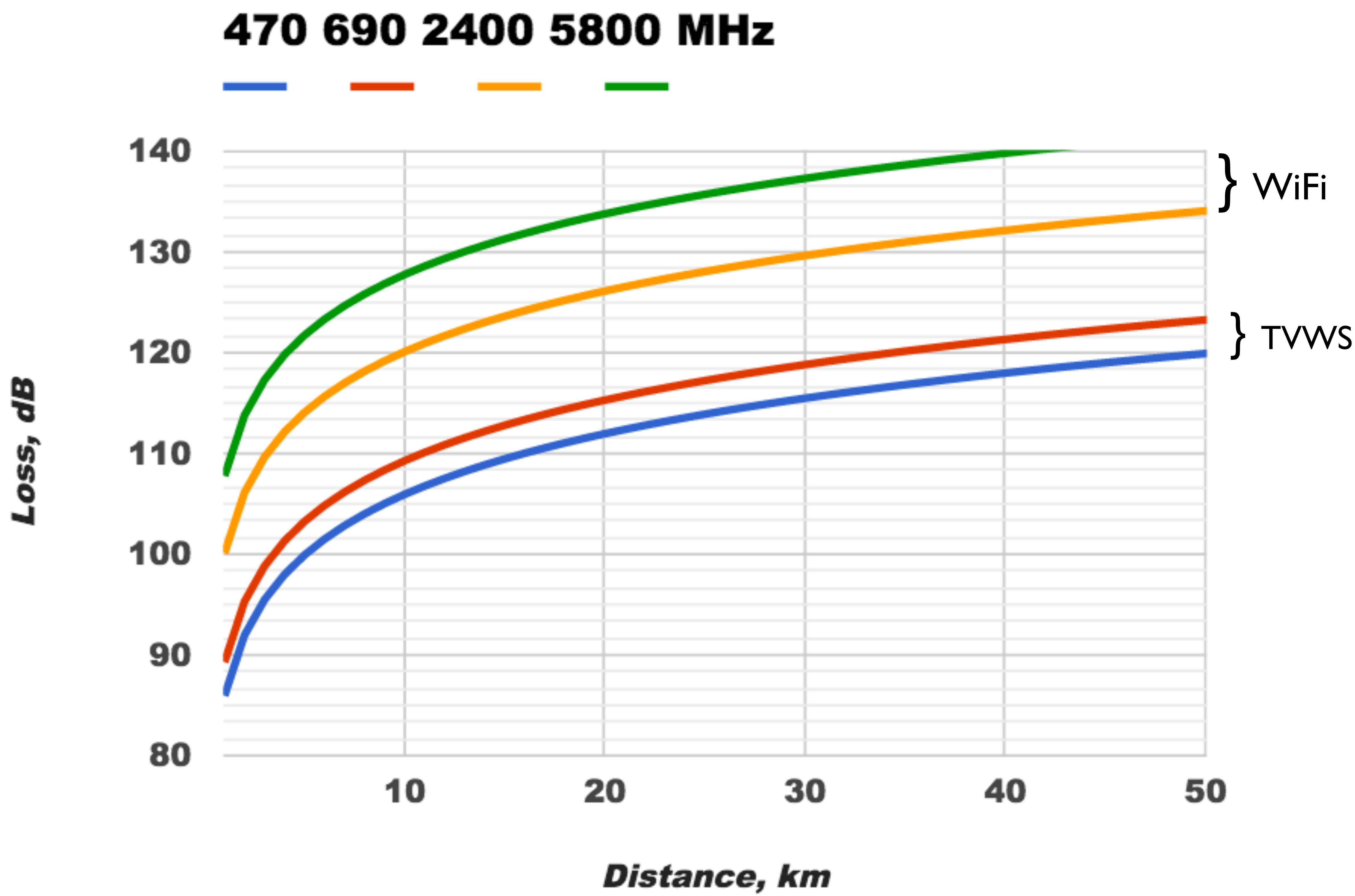
# Free Space Loss

- The Free Space Loss in decibels depends on the distance and the frequency according to:

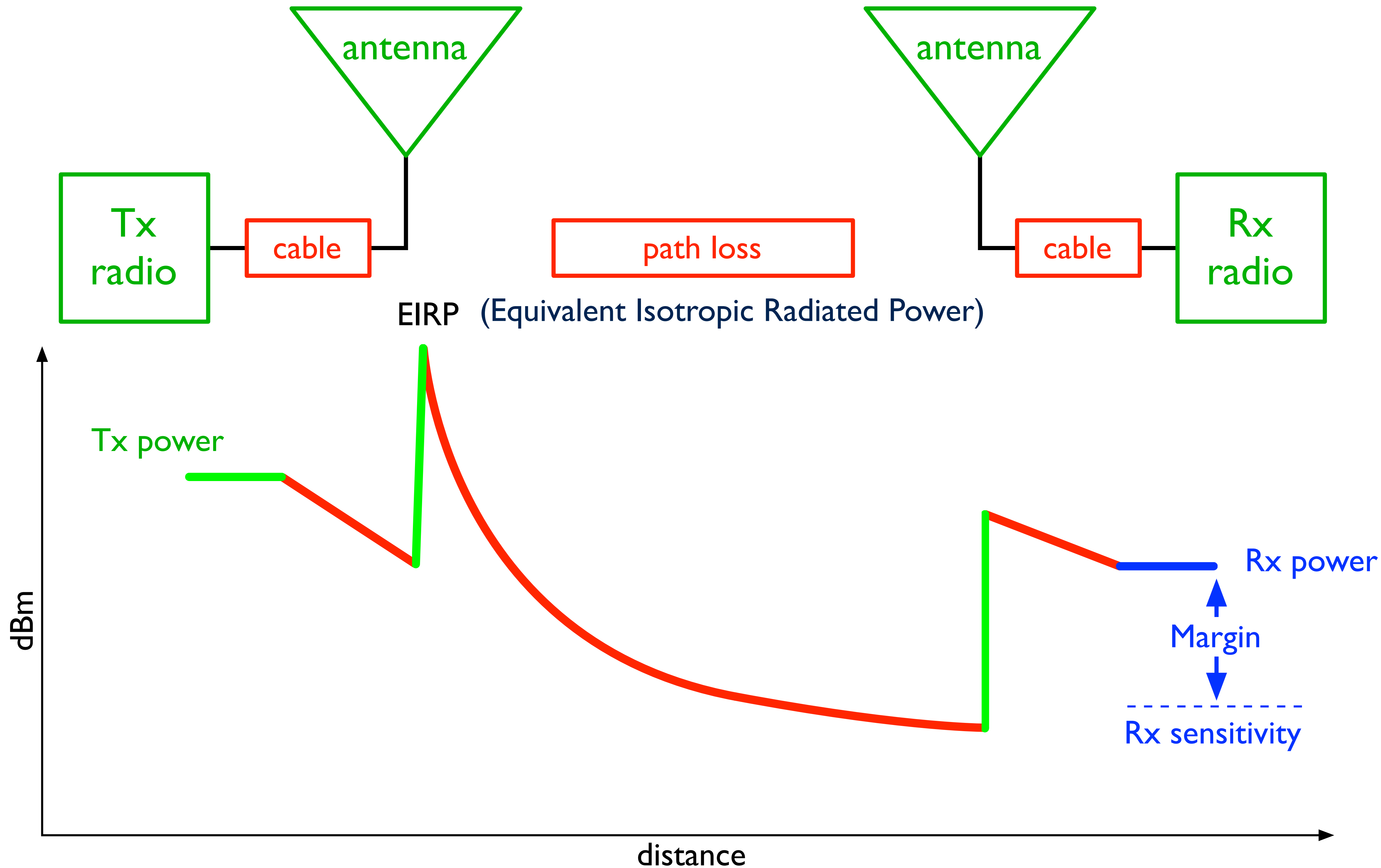
$$L_{fs} = 32.45 + 20*\log(d) + 20*\log(f)$$

- ...where $L_{fs}$ is expressed in dB, $d$ is in kilometers and $f$ is in MHz.

# Free Space Loss Versus distance for different bands



# Power in a wireless system



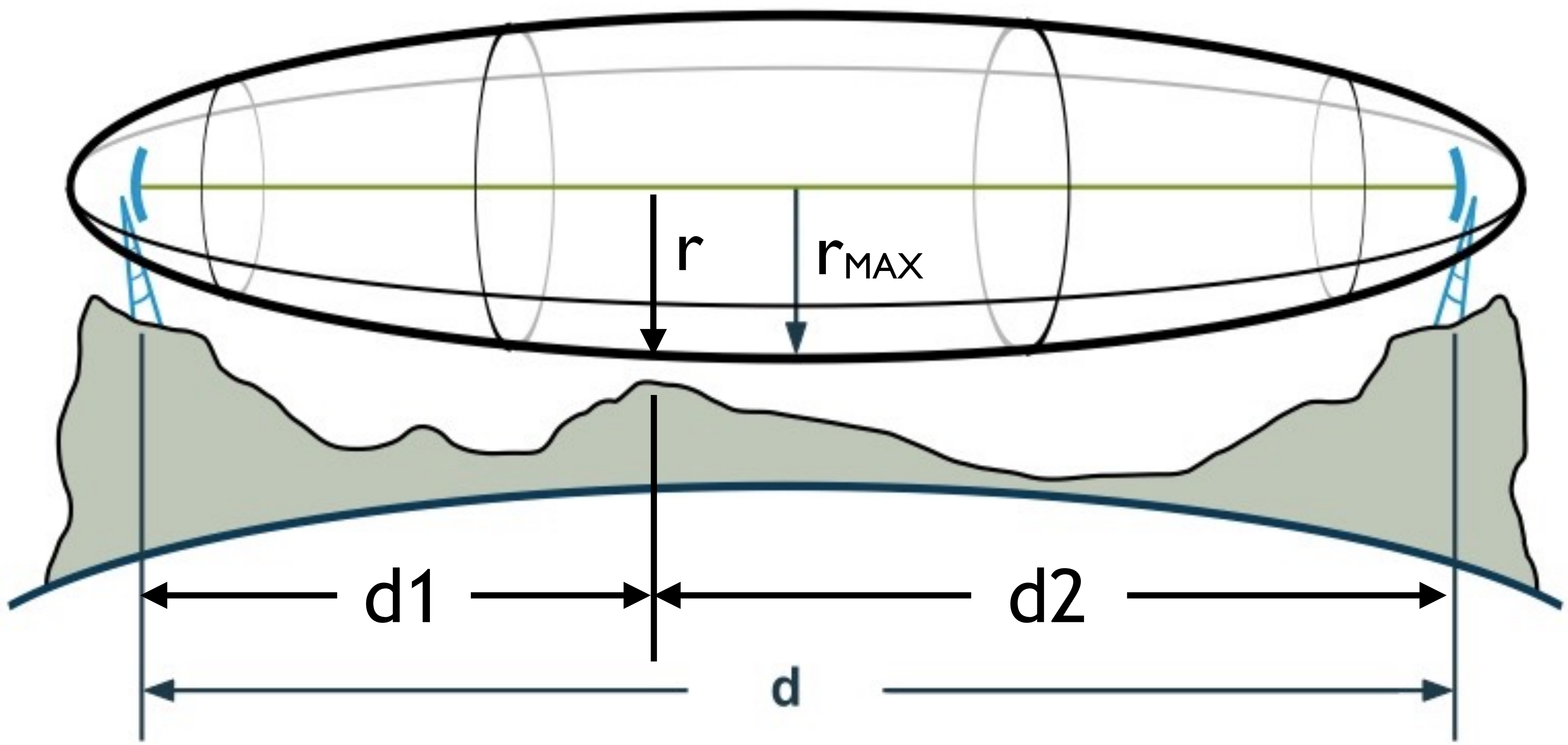
# Link budget

- The performance of any communication link depends on the quality of the equipment being used and the environment on the link.
- *Link budget* is a way of quantifying the link performance.
- The received power in an wireless link is determined by three factors: ***transmit power***, ***transmitting antenna gain***, and ***receiving antenna gain***.
- If that power, minus the path ***loss*** of the link path, is greater than the ***minimum received signal level*** of the receiving radio, then a link is possible.
- The difference between the minimum received signal level and the actual received power is called the *link margin*.
- The link margin must be positive, and should be maximized (should be at least 10 dB or more for reliable links).

# Fresnel Zone

- The First Fresnel Zone is an ellipsoid-shaped volume around the Line-of-Sight path between transmitter and receiver.
- The Fresnel Zone clearance is important to the quality of the RF link because it defines a volume around the LOS that must be clear of any obstacle for the the maximum power to reach the receiving antenna.
- Objects in the Fresnel Zone such as trees, hilltops and buildings can considerably attenuate the received signal, even when there is an unobstructed line between the TX and RX.

# Line of Sight and Fresnel Zones




$r = sqrt(\lambda*d1*d2/d)$

$r_{MAX} = 1/2* sqrt(\lambda*d)$

where all the dimensions are in meters

# Optical and Radio LOS

- Optical signals also occupy a Fresnel zone, but since the wavelength is so small (around $10^{-6}$ m), we don't notice it.
- Therefore, clearance of optical LOS does not guarantee the clearance of RADIO LOS.
- The lower the frequency, the bigger the Fresnel zone; but the diffraction effects are also more significant, so lower radio frequencies can reach the receiver even if there is **No Line of Sight.**

# Clearance of the Fresnel Zone and earth curvature

This table shows the minimum height above flat ground required to clear 60% of the first Fresnel zone for various link distances at 2.4 GHz.

Notice that earth curvature plays a small role at short distances, but becomes more important as the distance increases.

| Distance (km) | 1st zone (m) | 60% (m) | Earth curvature (m) | Required height (m) |
|---|---|---|---|---|
| 1 | 5.5 | 3,3 | 0.0 | 3.9 |
| 5 | 12.4 | 7,44 | 0,4 | 7,84 |
| 10 | 17.5 | 10,5 | 1,5 | 12 |
| 15 | 21.4 | 12,84 | 3,3 | 16,13 |
| 20 | 24.7 | 15,82 | 5,9 | 21,72 |
| 25 | 27.7 | 16,62 | 9,2 | 25,82 |
| 30 | 30.3 | 18,18 | 13,3 | 32,5 |

# Conclusions

The communication system must overcome the noise and interference to deliver a suitable replica of the signal to the receiver.
The capacity of the communication channel is proportional to the bandwidth and to the logarithm of the S/N ratio.
Modulation is used to adapt the signal to the channel and to allow several signals to share the same channel.
Higher order modulation schemes permit higher transmission rates, but require higher S/N ratio.
The channel can be shared by several users by employing different frequencies, different time slots or different codes.