Wireless Communications at the Physical Layer

Part 1: Fundamentals

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Outline

- Electromagnetic spectrum and allocation
- Frequency domain representation of signals
- Decibel notation
- Antennas
- Signal propagation modes
- Wireless transmission deterioration factors
- Signal-to-noise ratios

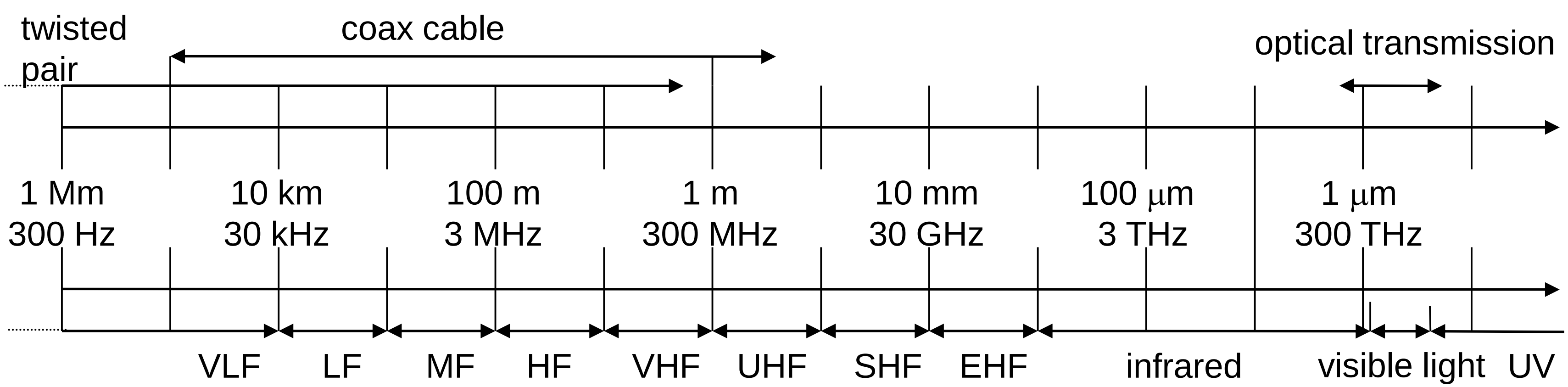
Electromagnetic spectrum and allocation

Frequencies for communication

- VLF = Very Low Frequency
- LF = Low Frequency
- MF = Medium Frequency
- HF = High Frequency
- VHF = Very High Frequency

UHF = Ultra High Frequency
SHF = Super High Frequency
EHF = Extremely High Frequency
UV = Ultraviolet Light

- Frequency and wavelength
  - $\lambda = c/f$
  - wavelength λ, speed of light $c \cong 3x10^8$m/s, frequency f

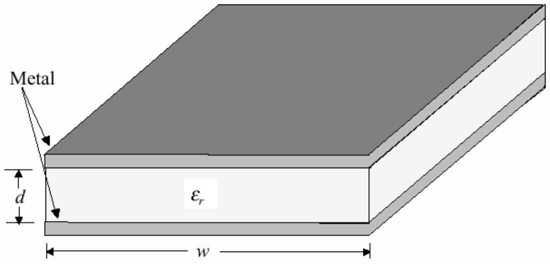


Frequency allocation

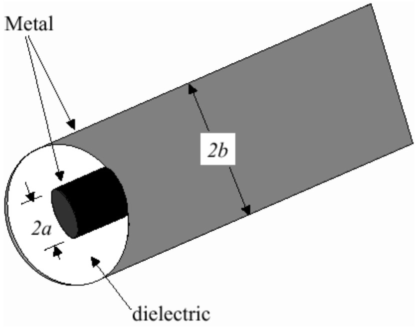
- Some frequencies are allocated to specific uses
  - Cellular phones, analog television/radio broadcasting, DVB-T, radar, emergency services, radio astronomy, …
- Particularly interesting: ISM bands ("Industrial, scientific, medical") – license-free operation

- Quadro Nacional de Atribuição de Frequências
  - http://www.anacom.pt/render.jsp?categoryId=290215

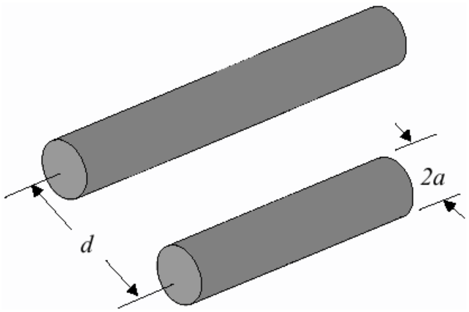
Some typical ISM bands	
Frequency	Comment
13,553-13,567 MHz	
26,957 – 27,283 MHz	
40,66 – 40,70 MHz	
433 – 464 MHz	Europe
900 – 928 MHz	Americas
2,4 – 2,5 GHz	WLAN/WPAN
5,725 – 5,875 GHz	WLAN
24 – 24,25 GHz	



Planos paralelos

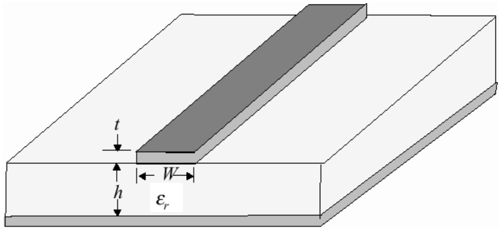


Cabo coaxial

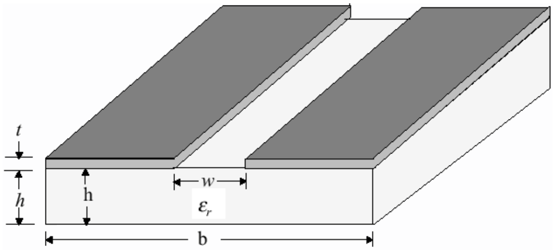


Condutores paralelos

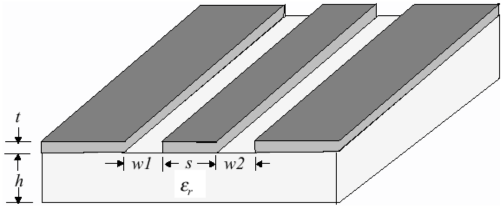
Tipo de Linhas de Transmissão



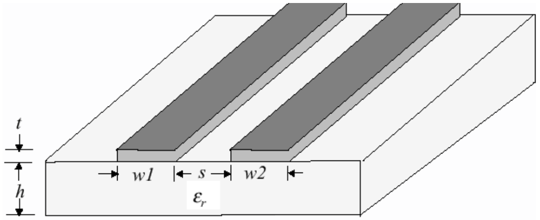
Linha Microstrip



Slotline

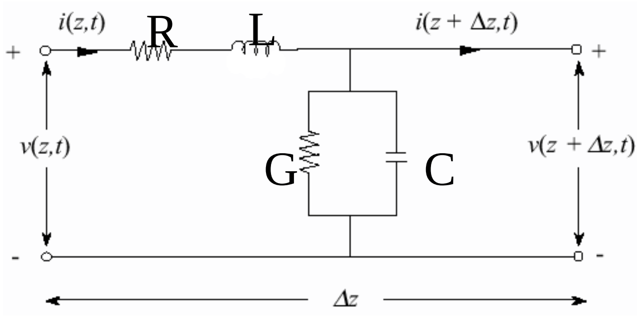


Guia de onda coplanar



Stripline coplanar

Parâmetros distribuídos de uma linha de transmissão



R – resistência por unidade de comprimento Ω/m
L – indutância por unidade de comprimento H/m
C – capacidade por por unidade de comprimento F/m
G – condutância por unidade de comprimento S/m

A solução geral em termos de I e V é dada por:

$$V = Ae^{-\gamma x} + Be^{\gamma x}$$

$$I = \frac{A}{Z_o}e^{-\gamma x} - \frac{B}{Z_o}e^{\gamma x}$$

$e^{-\gamma x}$ - onda incidente ou onda que sai da fonte

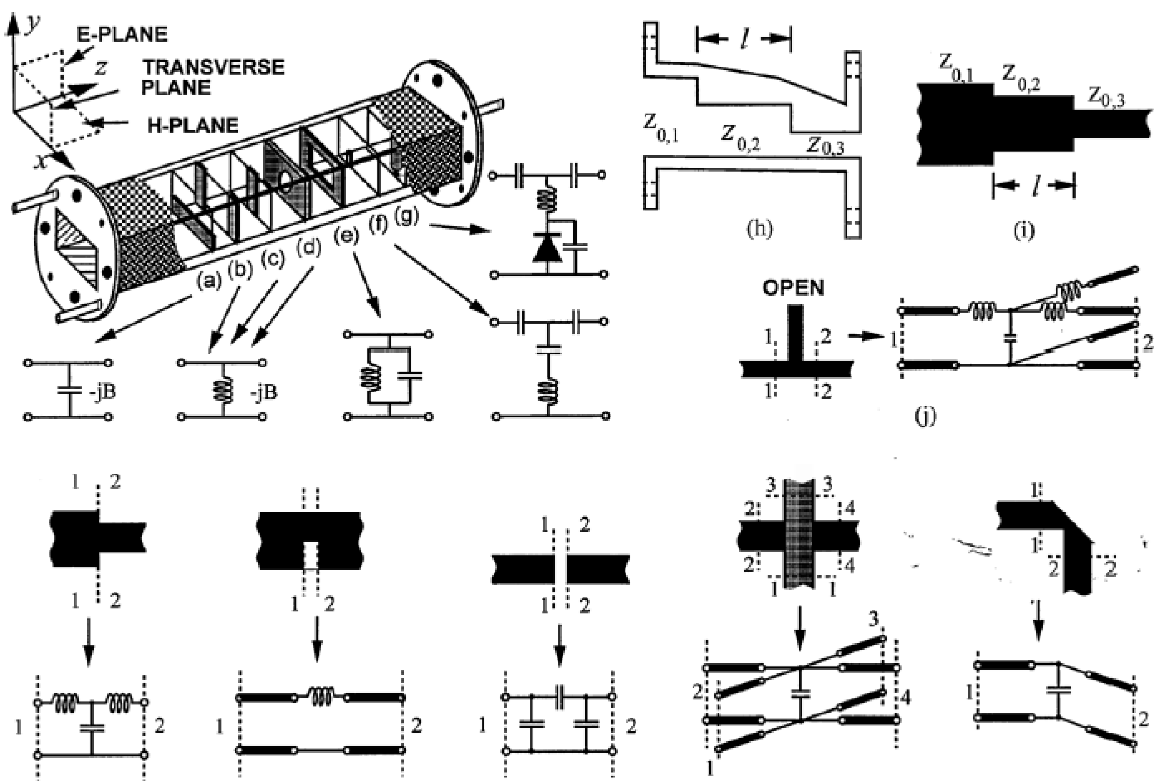
$e^{\gamma x}$ - onda reflectida ou onda recebida na fonte

Impedância característica

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

Linha sem perdas

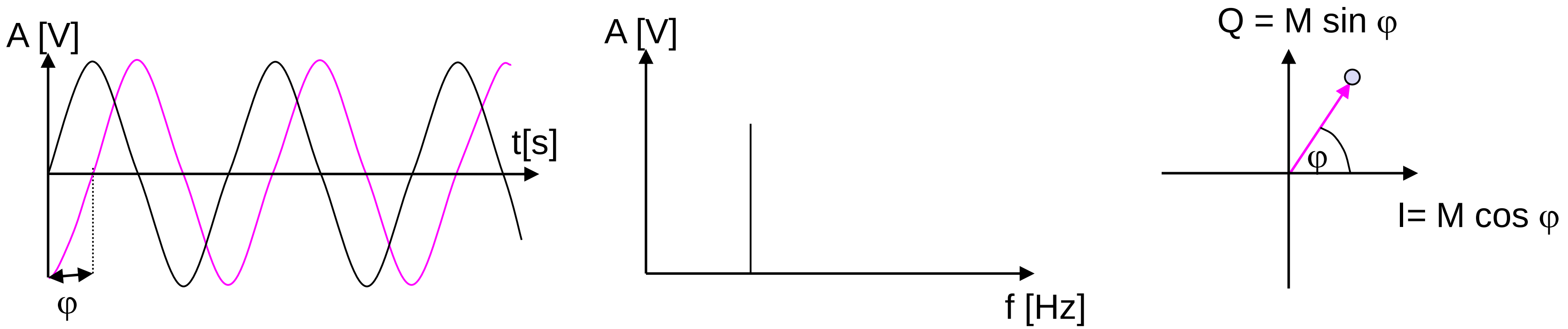
$$Z_o = \sqrt{L/C}.$$


E-PLANE
TRANSVERSE PLANE
H-PLANE
(a) (b) (c) (d) (e) (f) (g)
-jB
-jB
(h)
(i)
OPEN
(j)

Frequency domain representation of signals

Signals

- Different representations of signals
  - time (time domain)
  - frequency spectrum (frequency domain)
  - phase state diagram (amplitude M and phase φ in polar coordinates)

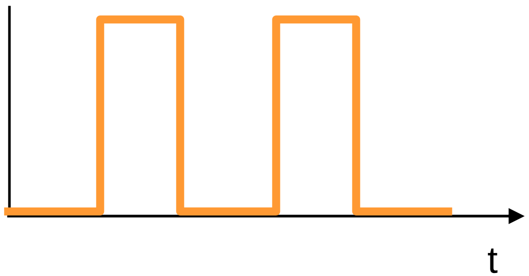


- Composed signals translated into frequency domain using Fourier transform
- Digital signals need
  - Modulation with a carrier frequency for transmission

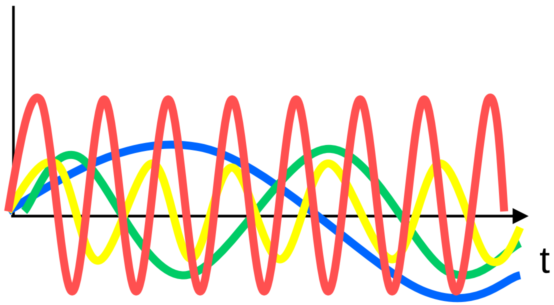
Fourier representation of periodic signals

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)$$

$c/2$ - DC component of the signal
n = 1 - fundamental
n = 2,3... - harmonics

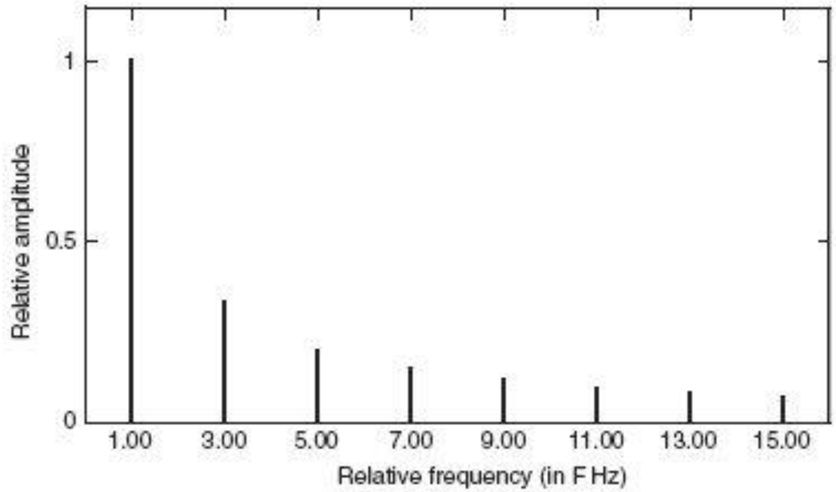


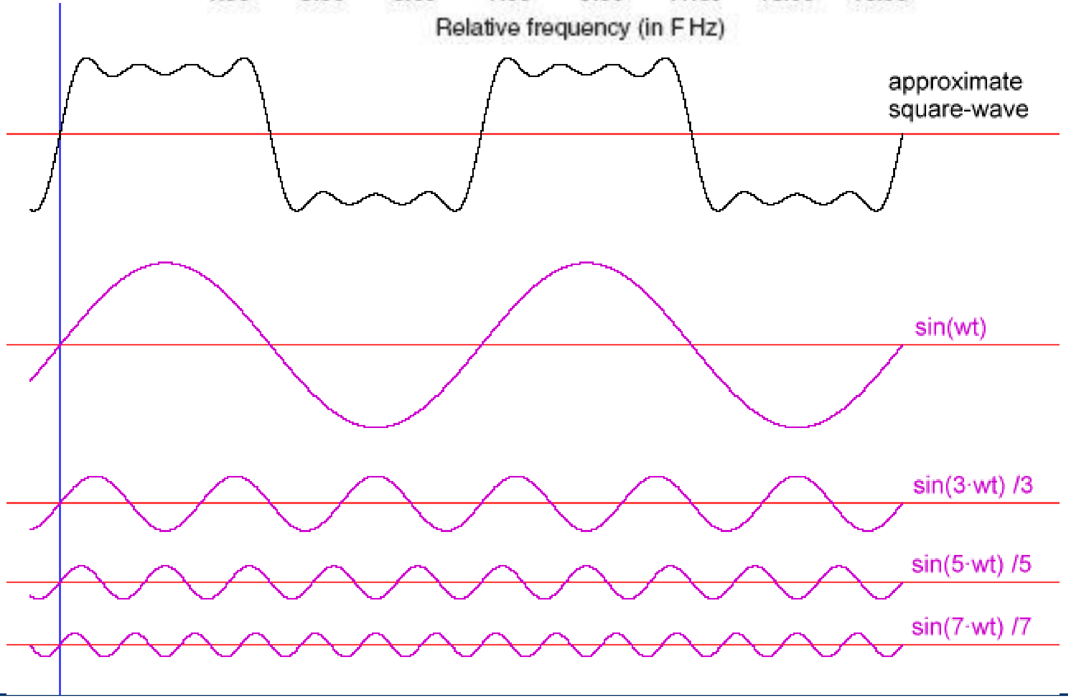
ideal periodic signal



real composition
(based on harmonics)

Example: square wave





Decibel notation

Decibel Notation (dB)

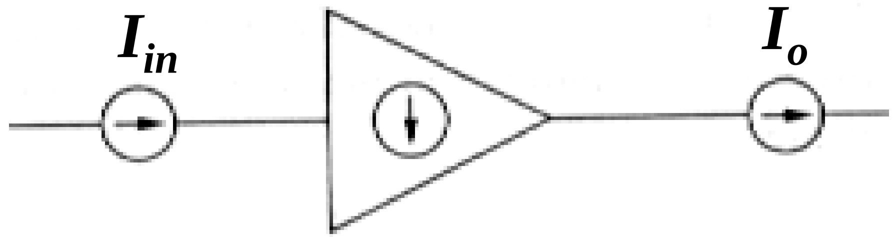
- Logarithmic ratio of two signal levels

$$\textbf{dB} \text{ (Decibel)} = 10 \log_{10} (P_2/P_1)$$

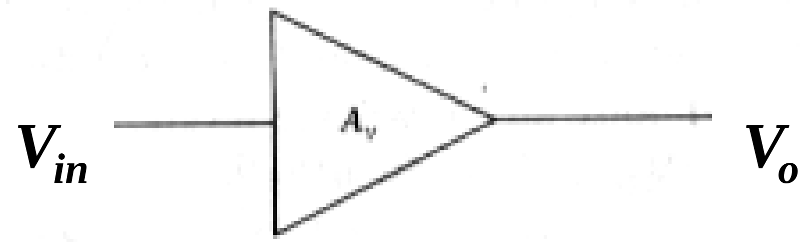
- A gain of **3 dB** represents **twice** the power
- A gain of **-3 dB** (loss of 3 dB) represents **half** of the power
- A gain of **10 dB** represents **10 times** the power
- A gain of **20 dB** represents **100 times** the power

Basic equations to calculate decibels

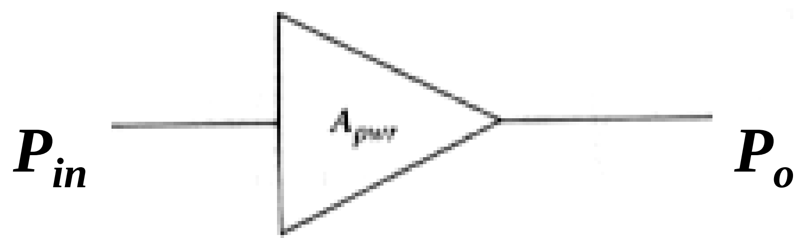
$$dB = 20\log\left(\frac{I_o}{I_{in}}\right)$$



$$dB = 20\log\left(\frac{V_o}{V_{in}}\right)$$



$$dB = 10\log\left(\frac{P_o}{P_{in}}\right)$$



Special decibel scales

- **dBm (dB miliWatt)**
- Power Relative to 1 mW, i.e. 0 dBm is 1 mW

$$P[dBm] = 10 \log (P[W]/1\ mW)$$

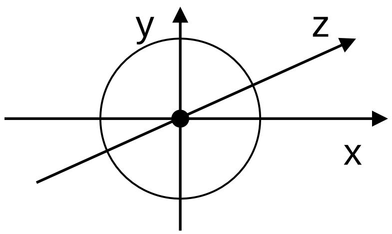
- Very used in radiofrequency measurements (RF)
- Ex: What is the signal level 9 mW as expressed in dBm?
  - P[dBm] = 10 log (9 mW/1 mW) = 9.54 dBm

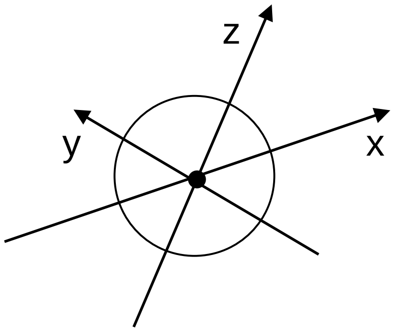
- **dBW (dB Watt)**
- Power Relative to 1 W, i.e. 0 dBW is 1 W

Antennas

Antennas

- For radiation and reception of electromagnetic waves
- In two-way communication, the same antenna can be used for transmission and reception
- Isotropic radiator: equal radiation in all directions (three dimensional) - only a theoretical reference antenna
- Real antennas always have directive effects (vertically and/or horizontally)
- Radiation pattern: measurement of radiation around an antenna

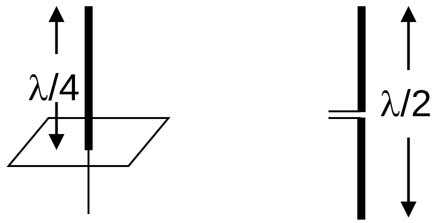




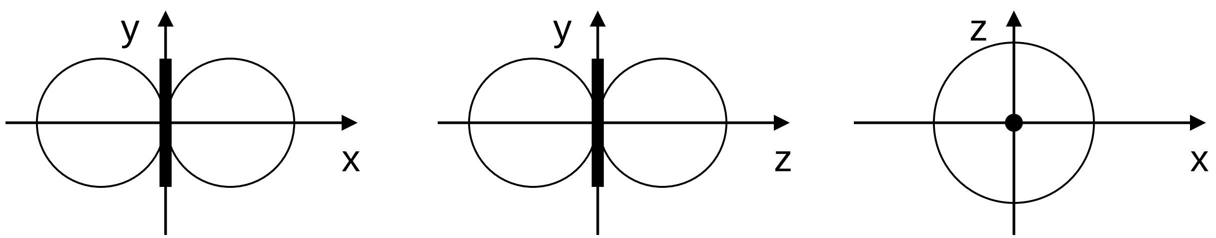
ideal
isotropic
radiator

Antennas: dipoles

- Real antennas are not isotropic radiators but, e.g., dipoles with lengths $\lambda/4$ on car roofs or $\lambda/2$ as Hertzian dipole
  ➔ size of antenna proportional to wavelength



- Example: Radiation pattern of a simple Hertzian dipole



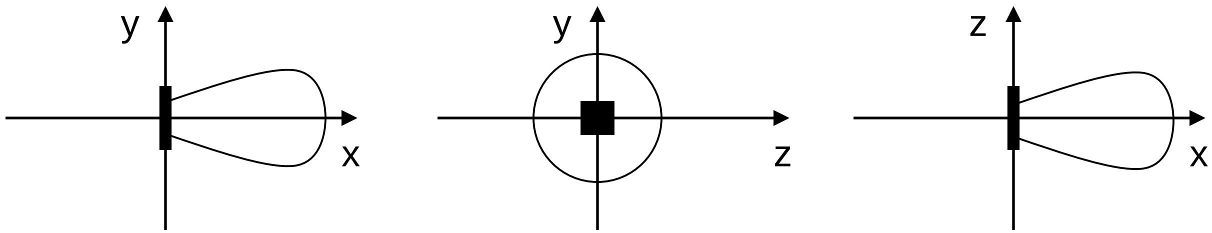
side view (xy-plane) side view (yz-plane) top view (xz-plane)

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)

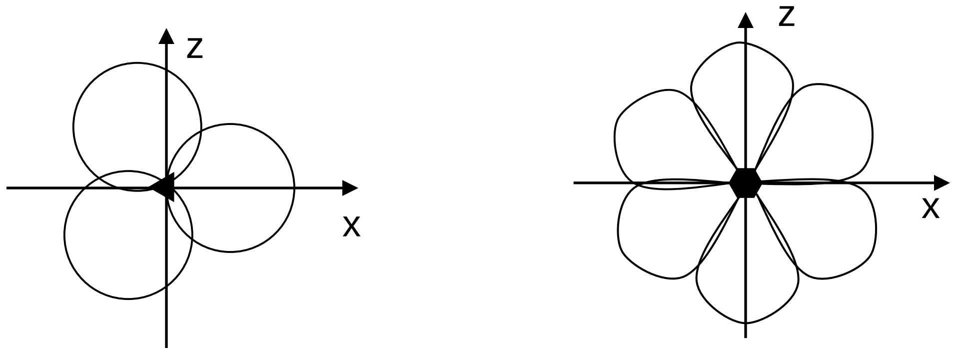
Antennas: directed and sectorized

- Often used for microwave connections or base stations for mobile phones (e.g., radio coverage of a valley)



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

directed antenna



top view, 3 sector top view, 6 sector

sectorized antenna

Antenna Gain

- Antenna gain
  - A measure of the directionality of an antenna.
  - Relation of power output, in a particular direction, compared to that produced by omnidirectional antenna (isotropic)
- Effective area
  - Equivalent area from which an antenna directed toward the source of an electromagnetic wave absorbs its energy
- Relationship between antenna gain and effective area

$$G = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi f^2 A_e}{c^2}$$

  - G = antenna gain
  - A_e = effective area
  - f = carrier frequency
  - c = speed of light (~ 3 x 10^8 m/s)
  - λ = carrier wavelength

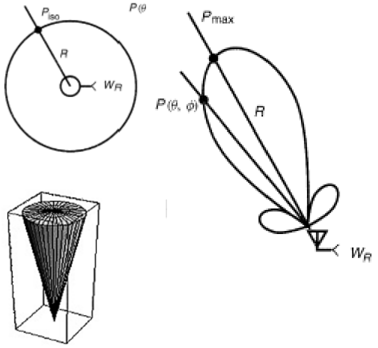
Antenna gain and effective area

Type of antenna	Effective area	Power gain
Isotropic	$\lambda^2/4\pi$	1
Infinitesimal dipole or loop	$1.5\lambda^2/4\pi$	1.5
Half-wave dipole	$1.64\lambda^2/4\pi$	1.64
Horn, mouth area A	0.81A	$10A/\lambda^2$
Parabolic, face area A	0.56A	$7A/\lambda^2$
turnstile	$1.15\lambda^2/4\pi$	1.15

Directividade

Por comparação com o radiador isotrópico

$$D(\theta,\varphi) = \frac{\text{Potência radiada por ângulo sólido}}{\text{Potência total radiada}/4\pi} = \frac{\Delta P_r(\theta,\varphi)/\Delta\Omega}{P_r/4\pi}$$



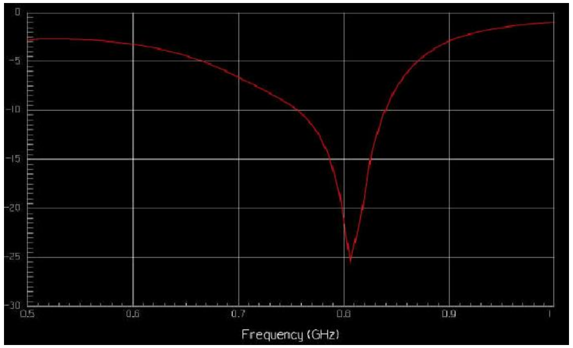
Ganho

$$G(\theta,\varphi) = \frac{\text{Potência radiada por ângulo sólido}}{\text{Potência total fornecida}/4\pi} = \frac{\Delta P_r(\theta,\varphi)/\Delta\Omega}{P_{in}/4\pi}$$

Eficiência

$$\eta \equiv \frac{P_r}{P_{in}} = \frac{G(\theta,\varphi)}{D(\theta,\varphi)}$$

Largura de banda

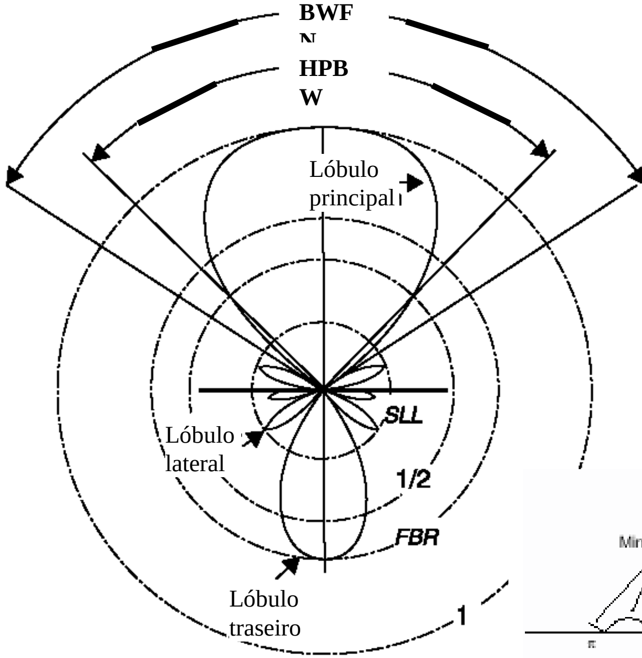


Reflexão - Impedância de entrada

$$\Gamma = \frac{Z_a - Z_0}{Z_a + Z_0}$$

Diagrama de radiação

Variação da intensidade do campo eléctrico ou magnético com a direcção



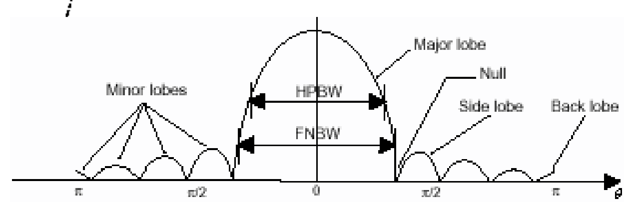
Figuras de mérito do diagrama de radiação

HPBW – *Half Power Beam Width*

BWFN – *Beam Width between firts nulls*

FBR – *Front to Back Ratio* $= \dfrac{U_{\max}}{U_{FBR}}$

SLL – *Side Lobe Level* $= \dfrac{U_{SLL}}{U_{\max}}$



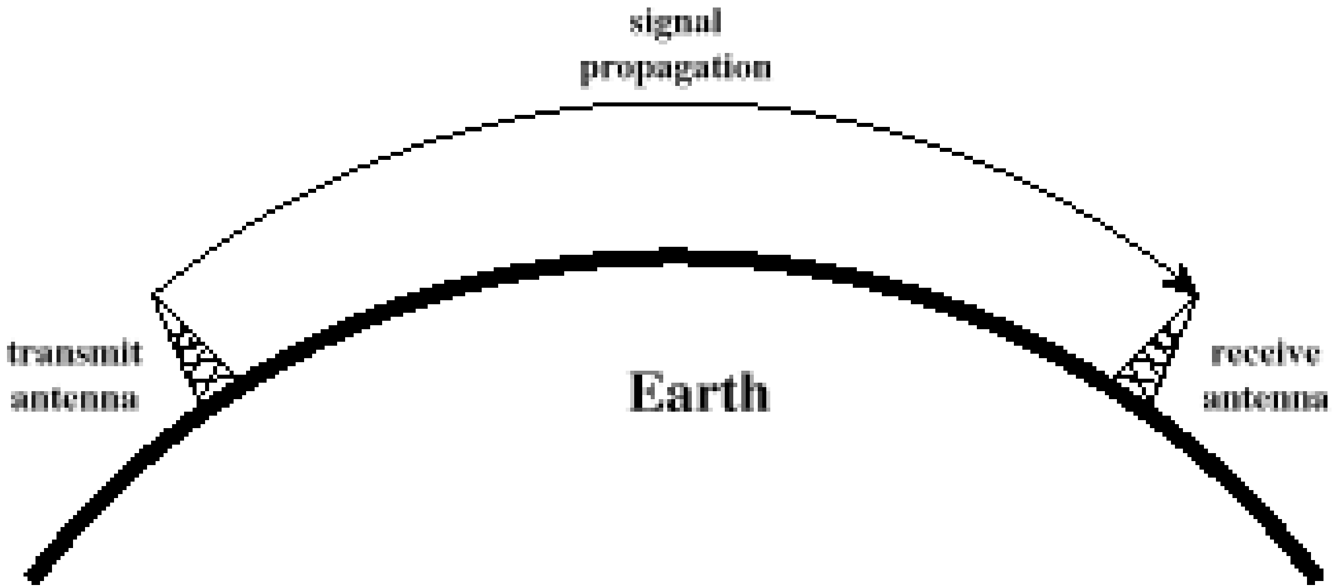
Nem sempre a antena com maior ganho é a mais adequada. (ex: wi-fi)

- Ground-wave propagation
- Sky-wave propagation
- Line-of-sight propagation

Signal propagation modes

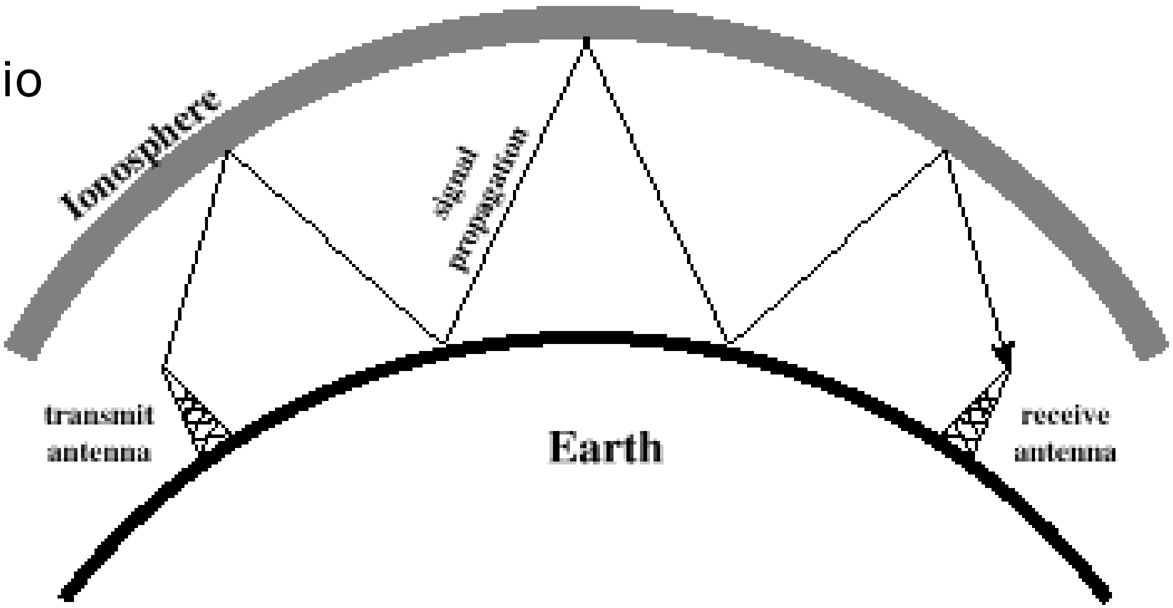
Ground Wave Propagation

- Follows contour of the earth
- Can Propagate considerable distances
- Frequencies up to 2 MHz
- Example
  - AM radio



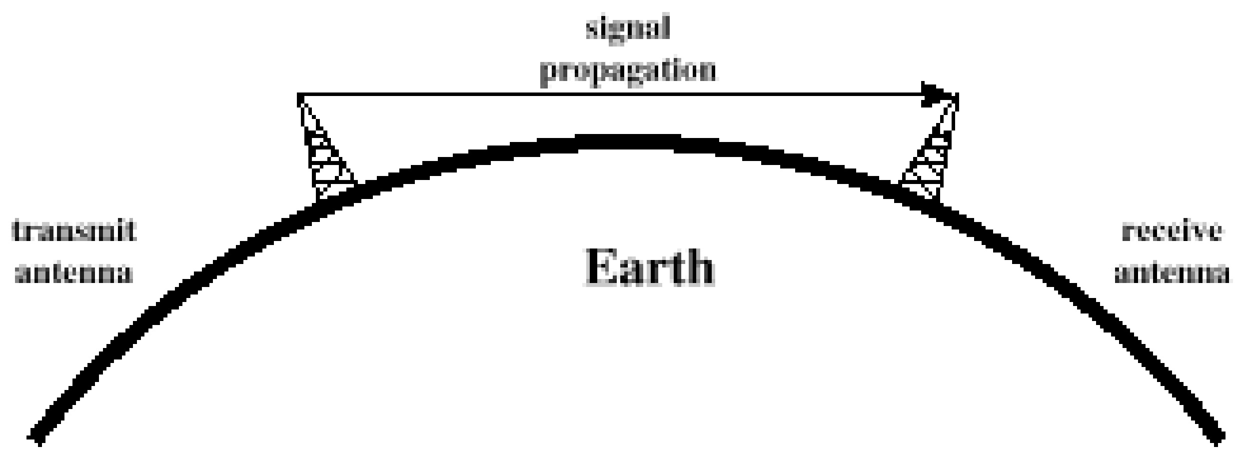
Sky Wave Propagation

- Signal reflected from ionized layer of atmosphere back down to earth
- Signal can travel a number of hops, back and forth between ionosphere and earth’s surface
- Frequencies around 2 to 30 MHz
- Reflection effect caused by refraction
- Examples
  - Amateur radio
  - CB radio



Line-of-Sight (LOS) Propagation

- Transmitting and receiving antennas must be within line of sight
  - Satellite communication – signal above 30 MHz not reflected by ionosphere
  - Ground communication – antennas within *effective* line of sight of each other due to refraction
- Refraction – bending of microwaves by the atmosphere
  - Velocity of electromagnetic wave is a function of the density of the medium
  - When wave changes medium, speed changes
  - Wave bends at the boundary between mediums



Line-of-Sight Equations

- Optical line of sight

$$d = 3.57\sqrt{h}$$

- Effective, or radio, line of sight

$$d = 3.57\sqrt{\mathrm{K}h}$$

  - d = distance between antenna and horizon (km)
  - h = antenna height (m)
  - K = adjustment factor to account for refraction, rule of thumb K = 4/3

Line-of-Sight Equations

- Maximum distance between two antennas for LOS propagation:

$$3.57\left(\sqrt{\mathrm{K}h_1} + \sqrt{\mathrm{K}h_2}\right)$$

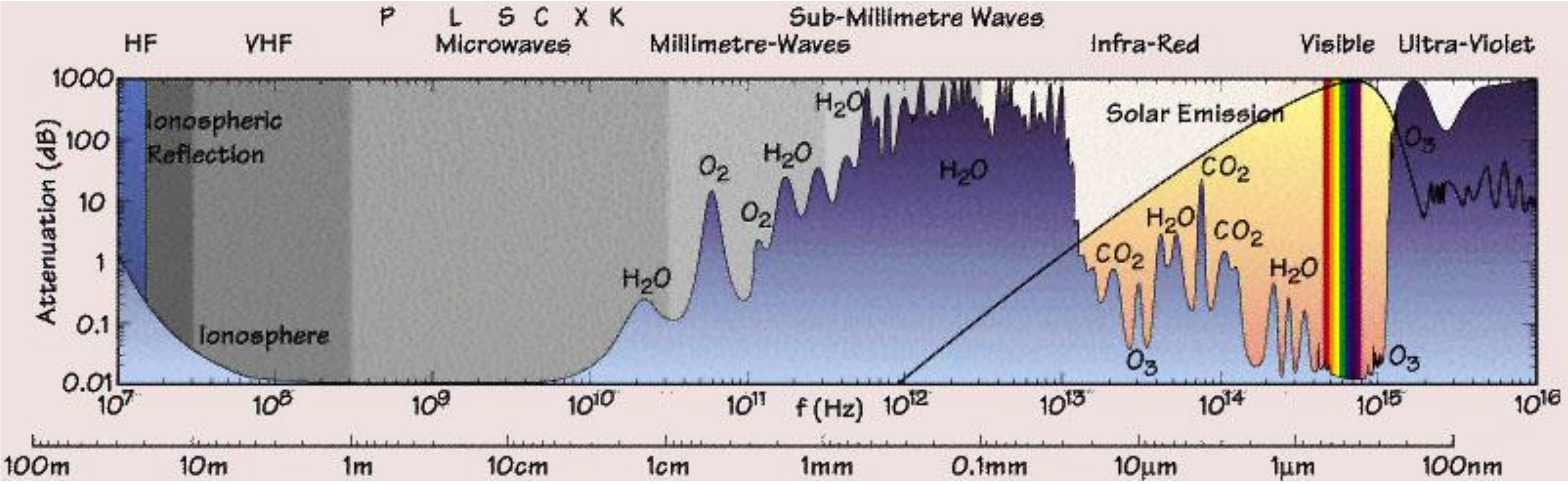
  - h_1 = height of antenna one
  - h_2 = height of antenna two

- Attenuation
- Free space loss
- Noise
- Interference
- Multipath

Wireless transmission deterioration factors

Attenuation

- Strength of signal (electromagnetic radiation) falls off with distance over transmission medium due to absorption or scattering of photons
- Absorption may vary according to medium/material and frequency



- Attenuation/path loss factors for unguided media
  - Received signal must have sufficient strength so that circuitry in the receiver can interpret the signal
  - Signal must maintain a level sufficiently higher than noise to be received without error

Free space loss

- Free space loss, ideal isotropic antenna

$$\frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2}$$

  - P_t = signal power at transmitting antenna
  - P_r = signal power at receiving antenna
  - λ = carrier wavelength
  - d = propagation distance between antennas
  - c = speed of light

  where d and λ are in the same units (e.g., meters)

Free space loss

- Free space loss equation can be recast:

$$L_{dB} = 10\log\frac{P_t}{P_r} = 20\log\left(\frac{4\pi d}{\lambda}\right)$$

$$= -20\log(\lambda) + 20\log(d) + 21.98\ \mathrm{dB}$$

$$= 20\log\left(\frac{4\pi f d}{c}\right) = 20\log(f) + 20\log(d) - 147.56\ \mathrm{dB}$$

* L_{dB} is the **path loss**, in dB

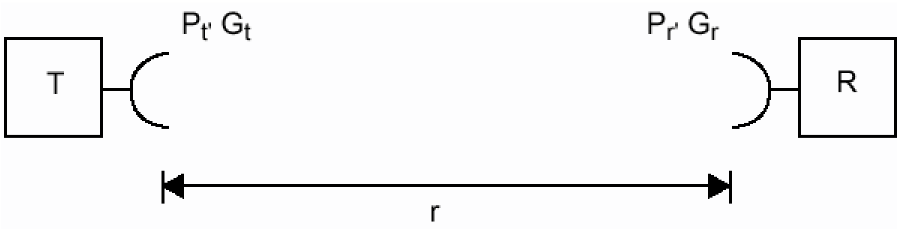
Free space loss

- Free space loss accounting for gain of antennas

$$\frac{P_t}{P_r} = \frac{(4\pi)^2 (d)^2}{G_r G_t \lambda^2} = \frac{(\lambda d)^2}{A_r A_t} = \frac{(cd)^2}{f^2 A_r A_t}$$

- G_t = gain of transmitting antenna
- G_r = gain of receiving antenna
- A_t = effective area of transmitting antenna
- A_r = effective area of receiving antenna

Considerando a propagação em meio livre



$$P_r = G_r G_t \left(\frac{\lambda}{4\pi r}\right)^2 P_t$$

Equação de transmissão de Friis

Válida quando

$r > 2D^2/\lambda$.

Free space loss equation

- Describes signal strength at distance d relative to some reference distance $d_0 < d$ for which strength is known
- $d_0 \geq$ *far-field distance (*depends on antenna technology)
- $L \geq 1$ accounts for system loss

$$P_{\text{recv}}(d) = \frac{P_{\text{tx}} \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi)^2 \cdot d^2 \cdot L}$$

$$= \frac{P_{\text{tx}} \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi)^2 \cdot d_0^2 \cdot L} \cdot \left(\frac{d_0}{d}\right)^2 = P_{\text{recv}}(d_0) \cdot \left(\frac{d_0}{d}\right)^2$$

* $P_{recv} \Leftrightarrow P_r$

$P_{recv}(d)$ – Power received (in W) at distance d

$P_{recv}(d_0)$ – Power received (in W) at distance d_0

Path loss equation

- Generalization of the free space loss equation, to take into account stronger loss than only caused by distance (e.g., walls absorption/reflexion), normally use a larger exponent ($\gamma > 2$)
  - γ is the ***path-loss exponent***

$$P_{\mathsf{recv}}(d) = P_{\mathsf{recv}}(d_0) \cdot \left(\frac{d_0}{d}\right)^{\gamma}$$

  - Knowing that:

$$P_{recv}(d)[dBW] = P_t[dbW] - PL(d)[dB]$$

  - Rewrite in logarithmic form (in dB):

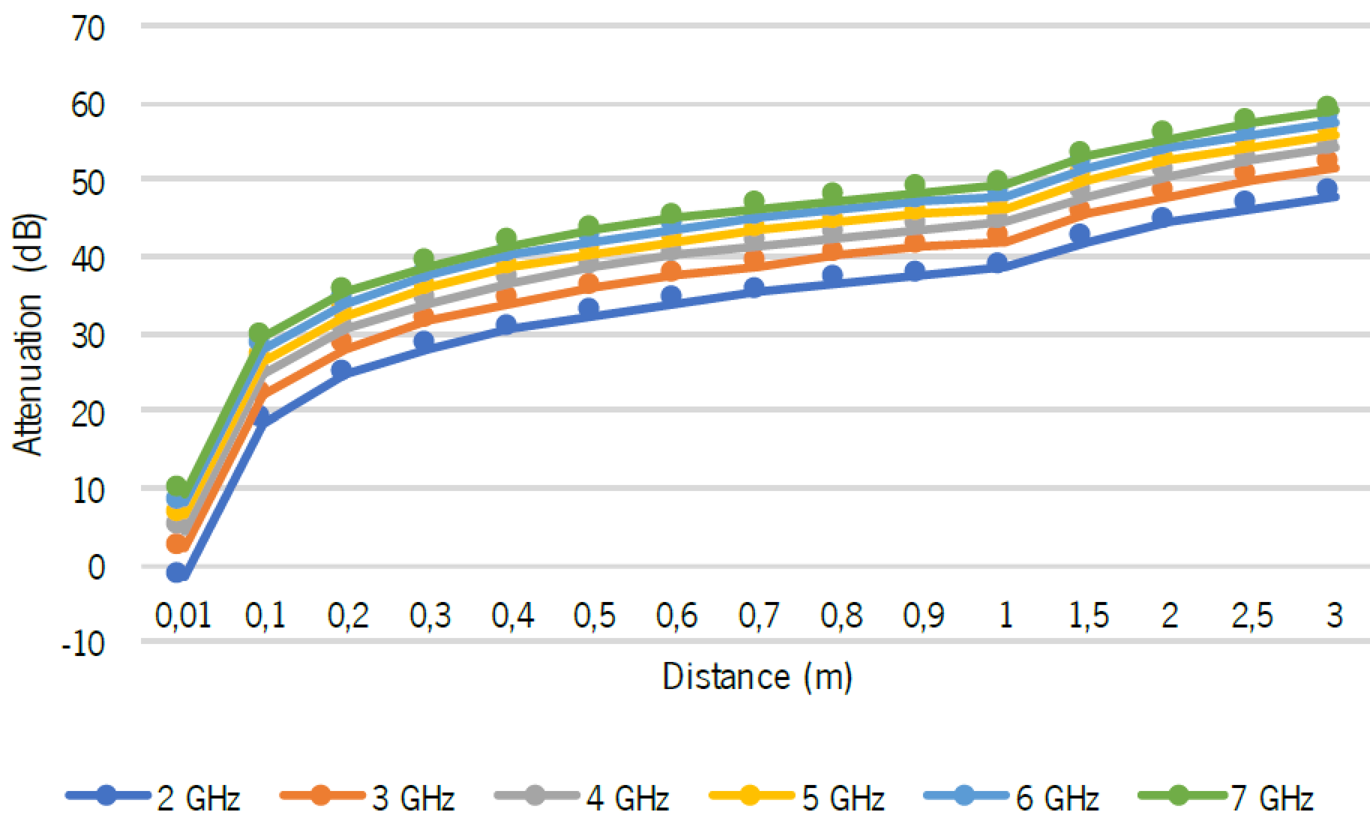
$$\mathsf{PL}(d)[\mathsf{dB}] \;=\; \mathsf{PL}(d_0)[\mathsf{dB}] \;+ 10\gamma \log_{10}\left(\frac{d}{d_0}\right)$$

* PL(d)[dB] ⇔ L_{dB} is the **path loss**, in dB, at distance *d*

Path loss equation (cont.)

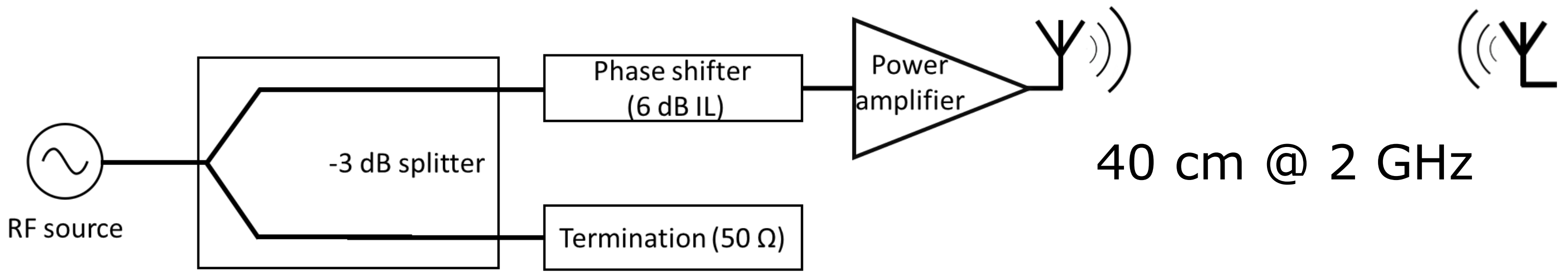
- Take shadowing/fading into account by a random variation
  - Add a Gaussian random variable to dB representation
    - with 0 mean, variance σ^2
  - Equivalent to multiplying with a lognormal distributed random variable in metric units => *lognormal fading*

$$\mathrm{PL}(d)[\mathrm{dB}] = \mathrm{PL}(d_0)[\mathrm{dB}] + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma[\mathrm{dB}]$$

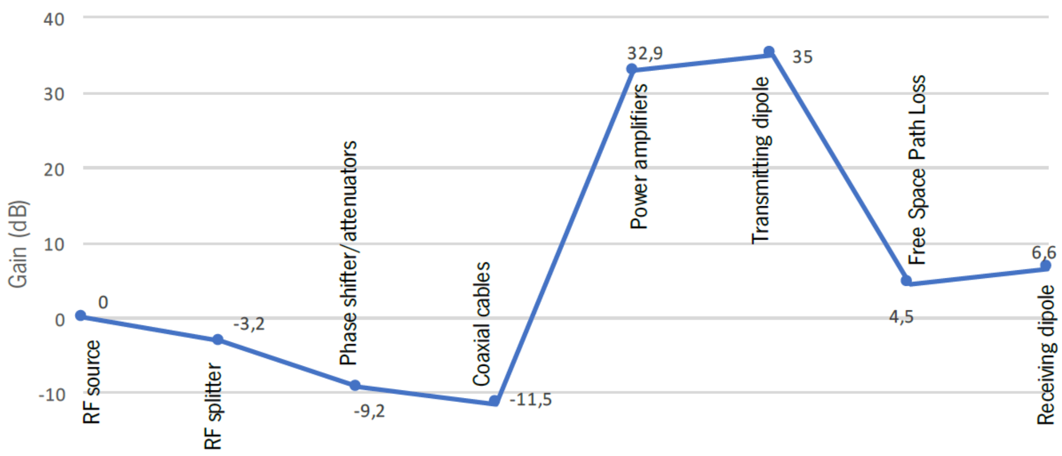


70
60
50
40
30
20
10
0
-10
Attenuation (dB)
0,01 0,1 0,2 0,3 0,4 0,5 0,6 0,7 0,8 0,9 1 1,5 2 2,5 3
Distance (m)
2 GHz
3 GHz
4 GHz
5 GHz
6 GHz
7 GHz

Link Budget

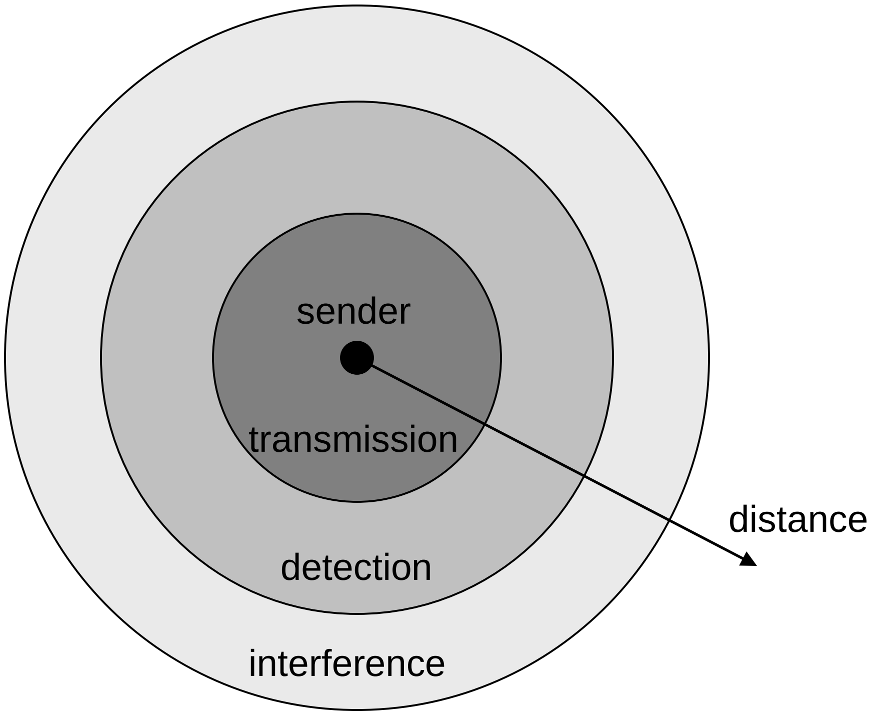


Component	Gain (dB or dBi)
RF splitter	-3.2
Phase shifter/ attenuators	-6
Coaxial cables	-2,3
Power amplifiers	44.4
Transmitting dipole	2,1
Free Space Path Loss	-30,5
Receiving dipole	2,1



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



Thermal noise

- Type of noise caused due to agitation of electrons
- Present in all electronic devices and transmission media
- Function of temperature
- Cannot be eliminated
- Amount of thermal noise to be found in a bandwidth of 1Hz in any device or conductor is:

$$N_0 = \mathrm{k}T\,(\mathrm{W/Hz})$$

  - N_0 = noise power density in watts per 1 Hz of bandwidth
  - k = Boltzmann's constant = 1.3803×10^{-23} J/K
  - T = temperature, in kelvins * (absolute temperature)

* [K] = [°C] + 273.15

Thermal noise

- Thermal noise is assumed to be independent of frequency (white)
- Thermal noise present in a bandwidth of *B* Hertz (in watts):

$$N = \mathrm{k}TB$$

or, in decibel-watts

$$N = 10 \log \mathrm{k} + 10 \log T + 10 \log B$$

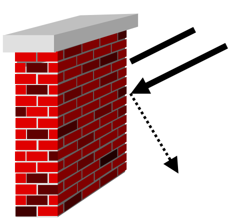
$$= -228.6\,\mathrm{dBW} + 10 \log T + 10 \log B$$

Interference

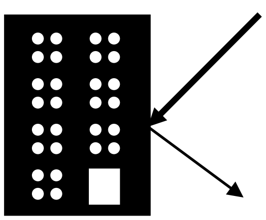
- Interference from other sources (third parties)
  - Co-channel interference: another sender uses the same spectrum
  - Adjacent-channel interference: another sender uses some other part of the radio spectrum, but receiver filters are not good enough to fully suppress it

Signal propagation phenomena

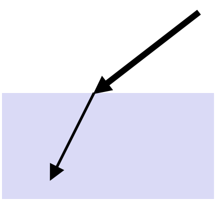
- Shadowing – obstruction of the signal
- Reflection – occurs when signal encounters a surface that is large relative to the wavelength of the signal
- Refraction – occurs when the density of a medium changes
- Scattering – scatters the incoming signal into several weaker outgoing signals. Occurs when incoming signal hits an object whose size in the order of the wavelength of the signal or less
- Diffraction – bends the signal. Occurs at the edge of an impenetrable body that is large compared to wavelength of radio wave



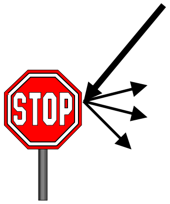
shadowing



reflection



refraction

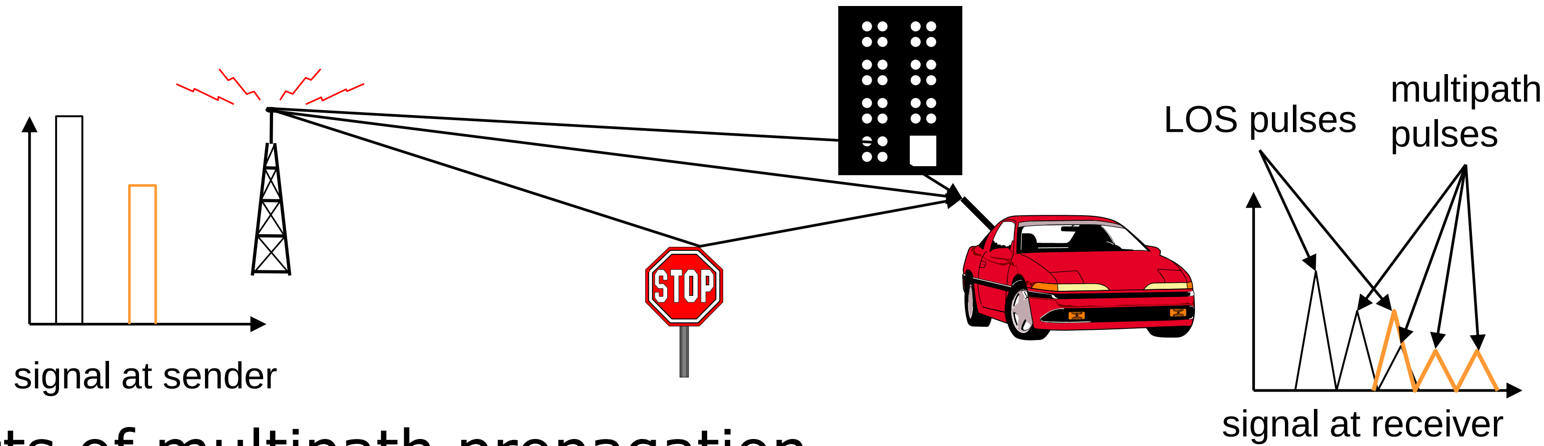


scattering

diffraction

Multipath propagation

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



- Effects of multipath propagation
  - Fading
    - Multiple copies of a signal arrive at different phases
    - If phases add destructively, the signal level declines, making detection more difficult
  - Intersymbol interference (ISI)
    - One or more delayed copies of a pulse may arrive at the same time as the pulse for a subsequent bit

Signal-to-noise ratios

Expression E_b/N_0

- Ratio of signal energy per bit to noise power density per Hertz

$$\frac{E_b}{N_0} = \frac{ST_b}{N_0} = \frac{S/R}{N_0} = \frac{S}{\mathrm{k}TR}$$

S – Signal power   Tb – Bit duration   R – Bit rate

- The bit error rate for digital data is a function of E_b/N_0
- As bit rate (R) increases, transmitted signal power (S) must increase to maintain required E_b/N_0

Expression E_b/N_0

- We can relate E_b/N_0 with SNR as follows:
  - The noise in a signal with bandwidth B_T is

$$N = N_0 B_T$$

  - Substituting, we have

$$\frac{E_b}{N_0} = \frac{S}{N_0 R} = \frac{S}{N}\frac{B_T}{R}$$