Facoltà di Scienze Matematiche, Fisiche e Naturali

Dipartimento di Scienze dell'Informazione

Corso di Laurea Specialistica in Scienze di Internet (SdI) e Informatica (Inf)

Sistemi e Reti Wireless

Luciano Bononi

(bononi@cs.unibo.it)

http://www.cs.unibo.it/~bononi/

Ricevimento: sempre aperto .
Si consiglia di concordare via e-mail almeno un giorno prima
(informazioni in tempo reale sulla home page personale)

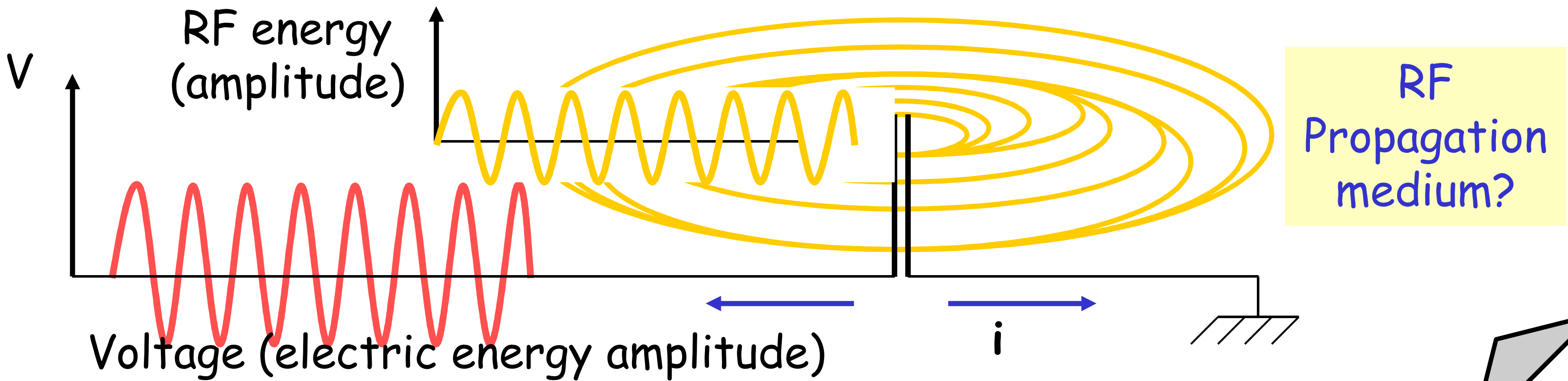
Figure-credits: some figures have been taken from slides published on the Web, by the following authors (in alfabethical order):

J.J. Garcia Luna Aceves (ucsc), James F. Kurose & Keith W. Ross, Jochen Schiller (fub), Nitin Vaidya (uiuc)

Background on wireless PHY layer

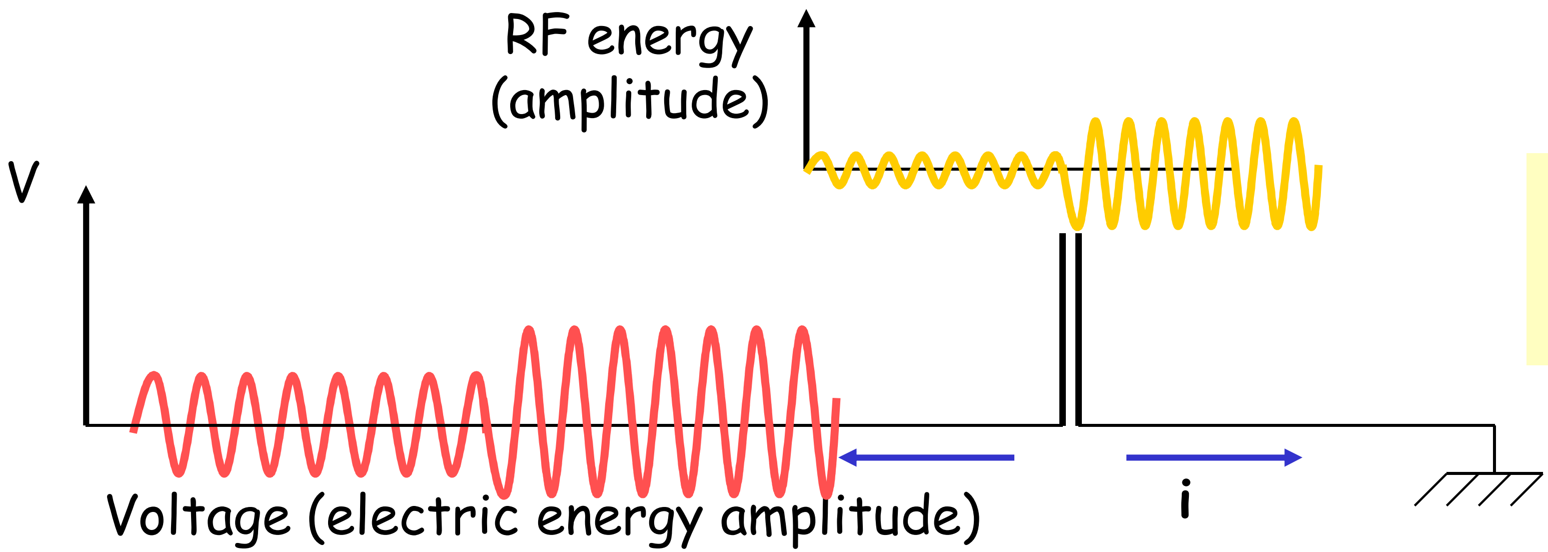
RF Properties

- **Understanding Radio Frequency**
  - Generation, coverage and propagation issues
  - Fundamental for wireless planning and management
- **Radio Frequency Signals**
  - Electromagnetic energy generated by high frequency alternate current (AC) in antennas
  - Antenna: converts the wired current to RF and viceversa



RF Properties

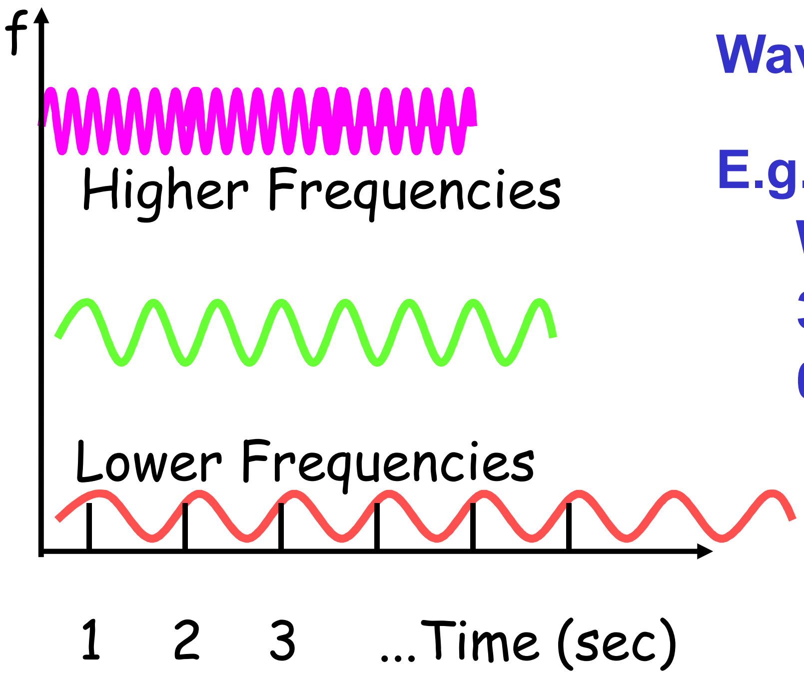
- **Amplitude**
  - Higher amplitude RF signals go farther
  - Transmission Power (Watts) = Energy / Time = Joule / Sec
    - More energy (voltage) moves more electrons (current)
    - Power = Voltage * Current



RF Propagation medium?

RF Properties

- **Frequency (and Wavelength)**
  - Wireless Spectrum (see next slides)
  - Portion of wireless spectrum regulated by regional authorities and assigned to wireless technologies



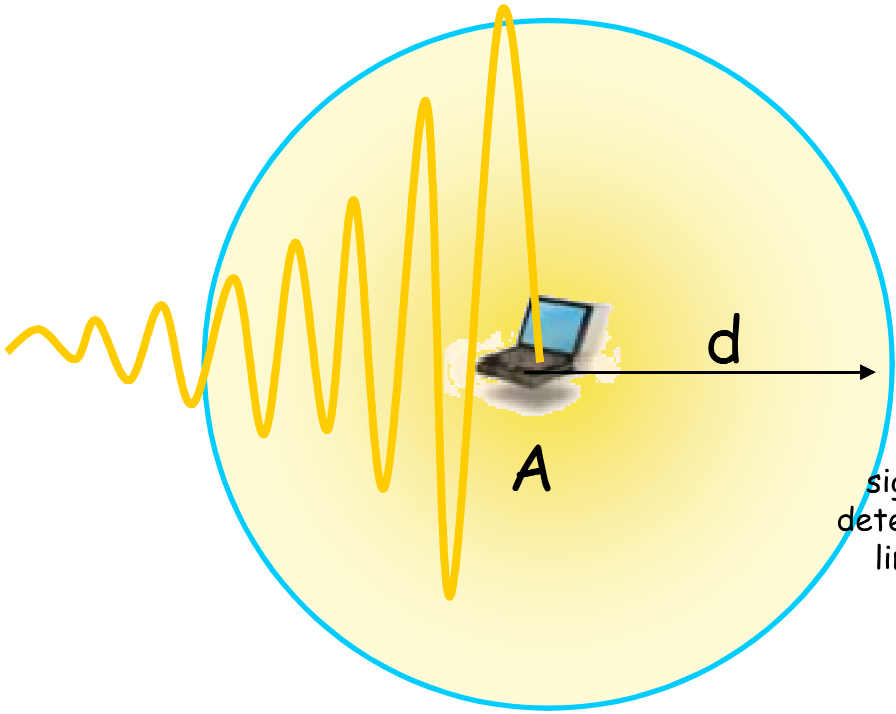
Wavelength = c / frequency

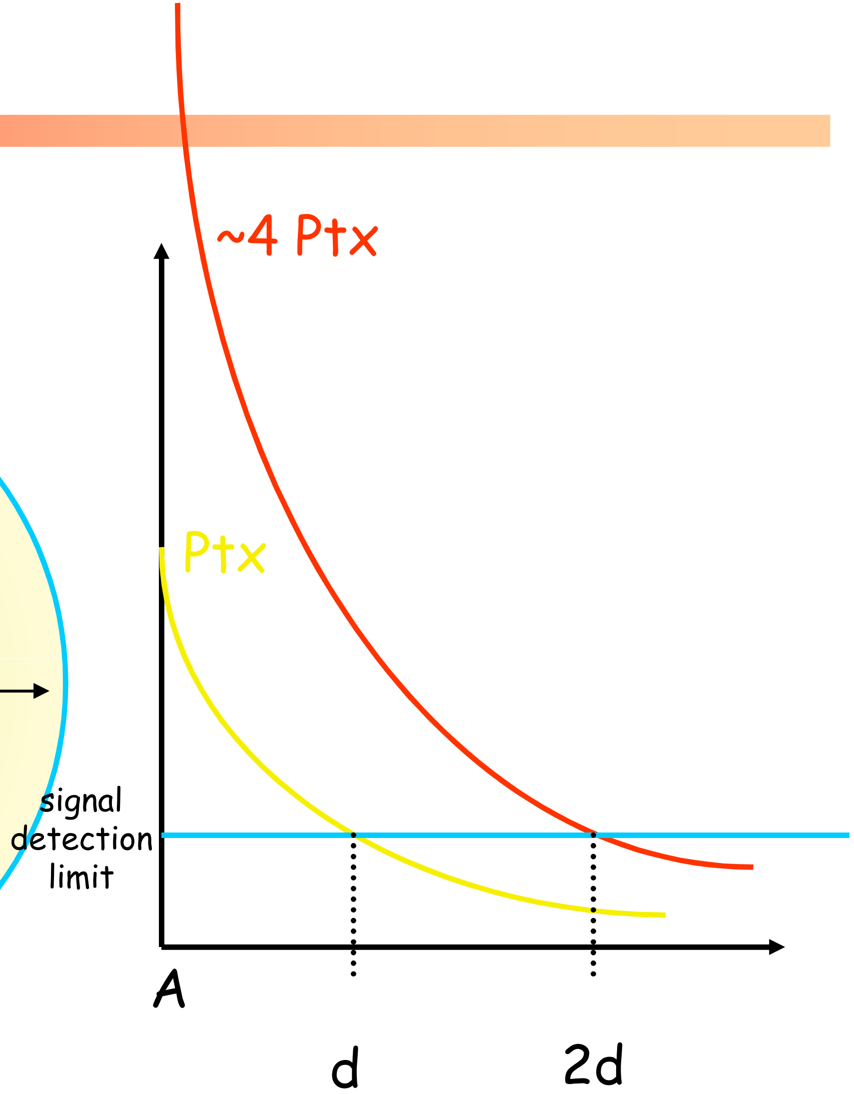
E.g. 2.4 GhZ (ISM band)
Wave Length =
300.000.000(m/s) / 2.400.000.000 Hz =
0.125 m = 12.5 cm

> In practice:
> Antennas work better with size = 1, ½, ¼ of wavelegth (try to measure antenna size of your IEEE 802.11 device)

RF propagation

- **Radio transmission coverage**



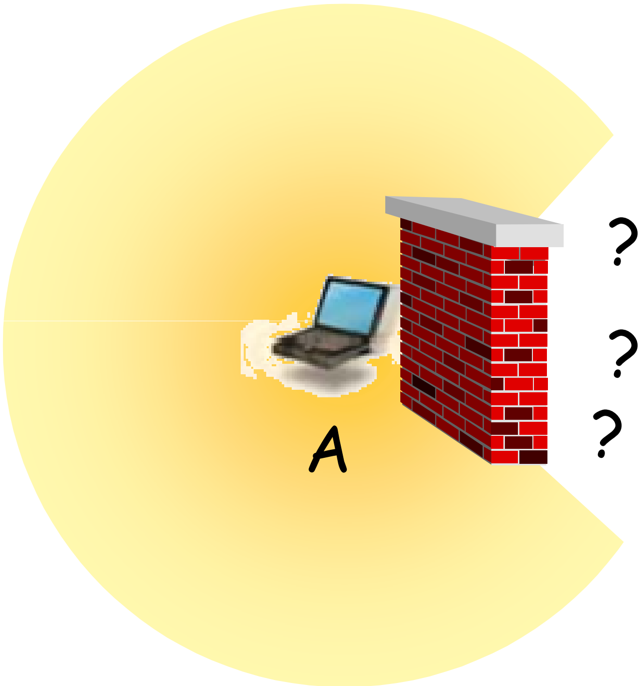


The range is a function of power transmission (Ptx)
Signal strength reduces with d^k ⟹
(K>=2..3, no obstacles, isotropic radiator)

In 3D, sphere:
$V=(4 \pi r^3/3)$
$S=(4 \pi r^2)$

Wireless networks' technology

- Radio transmission coverage



Rules of thumb:

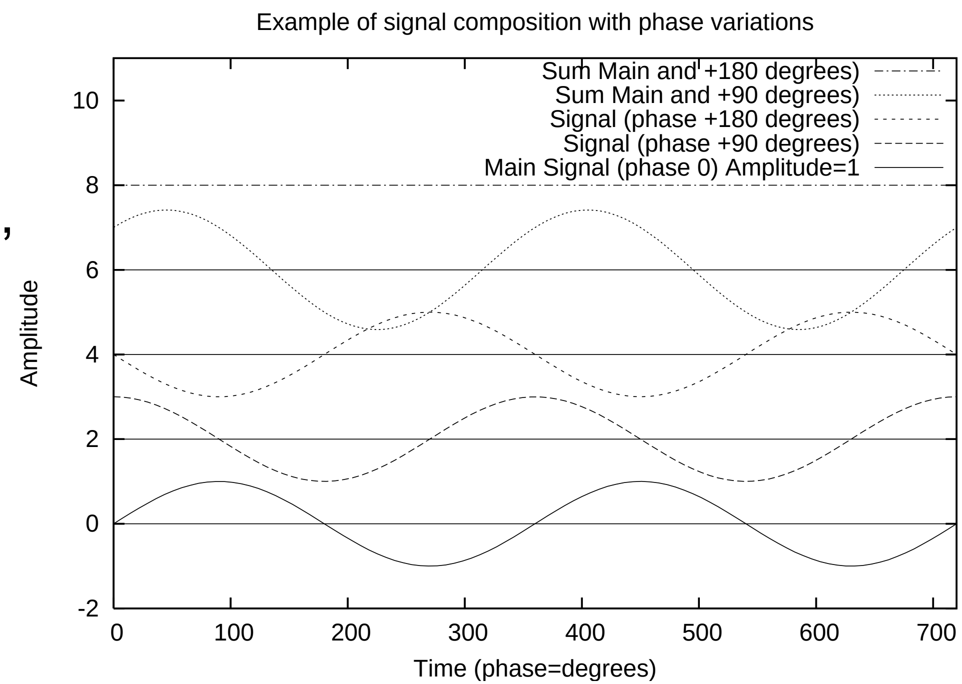
• high frequencies are good for short distances and are affected by abstacles

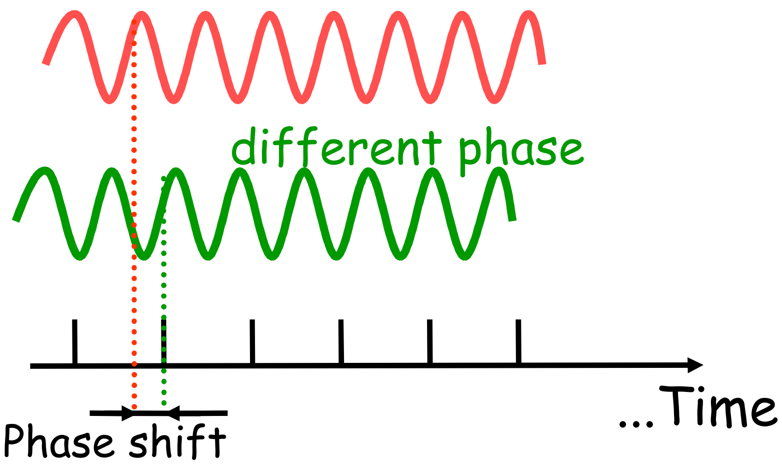
• low frequencies are good for long distances and are less affected by abstacles

obstacles can reflect or absorbe waves depending on materials and wave frequencies

RF Properties

- **Phase: shift of the wave (in degrees or radians)**
  - Positive phase (left-shift), early wavefront
  - Negative phase (right-shift), late wavefront

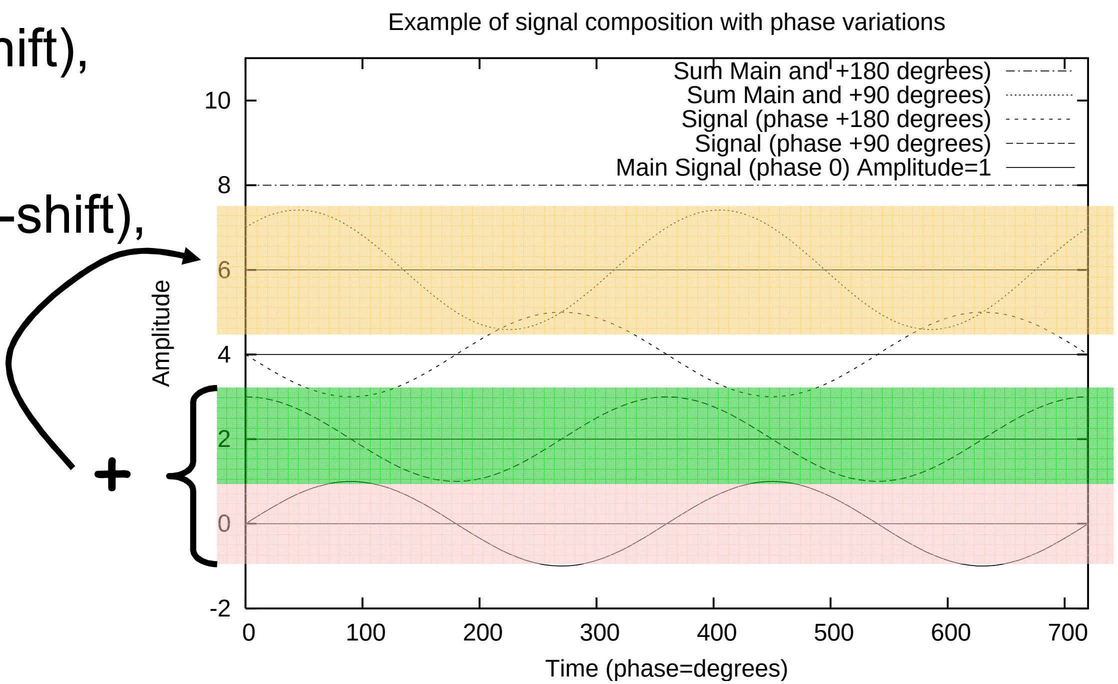


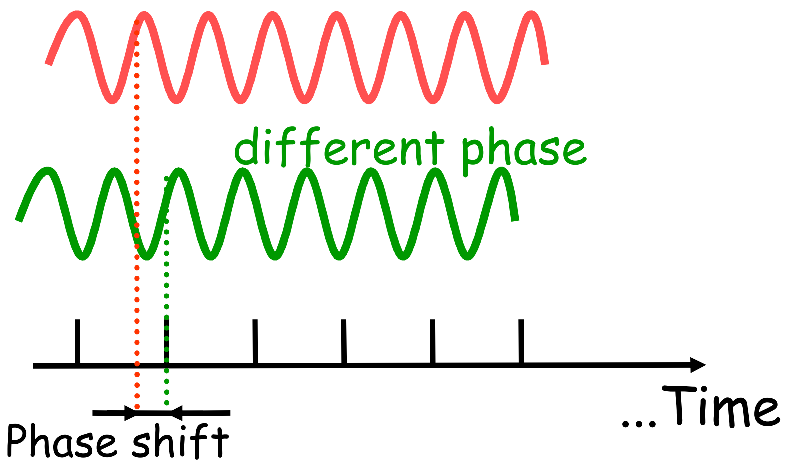


In practice:
RF echoes arriving at receivers with different phase may have positive or negative effects... Why?

RF Properties

- **Phase: shift of the wave (in degrees or radians)**
  - Positive phase (left-shift), early wavefront
  - Negative phase (right-shift), late wavefront

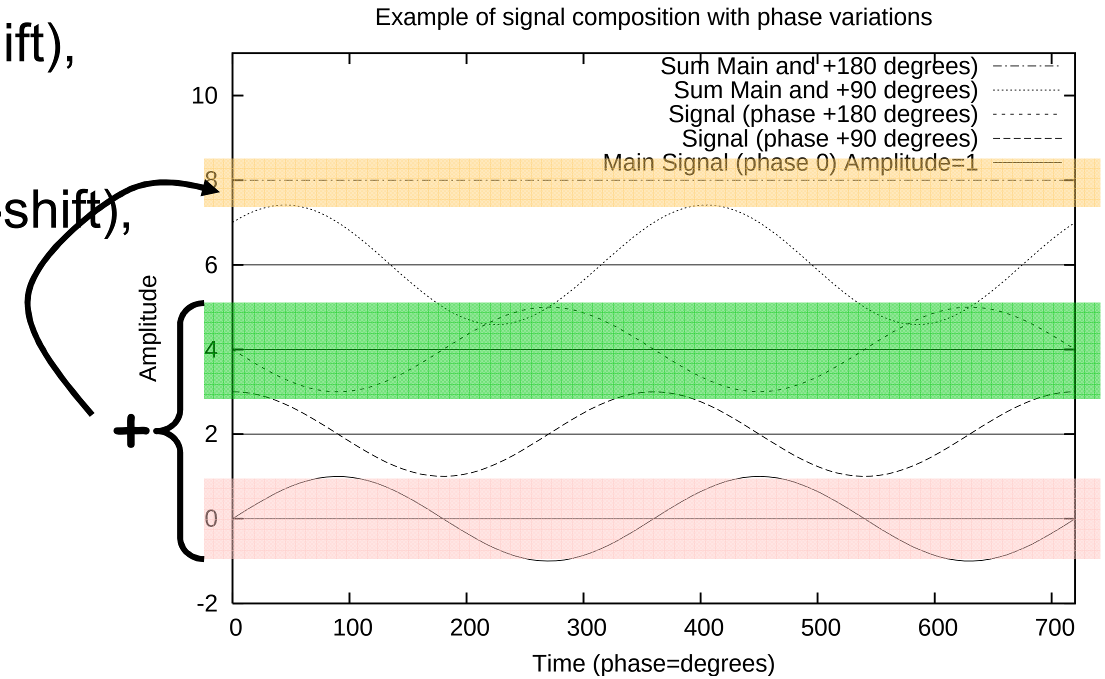


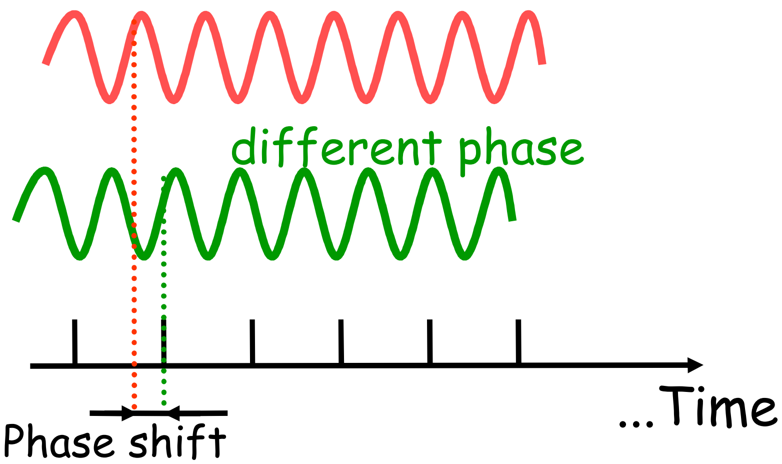


In practice:
RF echoes arriving at receivers with different phase may have positive or negative effects... Why?

RF Properties

- **Phase: shift of the wave (in degrees or radians)**
  - Positive phase (left-shift), early wavefront
  - Negative phase (right-shift), late wavefront

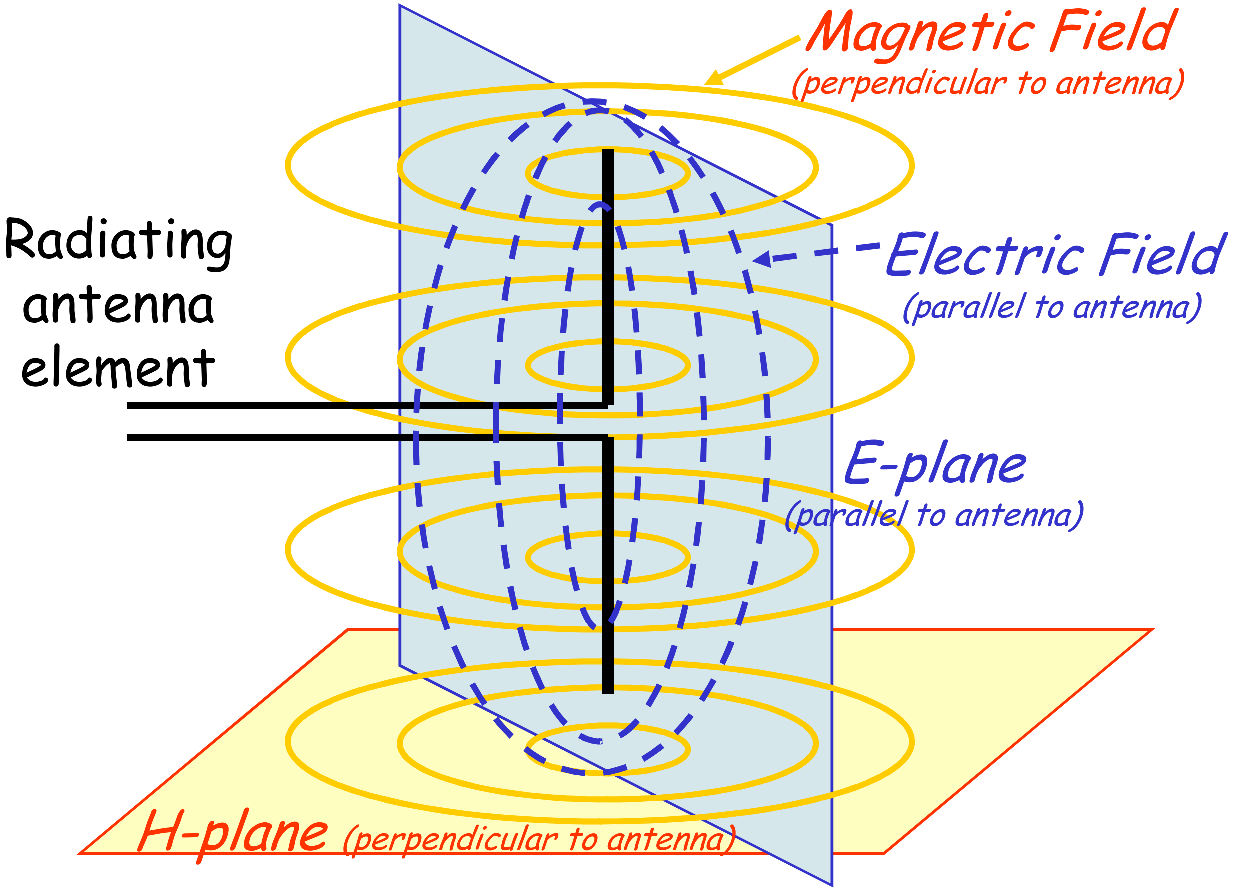


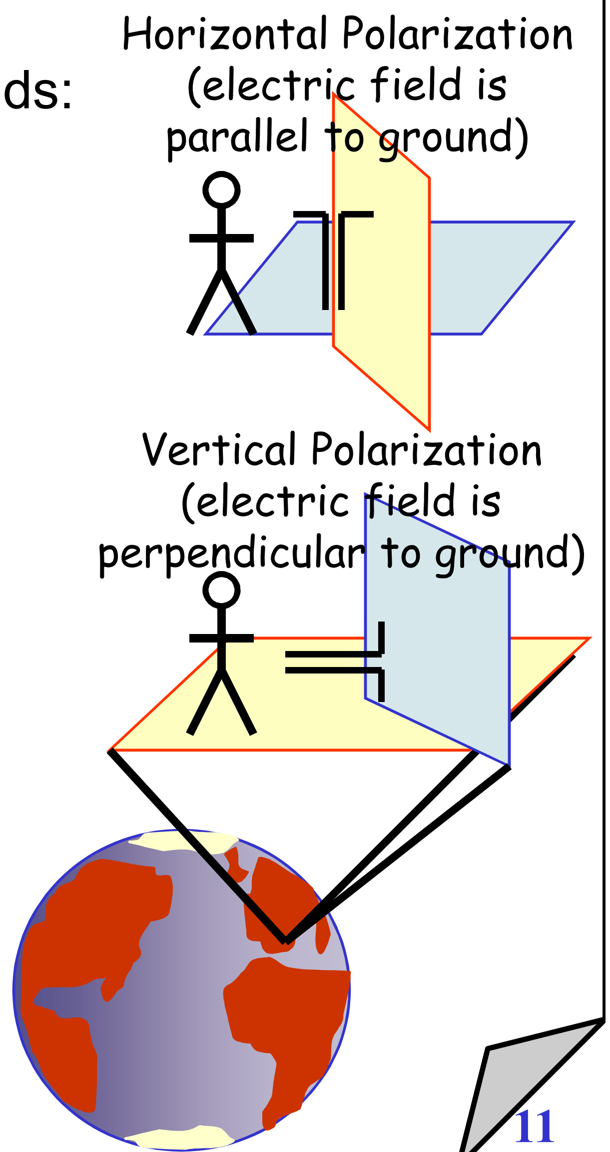


In practice:
RF echoes arriving at receivers with different phase may have positive or negative effects... Why?

RF Properties

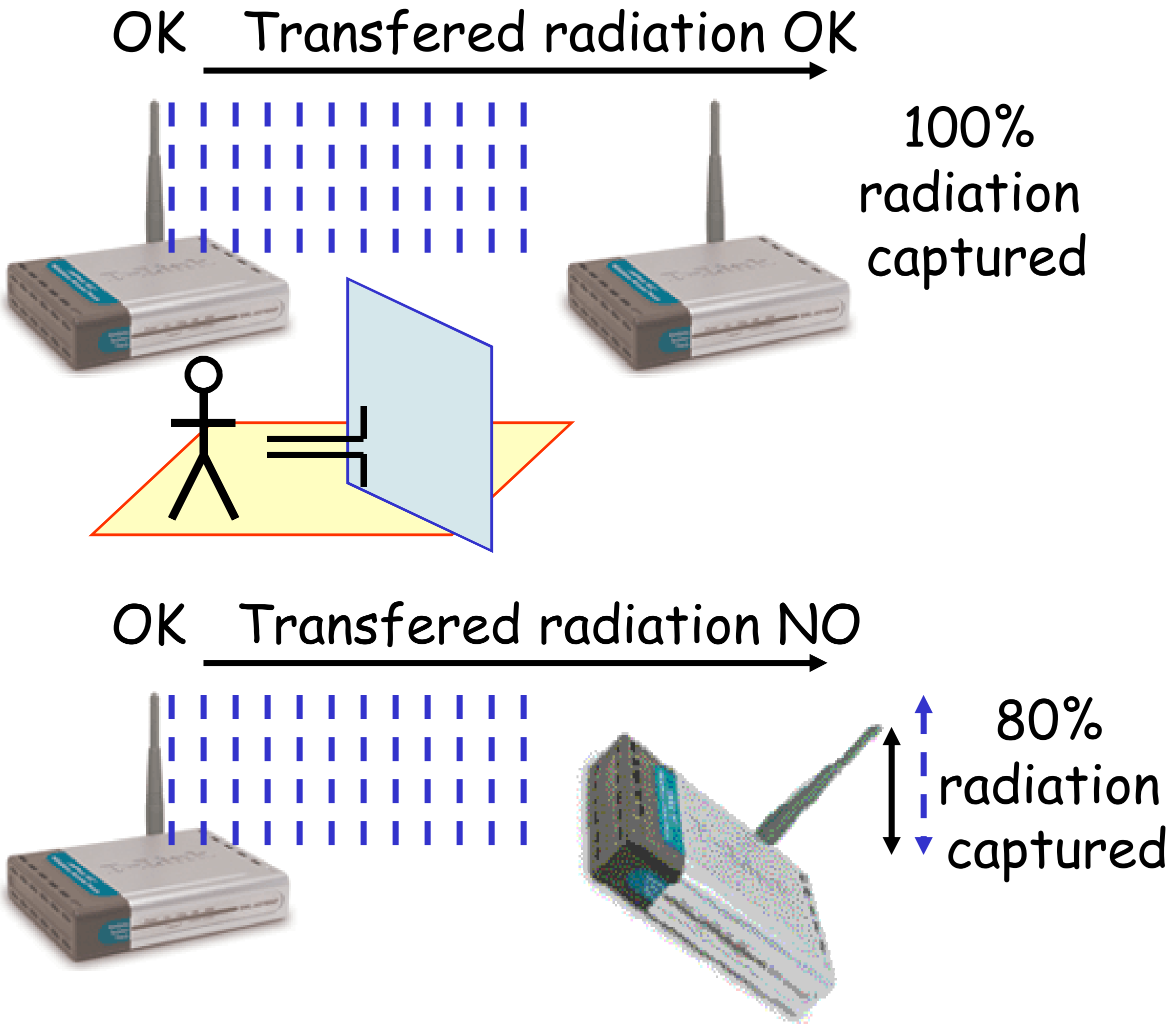
- **Polarization: (physical orientation of antenna)**
  - RF waves are made by two perpendicular fields:
    - Electric field and Magnetic field

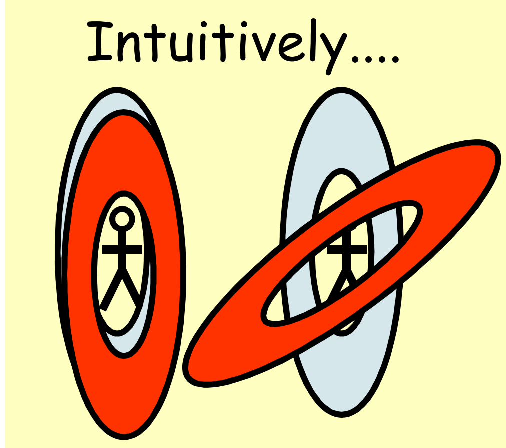


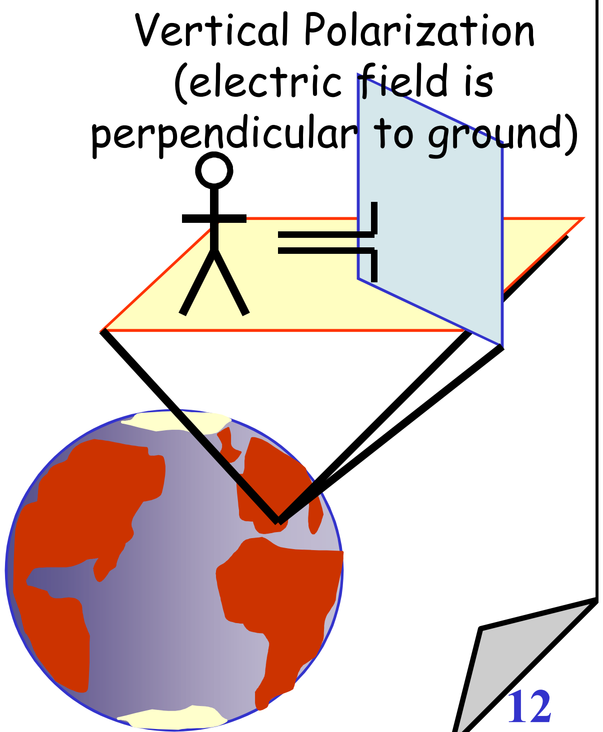


RF Properties

Vertical Polarization: typically used in WLANs



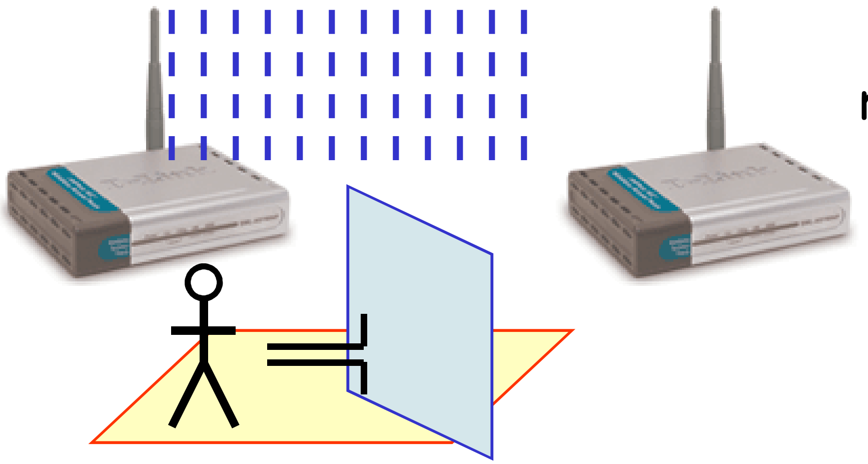




RF Properties

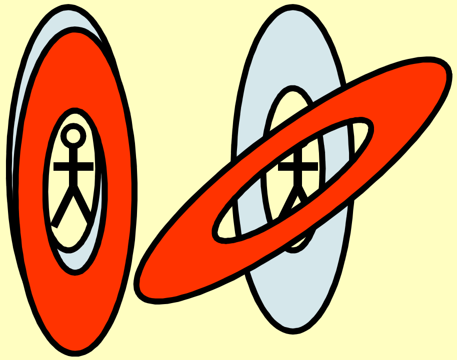
Vertical Polarization: the PCMCIA device problem

OK   Transfered radiation OK



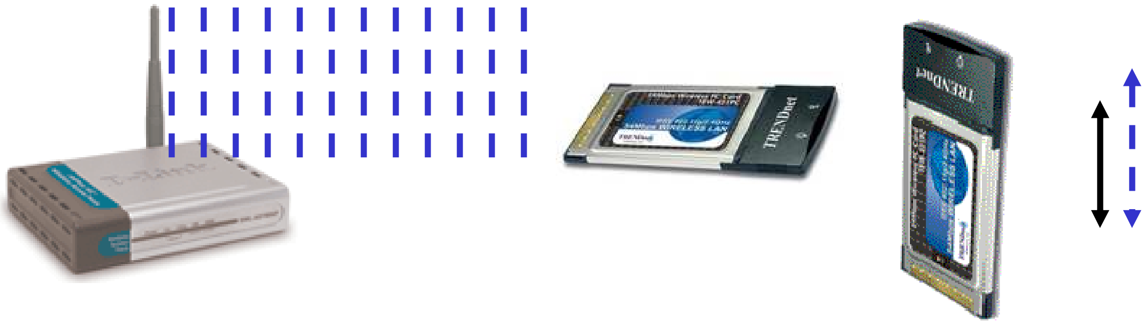
100%
radiation
captured

Intuitively....



N.B. the polarization problem is very much important when using distant devices and directional antennas. With short distances signal reflections help!

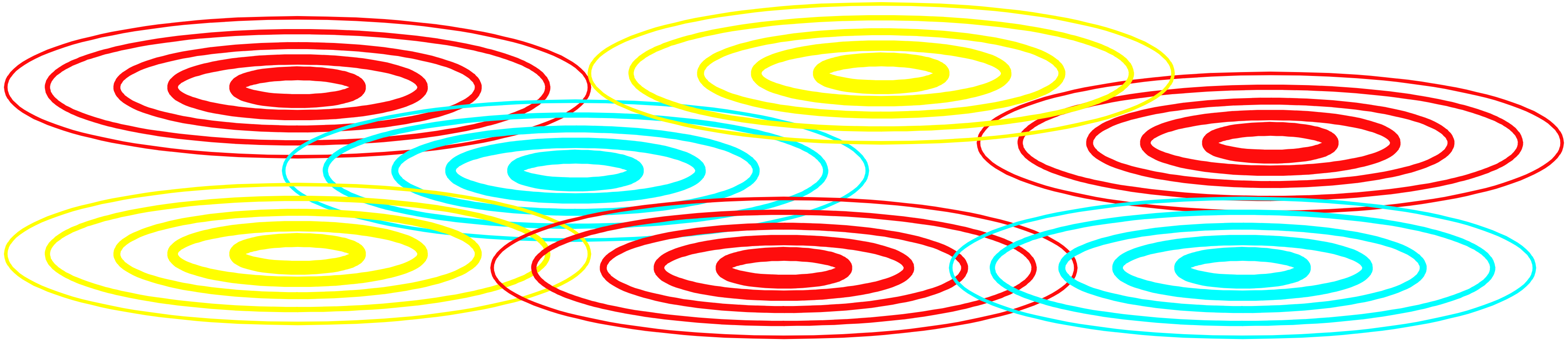
OK   Transfered radiation NO

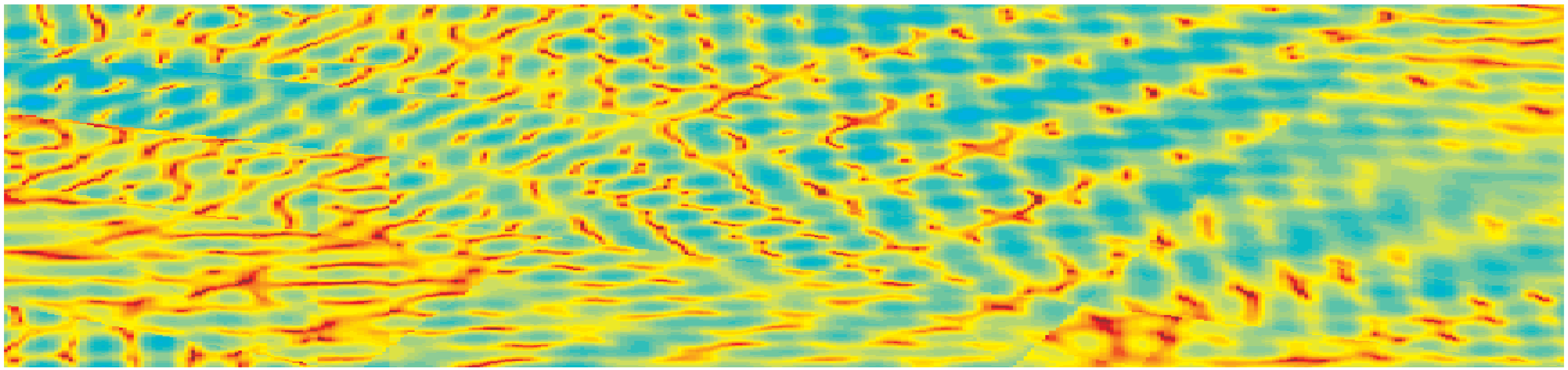


??%
radiation
captured

RF Behaviors

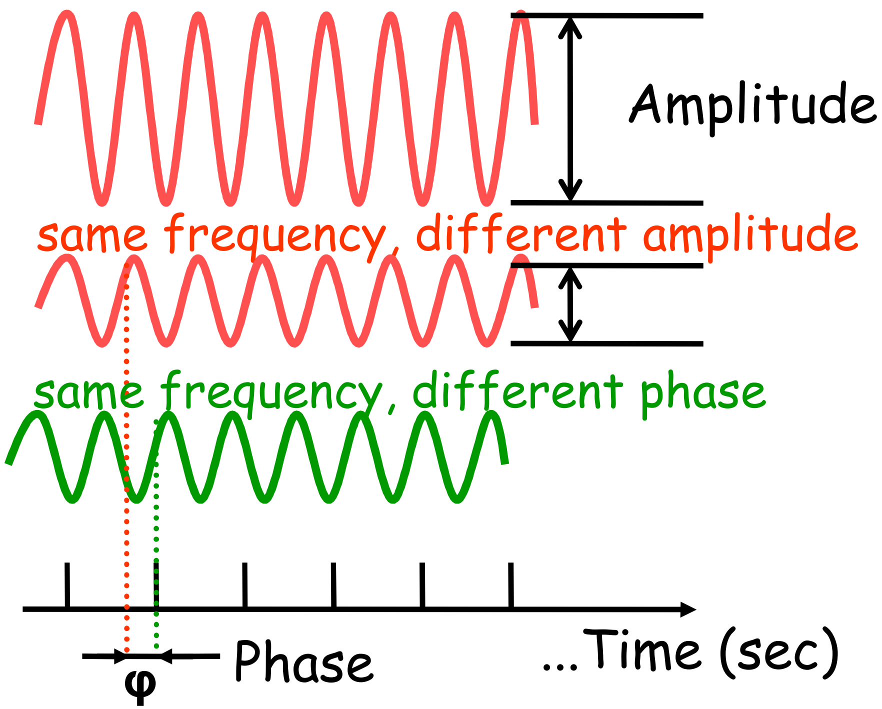
- **Radio transmission interference**

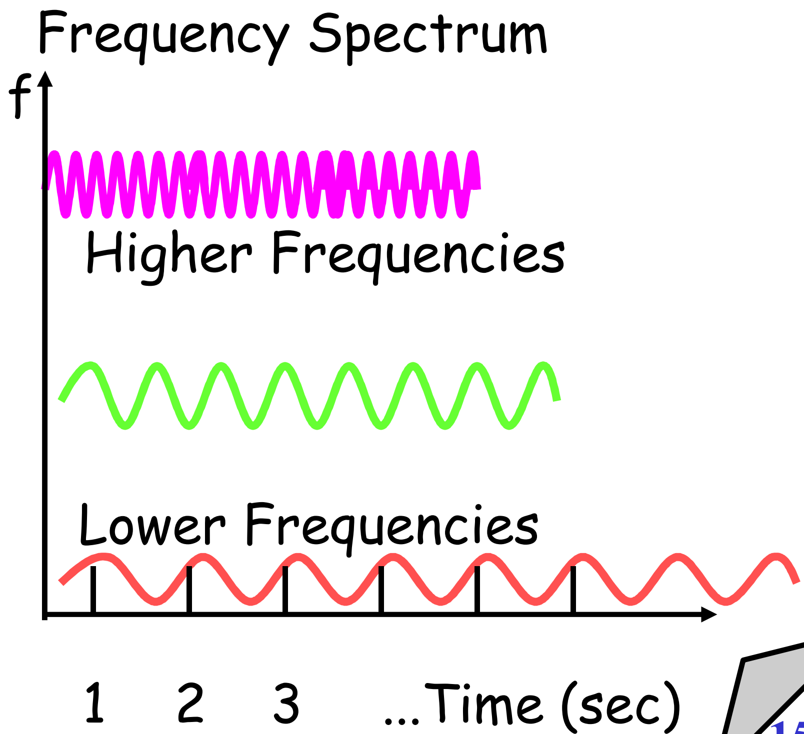




Wireless transmission: Electromagnetic waves

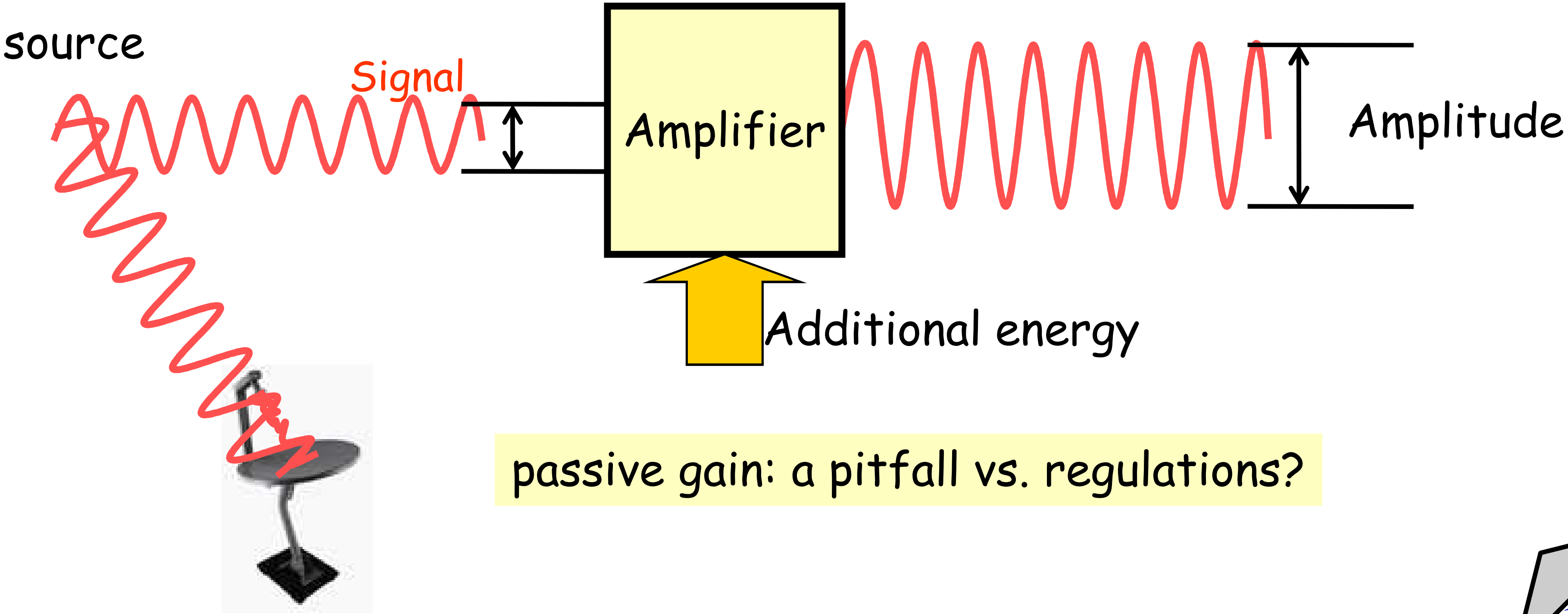
- **Different parameters of electromagnetic waves:**
  - amplitude **M** proportional to transmission energy (loudness)
  - frequency **f** (tone) measured in Hertz (Cycle/sec)
  - phase **φ** (peak shift with respect to reference signal) (rad)





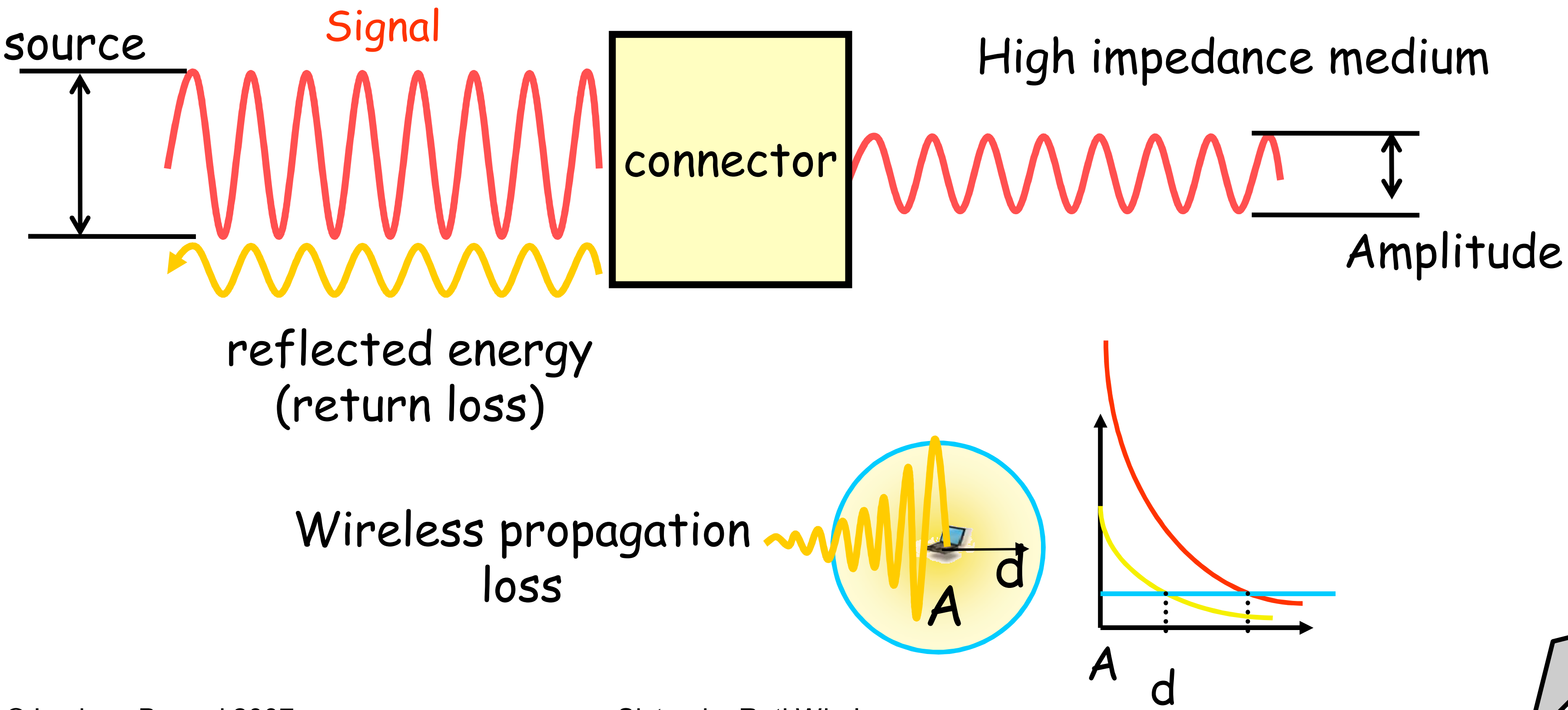
Wireless transmission

- **Signal Gain: (measured in Decibels, Db)**
  - Increase in amplitude **M** proportional to transmission energy
    - Active gain (amplifiers)
    - Passive gain (antennas focusing signal energy, and additive signal effects)



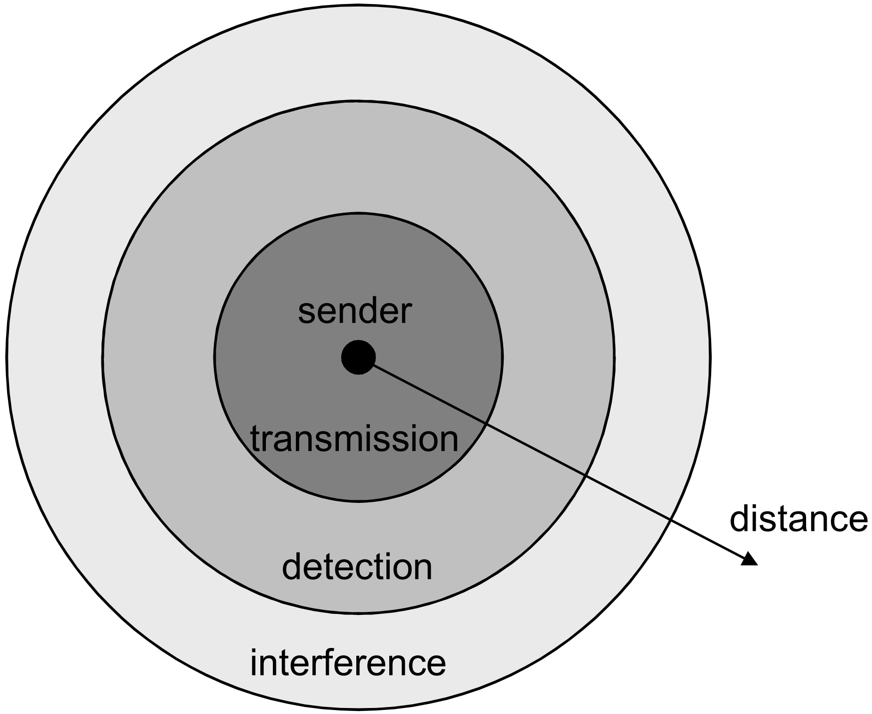
Wireless transmission

- **Signal Loss: (Db)**
  - Decrease in amplitude **M** proportional to energy waste
    - Intentional (resistance, signal attenuation -> heat)
    - Obstacles, e.g. (walls, water for 2.4 Ghz) and distance (wireless)



Wireless signal propagation ranges

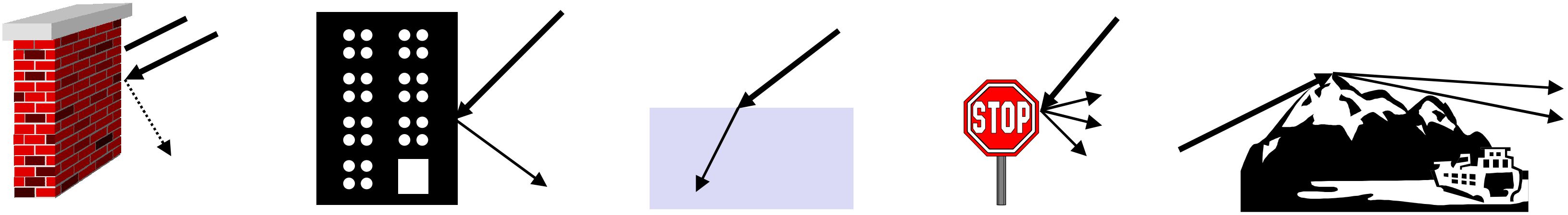
- **Transmission range**
  - communication possible
  - low error rate
- **Detection range**
  - detection of the signal possible
  - no communication possible
- **Interference range**
  - signal may not be detected
  - signal adds to the background noise



Ranges depend on receiver's sensitivity!

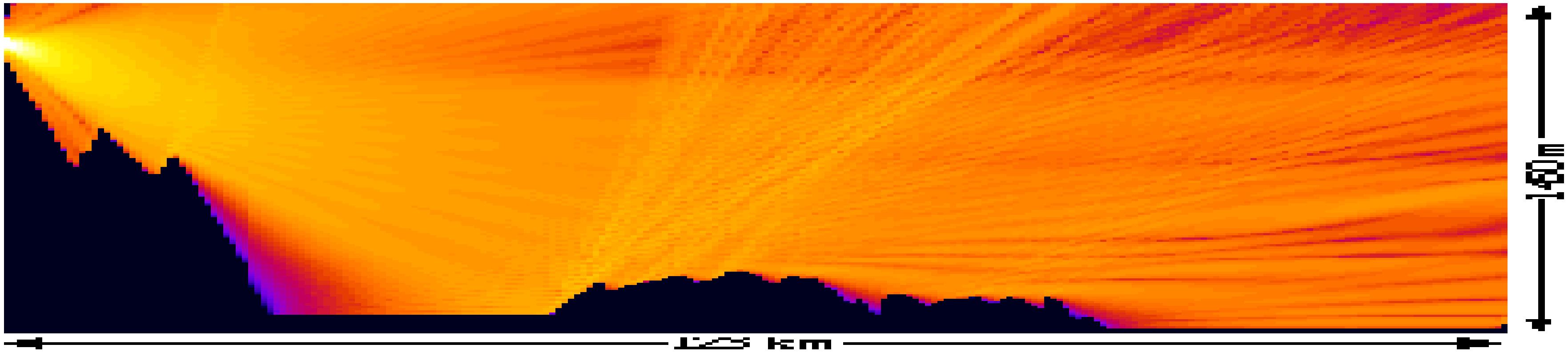
Wireless Signal propagation effects

- **Propagation in free space always like light (straight line)**
- **Receiving power proportional to $1/d^2$**
  (d = distance between sender and receiver)
- **Receiving power additionally influenced by**
  - fading (frequency dependent)
  - shadowing
  - reflection at large obstacles
  - refraction depending on the density of a medium
  - scattering at small obstacles
  - diffraction at edges



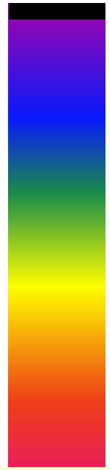
shadowing reflection refraction scattering diffraction

Real world example

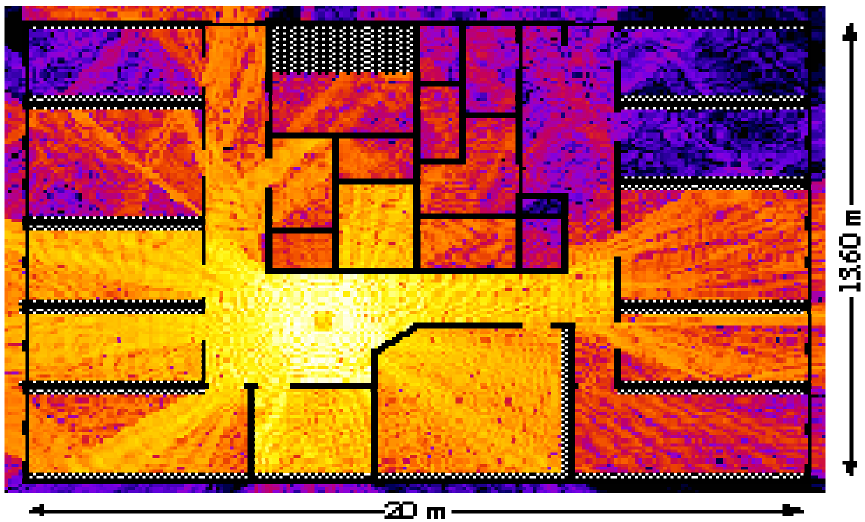


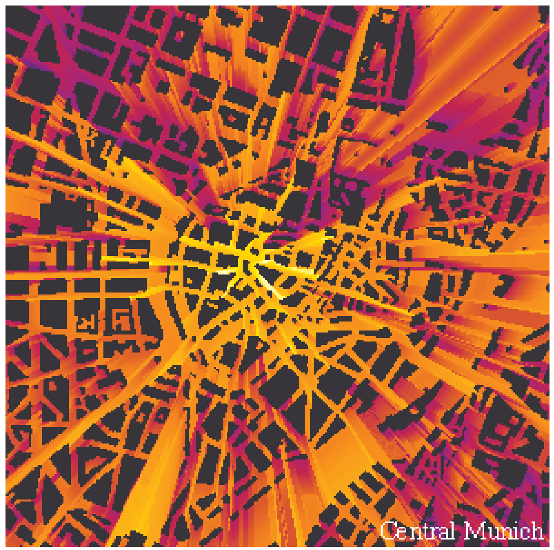
Raytracing examples

Low signal



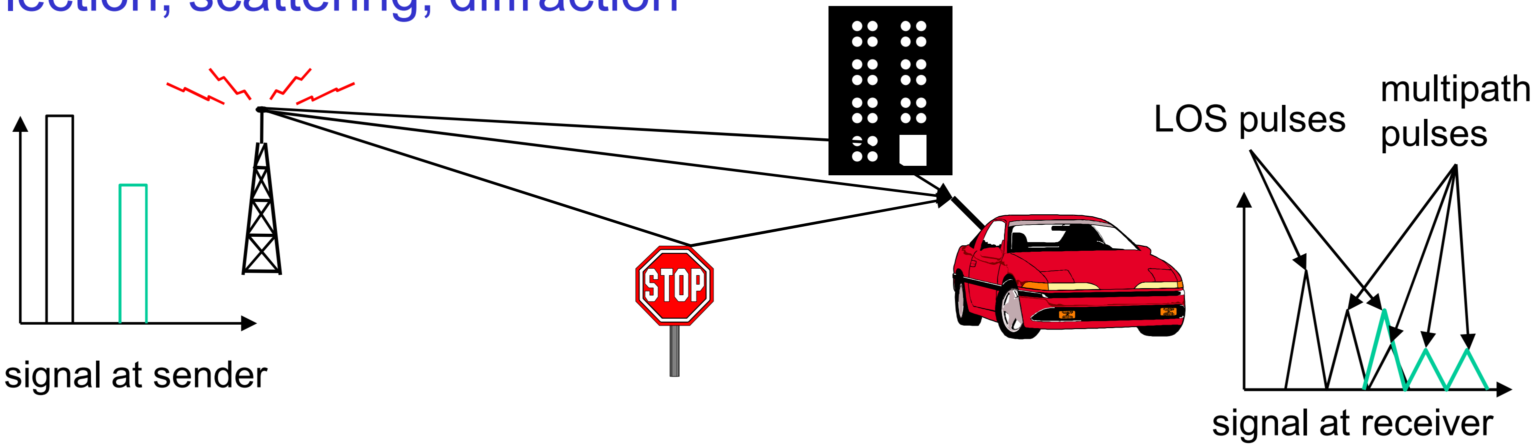
high signal





Multipath propagation

- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction



- Time dispersion: signal is dispersed over time
  ➔ interference with “neighbor” symbols, Inter Symbol Interference (ISI)

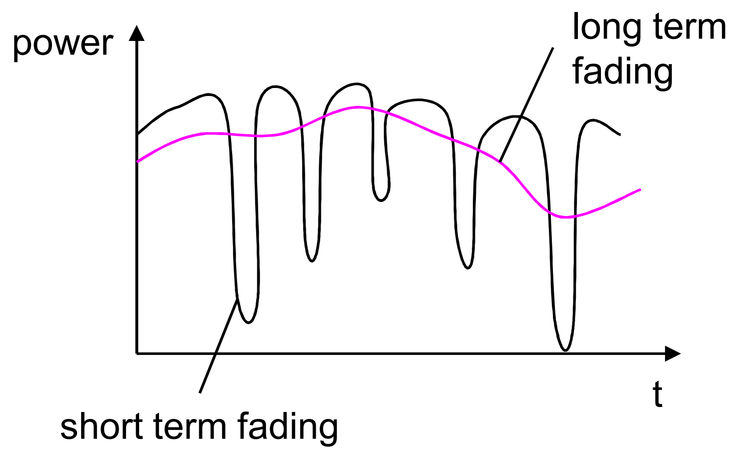
- The signal reaches a receiver directly and phase shifted
  ➔ distorted signal depending on the phases of the different parts

Effects of mobility

- **Channel characteristics change over time and location**
  - signal paths change
  - different delay variations of different signal parts
  - different phases of signal parts

➔ **quick changes in the power received (short term fading)**

- **Additional changes in**
  - distance to sender
  - obstacles further away

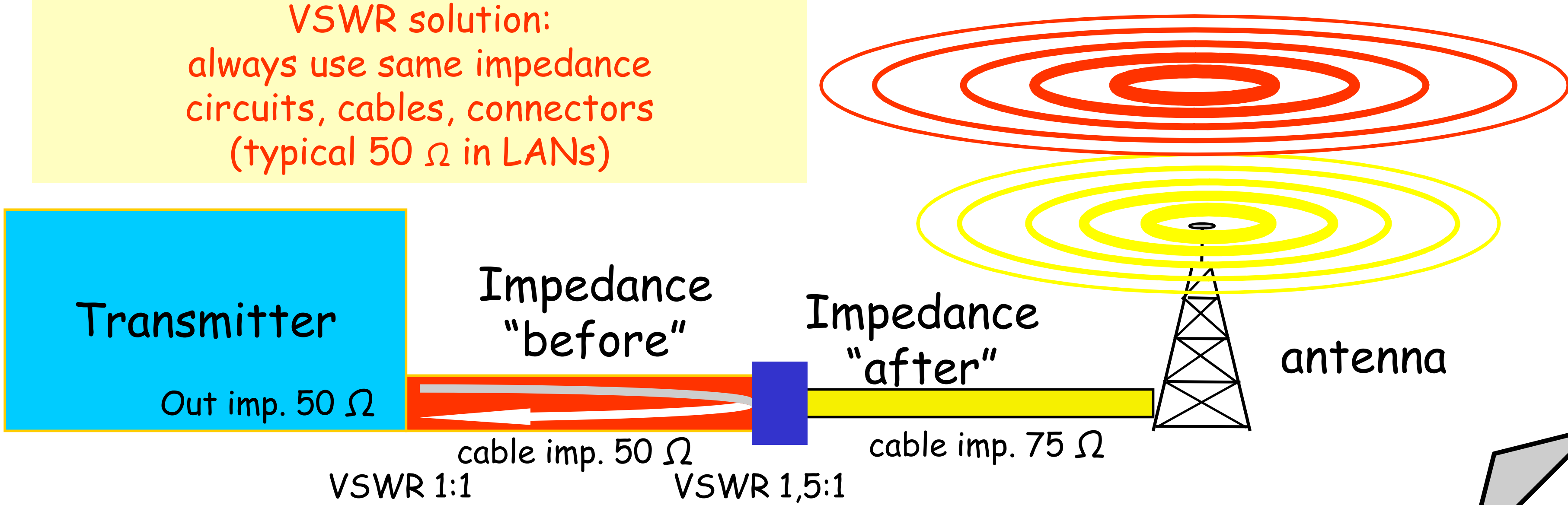


➔ **slow changes in the average power received (long term fading)**

Voltage Standing Wave Ratio (VSWR)

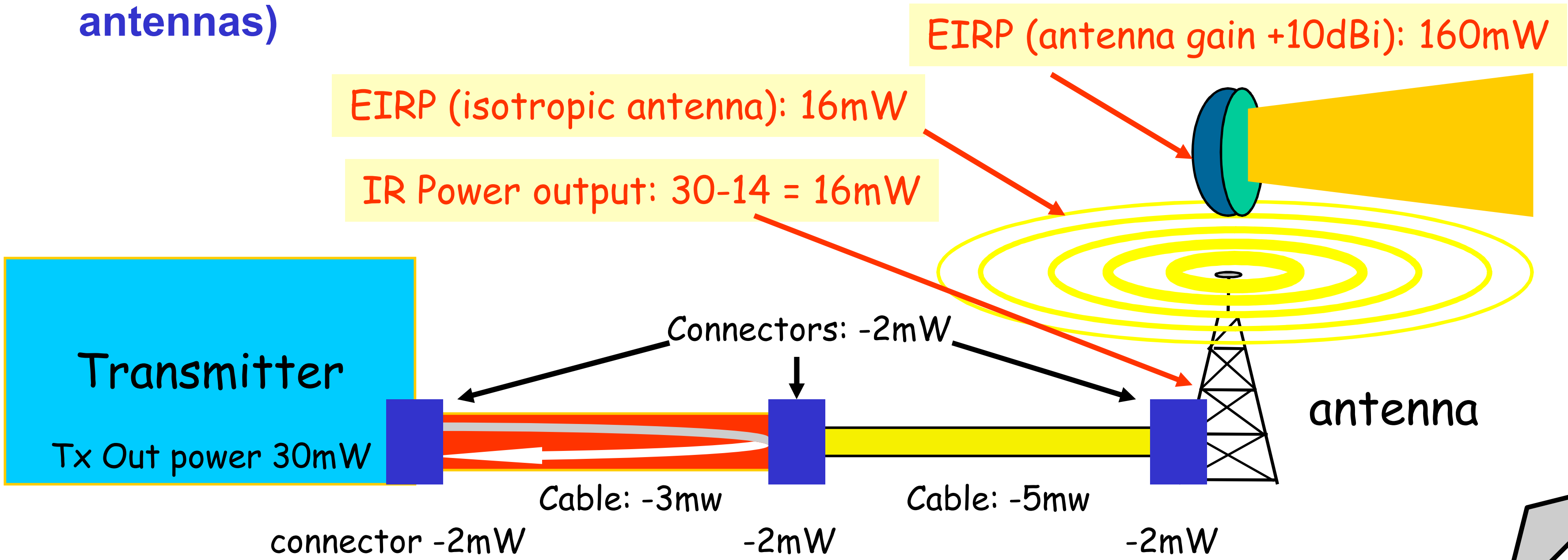
- **VSWR occurs with different impedance (Ohm) = resistance to AC current flow between transmitter and antenna**
  - VSWR is the cause of “return loss” energy towards the transmitter
  - Measured as ratio between impedance (before and after)
    - E.g. 1,5:1 (impedance ratio before/after is 1,5 times the ideal value)
    - 1 = normalized ideal impedance (1:1 means perfect VSWR)
  - VSWR Causes burnout of transmitter circuits, and unstable output levels

VSWR solution:
always use same impedance
circuits, cables, connectors
(typical 50 Ω in LANs)



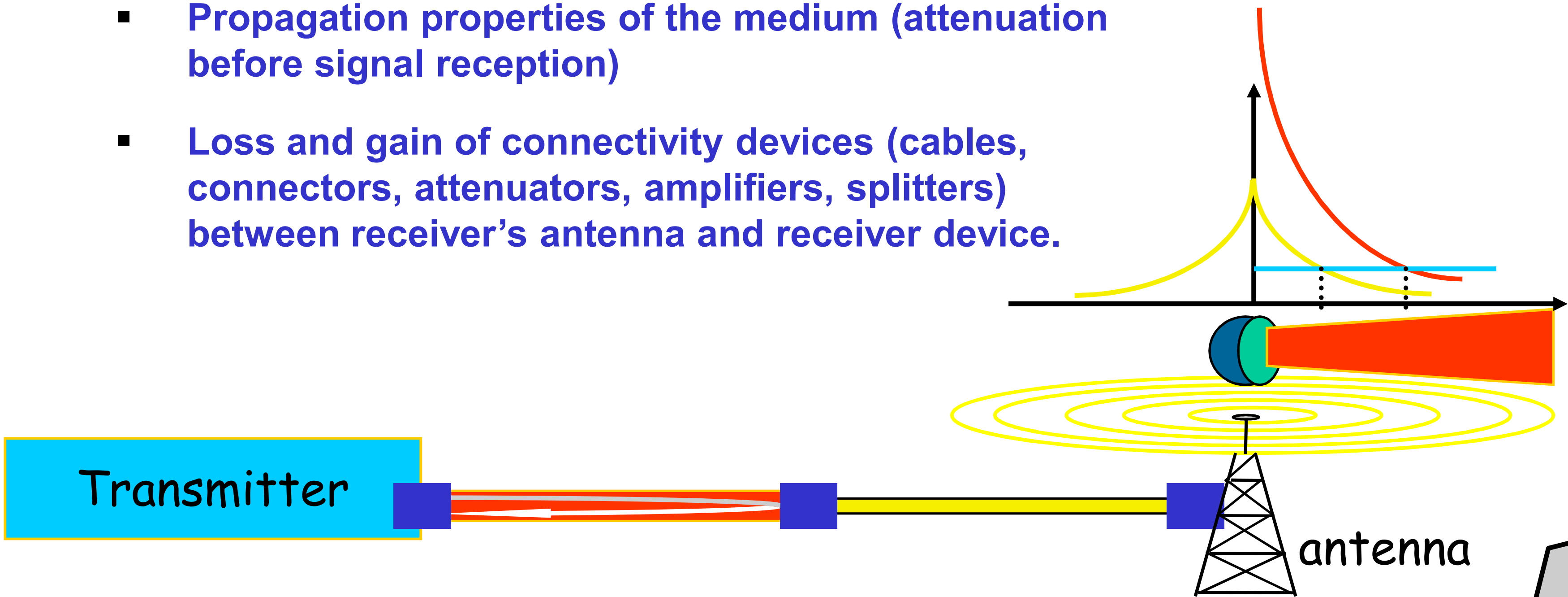
Intentional radiator and EIRP

- **(Intentional) radiator: (def.) RF device specifically designed to generate and radiate RF signals.**
  - ...Includes Tx RF device, cables and connectors (antenna excluded)
  - IR Power output: (subject to regulations) is the power output of last connector just before the antenna
- **Equivalent Isotropically Radiated Power (EIRP): the power radiated by the antenna (including the passive antenna gain effect of directional antennas)**



System design (under power viewpoint)

- Many factors must be considered in the design of Wireless systems:
  - Power of transmitting device
  - Loss and gain of connectivity devices (cables, connectors, attenuators, amplifiers, splitters) between transmission device and transmitter’s antenna
  - Power of the intentional radiator (last connector just before antenna)
  - Power radiated by antenna element (EIRP)
  - Propagation properties of the medium (attenuation before signal reception)
  - Loss and gain of connectivity devices (cables, connectors, attenuators, amplifiers, splitters) between receiver’s antenna and receiver device.



Power measurement

- WATT: electric power unit
  - 1 Watt = 1 Ampere * 1 Volt (P=V*I) also P= R*I^2 and P = L/t
    - Current (ampere) is the amount of charge (electrons) flowing as current in a wire
    - Voltage (Volt) is the "pressure" applied to the flow of charge
    - Resistance (impedance) is the obstacle to current flow
    - Power is the energy needed (in a given time unit) to apply a given "pressure" to a given "amount of charge", by resulting in a flow of current.
  - Watt and dBm are units used for absolute power measurement
  - Typical RF power for WLANs:
    - AP: 30..100 mW (up to 250 mW outdoor), PCMCIA: 15..30 mW

Power measurement

- Decibel (dB): a power measurement unit designed to express power loss
  - It is more practical to use given the logarithmic decay of wireless signals
  - It allows to make easy calculations on "resulting power"
- Decibel (dB) measures the logarithmic relative strength between two signals (mW are a linear absolute measure a energy)
  - $Log_{10}(X) = Y \iff 10^Y = X$

Exponential growth

- $1 = 10^0$, $\log_{10}(1) = 0$
- $10 = 10^1$, $\log_{10}(10) = 1$
- $100 = 10^2$, $\log_{10}(100) = 2$
- $1000 = 10^3$, $\log_{10}(1000) = 3$

Linear growth
"BEL" units (B)

  - How strong is a 10 dB signal? (it depends on the reference signal)

Power measurement

- Decibel (dB): 1/10 of a Bel
- E.g. 1000 is one Bel greater than 100 => 1000 is 10 dB greater than 100

Linear signal difference (factor)

- 1 = 10^0, $\log_{10}(1) = 0$
- 10 = 10^1, $\log_{10}(10) = 1$
- 100 = 10^2, $\log_{10}(100) = 2$
- 1000 = 10^3, $\log_{10}(1000) = 3$

10 dB
10 dB
10 dB
20 dB
20 dB
30 dB

- How strong is a 10 dB signal? (it depends on the reference signal)
  - Positive dB value is power gain, negative dB value is power loss
  - e.g. given 7 mW power, a +10 dB signal gain is 70 mW
  - e.g. given 7 mW power, a -10 dB signal gain (loss) is 0.7 mW
- Power Difference (in dB) between Tx and Rx signal:
  - Power Difference (dB) = 10 * log(Power Tx(Watt) / Power Rx (Watt))
- Gain and Loss are relative power measurements: dB is the unit

Power measurement

- Advantage of dB: what is better?
  - E.g.: A signal transmitted at [TX] 100 mW is received at [RX] 0.000005 mW
    - Power Difference (dB) = 10 * log([RX] /[TX]) = 10 * log(0.000005mW/100mW) = -73
    - A signal transmitted at 100 mW is received with gain (loss) –73 dB
- Advantage of dB: what is better?
  - E.g.: A signal transmitted at 100 mW is received at 0.000005 mW, then it is amplified (*100) to 0.0005 mW ….. ???
  - A signal transmitted at 100 mW is received with gain (loss) -73+20= -53 dB

-3 dB	½ power in mW (/ 2)
+3 dB	2x power in mW (* 2)
-10 dB	1/10 power in mW (/ 10)
+10 dB	10x power in mW (* 10)

Approximated table (values defined for ease of calculations)

Power measurement

- Practical example:
  - Signal Tx at 100 mW, cable –3dB loss, amplifier +10 dB gain
    - 100 mW / 2 (-3dB) = 50 mW * 10 (+10 dB) = 500 mW IR power output
  - Signal TX at 30 mW is received at the antenna as 6 mW (2/10 of TX power)
    - Intentional Radiator Gain (loss) = 30mW / 10 = 3mW *2 = 6 mW
    - Intentional Radiator Gain (loss) = -10 dB + 3 dB = -7 dB (≈1/5, 7dB ≈ 5x)
- N.B. dBs are additive measures of gain (loss): e.g. 6dB = +3+3 dB, 7dB = 10-3 dB
    - E.g. 100 mW –6 dB = 100 mW -3 -3 dB = 100 /2 /2 = 25 mW
    - E.g. 100 mW +7 dB = 100 mW +10 -3 dB = 100 *10 /2 = 500 mW
    - E.g. 10 mW + 5 dB = 10 mW (+10+10-3-3-3-3-3)dB = 1000/32 = 31.25 mW
    - E.g. 10 mW + 11 dB = ?
    - E.g. 50 mW – 8 dB = ?

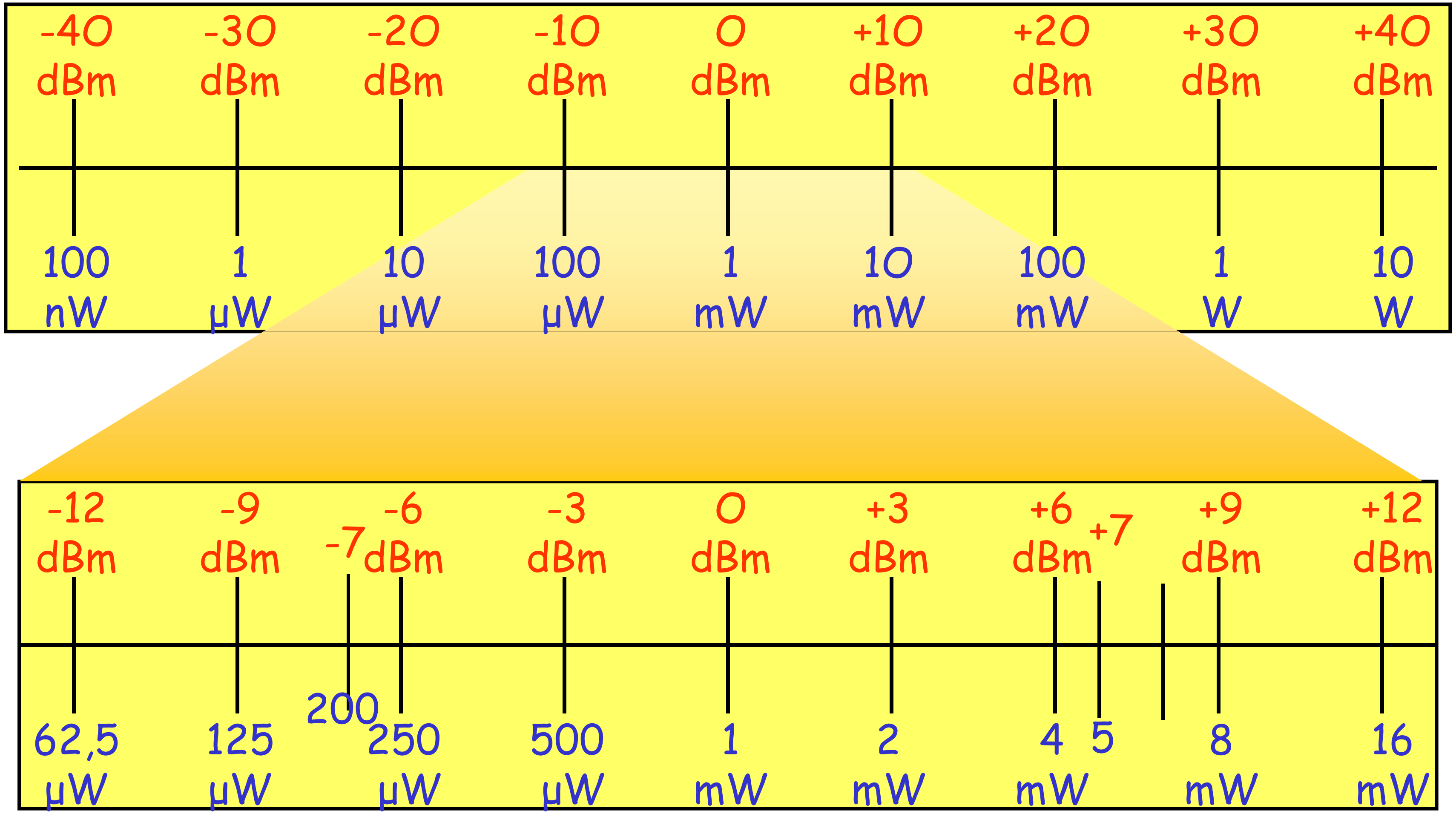
N.B. Approximated values (values defined for ease of calculations)

Power measurement

- dBm: dB-milliWatt, the absolute measure of signal power
  - Assumption: reference signal is 1 mW = 0 dBm(normalization factor)
  - Useful for gain/loss calculation without passing through mW
    - E.g. access point transmits 100 mW = 1mW (*10*10) =+20 dBm
    - PCMCIA card transmits at 30 mW = 1mW (*10*3) = +14.7 dBm
  - E.g. Tx= 30 mW, cable –2 dB, amplifier +9 dB:
    - 30 mW = 1mW *10 *3 = 14.7 dBm
    - IR power : 14.7 dBm –2dB +9dB = 21.7 dBm (147.91 mW)
  - In general, for converting mW to dBm and viceversa:
    - $P_{dBm} = 10 \log(P_{mW})$ and $P_{mW} = 10^{(PdBm/10)}$

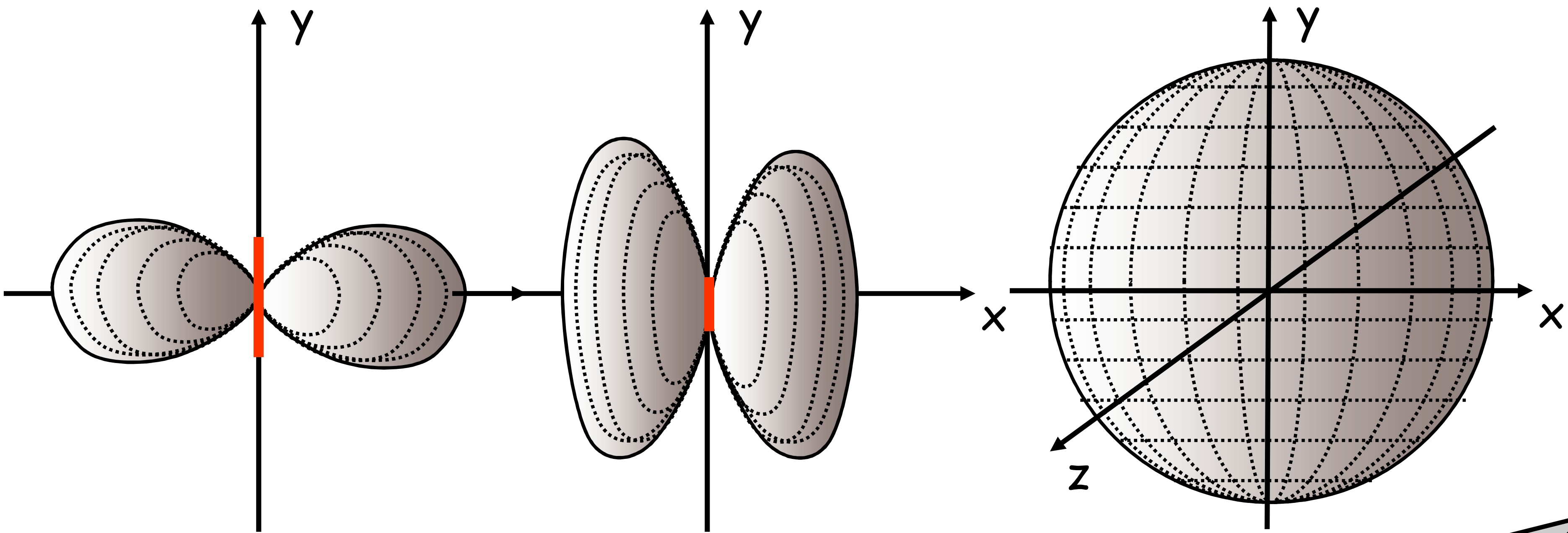
Power measurement

- **mW - dBm: conversion table**



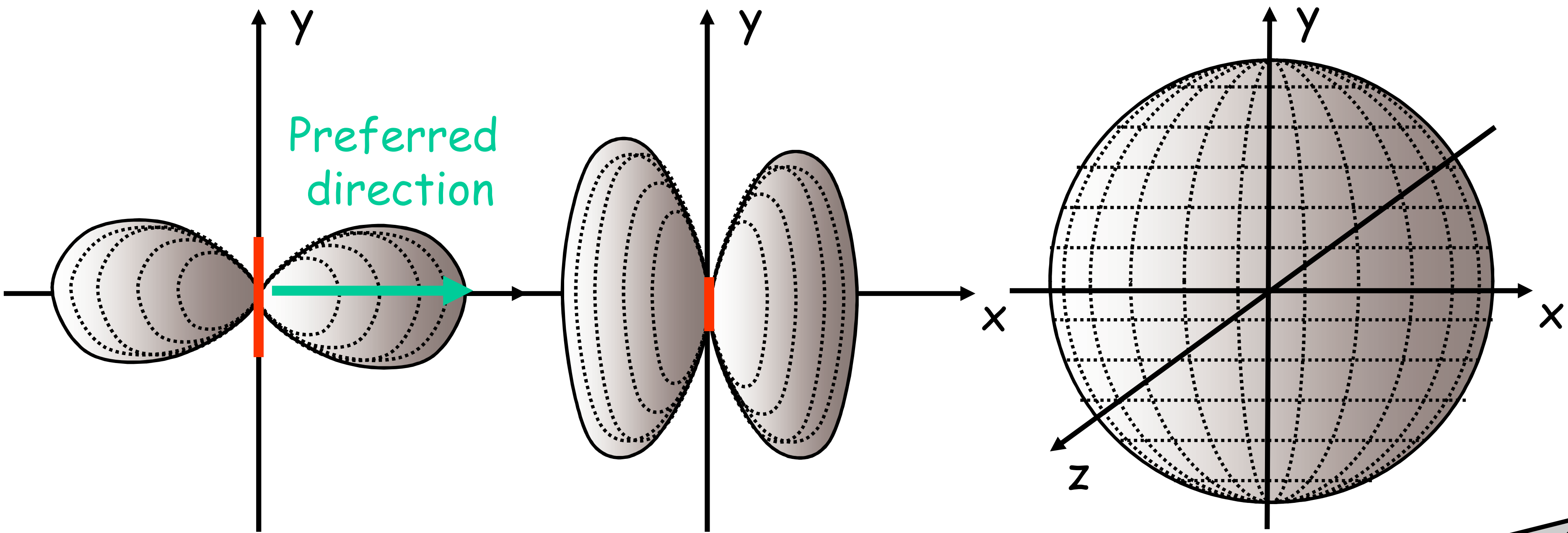
Power measurement

- dBi: dB-isotropic, the normalized measure of antenna passive gain
  - Assumption: an isotropic radiator has 100% efficiency in radiating energy in uniform way in every direction (e.g. the Sun)
  - Antennas concentrate energy in non-isotropic way, resulting in passive gain (space dependent). Ideal antenna: zero length dipole



Power measurement

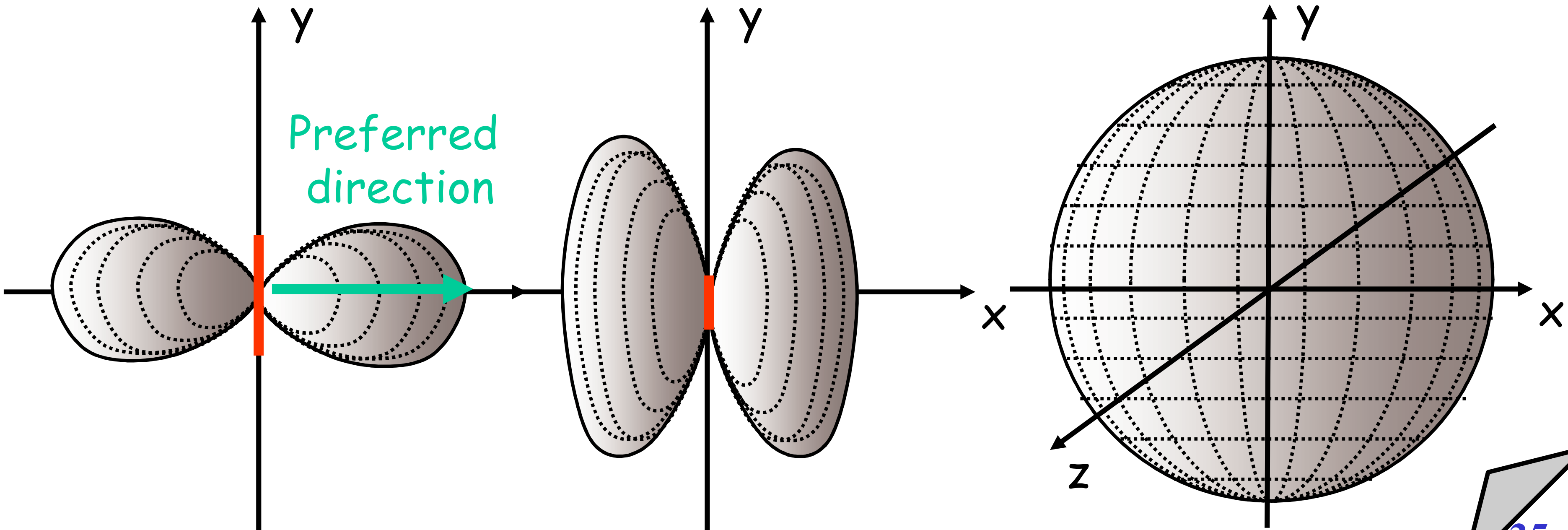
- dBi: dB-isotropic, the normalized measure of antenna passive gain
  - If an antenna located in the origin (0,0,0) has twice the radiated energy of an isotropic radiator in a given point (x,y,z), then the antenna gain in (x,y,z) can be defined as +3 dBi. If the energy is 10x the isotropic radiator, the gain is +10 dBi, etc.etc.
  - Q: If the antenna gain is 7 dBi in (x,y,z)?



Power measurement

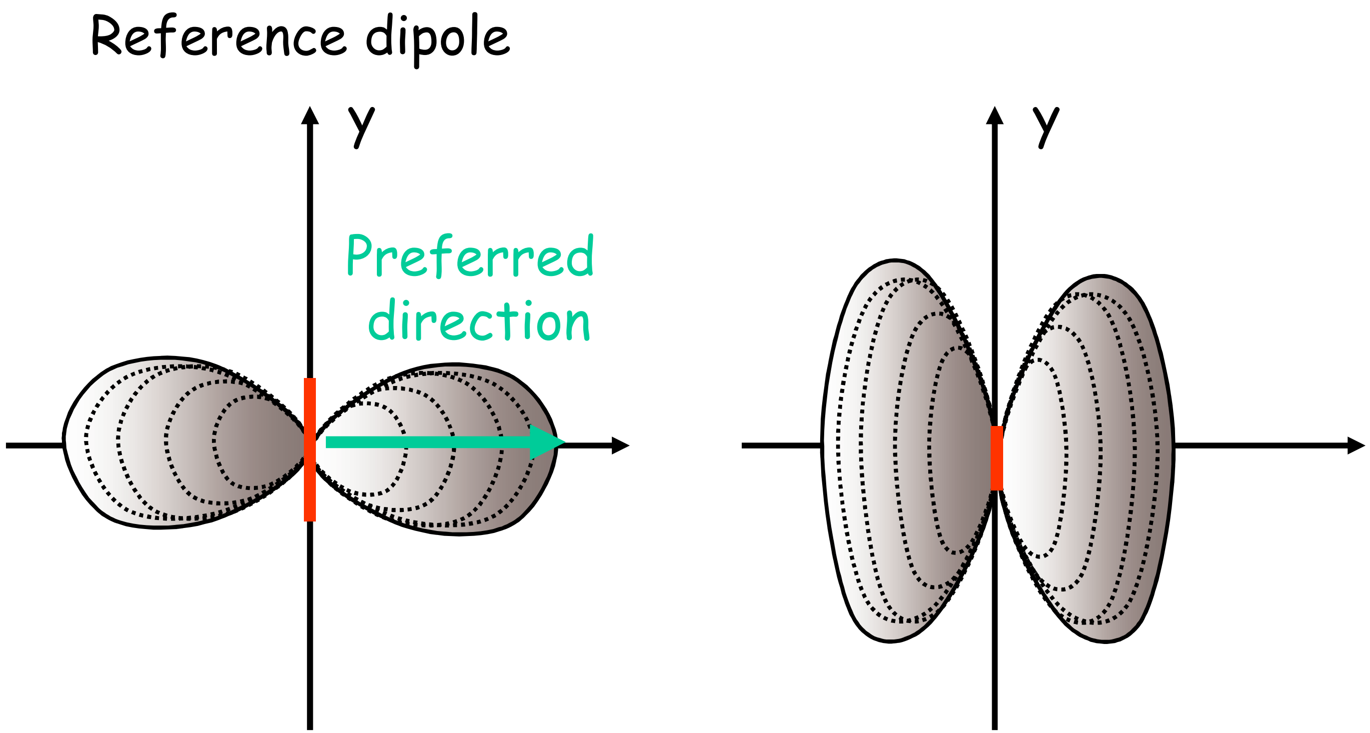
- dBi: dB-isotropic, the normalized measure of antenna passive gain
  - Real antennas always have a preferred direction where te power is greater than isotropic radiator: gain is always positive in the preferred direction!
  - Example: 1 mW IR power applied to directional antenna with +10 dBi gain in the preferred direction, would translate in EIRP?
    - EIRP = 1mW + 10 dBi = (10x) = 10 mW EIRP

N.B. this does not mean that antenna generates more power !
Antenna concentrates power in preferred direction.



Power measurement

- dBd: dB-dipole, the normalized antenna passive gain vs. 2,14 dBi half-wave dipole
  - Reference is a half wave dipole with 2.14 dBi gain in preferred direction!
  - Conversion rule:
    - 0 dBd = 2.14 dBi, dBd = (dBi - 2.14), dBi = (dBd + 2.14)



Power monitoring (e.g. IEEE 802.11 devices)

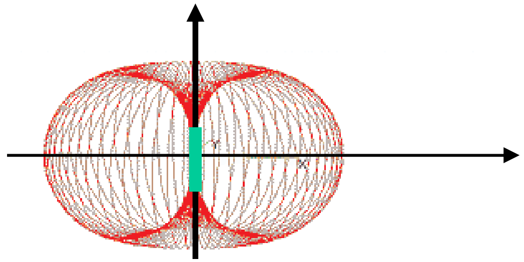
- (received) Power monitoring in IEEE 802.11 devices is needed for making device driver to work properly (typical sensitivity range is [–90..+10] dBm):
  - Detect signal (below or above the sensitivity threshold?)
  - Detect signal power (selection of coding technique... That is bitrate!)
  - Detect channel status: idle? Ok, transmit! Busy? Ok, wait.
- Received Signal Strength Indicator (RSSI)
  - Index defined for IEEE 802.11 devices (check device analyzer, if any)
  - RSSI = function (dBm or mW received) = pure number reported to device driver!
  - Unfortunately the RSSI scale is not standard, that is, device dependent!
    - This fact does not allow to compare if device A receives better than device B (assuming different manufacturer) based on RSSI mesurement
  - Problem: device A indicates maximum RSSI=255 (8 bits) with –10 dBm signal (0.1 mW), and device B indicates maximum RSSI=32 (5 bits) with –15 dBm (0.03 mW). Q: when both A and B in (x,y,z) receive –15 dBm, which one is better device? That is, which one would you buy if you are a system admin?

Antennas

- Illustration of general issues
  - Convert electrical energy in RF waves (transmission), and RF waves in eletrical energy (reception)
  - Size of antenna is related to RF frequency of transmission and reception
  - Shape (structure) of the antenna is related to RF radiation pattern
- Radiation patterns of different antenna types
- Positioning antennas
  - Maximum coverage of workspace
  - Security issues
- Real antenna types: omni-directional, semi-directional, highly-directional

Omnidirectional antenna

- **Omni-directional antenna: radiates RF power equally in all directions around the vertical axis.**
- **Most common example: dipole antenna (see Access Points)**
  - See how to make it (disclaimer: do not try this at home):
    http://www.nodomainname.co.uk/Omnicolinear/2-4collinear.htm
    http://www.tux.org/~bball/antenna/
  - Info & fun: http://www.wlan.org.uk/antenna-page.html
  - More info: http://www.hdtvprimer.com/ANTENNAS/types.html



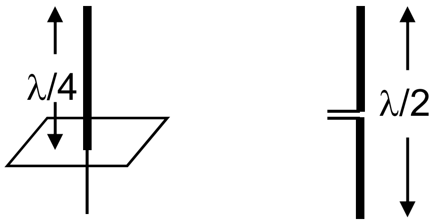
Q: Why TV dipole is bigger?
A: 100 Mhz vs. 2.4 Ghz

TV dipole

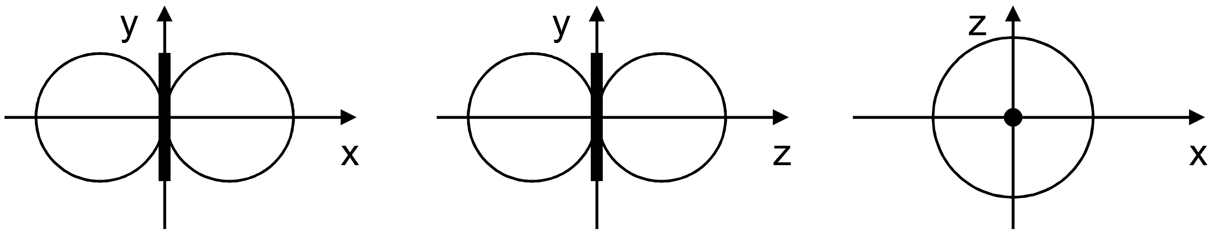
AP dipole

Omnidirectional antennas: simple dipoles

- Real antennas are not isotropic radiators but, e.g., dipoles
  ➔ shape of antenna proportional to wavelength



- Example: Radiation pattern of a simple Hertzian dipole



side view (xy-plane) side view (yz-plane) top view (xz-plane)

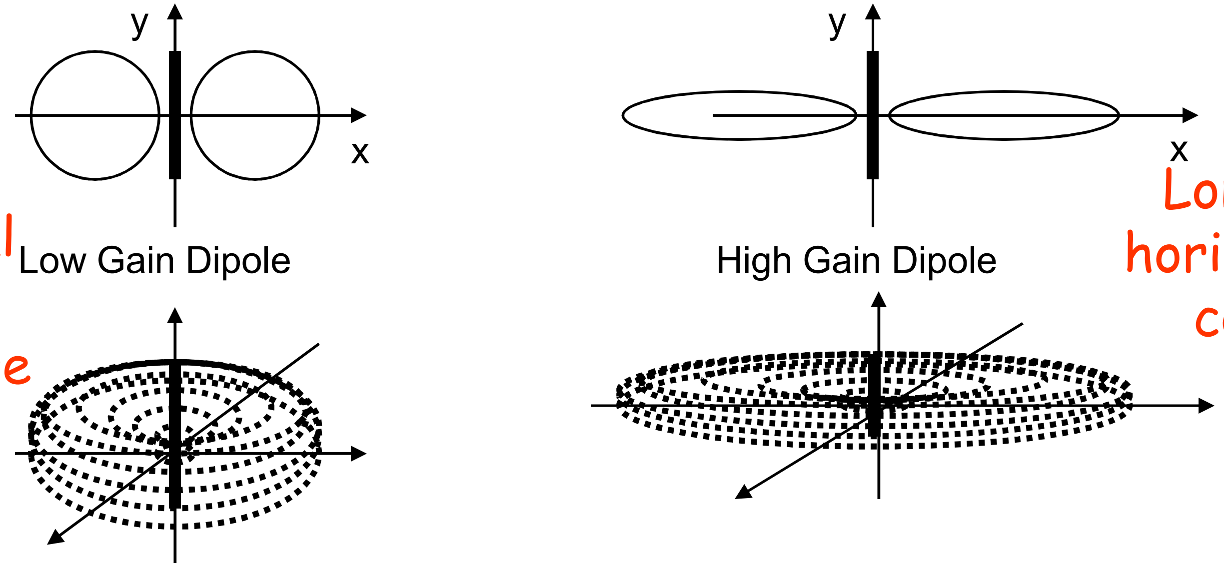
simple dipole

- Gain: maximum power in the direction of the main lobe compared to the power of an isotropic radiator (with the same average power)

Omnidirectional antennas: simple dipoles

- **Dipole: passive gain is due to concentration (shape) of radiation**

Short range, vertical area coverage

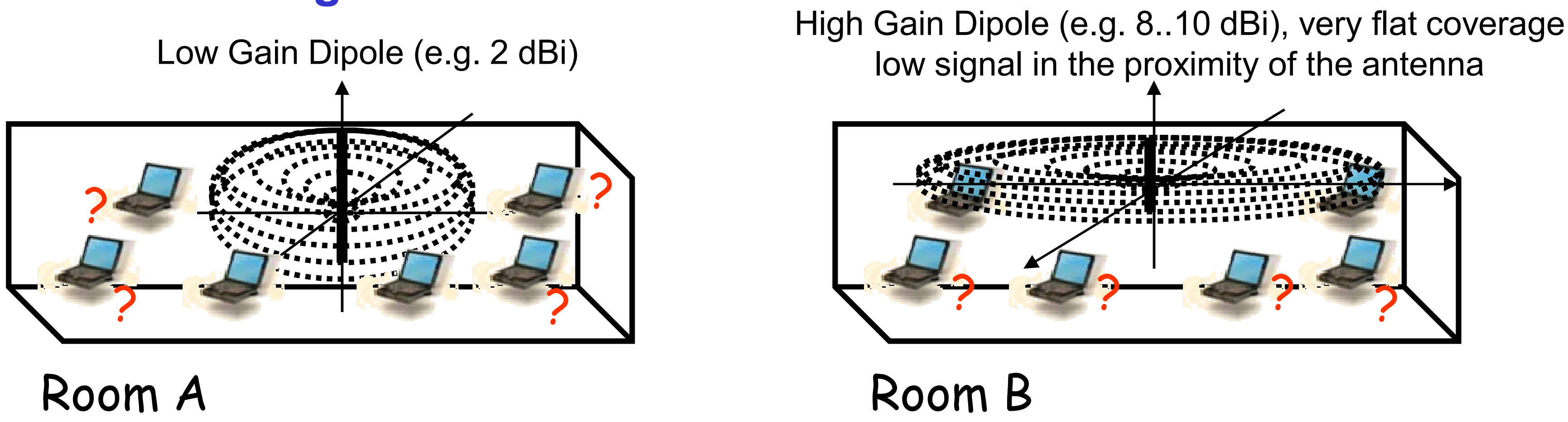


Long range, horizontal area coverage

- **Dipole: active gain is obtained with power amplifiers (needs external source of energy)**
- **N.B. near (below) the dipole the signal is weak! And better radiation is obtained in sub-areas around the dipole!**

Omnidirectional antennas: simple dipoles

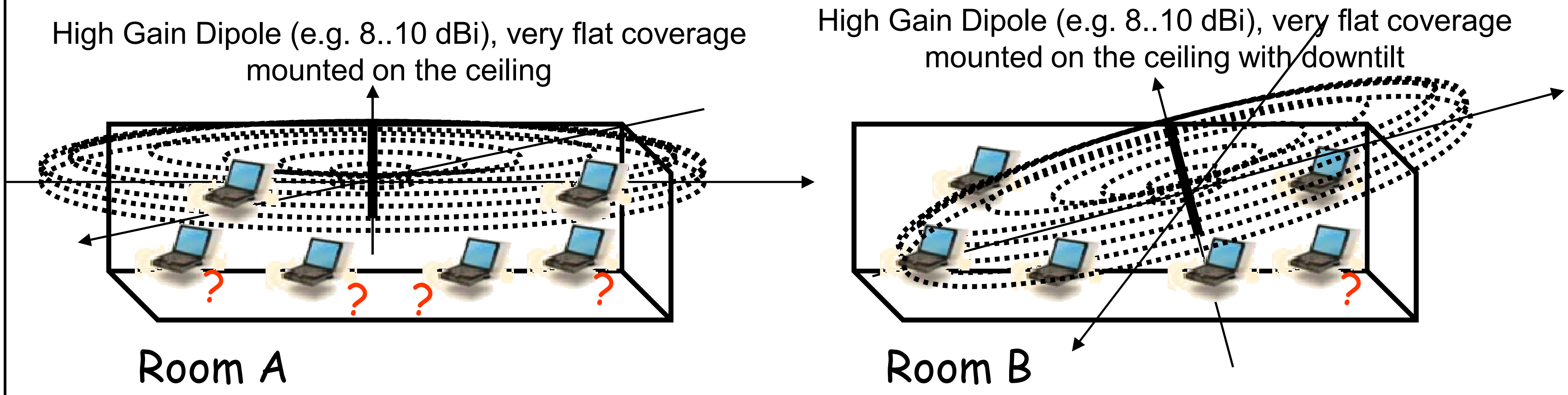
- **Problem: how and when to mount omidirectional antennas? And which gain is ok?**



- **How: Ceiling? Wall? Client positions? Area? Many factors influence the planning...**
- **When:**
  - **need for uniform radio coverage around a central point**
  - **Outdoor: point-to-multipoint connection (star topology)**

Omnidirectional antennas: simple dipoles

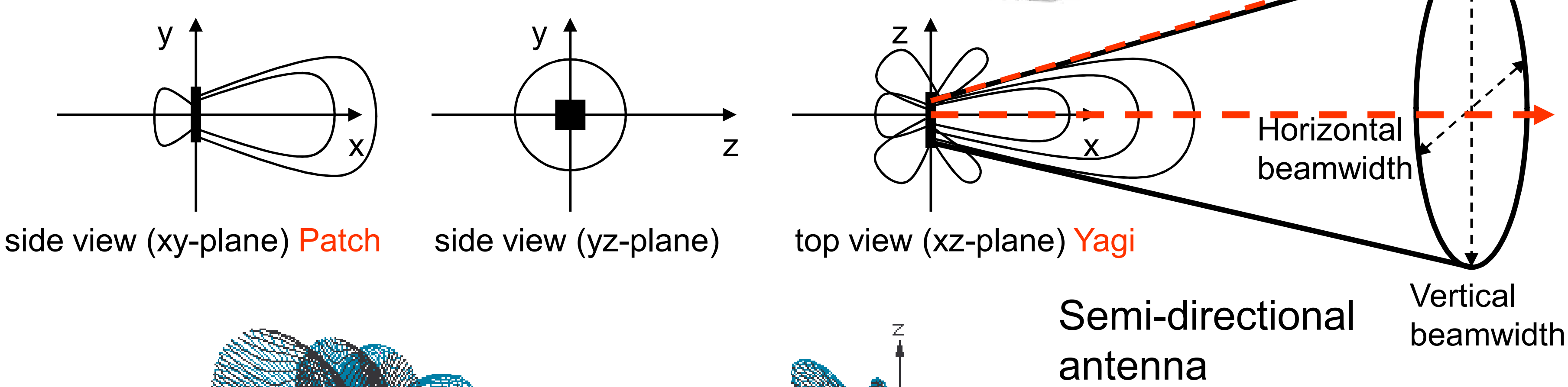
- **Antenna Tilt: degree of inclination of antenna with respect to perpendicular axis**

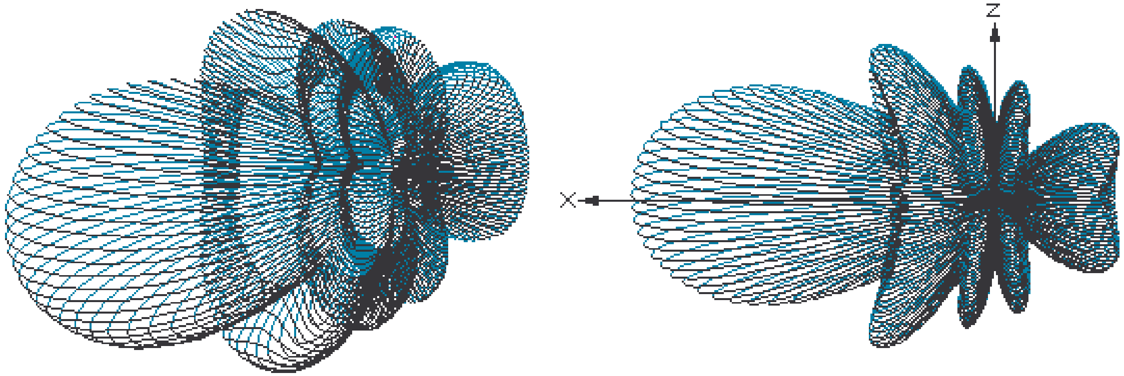


- **Some antennas allow a variable degrees downtilt.**
- **Half signal disperded "in the sky", 2nd half better exploited.**

Semi-directional antennas

- Patch (flat antennas mounted on walls)
- Panel (flat antennas mounted on walls)
- Yagi (rod with tines sticking out)



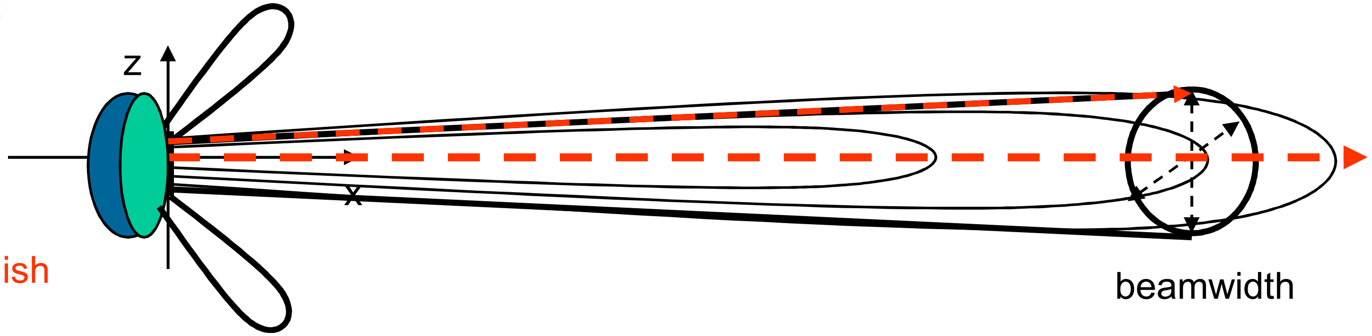


Credits: http://www.hdtvprimer.com/ANTENNAS/types.html

Beamwidth cone:
-3dB signal boundary off-axis

highly-directional antennas

- Parabolic Dish 
- grid 



top view (xz-plane) dish

Antenna type	H beamwidth	V beamwidth
Omni-dir.	360°	7°.. 80°
Patch/panel	30° .. 180°	6° .. 90°
Yagi	30° .. 78°	14° .. 64°
Parabolic dish	4° .. 25°	4° .. 21°

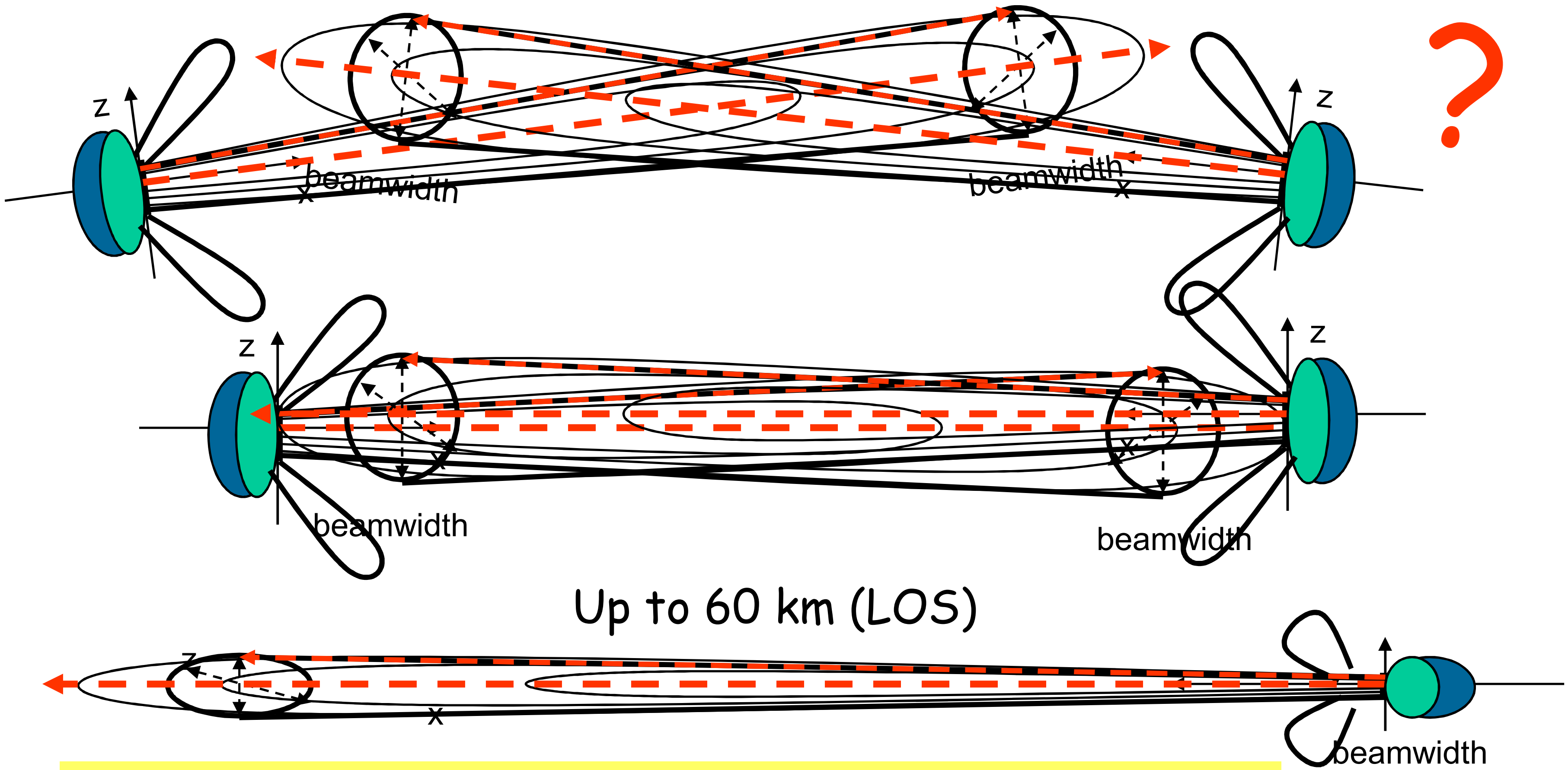
Semi-directional antenna

Beamwidth cone: -3dB signal boundary off-axis

highly-directional antennas

- **Common use: Point-to-point link**

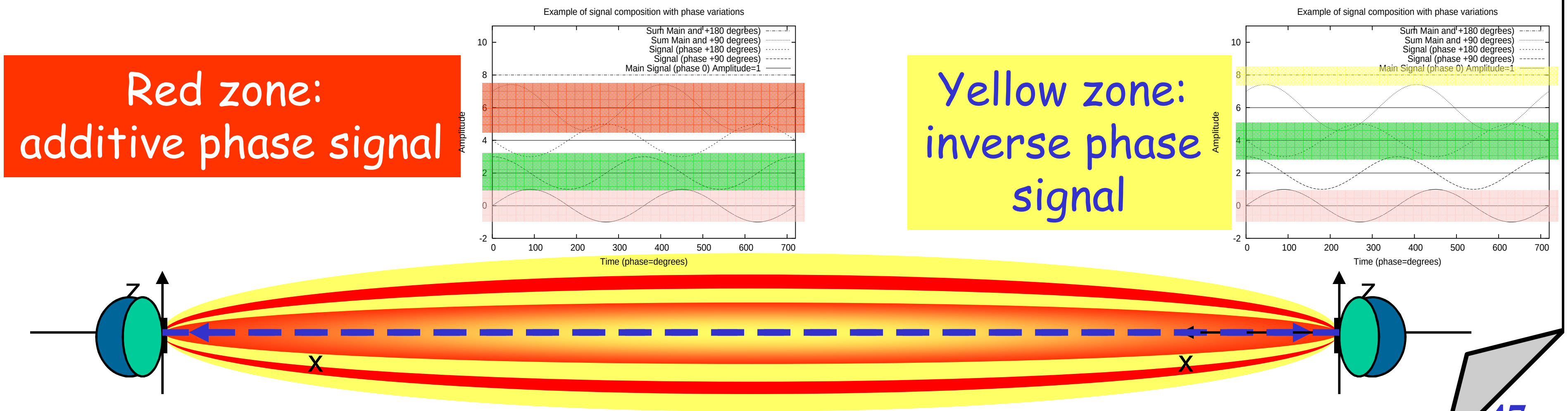
Out of beam alignment



Wind effect: better to have lower gain and wider beam

highly-directional antennas

- **Line of sight (LOS):**
  - Straigth line between transmitter and receiver
  - No obstructions (outdoor long range reduces reflections)
    - Polarization is more important than in indoor scenarios
- **Fresnel Zone: RF is not laser light, RF signals diffuse energy in space**
  - Ellipse shaped area centered on the LOS axis
  - Most additive RF signal is concentrated in the Fresnel Zone
  - It is important that Fresnel Zone is free from obstacles

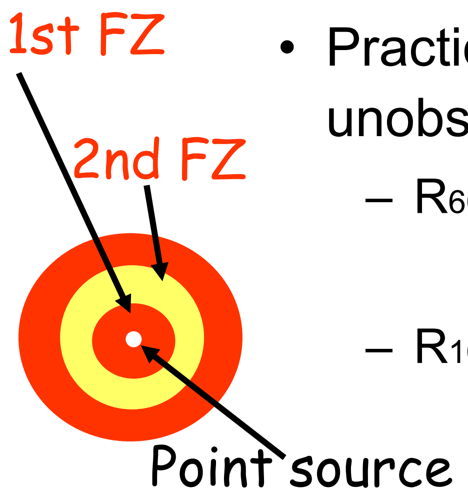


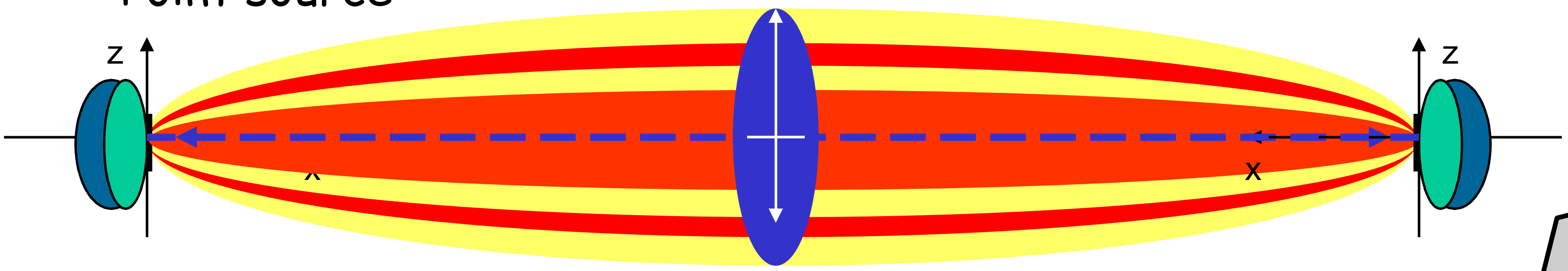
highly-directional antennas

- **Fresnel Zone (FZ)**
  - Blockage of Fresnel Zone causes link disruption
    - Caused by buildings, (growing) trees, foliage, etc.
    - Rule of thumb: < 20% obstruction of Fresnel Zone
    - Practical rule: calculate the radius of FZ leaving 60% unobstructed radius
      - $R_{60\%} = 43.3 \times \sqrt{(d/4f)}$
      - $R_{100\%} = 72.2 \times \sqrt{(d/4f)}$

R=radius of 60% central FZ (feet)
d=distance(Miles), f=freq (GhZ)

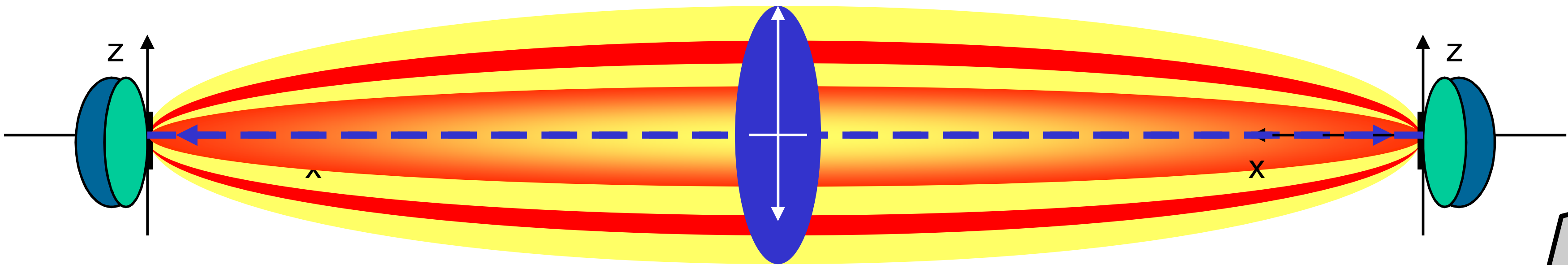
R=radius of 100% FZ (feet)
d=distance(Miles), f=freq (GhZ)





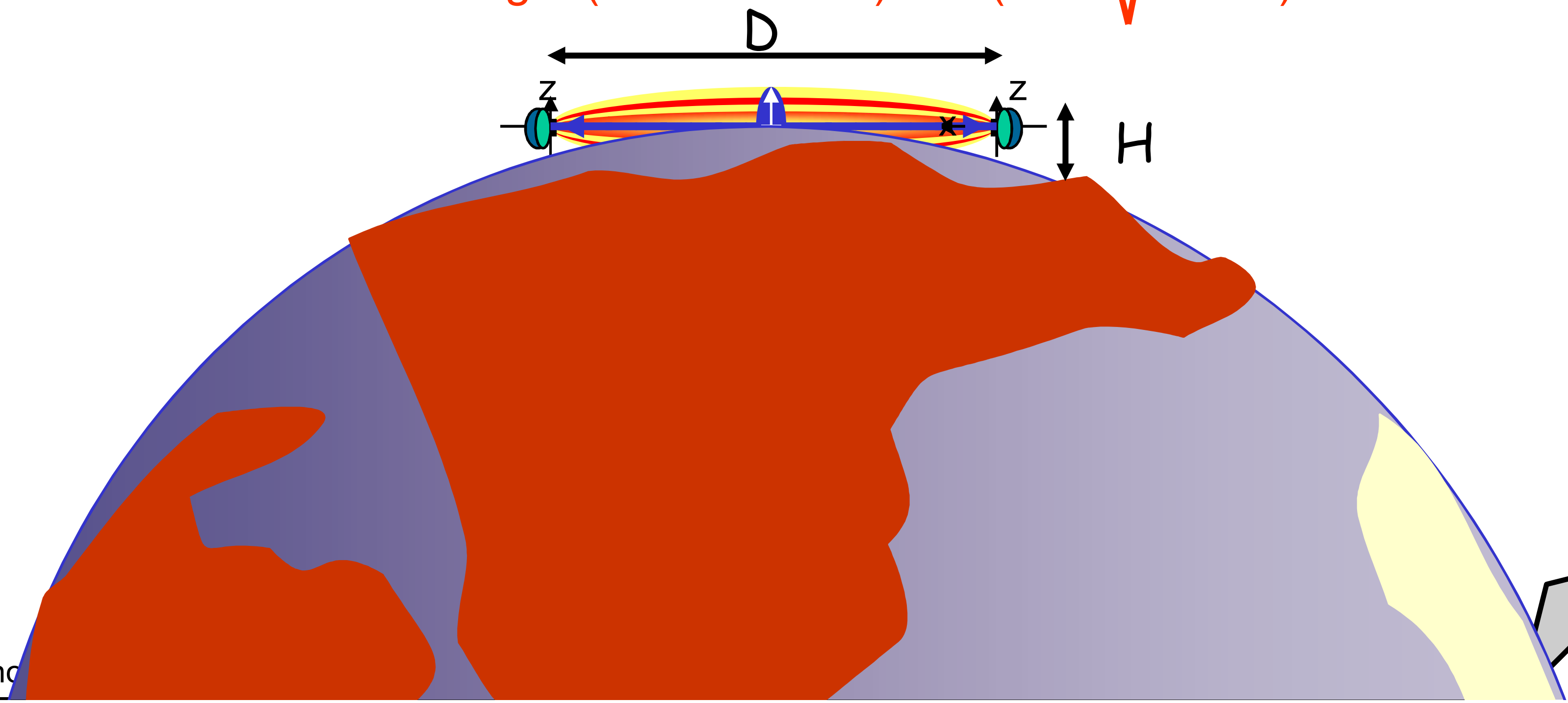
highly-directional antennas

- **Fresnel Zone (FZ)**
  - N.B. the FZ radius depends only on the distance d between antennas, and frequency f of RF signal!
  - Type of antenna, beam width (degree), and gain (dBi) have no effects!
    - E.g. +13 dBi Yagi (30 degree beam) vs. +24 dBi Dish (5 degrees) have the same FZ!!!!
  - In practice: if FZ is partially obstructed, it is not useful to use higher gain antennas (with small degree beam) !!!



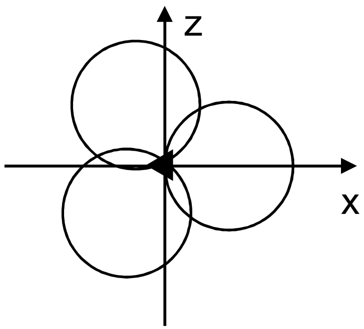
highly-directional antennas

- **Fresnel Zone (FZ)**
  - Is not relevant in indoor scenarios (due to reflections...)
- **Consider the Earth bulge!!!**
  - Very long point-to-point connections may have more than 40% FZ obstucted by Earth surface! Earth Bulge heigth = h (feet) = $D^2/8$
  - Minimum antenna heigth (link > 7 miles) $H = (43.3 \sqrt{D/4F}) + D^2/8$

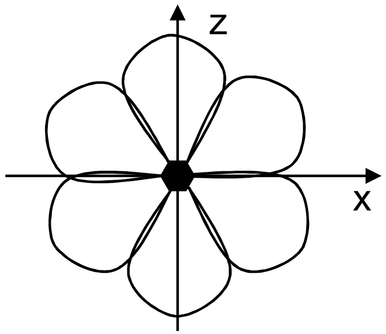


Sectorized-directional antennas

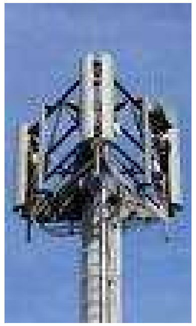
- **Arrays of sectorized directional antennas**



top view, 3 sector



top view, 6 sector

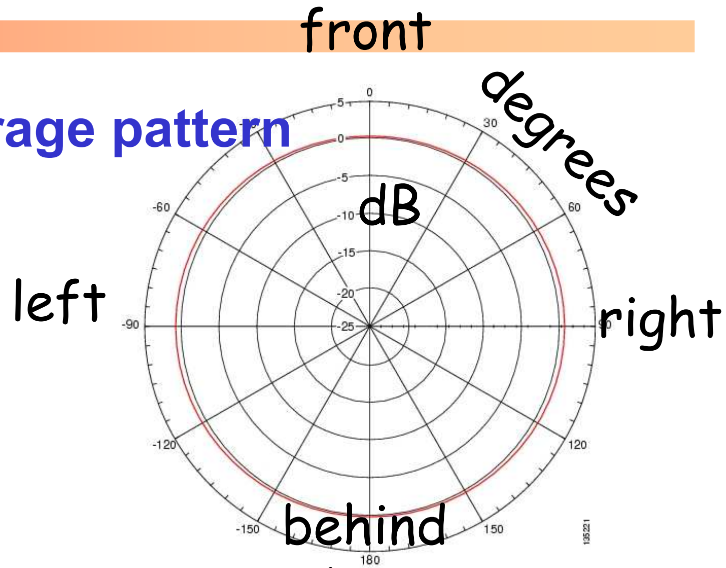


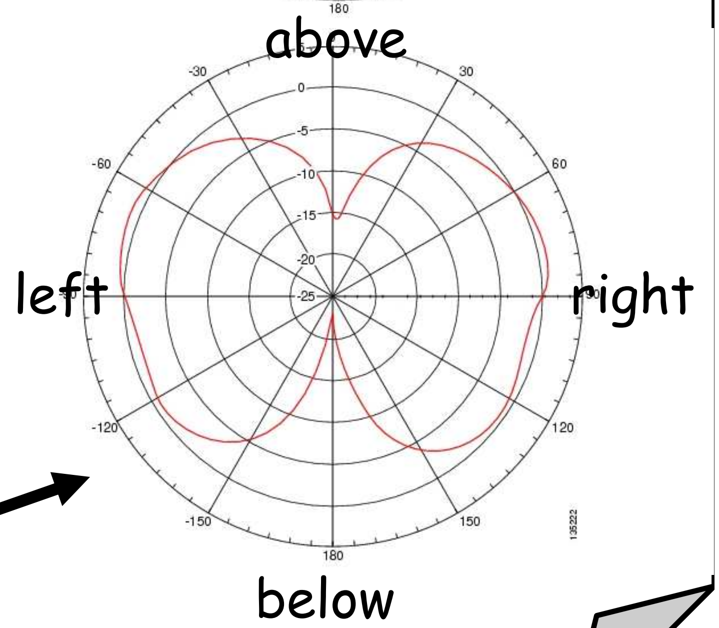
sectorized antenna

- **Space multiplexing (channel reuse)**

Azimuth and Elevation antenna charts

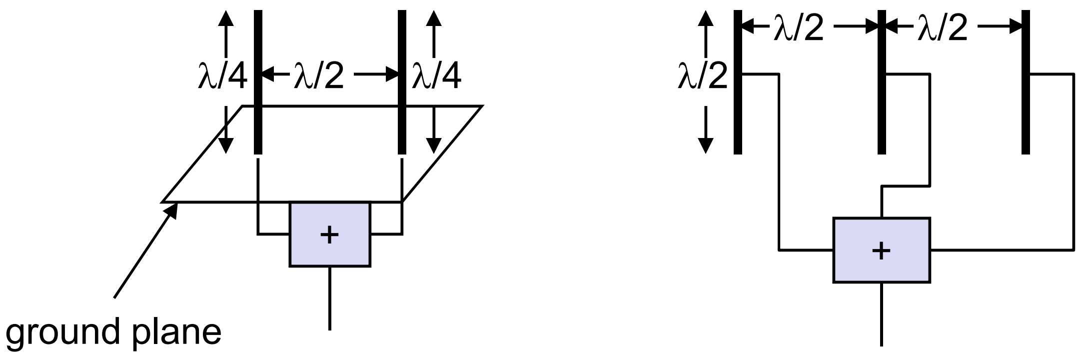
- **Charts for understanding antenna coverage pattern**
  - Azimuth chart (pattern seen from front/right/behind/left))
    - Obtained with spectrum analyzer with central antenna frequency
    - Signal measured in dB around the antenna
      - E.g. Dipole pattern: almost circular
      - E.g. yagi pattern: high in front, low beside
  - N.B. distance and Tx power is not relevant (signal strength in a location is relative to every other location in the chart, like with dB)
  - Elevation chart (pattern seen front/below/behind/above)





Antennas: diversity

- **Grouping of 2 or more antennas**
  - multi-element antenna arrays
- **Antenna diversity**
  - switched diversity, selection diversity
    - receiver chooses antenna with largest output
  - diversity combining
    - combine output power to produce gain
    - cophasing needed to avoid cancellation (phased antenna array... Requires processor)



Path Loss

- **Path Loss: RF signal "dispersion" (attenuation) as a function of distance**
  - E.g. Possible formulas (36.6 or 32.4)
    - Free space: Loss (in dB) = 36.6+(20*$\log_{10}$(F))+(20*$\log_{10}$(D))
    - F (Mhz), D (miles)
- **Link budget issue: 6 dB rule**
  - Each 6 dB increase in EIRP (signal x 4) implies double Tx range (e.g. see table below: 2.4Ghz Path Loss vs distance)

100 meters	- 80.23 dB
200 meters	- 86.25 dB
500 meters	- 94.21 dB
1000 meters	- 100.23 dB
2000 meters	- 106.25 dB
5000 meters	- 114.21 dB
10000 meters	- 120.23 dB

-6 dB (100 → 200 meters)
-6 dB (500 → 1000 meters)
-6 dB (1000 → 2000 meters)
-6 dB (5000 → 10000 meters)

Link Budget Calculation

- **"Link Budget" or "System Operating Margin"**
  - Excess of signal between transmitter and receiver
    - Calculated for outdoor point-to-point connections
  - Measured in dB (relative) or dBm or mW (absolute)
  - Calculation:
    - Receiver sensitivity RS (weakest detectable signal)
      - The lower the better: e.g. IEEE 802.11 card (see device manual), -95 dBm (1Mbps), -93 dBm (2 Mbps), -90 dBm (5.5 Mbps), -87 dBm (11 Mbps)
    - Link Budget: received power (in dBm) - RS (in dBm)
    - E.g. RS = -82 dBm, received power = -50 dBm
      - Link budget = -50 – (-82) = +32 dBm
    - This means the signal has margin of +32 dB before it becomes unviable
- **Fade margin: extra margin for link budget (to cope with multipath variation in indoor/outdoor scenarios): typical [+10..+20] dB**

Link Budget Calculation: example

- **Example: design of transmission system, needs amplifier?**