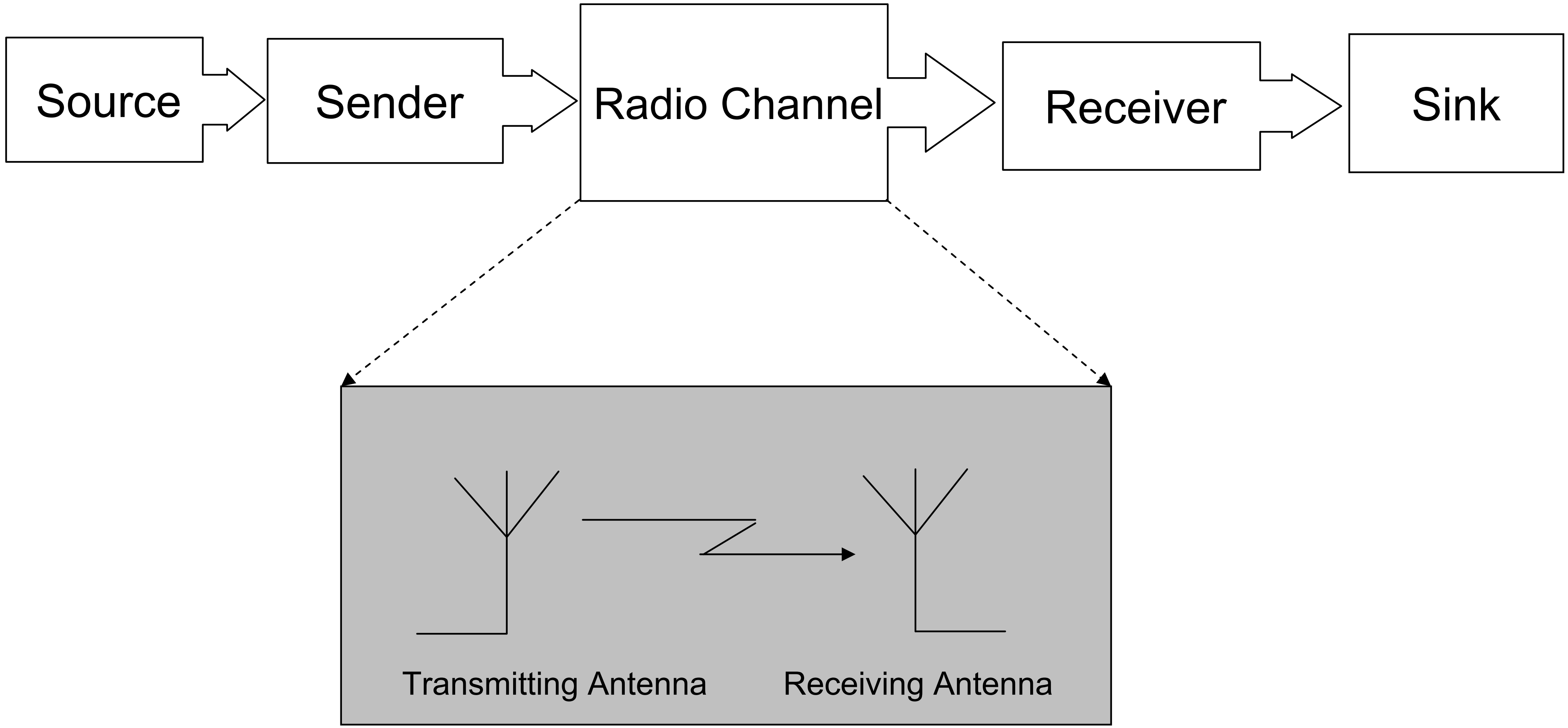
Introduction and technological Fundamentals Radio Channel Properties

Contents - Fundamentals - Radio Channel Properties

- Signal Propagation
- Channel Impairments: Noise and Interference

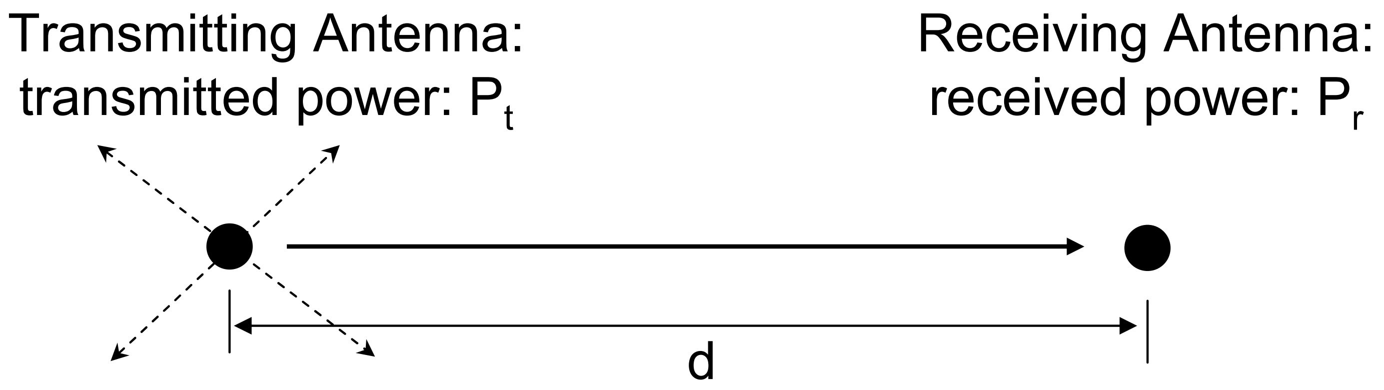
The Radio Channel



Effects: • **signal propagation**
• **channel impairments: noise and interference**

Signal Propagation

Theoretical Propagation Models: Free Space Propagation



received to transmitted power ratio:

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

G_t: gain of the transmitting antenna
G_r: gain of the receiving antenna

path loss:

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

Assumption: transmitting and receiving antennas are isotropic spot radiators $\Rightarrow$ $G_t = G_r = 1$

$$L_{|dB|} = 10 \log (P_t / P_r) \Rightarrow$$

$$L_{|dB|} = 32.4 + 20 \log d_{|km|} + 20 \log f_{|MHz|}$$

Free Space Propagation Path Loss - Derivation

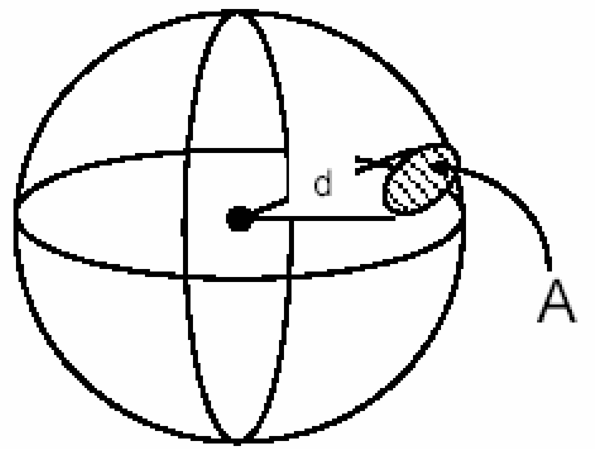
To determine the path loss in the ideal (free space) case, it is assumed that the transmitter and receiver are connected to an isotropic antenna.

The effective area of an isotropic (receiving) antenna is:

$$A_r = \lambda^2 / 4\pi$$

As the signal is propagated evenly in every direction the received signal power is calculated as follows:

$$P_r = \frac{P_t}{4\pi d^2} \cdot A_r = \frac{P_t}{4\pi d^2} \cdot \frac{\lambda^2}{4\pi}$$



Definition of the Antenna Gain

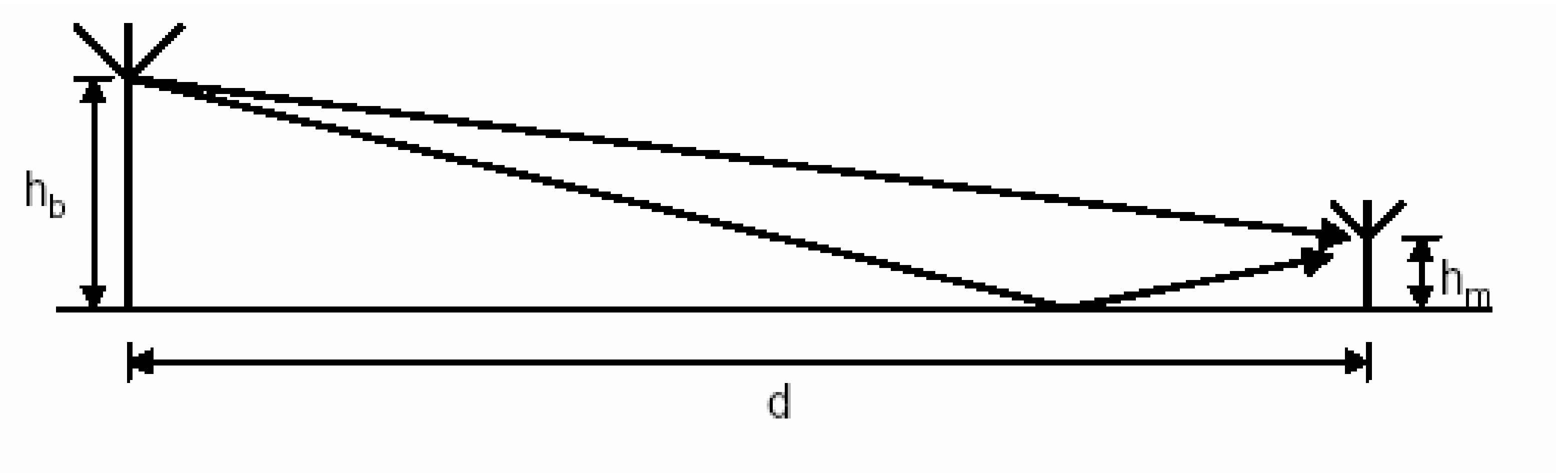
The antenna gain is defined as the ratio of the radiated power density of an antenna in the direction of its main beam and the radiated power density of an reference antenna:

Antenna gain: $G = E_{test} / E_{ref}$ or $G_{|dB|} = 10 \log_{10}(E_{test} / E_{ref})$

Typically the reference antenna is either a dipole or an isotropic antenna.

The antenna gain can be expressed in dB_i (reference = isotropic antenna) or dB_d (reference = dipole)

Theoretical Propagation Models: Plane Propagation



received to transmitted power ratio:

$$\frac{P_r}{P_t} \approx G_t G_r \left(\frac{h_m h_b}{d^2} \right)^2$$

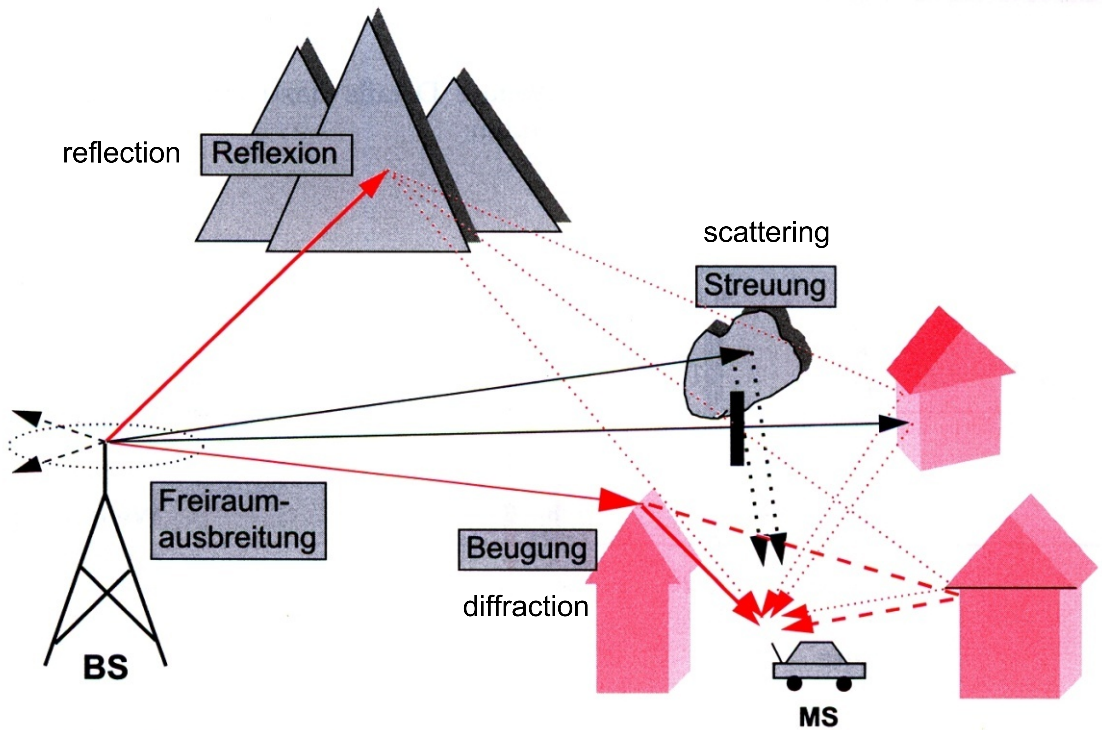
G_t: gain of the transmitting antenna
G_r: gain of the receiving antenna

path loss:

$$L_{|dB|} = 120 - 20 \log h_{m \cdot |m|} - 20 \log h_{b \cdot |m|} + 40 \log d_{|km|}$$

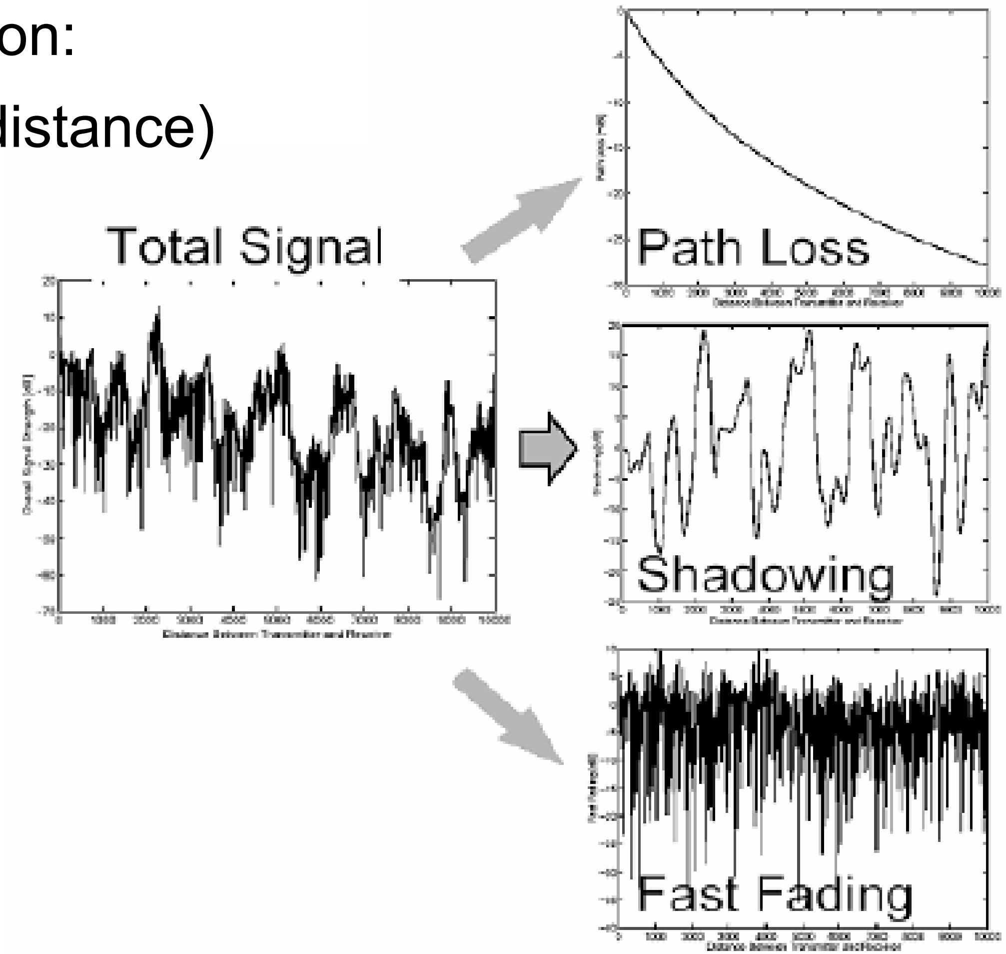
Real Propagation

- theoretical propagation models are insufficient to describe the real propagation
- the real propagation is characterized through:
  - diffraction
  - reflection
  - refraction
  - scattering
  - lossy mediums
- in general the signal reaches the receiver through multiple paths

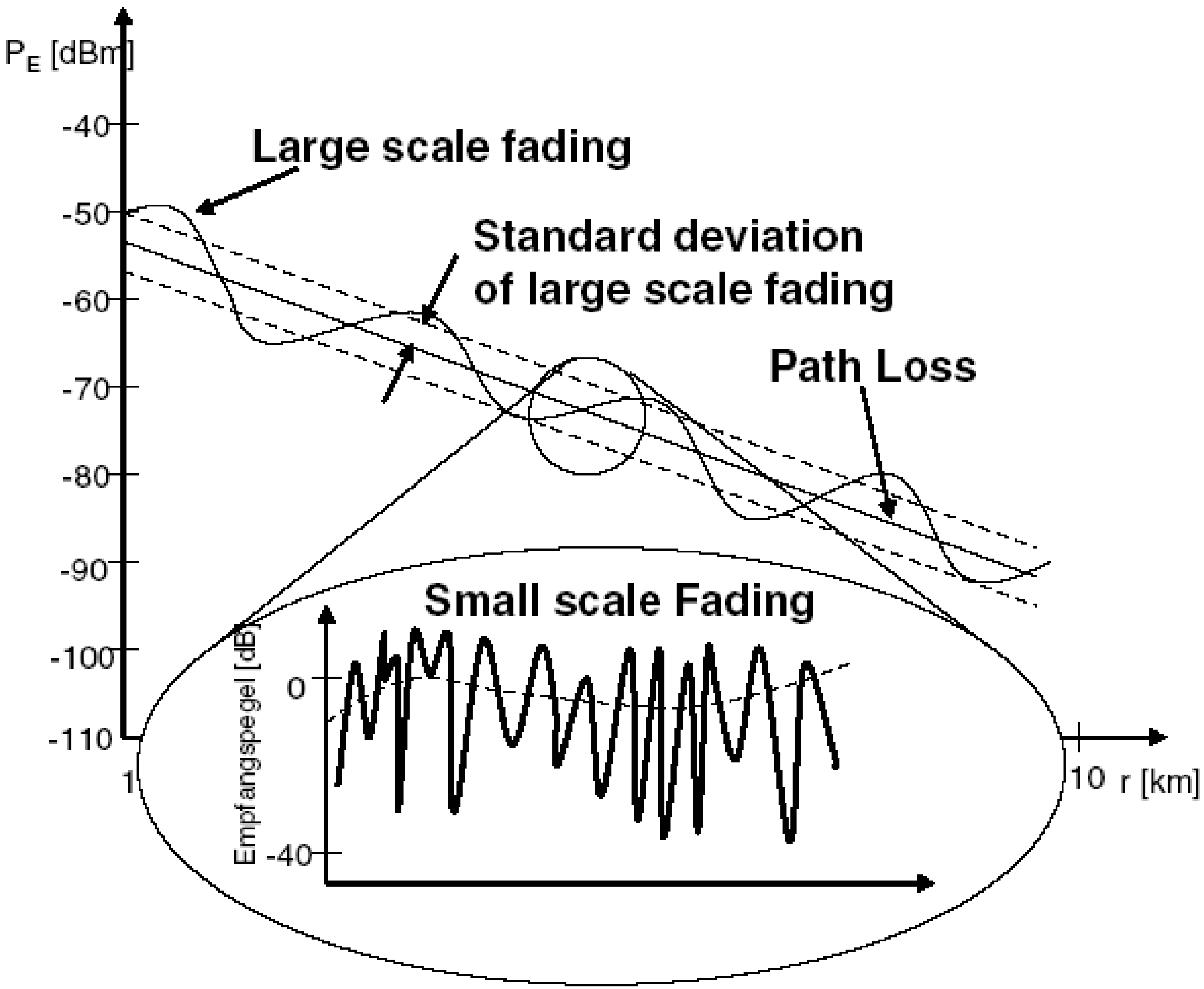


Modeling the real Propagation

- the real propagation conditions are to complex to model them accurately
- therefore usually statistical modeling approaches are used
- three components of real propagation:
  1. mean path loss (mainly due to distance)
  2. slow fading (shadowing)
  3. fast fading (multi-path propag.)

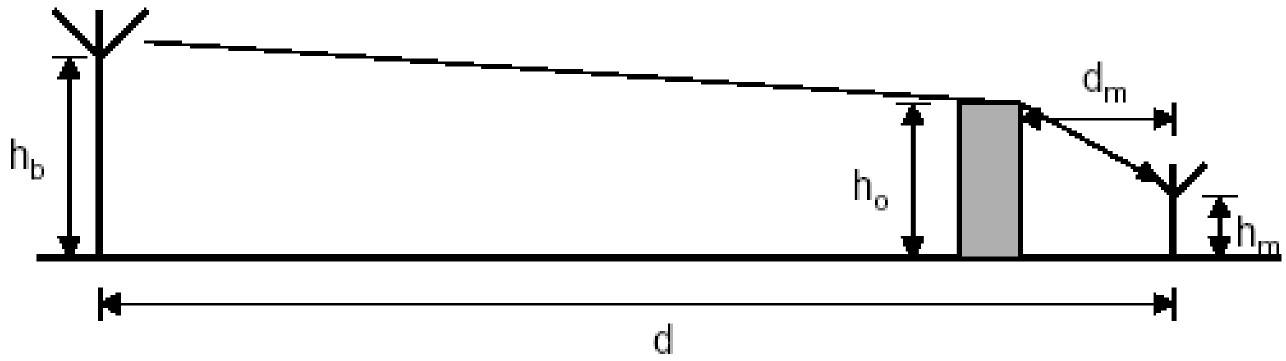


Path Loss and Fading in real Propagation Conditions



Empirical Path Loss Models

- empirical path loss models describe the mean path loss between transmitter and receiver depending on:
  - environmental conditions
  - radio frequency
  - height of transmitter and receiver
  - distance between transmitter and receiver



h_m: height of the mobile station (typically 1,5m)
h_b: height of the base station
d_m: distance between mobile station and the closest object (building)
h_o: height of the closest object
d: distance between base station and mobile station

Okumura-Hata Path Loss Model (1)

- empirical path loss model based on measurements in Tokyo and the surrounding area
- valid for:
  - $150\text{MHz} < f \leq 1500\text{MHz}$
  - $30\text{m} \leq h_b \leq 200\text{m}$
  - $1\text{m} \leq h_m \leq 10\text{m}$
  - $d > 1\text{km}$

Okumura-Hata Path Loss Model (2)

- path loss according to Okumura-Hata:
  - for urban environment: $L_{|dB|} = A + B \log d_{|km|} - E$
  - for suburban environment: $L_{|dB|} = A + B \log d_{|km|} - C$
  - for rural or open environment: $L_{|dB|} = A + B \log d_{|km|} - D$

- parameters: $A = 69{,}55 + 26{,}16 \log f_{|MHz|} - 13{,}82 \log h_b$

$$B = 44{,}9 - 6{,}55 \log h_b$$

$$C = 2(\log(f_{|MHz|} / 28))^2 + 5{,}4$$

$$D = 4{,}78(\log f_{|MHz|})^2 + 18{,}33 \log f_{|MHz|} + 40{,}94$$

Okumura-Hata Path Loss Model (3)

- parameters (cont.):
  - for big cities, f ≥ 300MHz:

$$E = 3{,}2(\log(11{,}75 h_m))^2 - 4{,}97$$

  - for big cities, f < 300MHz:

$$E = 8{,}29(\log(1{,}54 h_m))^2 - 1{,}1$$

  - for small and medium cities:

$$E = (1{,}1 \log f_{|MHz|} - 0{,}7) h_m - (1{,}56 \log f_{|MHz|} - 0{,}8)$$

COST 231-Hata Path Loss Model

- the COST 231-Hata path loss model is an enhancement of the original Okumura-Hata model for higher radio frequencies
- valid for: 1500MHz < f ≤ 2000MHz
- path loss according to COST231-Hata:

$$L_{|dB|} = F + B \log d_{|km|} - E + G$$

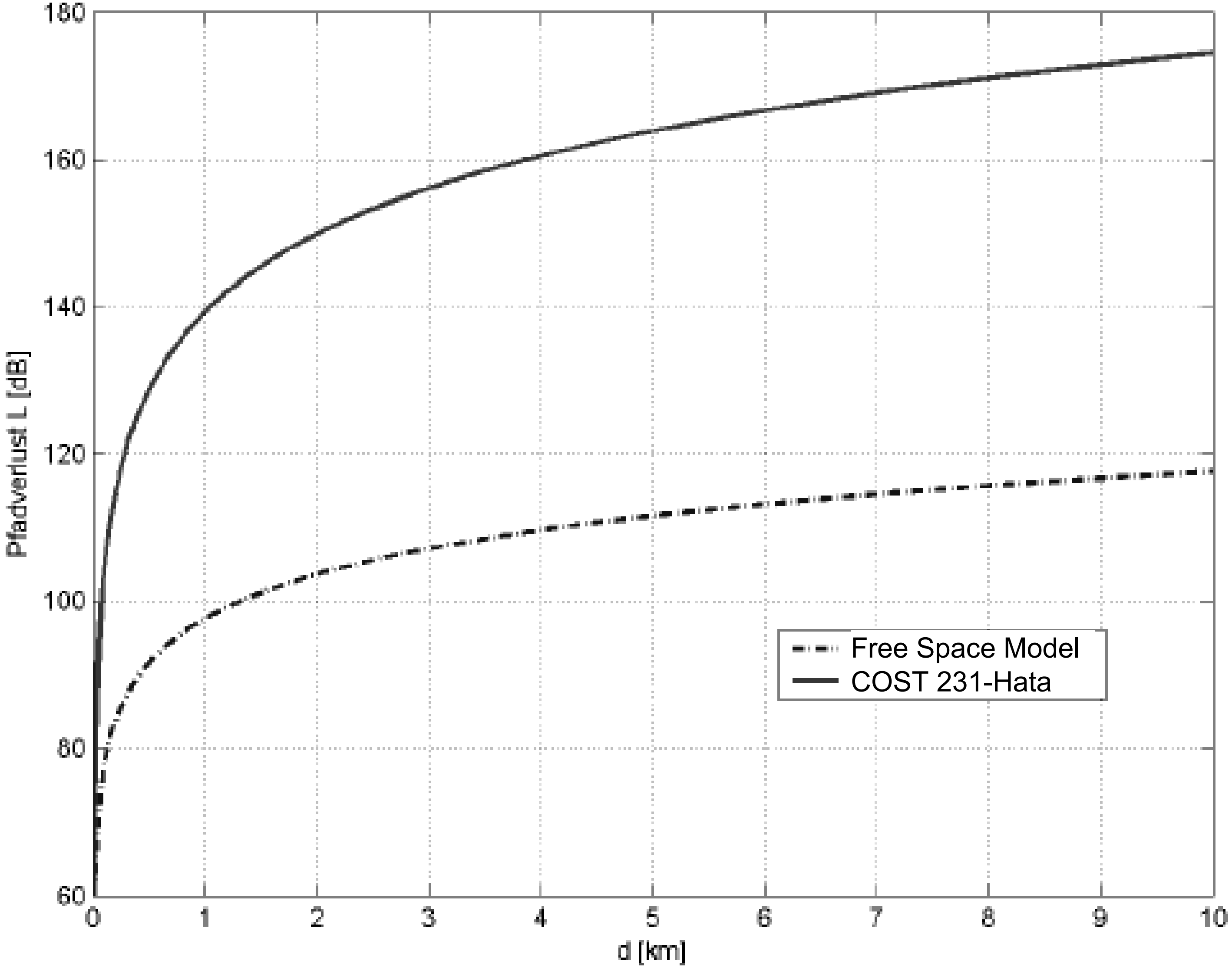
- parameters:

$$F = 46{,}3 + 33{,}9 \log f_{|MHz|} - 13{,}82 \log h_b$$

$$G = \begin{cases} 3\text{dB} & \text{for big cities} \\ 0\text{dB} & \text{otherwise} \end{cases}$$

B, E: equivalent to Okumura-Hata

COST 231-Hata Model vs. Free Space Propagation Model



Slow Fading (Shadowing)

- in real environments slow path loss variations occur even if the distance between sender and receiver is kept constant; this phenomenon is called **Slow Fading**
- even at constant distance the path between sender and receiver is composed of a high number N of individual components with different losses
- empirical data suggests that the power observed at a location is random and log-normal distributed around the “mean” power

Loss due to Slow Fading - Derivation

- even at constant distance the path between sender and receiver is composed of a high number N of individual components with different losses; therefore the overall path loss can be expressed as follows:

$$L = L_1 \cdot L_2 \cdot L_3 \cdot \ldots \cdot L_N$$

$$L_{|dB|} = L_{1,|dB|} + L_{2,|dB|} + L_{3,|dB|} + \ldots + L_{N,|dB|}$$

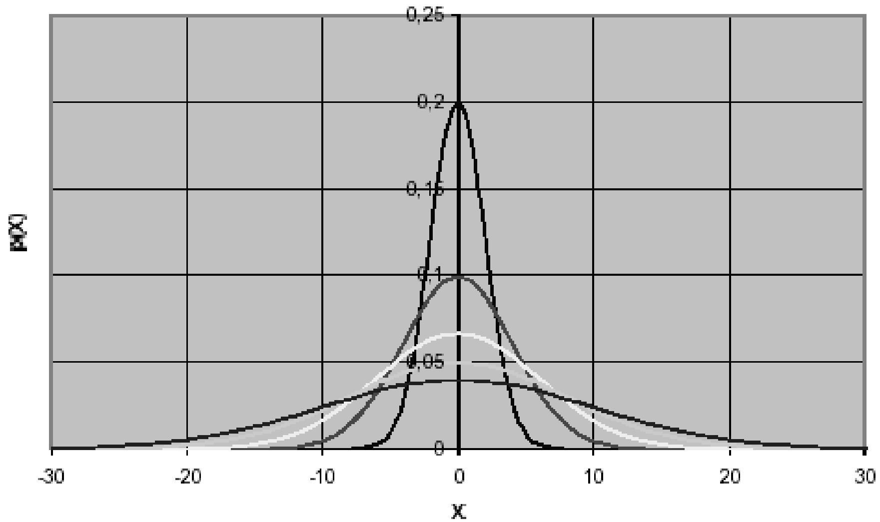
- each component can be considered as a random variable with unknown distribution

→ according to the central limit theorem the overall path loss $L_{|dB|}$ is normal distributed

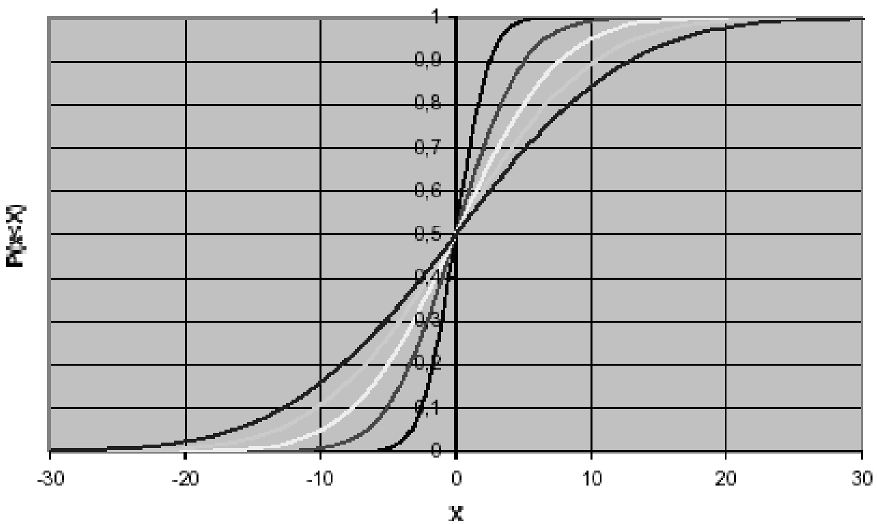
  - the mean value of $L_{|dB|}$ is the mean path loss $L_{M|dB|}$ (which can be calculated e.g. via the empirical path loss models)
  - the (superimposed) loss due to slow fading $L_{S|dB|}$ can be modeled via a normal distribution with mean value 0 and standard deviation σ_S

Loss due to Slow Fading - Normal Distribution Model

- the loss due to slow fading $L_{S|dB|}$ is normal distributed with standard derivation σ_S and mean value 0:



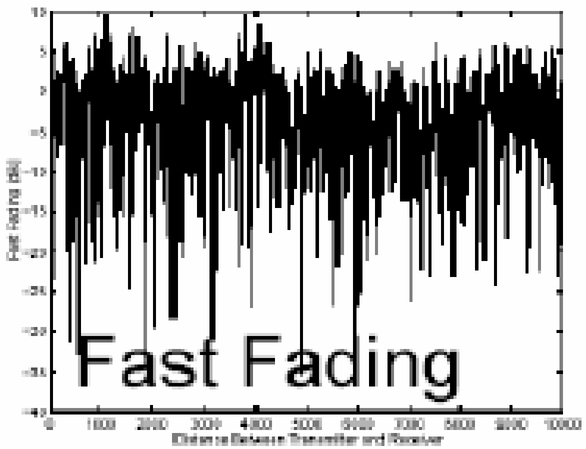
$$p(L_{S|dB|}) = \frac{1}{\sqrt{2\pi\sigma_S^2}} e^{-\frac{L_{S|dB|}^2}{2\sigma_S^2}}$$

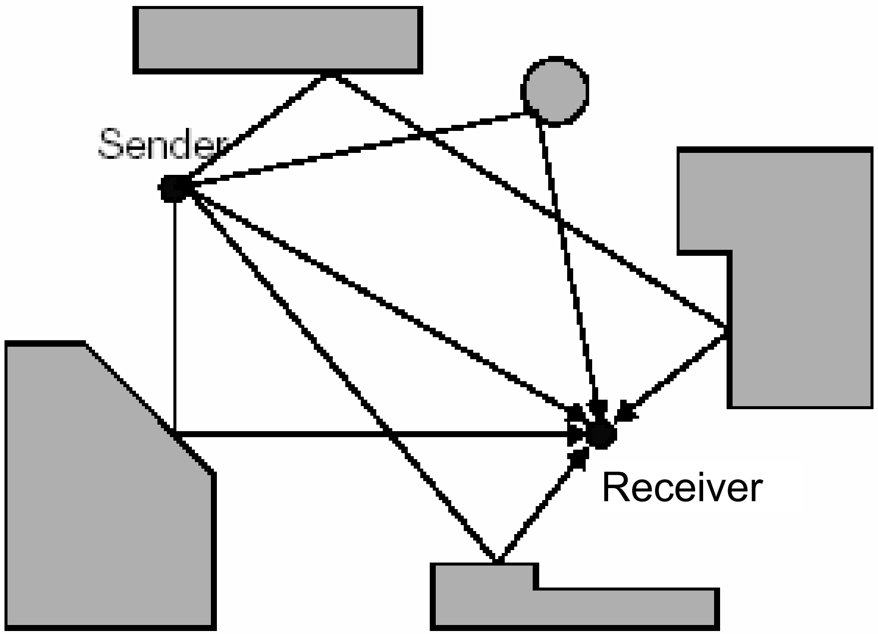


$$P(L_{S|dB|} < L_{|dB|}) = \frac{1}{\sqrt{2\pi\sigma_S^2}} \int_{-\infty}^{L_{|dB|}} e^{-\frac{L_{S|dB|}^2}{2\sigma_S^2}} dL_{S|dB|}$$

Fast Fading (Multi-Path Propagation)

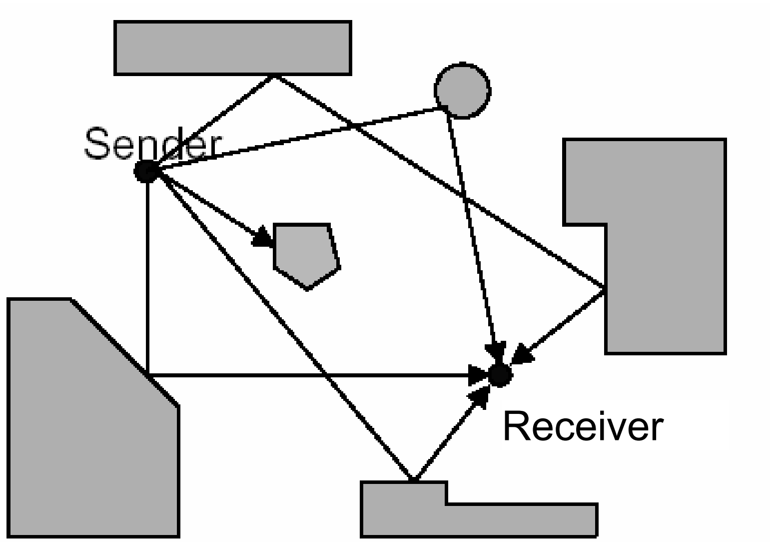
- in real environments the transmitted signal also will reach the receiver via various paths with different length
- the constructive and destructive interference of the signals result in a fast variation of the path loss - this phenomenon is called **Fast Fading**
- when the sender or receiver moves, the frequency of this variation depends on the Doppler frequency





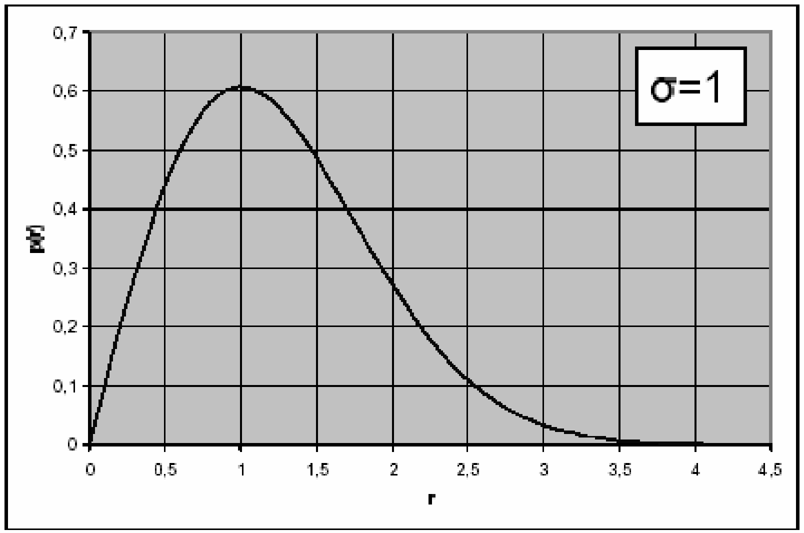
Loss due to Fast Fading - Rayleigh Distribution Model

- Case 1: no dominant path (e.g. no line of sight connection) between sender and receiver exists
- the variation of the signal field strength at the receiver is described by the Rayleigh distribution:



$$p(r) = \frac{r}{\sigma_F^2} e^{-\frac{r^2}{2\sigma_F^2}}$$

r = field strength at receiver



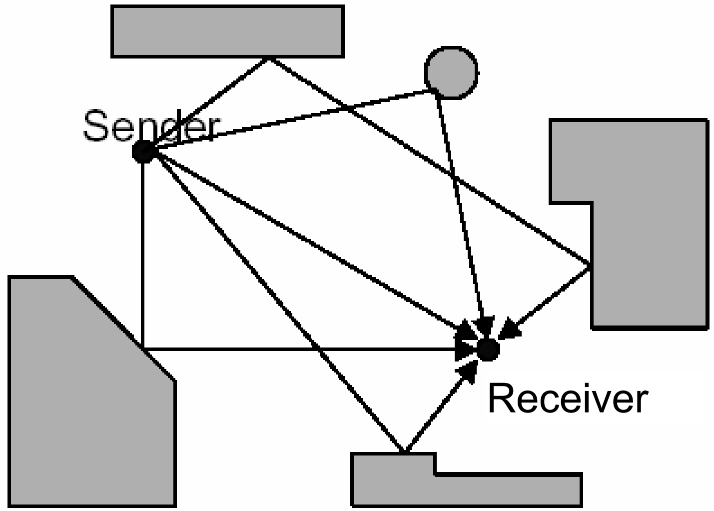
Loss due to Fast Fading - Rice Distribution Model

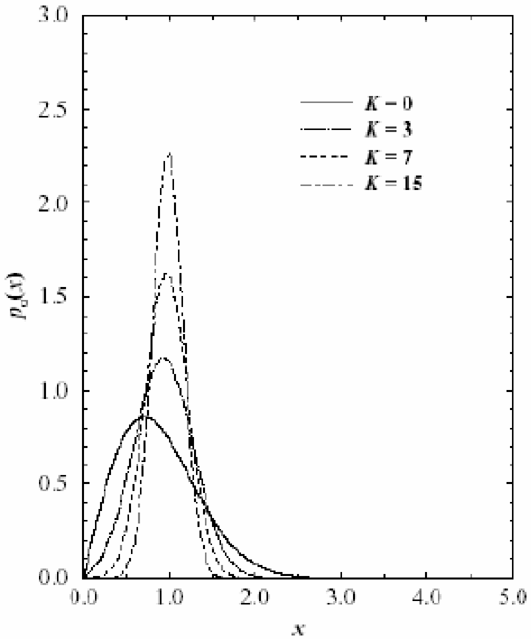
- Case 2: a line of sight connection between receiver and sender exists, that leads to a dominant path
- in this case the Rayleigh distribution model is not applicable
- the variation of the signal field strength at the receiver is described by the Rice distribution:

$$p(r) = \frac{r}{\sigma_F^2} e^{-\frac{r^2}{2\sigma_F^2}} e^{-k} I_0\left(\frac{r\sqrt{2k}}{\sigma_F}\right)$$

I_0: modified Bessel function of zero order

Rice Factor: $k = \frac{\text{transm. power over direct path}}{\text{transm. power over other paths}}$

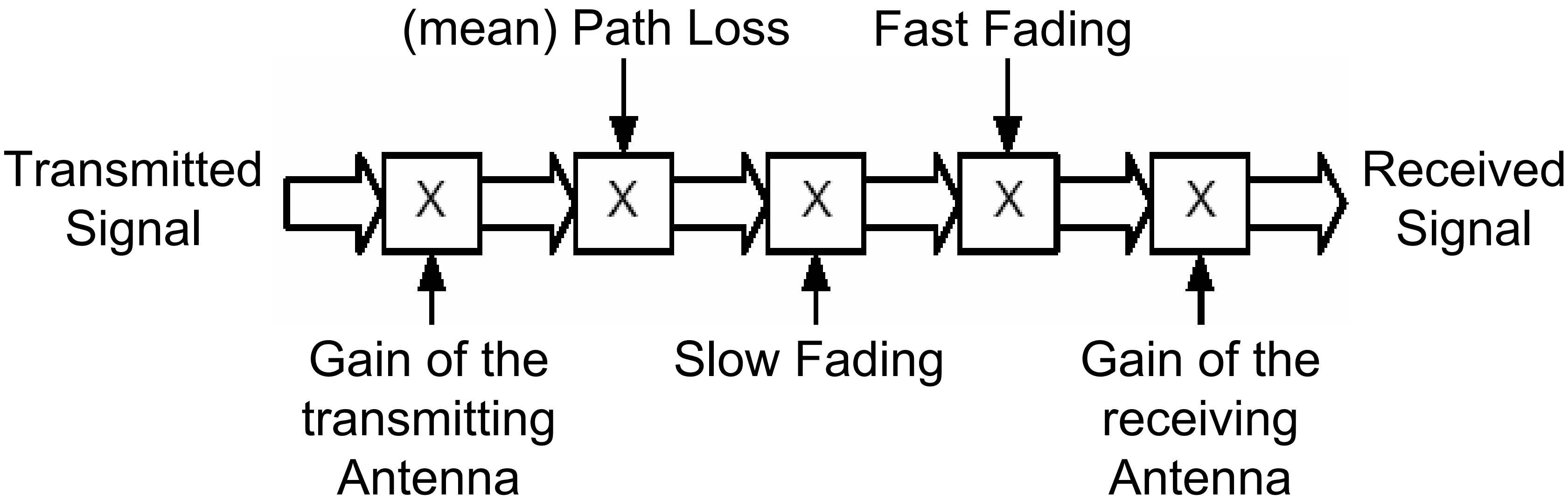




Fast Fading - Counter Measures

- time diversity
  - segmentation of data into blocks of defined length (= defined transmission time) → equalization of fast fading in the time domain
- frequency diversity
  - use of broadband channels or frequency hoping → equalization of fast fading in the frequency domain (assumption: fast fading is frequency dependent)
- antenna diversity
  - reception (and possibly transmission) via multiple antennas and combination of the received signals → equalization of fast fading by the use of multiple transmission paths
  - variants:
    - direction diversity
    - polarization diversity
    - space diversity
  - combination techniques:
    - Selection Combining (choice of the best signal)
    - Maximum Ratio Combining (weighted addition of the signals)

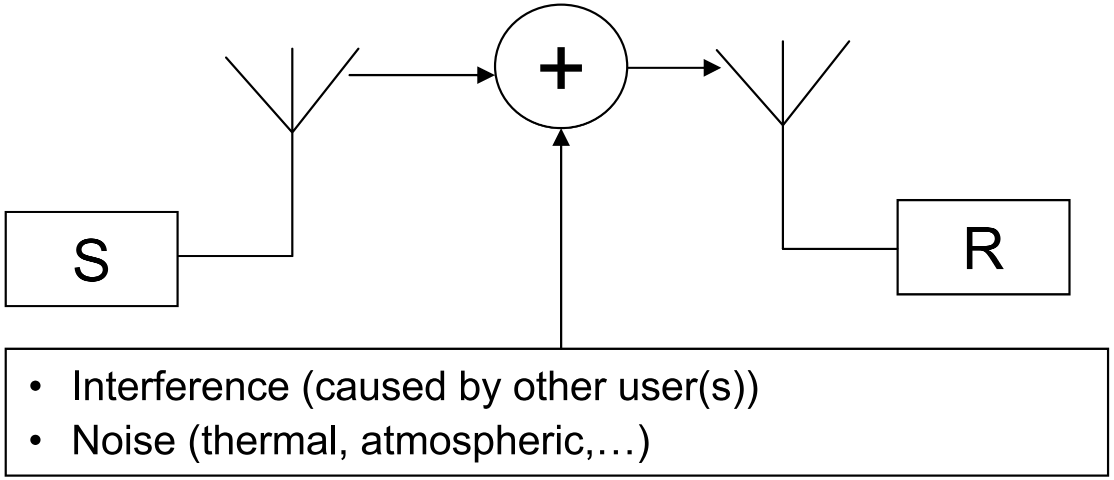
Path Loss at real Propagation Conditions - Summary



$$\boxed{\frac{P_r}{P_t} = \frac{G_t \cdot G_r}{L_M \cdot L_S \cdot L_F}}$$

Channel Impairments - Noise and Interference

Channel Impairments - Noise and Interference



- the received signal is the sum of the transmitted signal, the interference and the noise
- the channel impairments - noise and interference - could limit the performance of the wireless communication system
- remark: in some systems the impact of the interference is higher compared to the noise and therefore the connection quality decreases with an increasing number of users

Channel Impairments - Noise

- **Thermal Noise:** $$N = kT\Delta f$$

- **Receiver Noise:** $$P_N = (1 + F)kT\Delta f$$

k: Boltzmann Constant ($k=1.379*10^{-23}$ [W / (Hz K)])
Δf: Receiver Bandwidth
T: Receiver Temperature [K]
F: Noise Figure

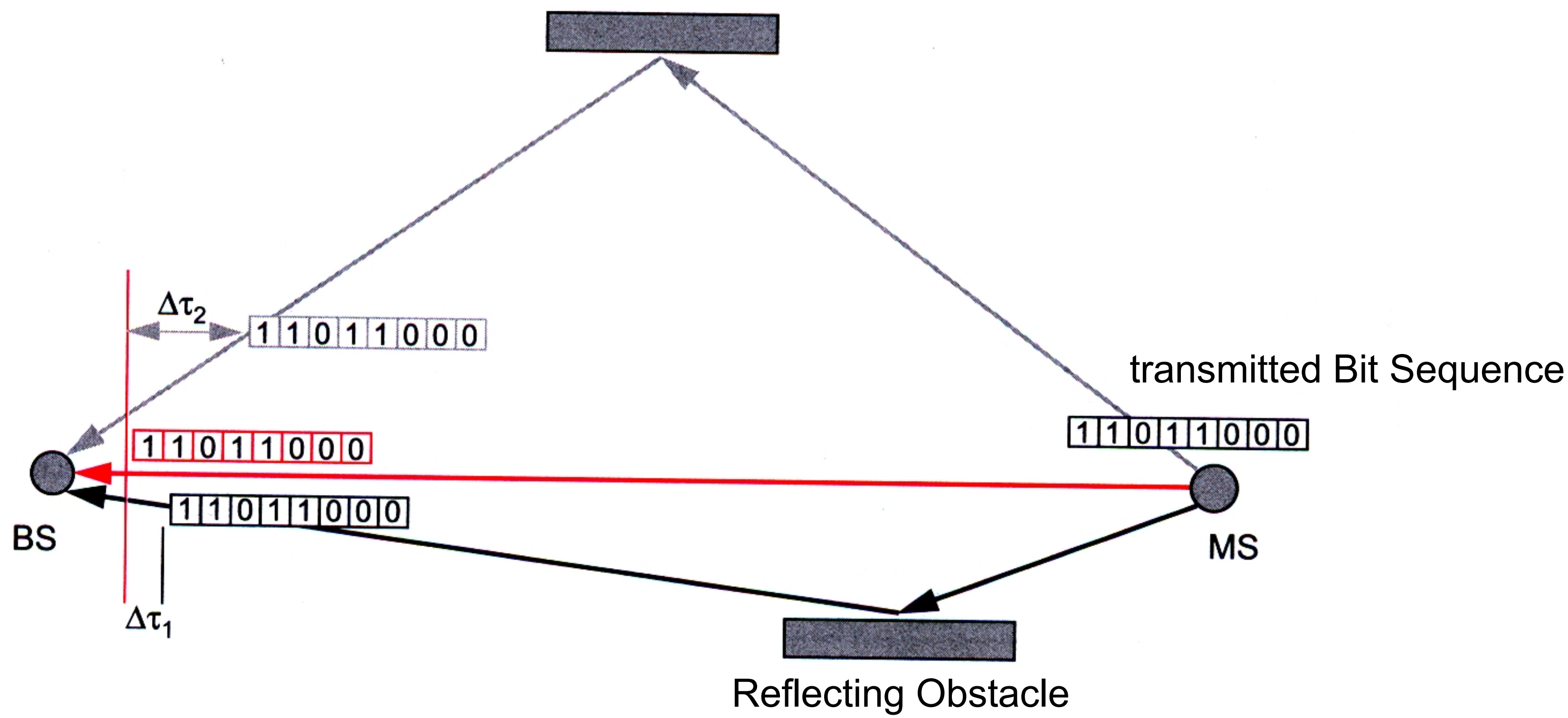
Channel Impairments - Interference

- interference is caused by:
  - interferers on the same frequency (“co-channel interference")
  - interferers on neighboring frequencies

  remarks:
    - in theory each time constrained signal has an infinite frequency range
    - as receive filter are non-ideal (i.e. they have a finite edge steepness) neighboring channels always will contribute to interference
- interfering signals add to the desired signal (additive superposition)

Channel Impairments - Intersymbol Interference

- intersymbol interference is caused by the superposition of delayed pulses (bit sequences)
- the pulse delay may be caused by reflection, diffraction or diffusion



Maximum Channel Throughput (Shannon Theorem)

- **Shannon Theorem*:**
  - the maximum achievable channel throughput *T* is proportional to the channel bandwidth *Δf*:

$$T = \Delta f \cdot \log_2\left(1 + \frac{P_r}{P_I + P_N}\right) = \Delta f \cdot \log_2(1 + SNR)$$

$$\log_2(x) = ld(x) = \frac{\log_{10}(x)}{\log_{10}(2)}$$

P_I: Overall Interference (Power)

P_N: Receiver Noise (Power)

S(I)NR: Signal-to-(Interference and) Noise Ratio

*Reference: C.E. Shannon, „A Mathematical Theory of Communication“

Options to increase the Channel Throughput

- **increasing the signal transmission power:**
  - problems:
    - limited applicability due to transmission power constraints (due to cost, regulatory restrictions, limited electical power consumption)
    - increasing the transmission power will also increase the interference ("co-channel interference")
- **interference reduction:**
  - by appropriate system design
  - via transmission power control
  - by use of directional or adaptive antennas
- **noise reduction:**
  - by use of advanced (low-noise) technology
  - however: lower bound due to unavoidable thermal noise