Mobile Communications

Wireless Transmission

Path Loss, Shadowing, Multipath, Capacity

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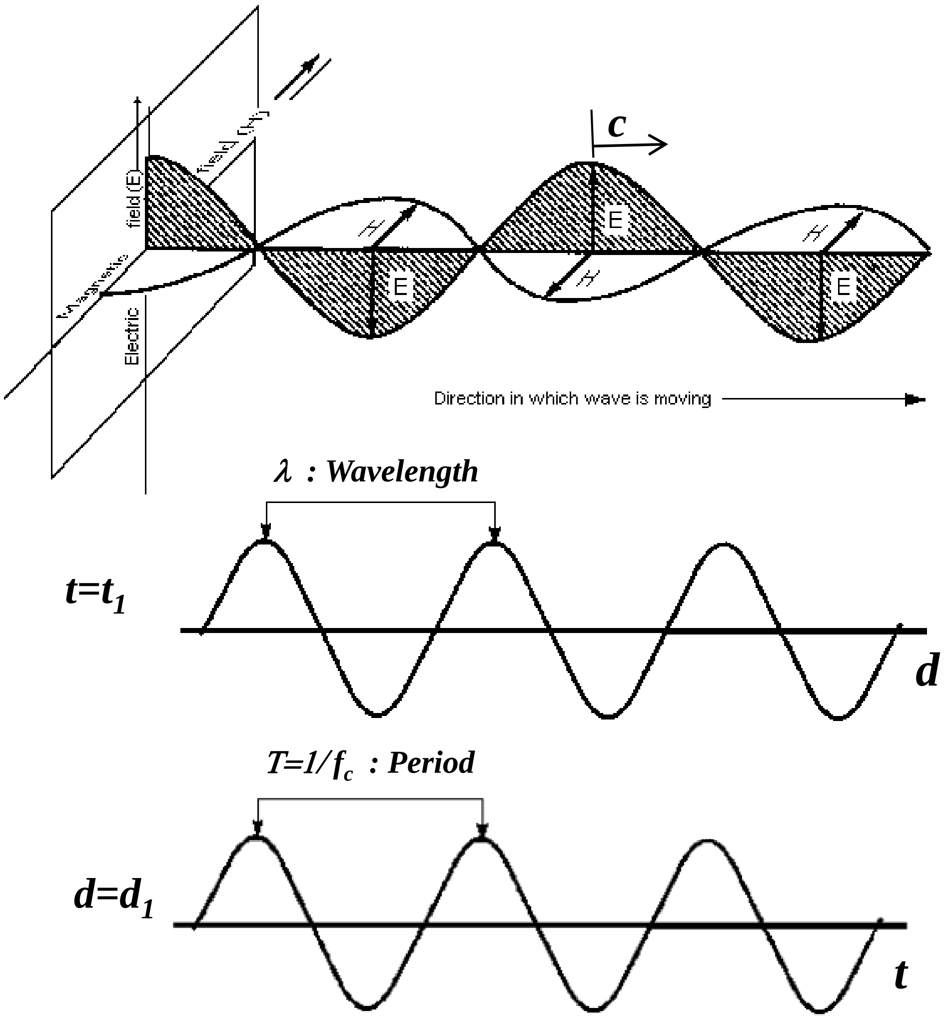
- *How does an EM wave propagate in a wireless channel?*
- *What is antenna and its gain?*
- *What is shadowing, reflection, refraction, scattering, and diffraction?*
- *What is path loss? How to model it?*
- *How to model shadowing?*
- *What is multipath? How to model it?*
- *What is the maximum theoretical capacity of a wireless channel?*

Electromagnetic Wave



$$\lambda = c/f$$

$c = 3\times10^{8} \quad m/s,$ speed of light

f_c= 300 MHz ➔ λ = 1m
f_c= 1 GHz ➔ λ =30 cm
f_c= 3 GHz ➔ λ =10 cm
f_c= 30 GHz ➔ λ =10 mm
f_c= 300 GHz ➔ λ =1 mm

Frequencies for Radio Transmission

Frequency bands defined by ITU-R ***Radio Regulations***

$$band_i \in [0.3 \times 10^i Hz, 3 \times 10^i Hz[.$$

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

Band Number	Symbol	Frequency Range
4	VLF	3-30 kHz
5	LF	30-300 kHz
6	MF	3000-3000 kHz
7	HF	3-30 MHz
8	VHF	30-300 MHz
9	UHF	300-3000 MHz
10	SHF	3-30 GHz
11	EHF	30-300 GHz
12		300-3000 GHz

f_c= 300 MHz ➔ $\lambda = 1m$

f_c= 3 GHz ➔ $\lambda = 10\ cm$

f_c= 30 GHz ➔ $\lambda = 10\ mm$

f_c= 300 GHz ➔ $\lambda = 1\ mm$

Frequency Allocation to Radio Services in Portugal

ANACOM manages the electromagnetic spectrum, in Portugal

www.anacom.pt , Quadro Nacional de Atribuição de Frequências (QNAF)

Antenna – The Isotropic Radiator

- Antenna

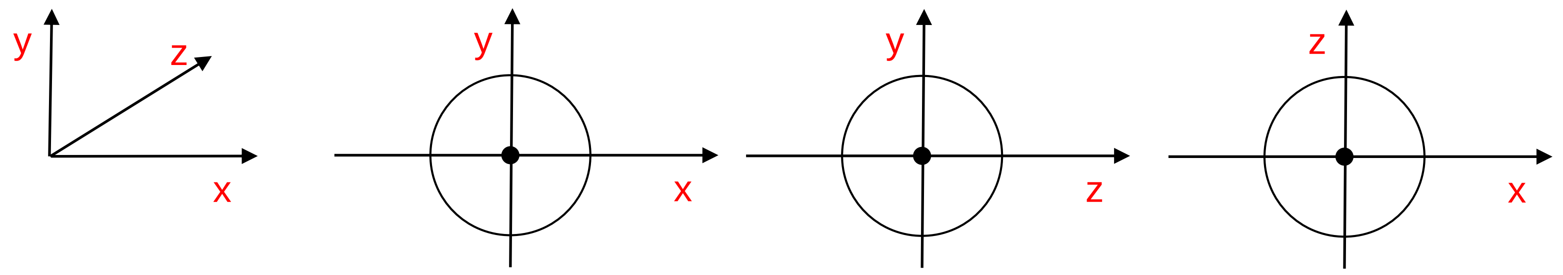
  couples wires to space, for electromagnetic wave transmission or reception

- Radiation pattern

  pattern of electomagnetic radiation around an antenna

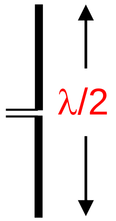
- Isotropic radiator
  - » equal radiation in 3 directions (**x**, **y**, **z**)
  - » theoretical reference antenna

Isotropic radiator

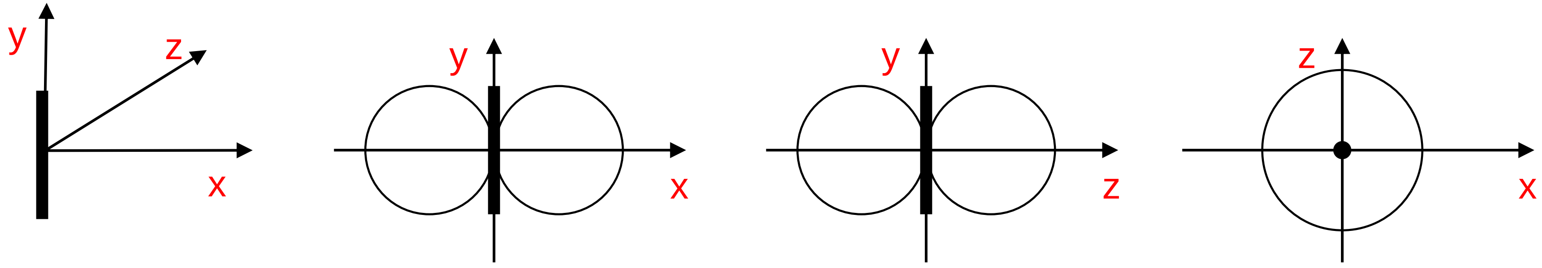


Antennas - Simple Dipoles

- Real antennas are not isotropic radiators
- Simple antenna dipole
  - » Length λ/2 ➔ Hertzian dipole



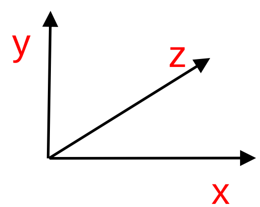
- Shape (length) of antenna is proportional to λ
- Radiation pattern of a simple Hertzian dipole

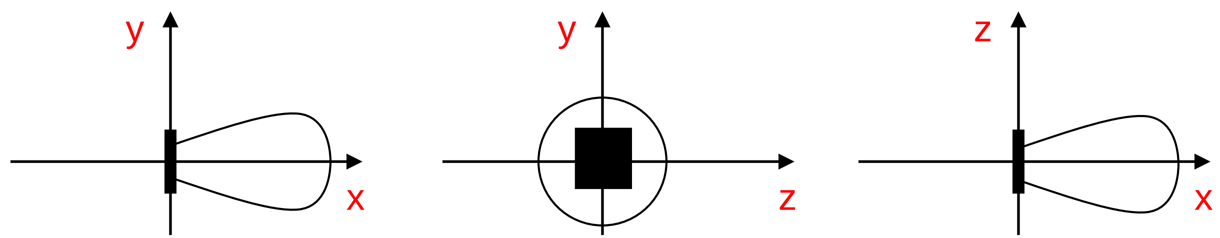


Antennas - Directed and Sectorized

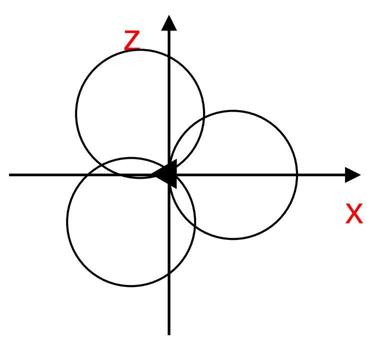
Used for microwave connections or base stations for mobile phones

Directed antenna

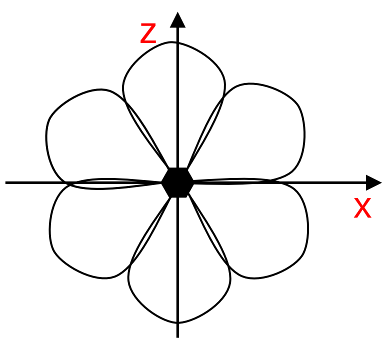




Sectorized antenna

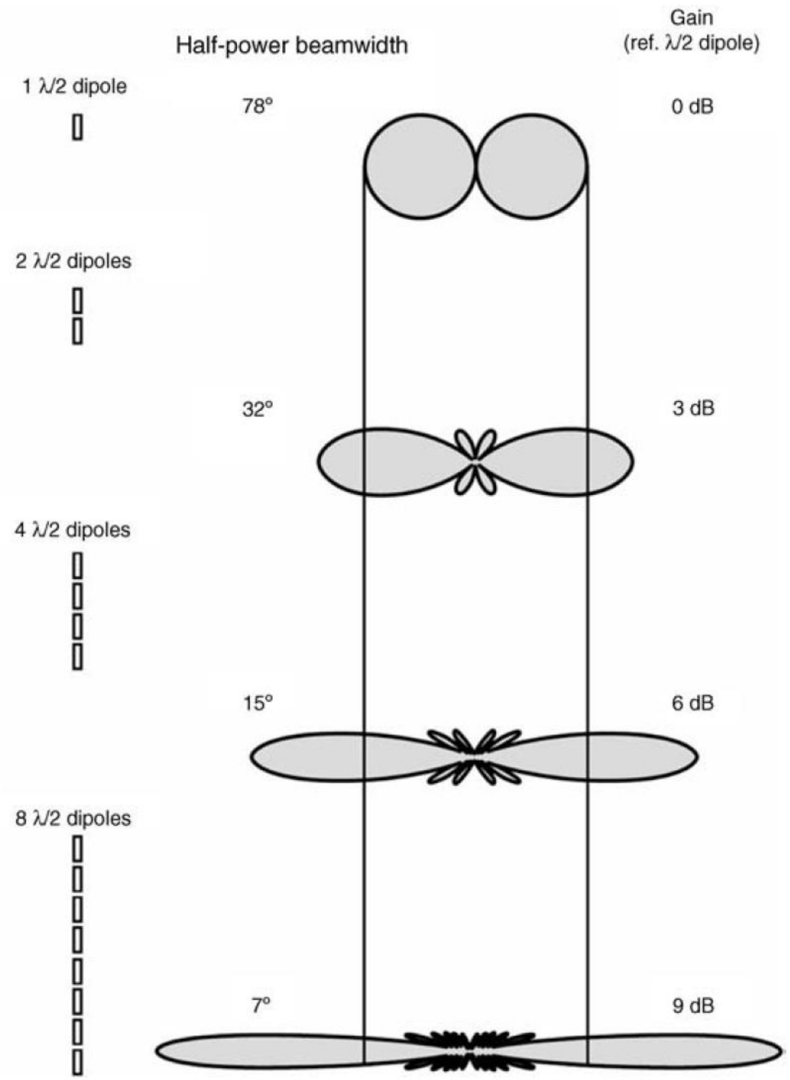


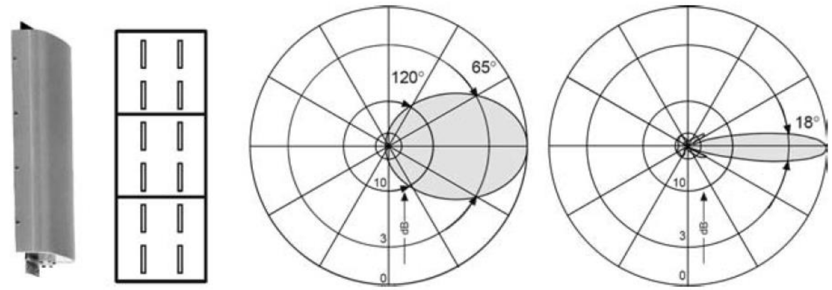
top view, 3 sector



top view, 6 sector

More on Antennas…

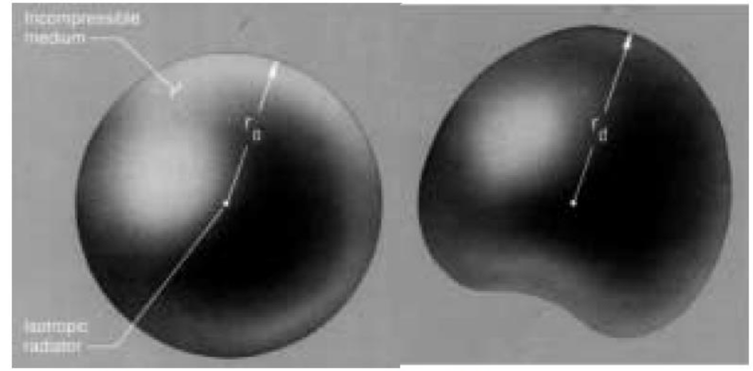




How does the power of a received signal depend on the distance to the transmitter and on the wavelength (λ)?

Why?

Antenna Gain, EIRP



a) Symmetric radiation pattern of an isotropic radiator. b) Directive radiation pattern.

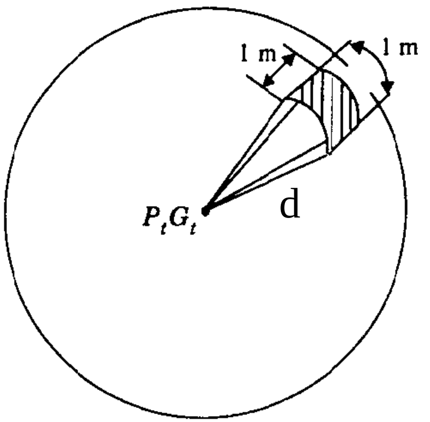
- Antenna Gain, $G = \dfrac{P_{main\_lobe}}{P_{iso}}$
  - maximum power in direction of the main lobe (P_{main_lobe}), compared to power of an isotropic radiator (P_{iso}) transmitting the same average power
  - *similar to an incompressible balloon*
- A_e – Antenna aperture (area of antenna), $A_e = G\dfrac{\lambda^2}{4\pi} \quad [m^2]$
  - Depends on physical antenna characteristics
  - The longer the wavelength λ, the larger A_e
- *Effective Isotropic Radiate Power (EIRP)*
  - $EIRP = P_t\, G_t$
  - Maximum radiated power in the direction of maximum antenna gain

Received Power at Distance d - $P_r(d)$

- Power flow density P_d (W/m²)

$$P_d = \frac{EIRP}{4\pi d^2} = \frac{P_t G_t}{4\pi d^2} \quad \left[W/m^2 \right]$$

sphere's area



- Received Power at distance d, $P_r(d)$

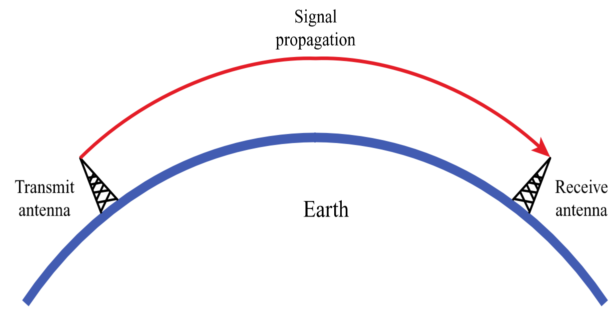
$$P_r(d) = P_d A_e = \frac{P_t G_t}{4\pi d^2} \frac{G_r \lambda^2}{4\pi} = G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 P_t \quad [W]$$

*Aperture (area) of **receiving** antenna*

» Also known as the ***Friis transmission equation***

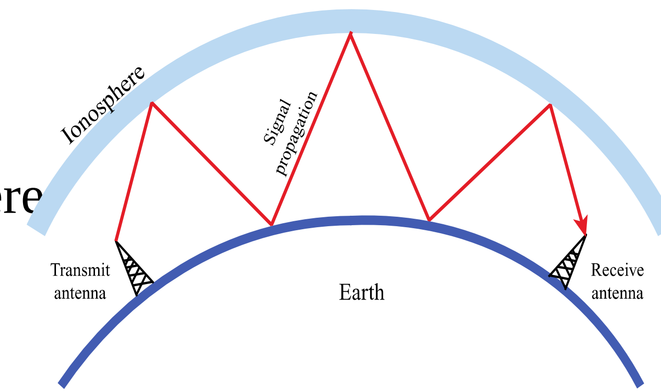
Propagation Modes

- Ground-wave propagation
  - » Follows contour of the earth
  - » Can propagate considerable distances
  - » Frequencies up to 2 MHz



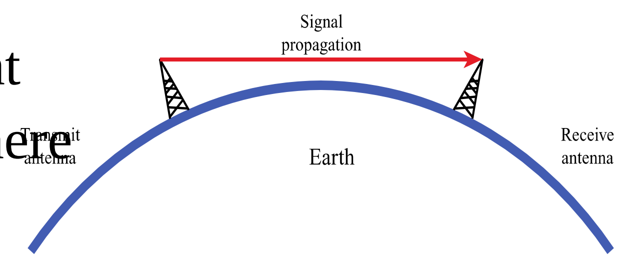
(a) Ground wave propagation (below 2 MHz)

- Sky-wave propagation
  - » Signal reflected from ionized layer of atmosphere
  - » Frequencies between 2 MHz and 30 MHz



(b) Sky wave propagation (2 to 30 MHz)

- Line-of-sight propagation
  - » Transmitting/receiving antennas in line of sight
  - » Signal above 30 MHz not reflected by ionosphere



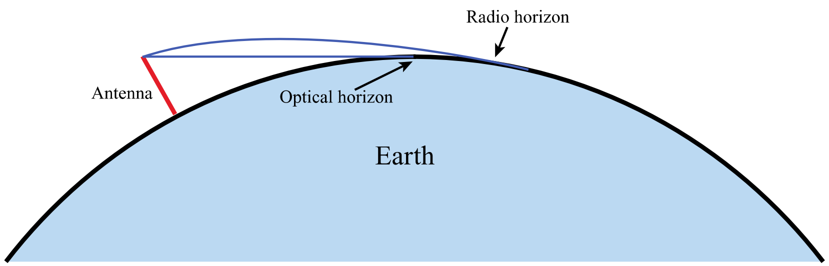
(c) Line-of-sight (LOS) propagation (above 30 MHz)

Radio Horizon

- Maximum distance between two antennas for LOS propagation
  - » Considering earth curvature and atmosphere refraction

$$d = 3570 * \left(\sqrt{\mathrm{K}h_1} + \sqrt{\mathrm{K}h_2} \right)$$

- – h_1 = height of first antenna (m)
- – h_2 = height of second antenna (m)
- – d = distance (m)
- – K= 4/3



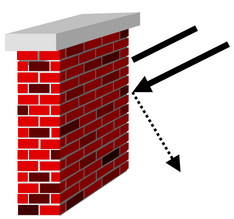
What other factors,

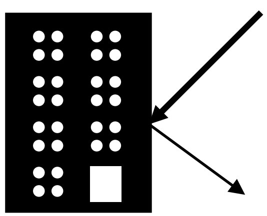
besides frequency and distance,

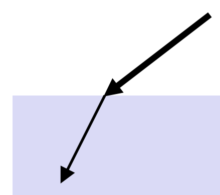
may affect the **power received** by a mobile phone?

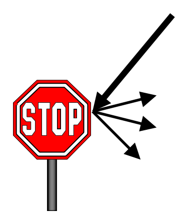
Signal Propagation – Key Concepts

- Propagation often modeled as rays (light)
- Line-of-Sight (LOS) – direct ray the receiver gets from transmitter
- Relevant concepts
  - Shadowing, Reflection ➔ caused by objects much larger than the wavelength
  - Refraction ➔ caused by different media densities
  - Scattering ➔ caused by surfaces in the order of wavelengths
  - Diffraction ➔ similar to scattering; deflection at the edges

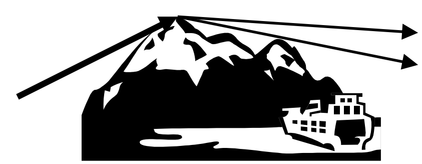

shadowing


reflection

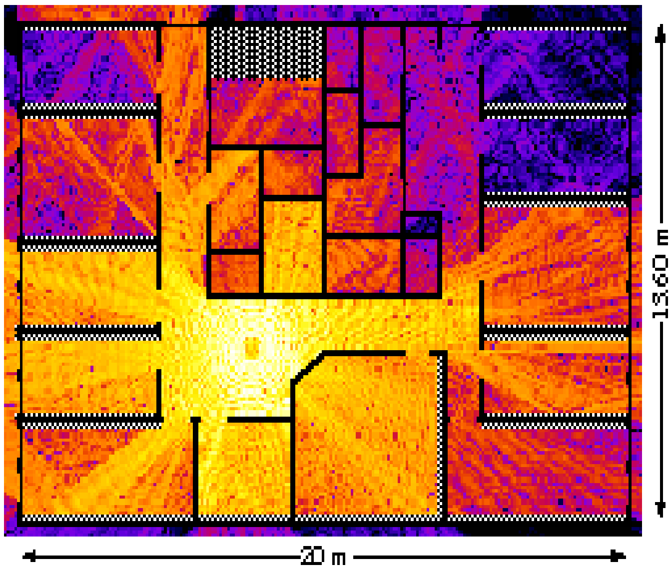

refraction

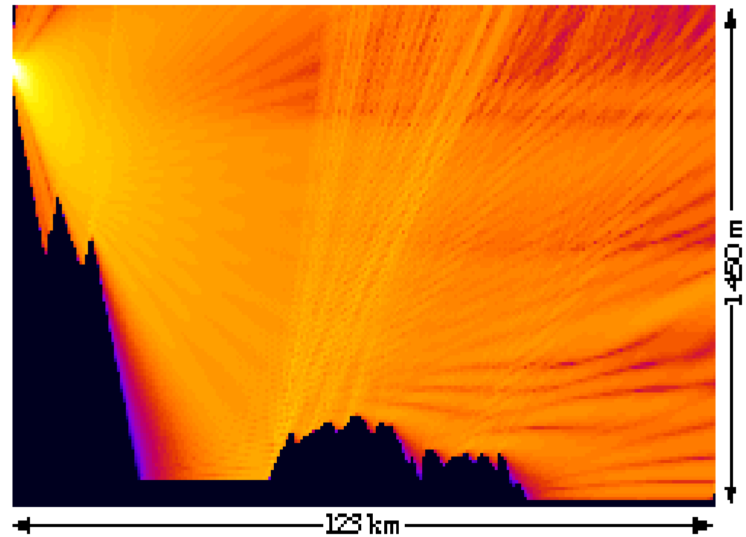


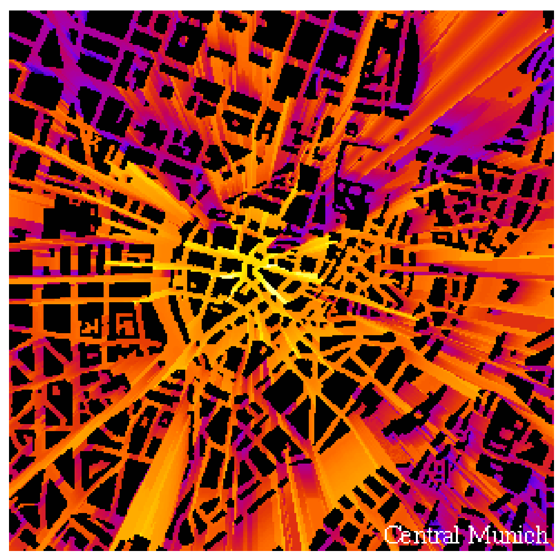
scattering


diffraction

Real World Examples



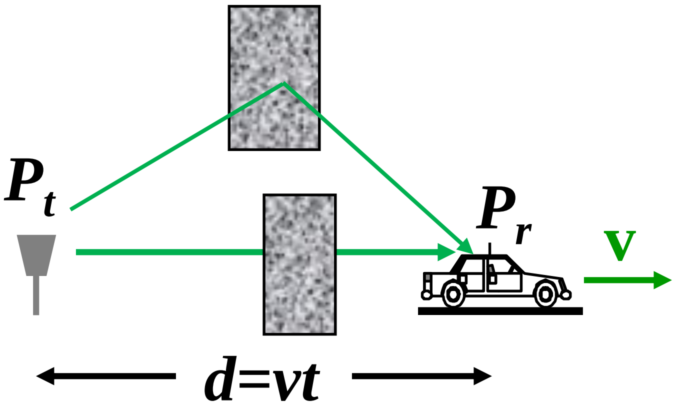


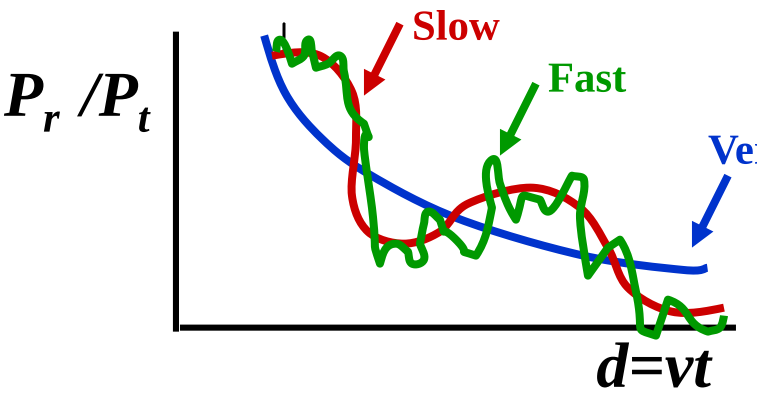


Signal Propagation and Wireless Channels

Received Power can be *modelled* by 3 factors

- **Path loss**
  - Caused by **dispersion of radiated power in all directions**, as discussed previous slides
  - Depends mainly on the sender-receiver distance
- **Shadowing**
  - Caused by obstacles between the transmitter and the receiver
  - Depends on the **obstruction of large objects**
- **Multipath**
  - Constructive and destructive **addition of multiple signal components** (rays) at the receiver. Fast fading





Path Loss Models

- Free space path loss model (Friis)

  Too simple; far from reality

- Two-Ray model

  Considering 2 rays: LOS-direct and ground-reflected

- Empirical models

  Based on measurements; do not generalize to other environments

- Simplified model

  Good for high-level analysis

W, dBW, dBm, dB, $Gain$

$$P_{r_W}, \left(Power = \frac{Energy}{Time} \right), \quad 1W = \frac{1J}{1s}$$

$$P_{r_{dBW}} = 10.\log\left(\frac{P_{r_W}}{1W}\right) = 10.\log P_{r_W}$$

$$P_{r_{dBm}} = 10.\log\left(\frac{P_{rW}}{1mW}\right) = P_{r_{dBW}} + 30dB$$

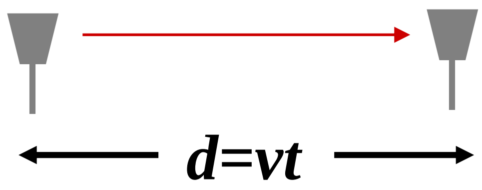
$$Gain_{dB} = 10.\log\left(\frac{P_{r_W}}{P_{s_W}}\right) = 10.\log P_{r_W} - 10.\log P_{s_W} = P_{r_{dBW}} - P_{s_{dBW}} = P_{r_{dBm}} - P_{s_{dBm}}$$

$$Loss_{dB} = Atenuation_{dB} = 10.\log\left(\frac{P_S}{P_r}\right) = P_{s_{dBW}} - P_{r_{dBW}} = P_{s_{dBm}} - P_{r_{dBm}} = -Gain_{dB}$$

$$FreeSpaceLoss_{dB} = 10\log\left(\frac{P_t}{P_r}\right) = 10\log\left(\frac{(4\pi d)^2}{G_t G_r \lambda^2}\right) = 20\log(4\pi) + 20\log d - 20\log\left(\sqrt{G_t G_r}\right) - 20\log\lambda$$

Path Loss - Free Space Model (LOS, Friis)

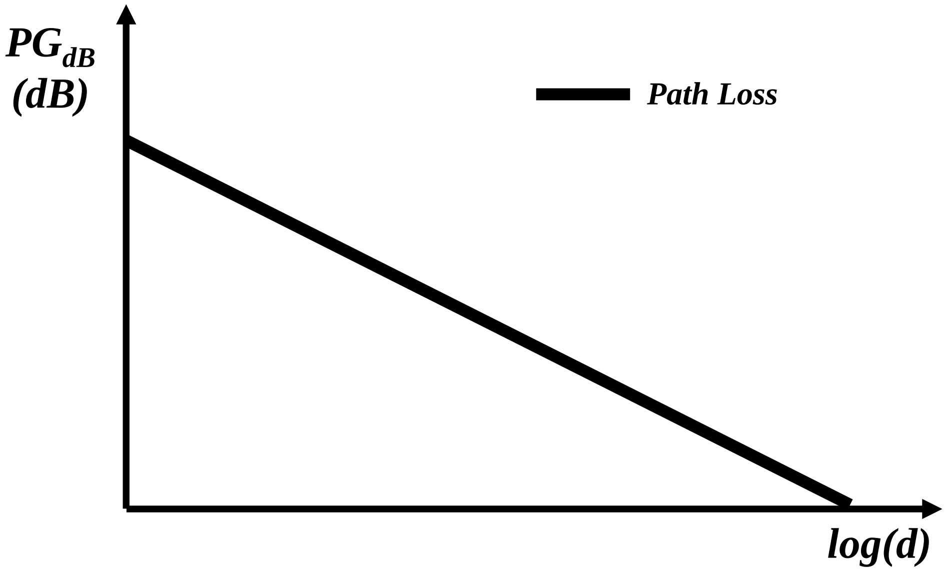
- Path loss (PL) for unobstructed LOS path
- Power falls off
  - » Proportional to $1/d^2$
  - » Proportional to λ^2 (inversely proportional to f^2)



$$P_r/P_s = \left[\frac{\lambda\sqrt{G_l}}{4\pi d}\right]^2 \qquad G_l = \sqrt{G_s G_r}$$

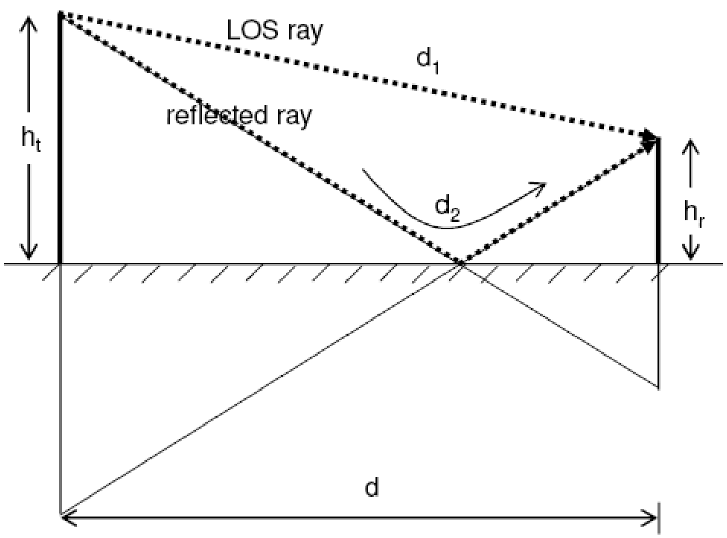
$$PG_{dB} = 10.\log\left(\frac{P_r}{P_s}\right) = 10.\log\left(\frac{\lambda\sqrt{G_l}}{4\pi d}\right)^2$$

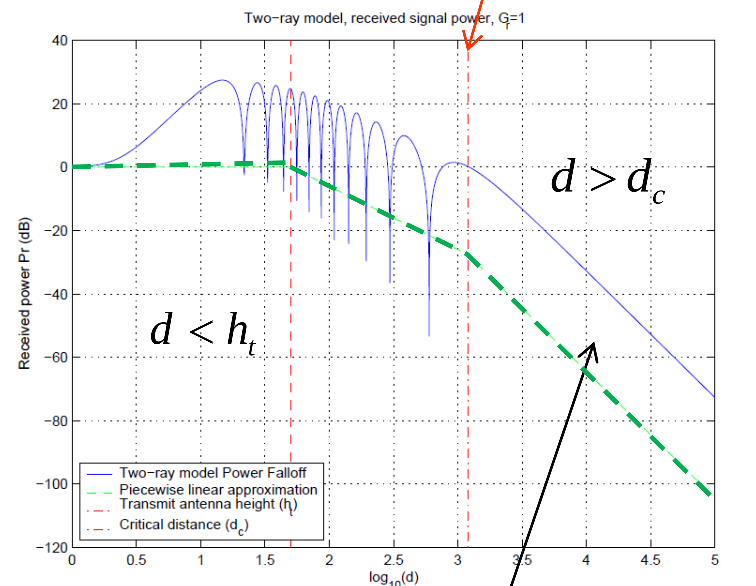
$$PG_{dB} = 20.\log\left(\frac{\lambda\sqrt{G_l}}{4\pi}\right) - 20.\log(d)$$



Path Loss – Two-Ray Model

- One LOS ray + one ray reflected by ground
- Ground ray cancels LOS path above critical distance $d_c = 4h_t h_r/\lambda$
- Power falls off
  - » Proportional to d^2 $\quad (h_t < d < d_c)$
  - » Proportional to d^4 $\quad (d > d_c)$





$$P_r \text{ dBm} = P_t \text{ dBm} + 10\log_{10}(G_l) + 20\log_{10}(h_t h_r) - 40\log_{10}(d)$$

Path Loss – Empirical Models

- Okumura model
  - » Empirically based (site/freq specific); 150-1500 MHz, Tokyo
  - » Empirical plots
- Hata model

  Analytical approximation to Okumura model
- Cost 231 Model

  Extension Hata model to higher frequency (1.5 GHz < f_c < 2 GHz)
- Walfish/Bertoni

  Extends Cost 231 include diffraction from rooftops
- There are others …

Path Loss - Simplified Model

- Used when path loss is dominated by reflections

$$P_r = P_s K \left(\frac{d_0}{d} \right)^{\gamma}, \qquad 2 \le \gamma \le 8$$

$$P_{r_{dBm}} = P_{s_{dBm}} + K_{dB} - 10\ \gamma\ log \left[\frac{d}{d_0} \right]$$

$$d_0 \approx 10\lambda$$

Environment	γ
Urban macrocells	3.7 - 6.5
Urban microcells	2.7 - 3.5
Office building	1.6 - 3.5
Store	1.8 - 2.2
Factory	1.6 - 3.3
Home	3

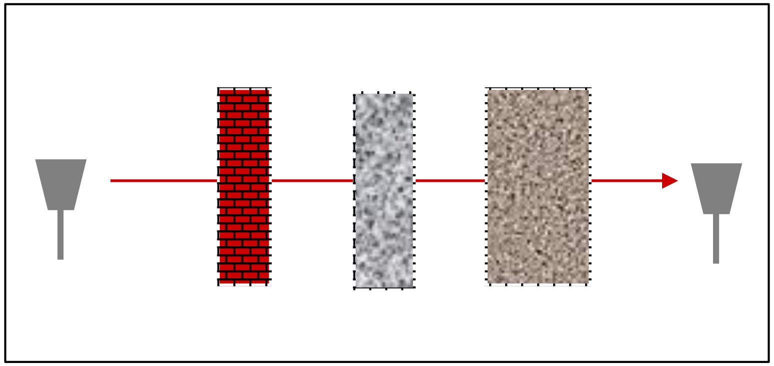
- K
  - » determined by measurement of power at $d = d_0 \Rightarrow \quad K_{dB} = P_{r_{dBm}} - P_{s_{dBm}}$
  - » Or assuming Friis for $d = d_0$ ➔ $K_{dB} = 10\ log \left[\frac{\lambda}{4\pi d_0} \right]^2$
- Path loss exponent γ is determined empirically

Path Loss – Indoor Factors

- Walls, floors, layout of rooms, location and type of objects
  - Increase the path loss with deterministic (well-known) values
  - These losses introduced **must be added** to the free space losses

Partition	Loss (dB)
hollow brick	8
concrete wall	13
aluminum siding	20
window	6
floor	10

Shadowing



- Models attenuation introduced by obstructions
- Random due to random number and type of obstructions ➔ ψ

$$\left(\frac{P_r}{P_s}\right)_{dB} = 10\ logK - 10\gamma\ log\frac{d}{d_0} - \psi_{dB}$$

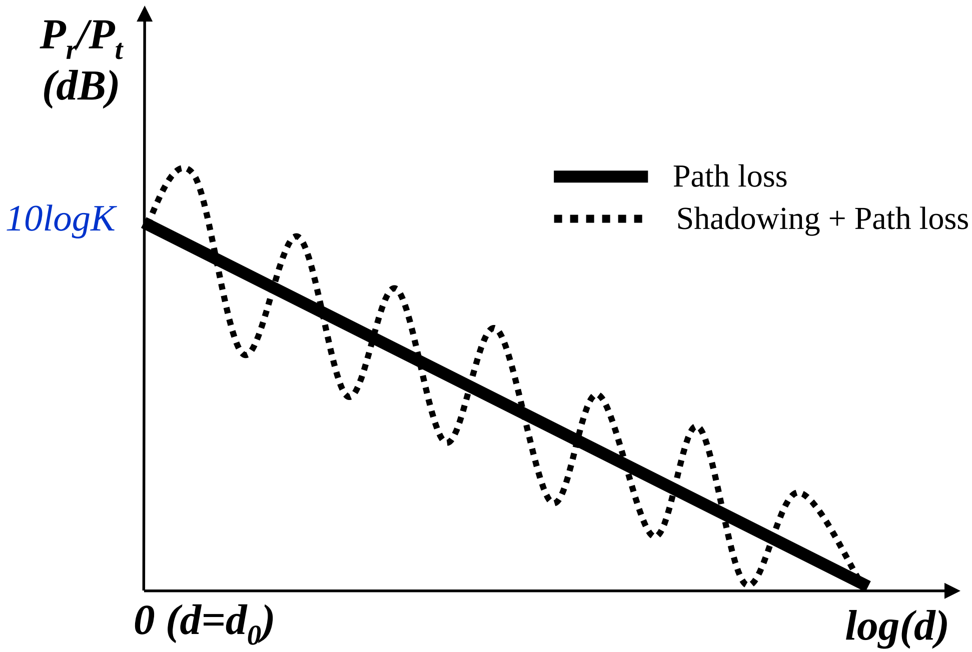
where ψ_{dB} is a Gaussian distributed random variable

$\boxed{\text{characterized by } \mu_{\psi_{dB}} = 0 \text{ and } \sigma_{\psi_{dB}}}$

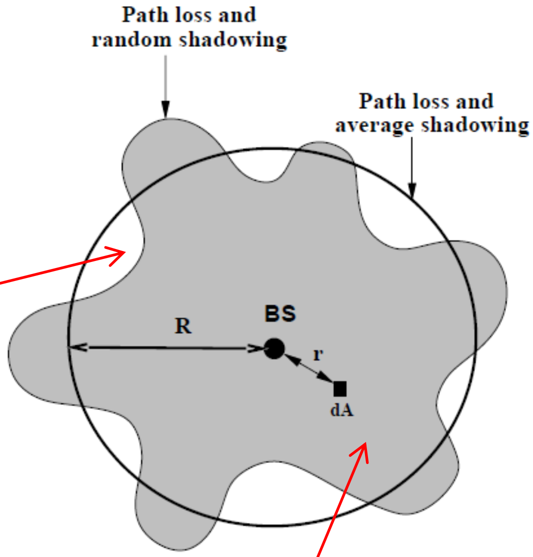
Combined Path Loss and Shadowing

$$\frac{P_r}{P_s}(dB) = 10\log_{10} K - 10\gamma \log_{10}\left(\frac{d}{d_0}\right) - \psi_{dB},$$

$$\psi_{dB} \sim N(0, \sigma_\psi^2)$$



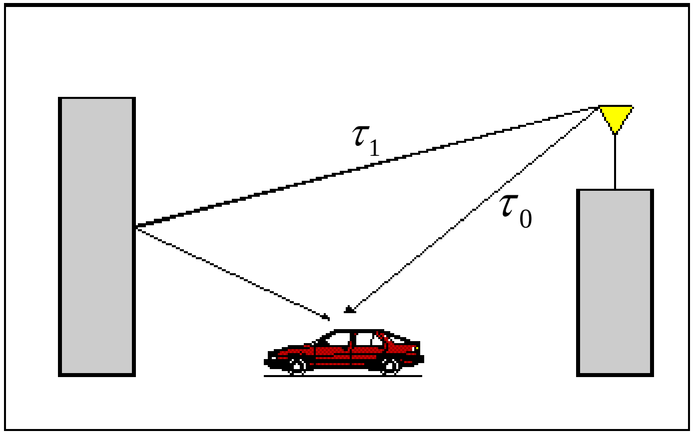
Outage Probability and Cell Coverage Area



- Path loss model ➔ circular cells
- Path loss + shadowing ➔ amoeba cells
- Outage probability
  - » Probability received power below given minimum
  - » *Assuming a circular cell*
- Cell coverage area ➔ % of cell locations above a minimum power
  - » Increases as shadowing variance (σ_ψ) decreases

Multipath

- Multipath → multiple rays received
  - » multiple delays from transmitter to receiver → τ_i
  - » time delay spread $T_m = max_n|\tau_n - \tau_0|$
- Multipath channel has a time-varying gain, caused by
  - » transmitter / receiver movements
  - » location of reflectors which originate the multipaths



Transmit and Receive Signal Models

- Transmitted signal modeled as

$$\begin{aligned} s(t) &= \Re\left\{u(t)e^{j2\pi f_c t}\right\} \\ &= \Re\{u(t)\}\cos(2\pi f_c t) - \Im\{u(t)\}\sin(2\pi f_c t) \\ &= s_I(t)\cos(2\pi f_c t) - s_Q(t)\sin(2\pi f_c t) \end{aligned}$$

- The received signal

$$r(t) = \Re\left\{v(t)e^{j2\pi f_c t}\right\},$$

- If *s(t)* is transmitted through a time-invariant channel ***c*** then

$$v(t) = u(t) * c(t) \qquad V(f) = H_l(f)U(f).$$

where

» $c(t)=h_l(t)$ is the equivalent lowpass impulse response of the channel

» $H_l(f)$ is the equivalent lowpass frequency response of the channel

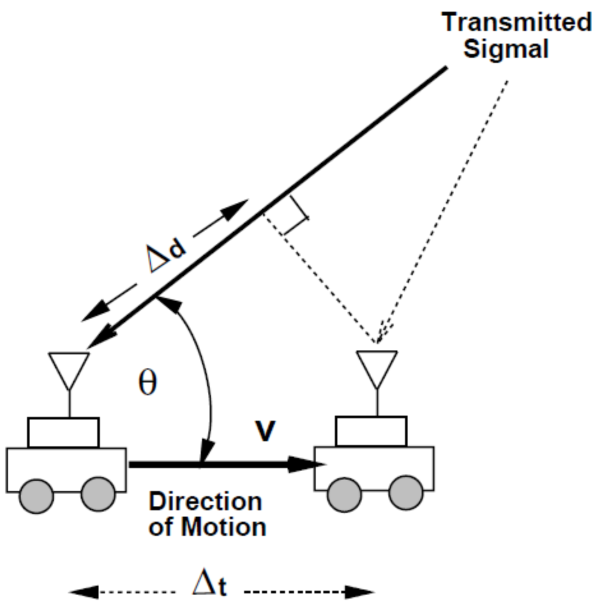
Doppler Shift

- The received signal may have a phase Doppler shift ϕ_D

$$\phi_D = 2\pi \frac{\Delta d}{\lambda}$$

$$\Delta d = v \Delta t \cos\theta$$

$$\phi_D = 2\pi \frac{v \Delta t \cos\theta}{\lambda}$$



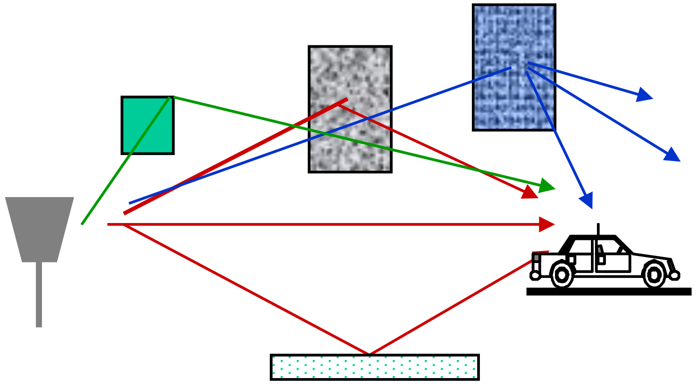
- Doppler frequency, f_D

$$\phi_D = 2\pi f_D \Delta t$$

$$\boxed{f_D = \frac{1}{2\pi} \frac{\phi_D}{\Delta t} = \frac{v\cos\theta}{\lambda}}$$

Multipath Model

- Random number *N(t)* of multipath components received, each with
  - » random amplitude, $\alpha_n(t)u(.)$
  - » random delay, $\tau_n(t)$
  - » random phase, $2\pi f_c \tau_n(t)$
  - » random Doppler shift, ϕ_{Dn}



- Received signal

$$r(t) = \Re\left\{\left[\sum_{n=0}^{N(t)} \alpha_n(t) e^{-j\underline{\phi_n(t)}} u(t - \underline{\tau_n(t)})\right] e^{j2\pi f_c t}\right\} \qquad \phi_n(t) = 2\pi f_c \underline{\tau_n(t)} - \underline{\phi_{D_n}}$$

- Leads to channel characterized by time-varying impulse response

Multipath – Narrowband Channel

- In a narrowband channel

  low B (Hz) → low symbol rate (B symbol/s) → large time/symbol (1/B)

  → multipath components arrive in the time interval of their symbol

  $T_m = max_n|\tau_n - \tau_0|$ $\qquad$ $T_m << B^{-1}$

- In this case we may assume $u(t-\tau_i) \approx u(t)$ (same symbol)

- Received signal given by $r(t) = \Re\left\{u(t)e^{j2\pi f_c t}\left[\sum_{n=0}^{N(t)} \alpha_n(t)e^{-j\underline{\phi_n(t)}}\right]\right\}$

  » No spreading in time (no distortion)

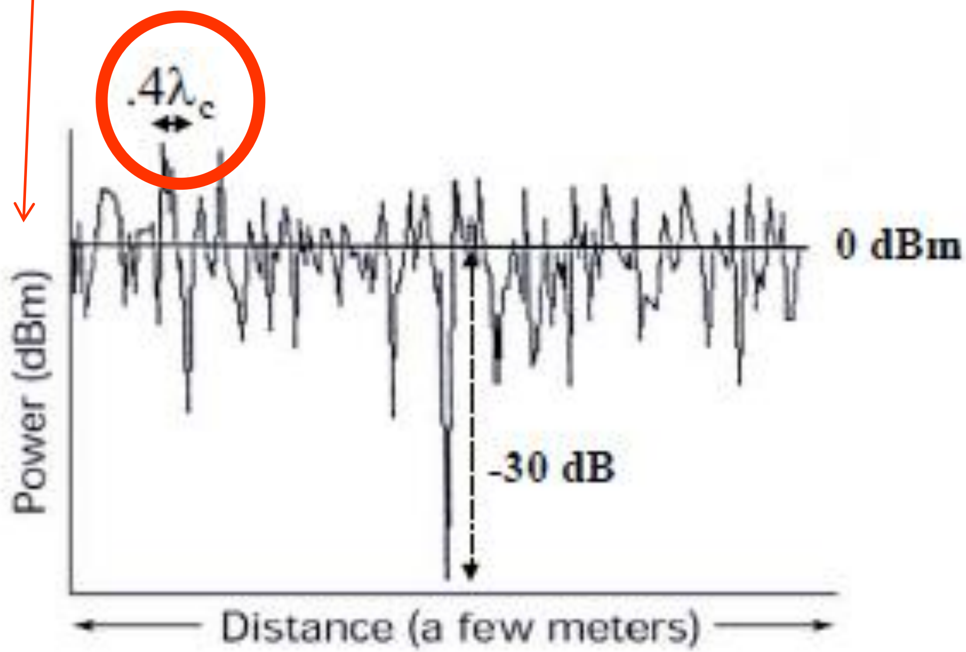
  » Multipath affects complex scale factor in brackets

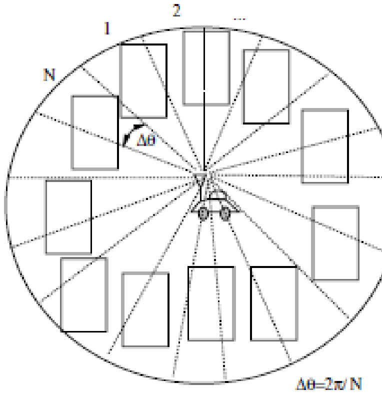
  » Doppler effect (velocity) may be important

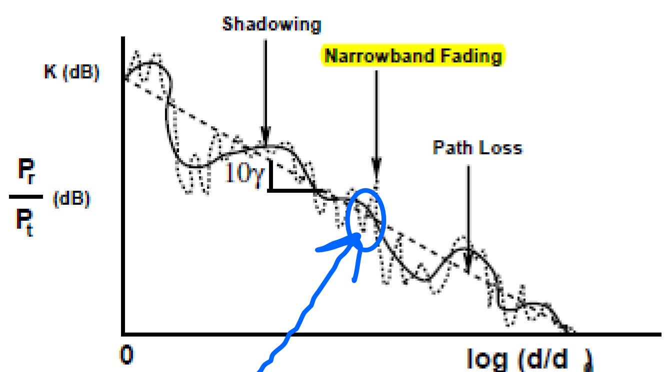
$$\phi_n(t) = 2\pi f_c \tau_n(t) - \phi_{D_n}$$

Multipath – Narrowband Channel

- Let us assume an Uniform Angle of arrival in $[0,2\pi]$
- Power received, considering no path loss nor shadowing





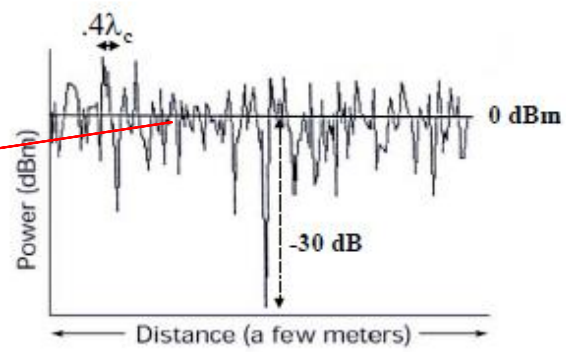


Multipath, Narrowband Channel – Rayleigh Fading

- If there is no Line-of-Sight (LOS) component
  - » **Power received** (in Watts) may be modeled by an exponential probability density function

$$\boxed{p_{Z^2}(x) = \frac{1}{P_r} e^{-x/P_r}}$$

statistical characterization of a signal like this



  - » The random variable Z is the $P_{received}$
  - » $\boldsymbol{P_r}$ – **average** received power (path loss + shadowing)

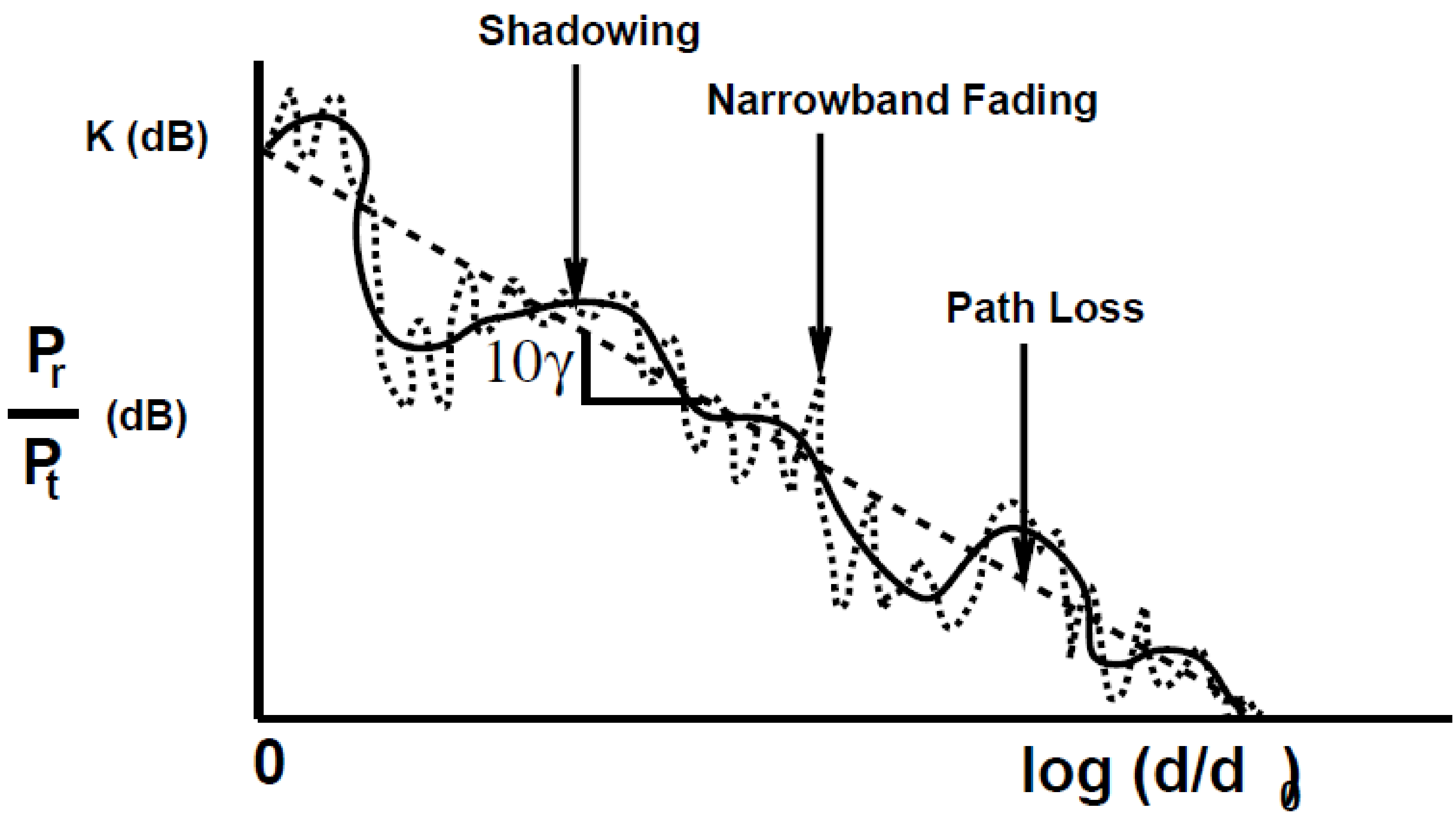
- If there is LOS
  - » Power received may be modelled by a Ricean distribution

Suppose you are the receiver.

What information does this exponential distribution provide to you?

$$p_{Z^2}(x) = \frac{1}{P_r} e^{-x/P_r}$$

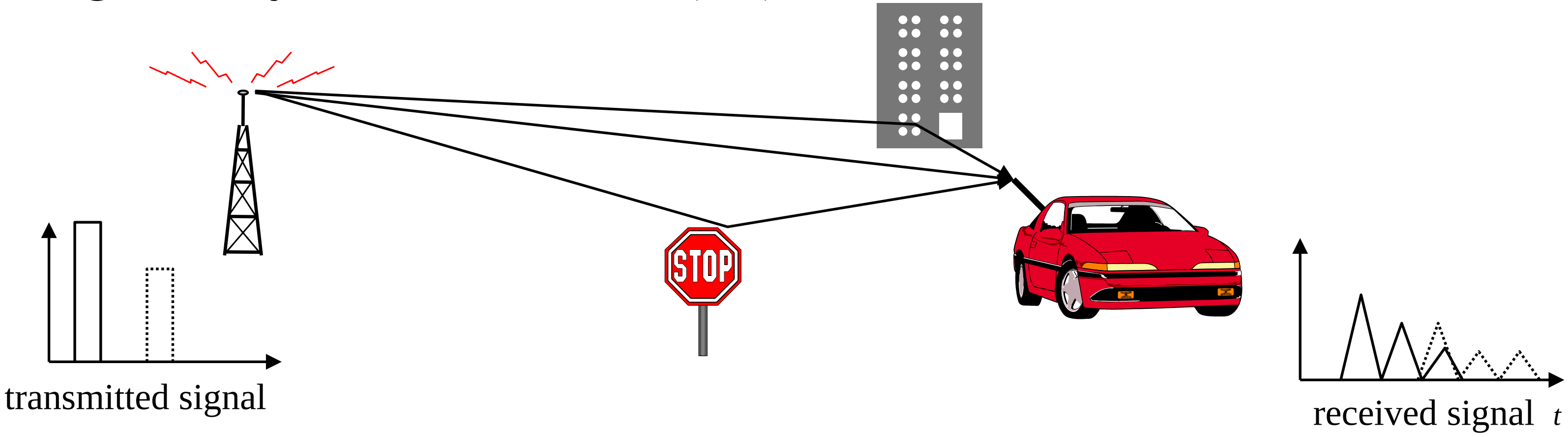
Multipath + Shadowing + Path Loss



Multipath – Wideband Channel

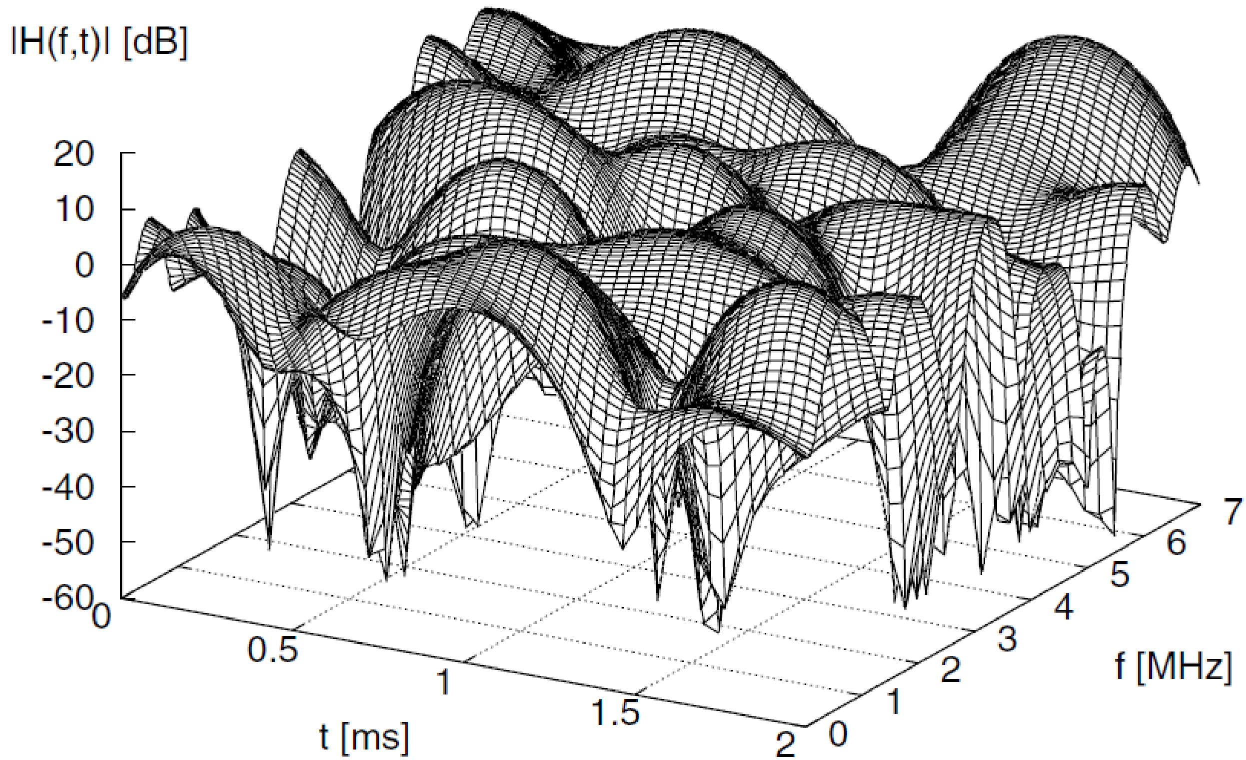
$$T_m = \max_n |\tau_n - \tau_0|, \quad T_m >> B^{-1}$$

- Multipath components
  - » may arrive at the receiver within the time period of the next symbol
  - » causing Inter-Symbol Interference (ISI)



- Techniques used to mitigate ISI
  - » multicarrier modulation - OFDM
  - » spread spectrum - CDMA

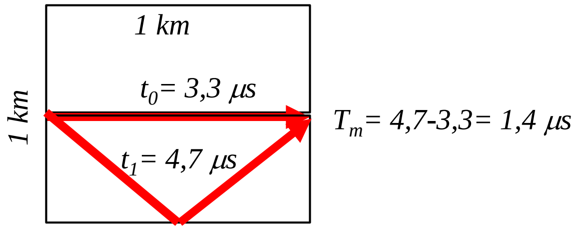
Gain in a Wideband Channel caused by Fading



- H(f) is the channel gain (P_r/P_t)
- Time and frequency variable gain

Coherence Time, Coherence Bandwidth

- Coherence time, $T_c \approx \dfrac{1}{2\pi f_D}$
  - » **Time** interval during which the wireless channel roughly has a constant gain
    - – f_D – Doppler frequency
    - – v= 5 km/h ➔ T_c = 34 ms (considering f_c= 1 GHz)
    - – v= 300 km/h ➔ T_c= 0.57 ms (f_c= 1 GHz)
  - » Slow fading channel if $T_{\mathbf{symbol}} < 0.1 {*} T_c$; Fast fading otherwise
- Coherence bandwidth, $B_c \approx \dfrac{1}{2\pi T_m}$
  - » **Bandwidth** for which the channel gain does not change significantly
    - – T_m – (rms) time delay spread
    - – T_m = 2 µs ➔ B_c= 80 kHz (c=3,3 μs/km)



  - » Avoidance of channel ISI demands symbol rate B < 0.1*B_c,

Capacity of a Wireless Channel

- Assuming **A**dditive **W**hite **G**aussian **N**oise (AWGN)
  - » Given by Shannon´s law

$$\boxed{C = B\ log_2(1+\gamma) \quad \text{[bit/s]}}$$

$$\gamma = SNR = \frac{P_r}{N_0 B}, \quad \gamma = SNIR = \frac{P_r}{N_0 B + \sum_{i=1}^{I} P_{r_i}}$$

N_0 – Noise power spectral density

$\sum_{i=1}^{I} P_{r_i}$ - Power received from interfering nodes

- Capacity in a fading channel (multipath)
  - ➔ smaller than the capacity of an AWGN channel

$$C = \int_0^\infty B.\log_2\left(1+\frac{x}{N_0 B}\right)\cdot\frac{1}{P_r}\cdot e^{-\frac{x}{P_r}}.dx$$

Capacity of a Wireless Channel

$$P_r(d) = (d_0/d)^3\, P_t, \text{ for } d_0 = \ 10m$$

d (m)	$\gamma = P_r(d)/(N_0 B)$	$SNR = \gamma_{dB} = 10\ log\gamma$ (dB)	$C = B\ log_2(1+\gamma)$ $(kbit/s)$	Efficiency (bit/s/Hz)
50	267	24	242	8
100	33	15	153	5.1
500	0.27	-6	10	0.3
1000	0.033	-15	1.4	0.05

Table 2.6: Shannon capacities for wireless channels. The limiting capacities of wireless channels depend on the channel bandwidth and on the power received. The capacity C of the channel and its efficiency are given for a transmitted power $P_s = 1\,W$, $d_0 = 10\ m$, a narrow bandwidth of $30\ kHz$ and a noise power spectral density $N_0 = 10^{-9}\ W/Hz$. The capacity decreases significantly as the distance between the sender and the receiver increases

Homework

- Review slides
  - use them to guide you through the recommended books
- From Goldsmith
  - Chap. 2, Chap. 3 (sections 3.1, 3.2, 3.3), Chap. 4 (section 4.1)
  - Detailed information. Aligned with the lecture
- Read from Vijay Garg
  - Chap. 3
  - Very good overview. Must read
- Read from Schiller
  - Chap. 2 (sections 2.1, 2.2, 2.3, 2,4)
  - Descriptive, good introductory text
- Rappaport also provides an excellent description of these topics
  - See Chap. 3 and Chap. 4
- Answer questions at moodle