Non-LOS Propagation and Link Budget Analysis

WIRELESS SHORT COURSE

PROF. SUNDEEP RANGAN

Learning Objectives

- ❑ Compute the noise power density given a noise figure
- ❑ Compute noise figure in a cascade of elements
- ❑ Relate key parameters of a communication system:
  - Bandwidth, coding rate, modulation
- ❑ Describe communication requirements and perform simple link budget calculations
- ❑ Qualitatively describe various propagation mechanisms in real world settings
- ❑ Qualitatively determine which propagation mechanisms are dominant
- ❑ Compute probabilities of outage from a statistical channel model

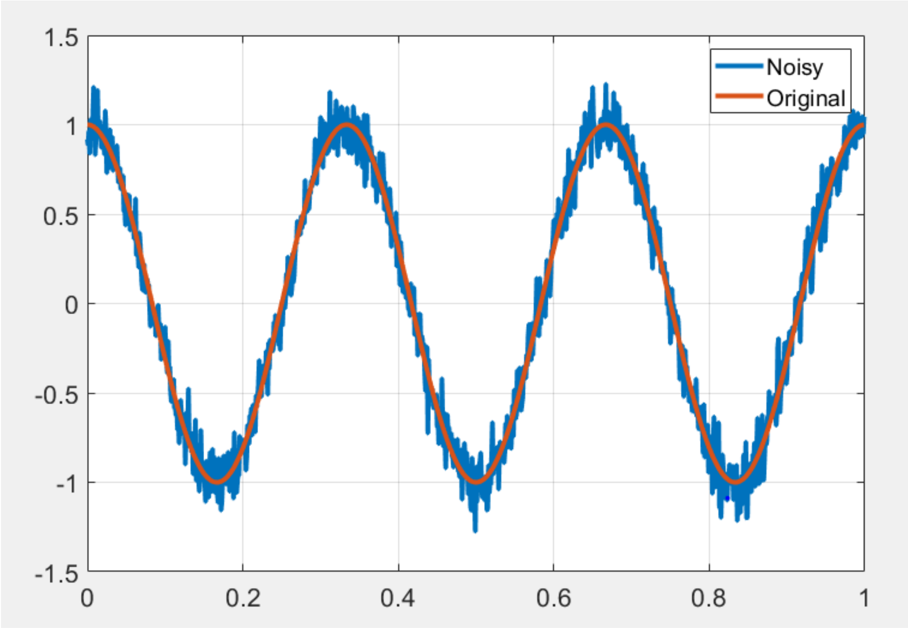
Outline

- ❑Noise and Noise Figure
- ❑Communication Requirements and Link Budget Analysis
- ❑Non-LOS Propagation
- ❑Statistical Models for Path Loss

What is Noise?

- ❑ Noise: Any unwanted component of the signal

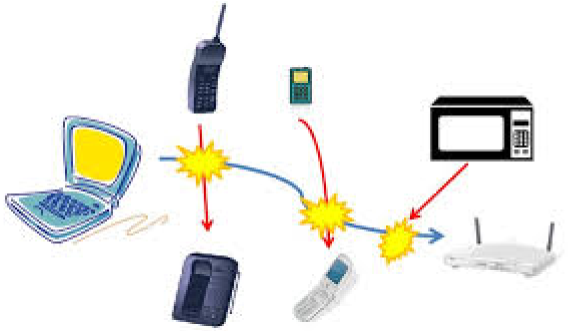
- ❑ Key challenge in communication:
  - Estimate the transmitted signal in the presence of noise



Types of “Noise”

- Internal / thermal noise:
  - From imperfections in the receiver
  - Thermal noise: From random fluctuations of electrons
  - Other imperfections: Phase noise, quantization, channel estimation errors

- External Interference
  - Signals from other sources
  - In-band: Transmitters in the same frequency
    Ex: Multiple devices in a cellular band
  - Out-of-band: From leakage out of carrier
  - Some texts do not consider “interference” as noise



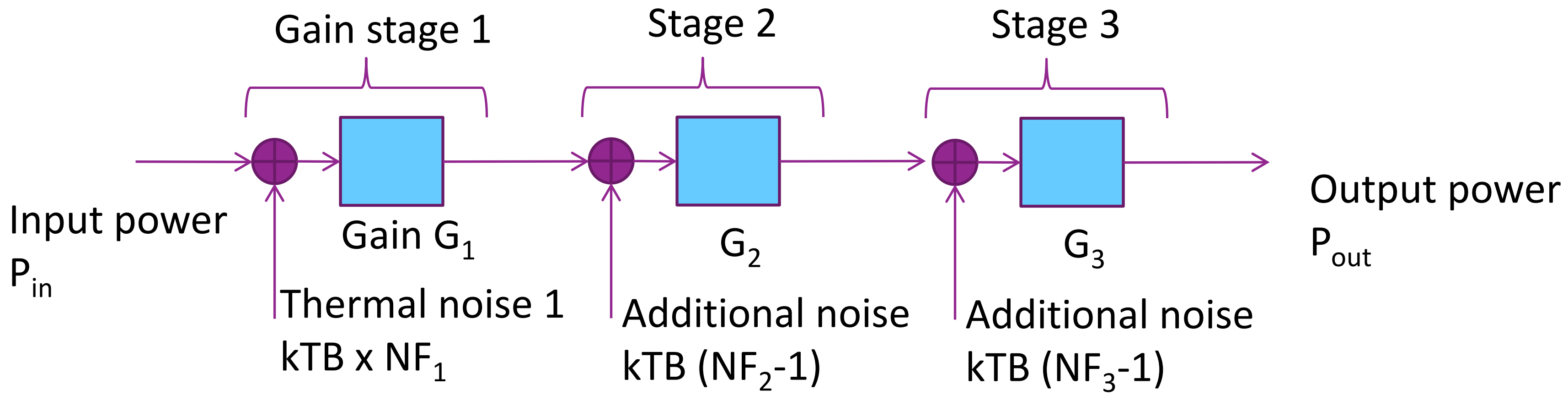
Thermal Noise

- Thermal noise: Caused by random fluctuations of electrons
  - Typically modeled as AWGN with power spectral density N_0
- Units:
  - Linear scale N_0 = W/Hz = Joules
  - Represents energy per degree of freedom = noise energy in any orthongonal sample
  - Often written in dB scale: $N_0 = 10\log_{10}\left(\frac{N_{0,lin}}{1\,mJ}\right)$ [dBm/Hz]
- Fundamental limit determined by statistical physics: $N_0 = kT$
  - k = Boltzman constant, T = temperature in Kelvin
  - At room temperature (T=300 K), $10\log_{10}(kT) = -174$ dBm/Hz
- Practical systems see higher noise power due to receiver imperfections

$$N_0 = 10\log_{10}(kT) + NF \ \ (\mathrm{dBm/Hz})$$

  - $NF =$ Noise figure
  - Typical values are 2 to 9 dB in most wireless systems

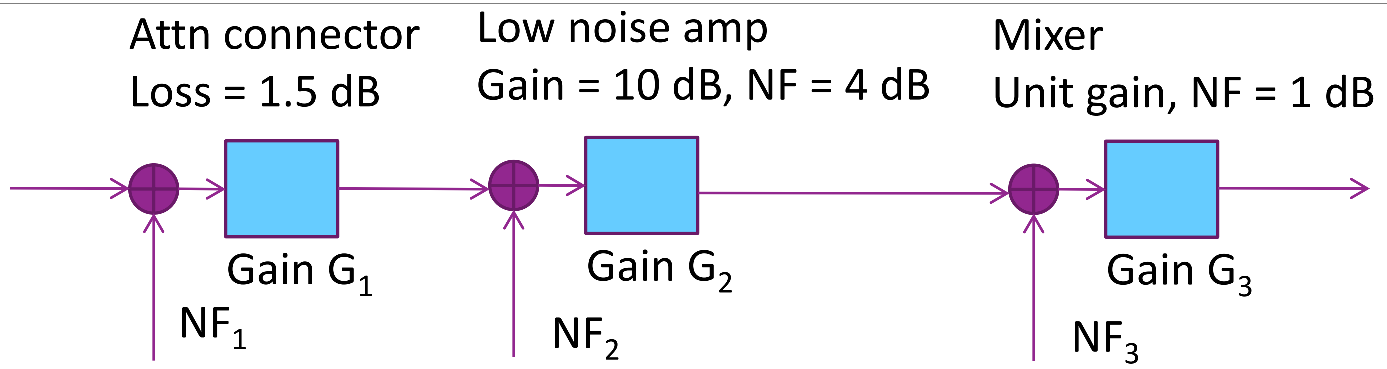
NF for Cascade of Elements



- ❑ Most receivers are built with multiple stages
  - Each stage has a gain and noise figure
  - Some stages (typically amplifiers) add noise with a noise figure
- ❑ Total noise figure given by: $NF_{tot} = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \cdots$
  - With large initial gain (G_1), init noise figure (NF_1) is dominant. Must make small.
  - Hence usual first stage is a low noise amplifier (LNA)

Example Problem

Molisch 3.1

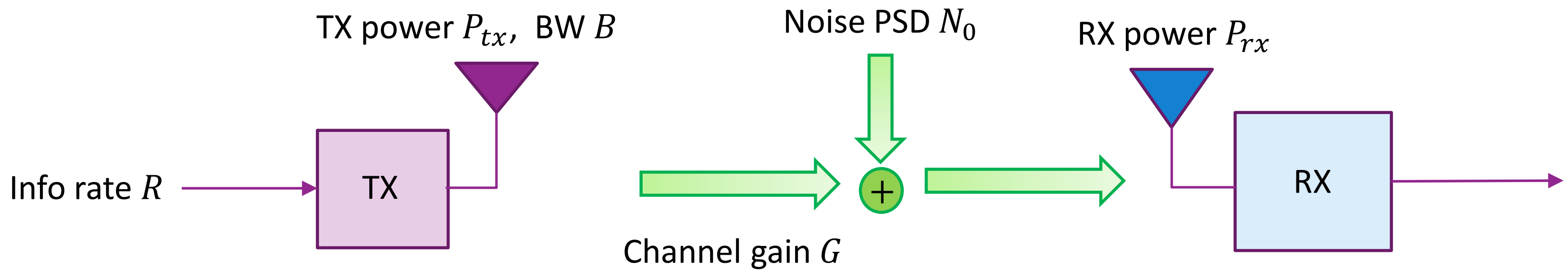


- What is total NF and gain?
- Answer: Compute G and NF (in linear units) for each stage:
  - Attenuator: NF1=1 (does not add noise), G1=$10^{-0.1(1.5)}$=0.707 (note sign)
  - LNA: NF2=$10^{0.1(4)}$=2.51, G2=$10^{-0.1(10)}$=10
  - Mixer: NF3=$10^{0.1(1)}$=1.25, G3=1 (unit gain)
  - Total gain: $G = -1.5 + 10 + 0 = 8.5$ dB
  - Noise figure $NF_{tot} = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} = 1 + \frac{2.51 - 1}{0.707} + \frac{1.25 - 1}{(0.707)(10)} = 3.15 \approx 5.0$ dB

Outline

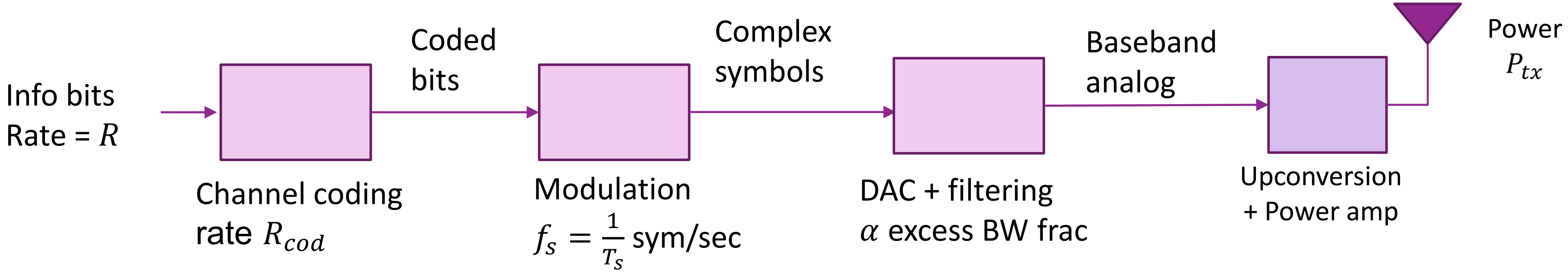
- ❑Noise and Noise Figure
- ❑Communication Requirements and Link Budget Analysis
- ❑Non-LOS Propagation
- ❑Statistical Models for Path Loss

Communication Requirements



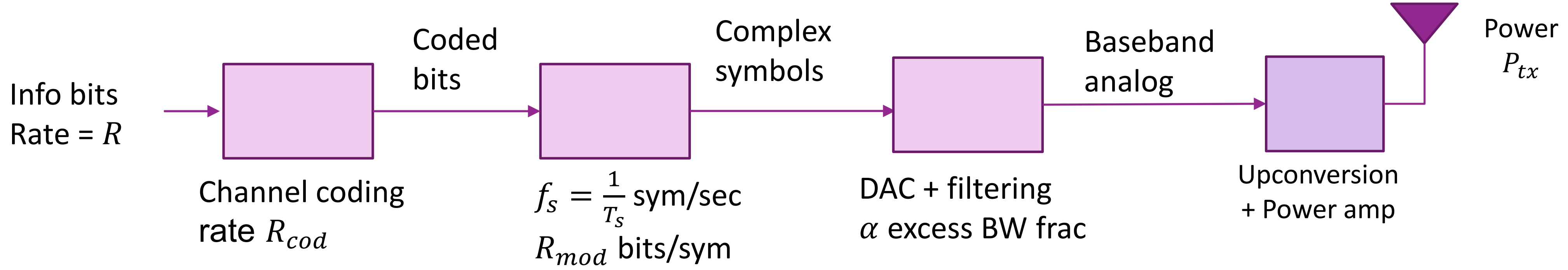
- Basic questions:
  - How does TX and RX power effect achievable rate for a communication system?
  - What level of path loss can a system sustain?
  - How much rate can be reliably transmitted?
- Answer: We review some basic concepts from Digital Communications

Typical Transmitter Steps



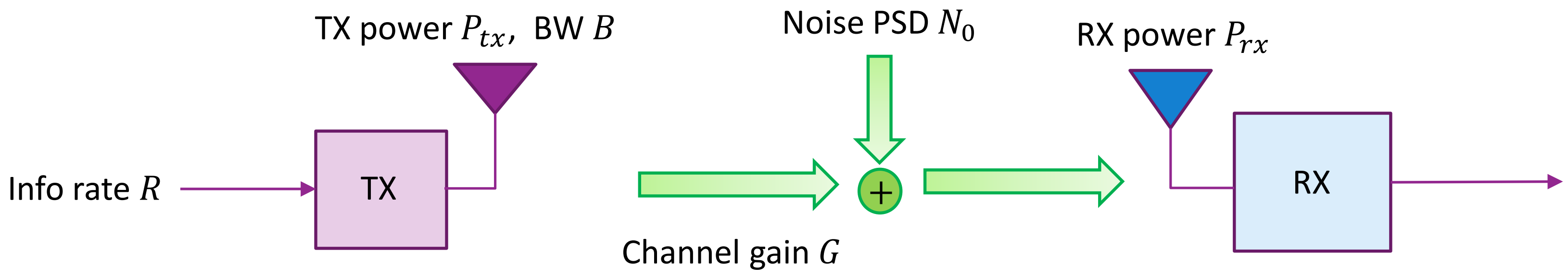
- Communication systems typically use three stages
  - Channel coding: ex. Convolutional, turbo, LDPC
  - Modulation: QPSK, 16-QAM, 64-QAM, …
  - Pulse shaping
- Determines modulation + coding scheme (MCS)

Key Transmitter Relations



- Information rate: $R = R_{cod} R_{mod} f_s$
- Signal bandwidth: f_s
- Occupied bandwidth: $B = (1+\alpha) f_s$
- Ex: A system transmits with rate ½ coding, 16-QAM, 10 Msym/s and excess BW 10%
  - Data states: $R_{cod} = \frac{1}{2}$; $R_{mod} = 4$ (16-QAM); $f_s = 10$ Msym/s; $\alpha = 0.1$
  - Hence information rate is $R = R_{cod} R_{mod} f_s = (0.5)(4)(10) = 20$ Mbps
  - Occupied bandwidth = $B = (1+\alpha) f_s = (1.1)(10) = 11$ MHz

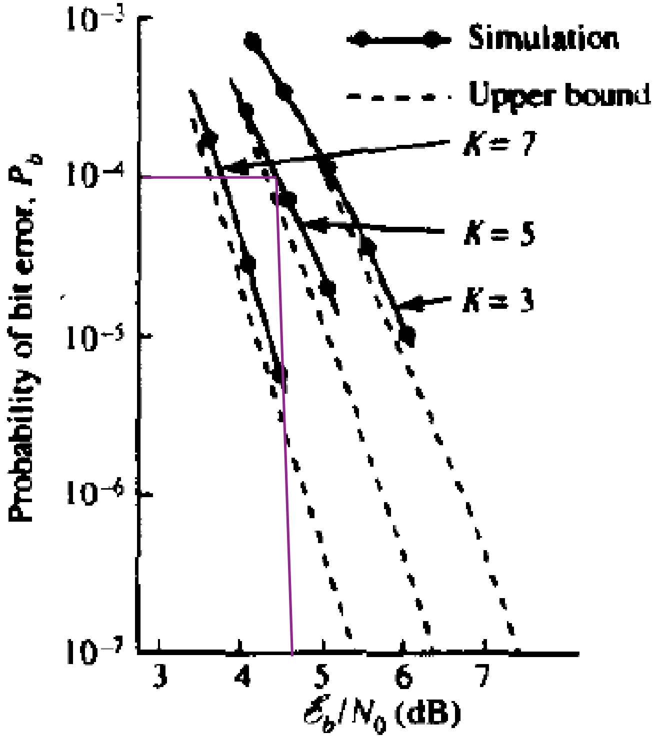
Receiver Requirements



- Power relations
  - Power at receiver is $P_{rx} = GP_{tx}$
  - Noise energy per degree of freedom = Noise PSD: N_0
- Requirements at the receiver are typically specified by two key parameters
  - SNR per bit $\frac{E_b}{N_0} = \frac{P_{rx}}{N_0 R}$ (pronounced “ebb-no”) or SNR per symbol: $\frac{E_b}{N_0} = \frac{P_{rx} T_S}{N_0}$
  - Spectral efficiency $\frac{R}{B}$ (Units are bps/Hz or bits/DOF)
- The receiver requirements will depend on the MCS and implementation of the receiver

Example Problem

- A system uses:
  - Convolutional code shown ($K = 7$) and $R_{cod} = \frac{1}{2}$, 16-QAM
  - Symbol rate $f_s = 100$ Msym/s. No excess bandwidth
  - Transmit power: 23 dBm
  - RX noise PSD: -170 dBm/Hz (including NF)
- For a BER of 10^{-4} find the maximum path loss
- Solution:
  - From graph we need $\gamma_b = \frac{E_b}{N_0} \approx 4.5$ dB
  - Information rate is $R = R_{cod} R_{mod} f_s = (0.5)(4)(100) = 200$ Mbps
  - $\gamma_b = \frac{E_b}{N_0} = \frac{P_{rx}}{N_0 f_s}$.
  - In dB scale: $P_{rx} = \gamma_b + 10\log_{10}(R) + N_0 = 4.5 + 3 + 80 - 170 = -82.5$ dBm
  - Hence, max path loss is $G = P_{rx} - P_{rx} = 23 - (-82.5) = 105.5$ dB



Shannon Capacity

- Capacity = max rate achievable given bandwidth and SNR
  - Rate optimized over all possible MCSs and communication schemes.
- Given by classic Shannon formula

$$C = B\log_2(1+\gamma), \qquad \gamma = SNR = \frac{P_{rx}}{N_0 B}$$

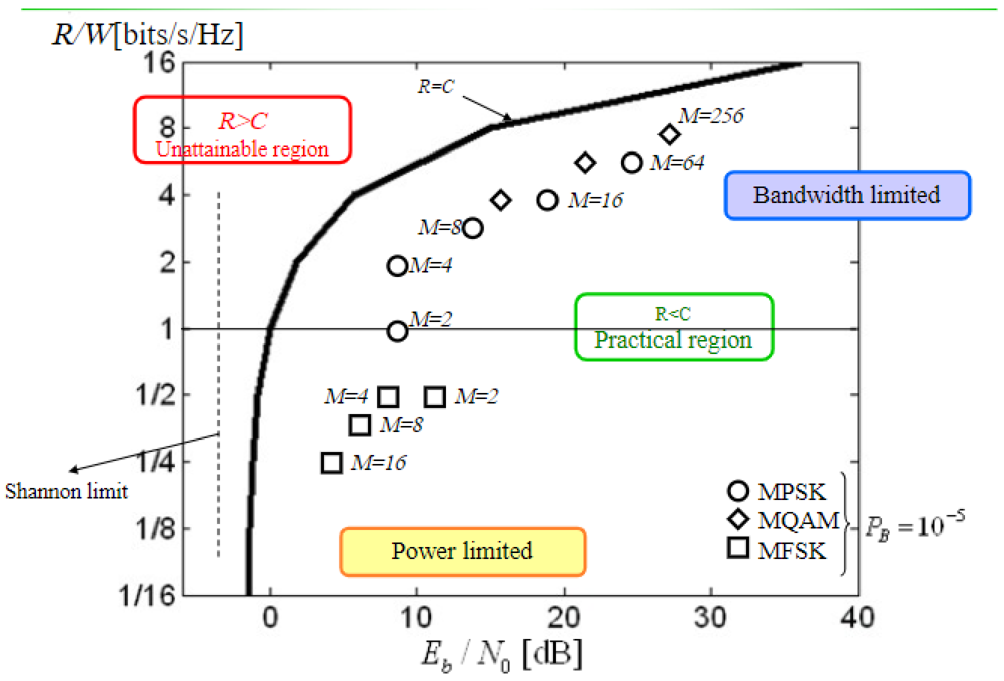
- Capacity relates theoretical rate to two key parameters:
  - B = bandwidth in Hz
  - SNR in linear scale (not dB!!!)
- Mathematical result from classic paper in 1948.

Bandwidth and Power-Limited Regions

- Shannon formula:

$$C = B\log_2(1+\gamma) = B\log_2\left(1+\frac{P_{rx}}{N_0 B}\right)$$

- Power-Limited region:
  - As $B \to \infty, C \to \log_2(e)\frac{P_{rx}}{N_0}$
  - Rate linearly increases with power / SNR $\frac{P_{rx}}{N_0}$
- Bandwidth-limited region:
  - For large SNR, $C \approx B\log_2(\gamma)$
  - Linearly increases in bandwidth,
  - Logarithmically increase in SNR.
  - Increasing SNR has little practical value



Actual Rate vs. Shannon Capacity

- Theoretical Shannon capacity cannot be achieved
  - Needs infinite computation and delay.
- Practical modems achieve a rate below Shannon limit.
- Useful model:

$$R = (1 - \Delta) B \log_2(1 + \beta\gamma)$$

  - Δ=fraction overhead
  - β=loss factor, usually quoted in dB
  - Often say “system is β dB below capacity”
  - $\gamma_{\text{eff}} = \beta\gamma$ can be thought of as an “effective” SNR
- Usually loss from capacity is at least 3dB
  - Often higher depending on receiver complexity and other factors

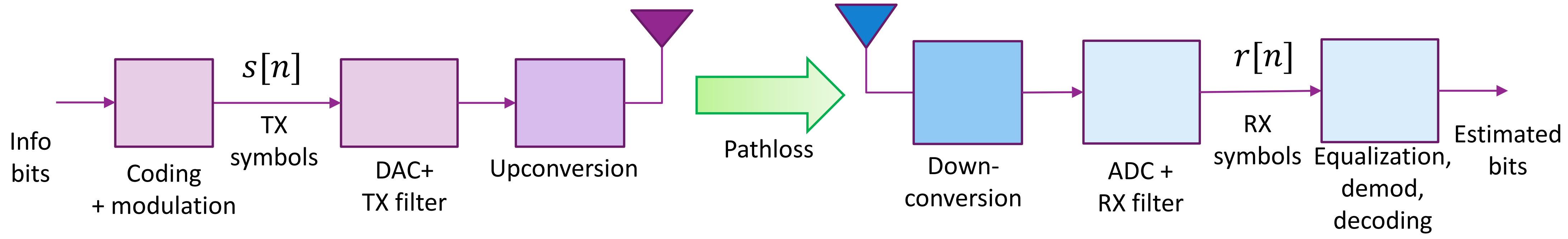
Rate vs. Capacity Example

- What is the maximum rate for a system:
  - 20% overhead, 10 MHz bandwidth, SNR=12 dB
  - Operates at 3dB below Shannon capacity
- Answer:
  - Effective SNR: $\gamma_{\text{eff}} = 12 - 3 = 9$ dB. In linear scale $\gamma_{\text{eff}} = 8$ (since 9=3(3))
  - Therefore,

$$R = (1 - \Delta)B \log_2(1 + \beta\gamma) = (0.8)(10) \log_2(1 + 8) = 25.3 \text{ Mbps}$$

  - Note the final units are in Mbps

Communication Requirements



- Basic questions:
  - How does TX and RX power effect achievable rate for a communication system?
  - What level of path loss can a system sustain?
- Can review in the digital communications class

Example Link Budget

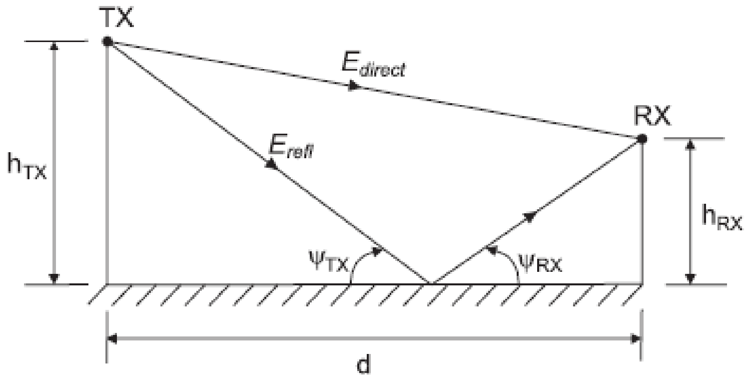
Item	Value	Remarks
Transmit power (dBm)	23.0	200 mW transmitter
Distanced based path loss (dB)	90.0	Will depend on propagation model
Shadowing (dB)	20.0	Will depend on obstructions
Receive power (dBm)	-87.0	TX power - path loss - shadowing
Bandwidth (MHz)	20.0	BW of 802.11 signal
Noise figure	5.0	Will depend of implementation of receiver
Noise power (dBm)	-96.0	-174 +10log(BW) + NF
SNR (dB)	9.0	RX pow - Noise pow

- Link budget: Measures final SNR as a function of TX power and all impairments

Outline

- Noise and Noise Figure
- Communication Requirements and Link Budget Analysis
- Non-LOS Propagation
- Statistical Models for Path Loss

Propagation Loss with Reflections



$$\frac{P_r}{P_t} = G_1 G_2 \frac{h_{tx}^2 h_{rx}^2}{d^4}$$

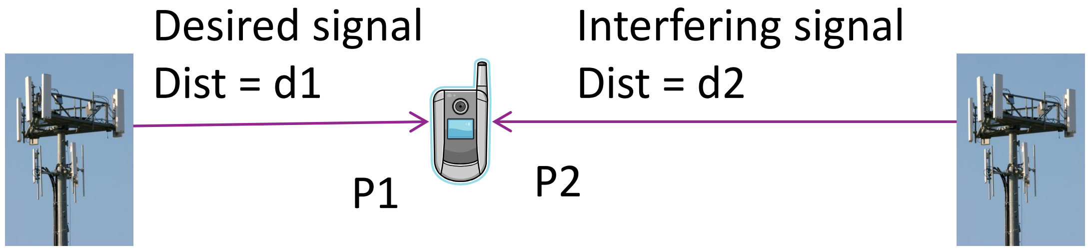
- In free space, we saw power density decays as d^2
- Due to ground reflections, power decays faster than d^2
- For d large, decays as d^α, α= path loss exponent.
  - α has been observed from 1.5 to 5.5, but usu. btw 3 and 5.
- For single ground reflection, can show α=4.
  - Based on reflected wave canceling direct wave
  - See www.wiley.com/go/molisch Appendix 4-A

Path Loss Exponent, Coverage & Interference

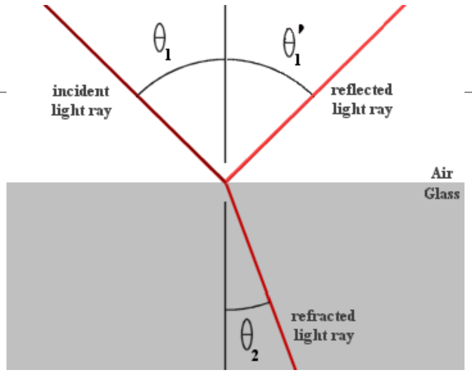
- For coverage-limited systems, low α is good
  - Power decays slower => signals have greater range

- For interference-limited systems, high α is good
  - Ex: If thermal noise is negligible:

$$SINR = \frac{P_1}{P_{noise} + P_2} \approx \frac{P_1}{P_2} = \left(\frac{d_2}{d_1}\right)^{\alpha}$$



Transmission & Reflection



- ❑ At any discontinuity in refractive index, incident wave will be transmitted and reflected.
  - Angle of incidence = angle of reflection
  - Refraction angle determined by Snell's Law
- ❑ Amount of reflected and transmitted power:
  - Depends on refractive indices of two mediums, angle of incidence and wave's polarization
- ❑ Conducting materials may also result in absorption of power

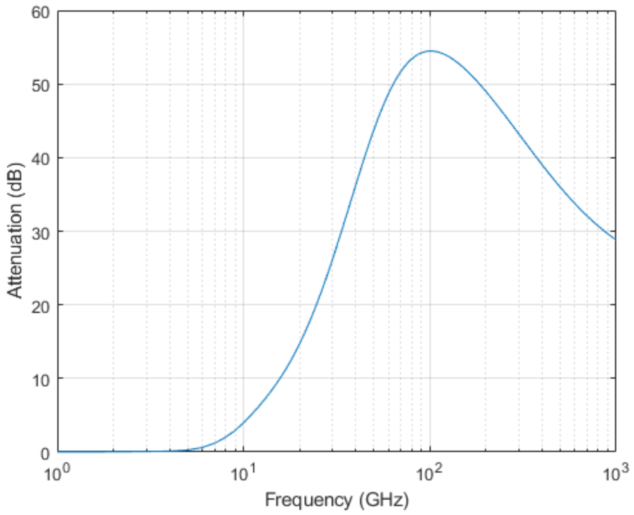
Transmission Through Typical Materials

Building Material	2.4 GHz Attenuation
Solid Wood Door1. 75"	6 dB
Steel Fire/Exit Door 1.75"	13 dB
Steel Fire/Exit Door 2.5"	19 dB
Brick 3.5"	6 dB
Concrete Wall 18"	18 dB
Glass Divider 0.5"	12 dB
Interior Solid Wall 5"	14 dB
Marble 2"	6 dB
Exterior Double Pane Coated Glass 1"	13 dB
Exterior Single Pane Window 0.5"	7 dB

- Radio waves can transmit through materials, but with attenuation
- Source: City of Cumberland, Maryland WiFi study

Attenuation Models in MATLAB

- MATLAB Phased Array Toolbox has many models atmospheric attenuation
  - Commands for free space path loss, and attenuation for fog, gas and rain
  - Based on well-studied measurements
- Note: Rain fades are particularly important to model for mmWave!



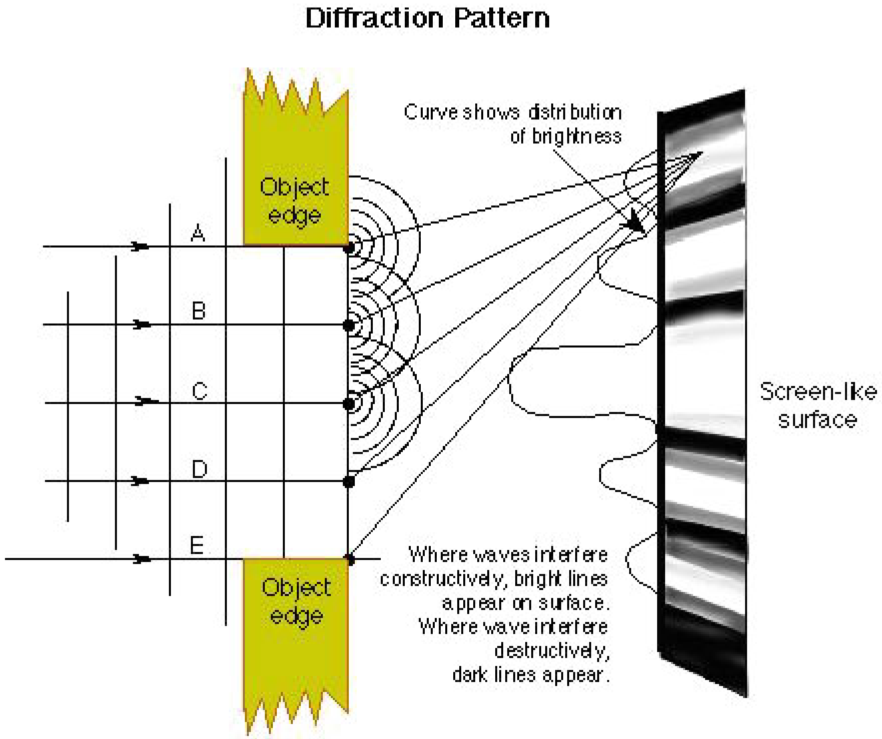
Rain attenuation vs. Freq

10 km distance

Rate rate = 20 mm/hr (very heavy rain)

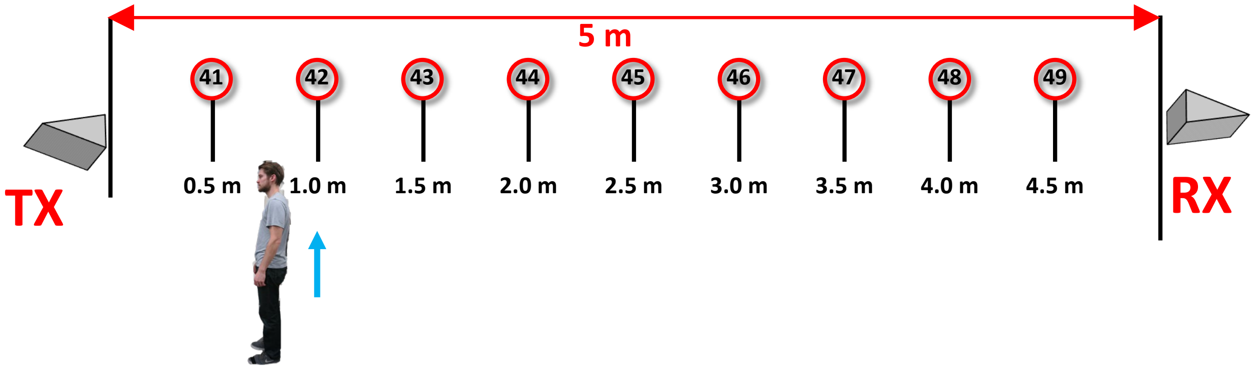
```
rr = 20.0;
freq = [1:1000]*1e9;
L = rainpl(10000,freq,rr);
semilogx(freq/1e9,L)
grid
xlabel('Frequency (GHz)')
ylabel('Attenuation (dB)')
```

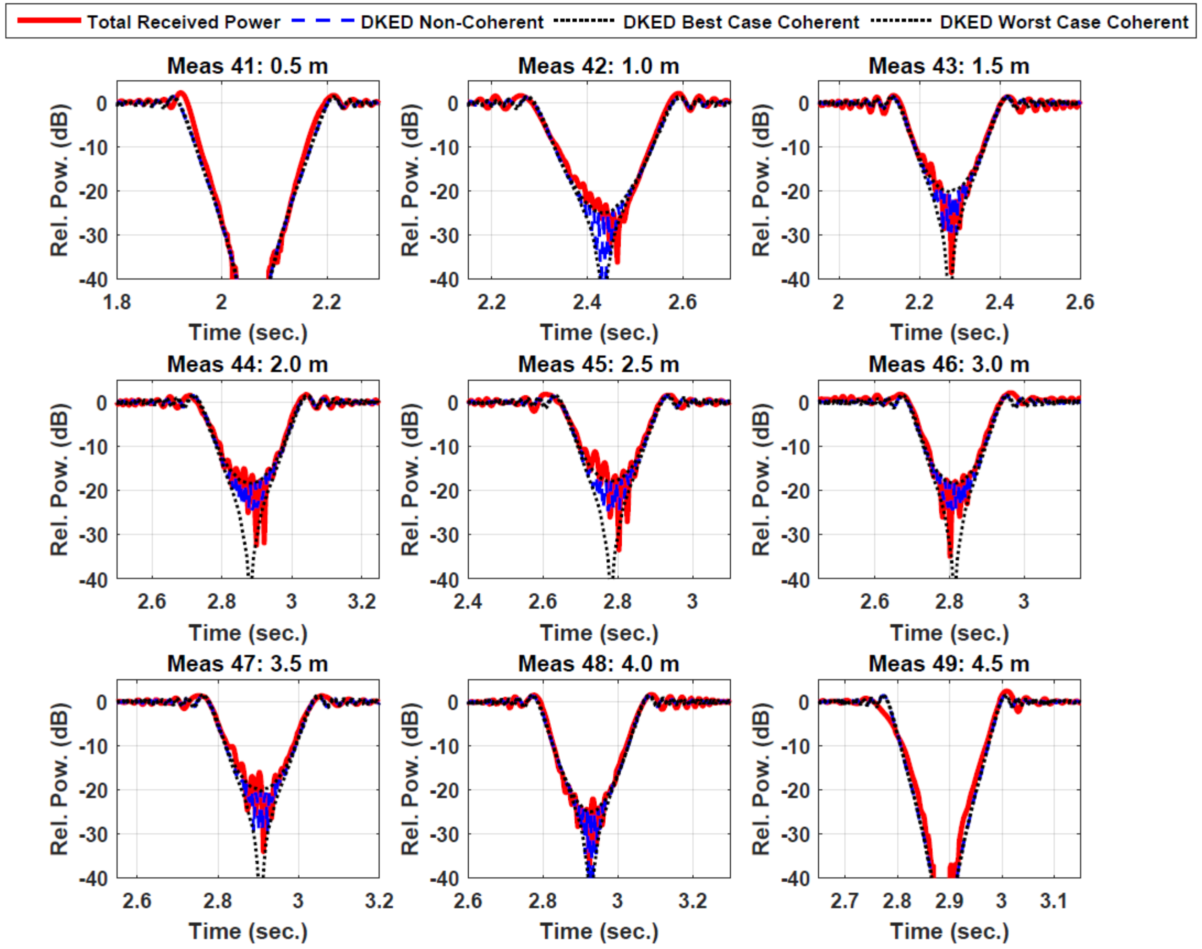
Diffraction



- ❑ Interfering objects (IOs) do not result in sharp shadows.
  - Due to wave nature of EM radiation
  - Simple ray model is not correct.
- ❑ Waves diffract at IO boundaries,
  - Intensity after IO can be stronger in parts than with no IO!

Human Blocking at 73GHz Example

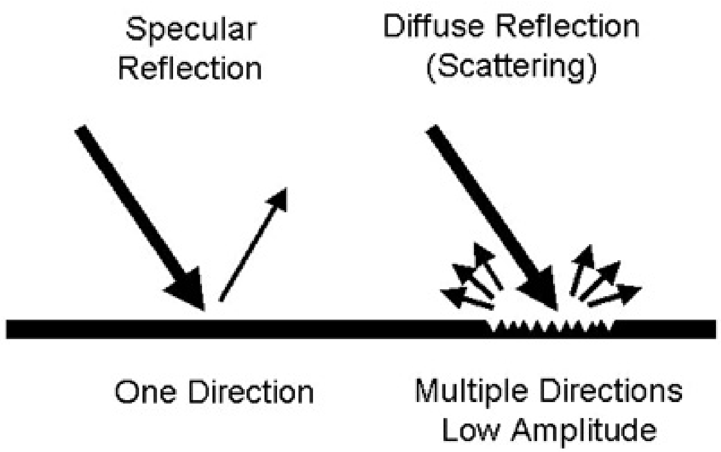




- Between 25 and 40 dB blockage
  - Depends on distance
- Total power predicted by knife edge diffraction
- Piecewise linear model used by 3GPP

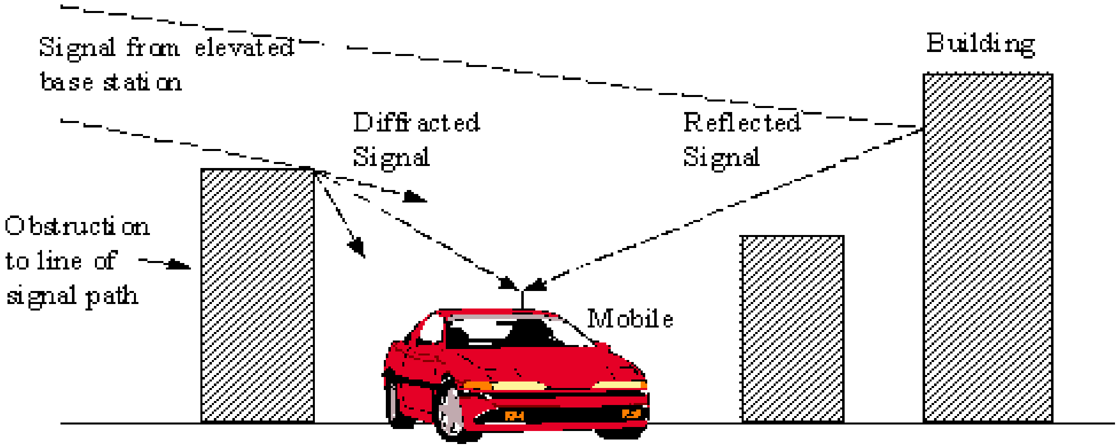
G. R. MacCartney, Jr., S. Deng, S. Sun, and T. S. Rappaport, "73 GHz Millimeter-Wave Human Blockage and Dynamic Measurements," IEEE VTC 2016

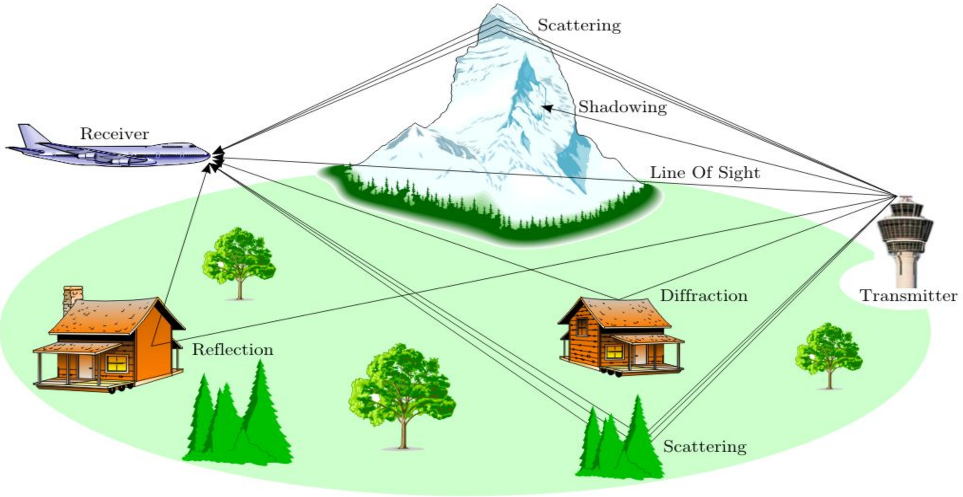
Specular Reflections & Scattering



- Due to surface roughness, reflected radio waves can be scattered in many directions.
- Amount of power loss in specular component related to height of surface irregularities.
- Texts provides probabilistic models to estimate power loss based on random height variations.

Radio Waves Have Many Paths



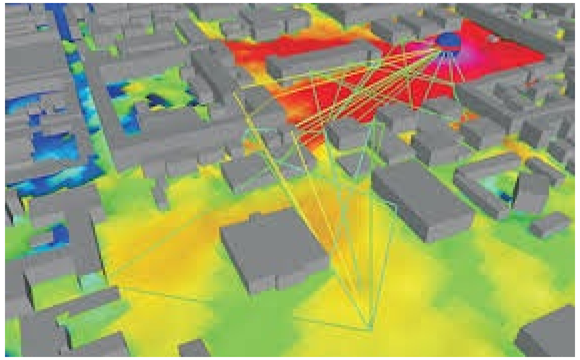


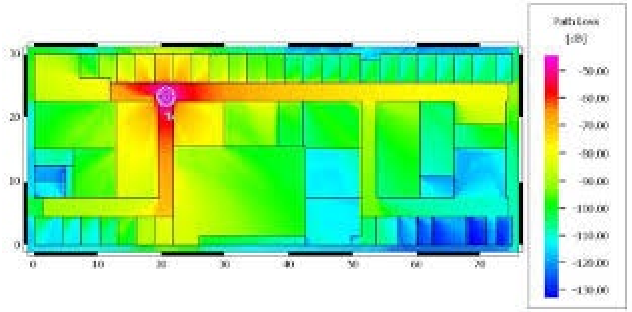
Outline

- ❑Noise and Noise Figure
- ❑Communication Requirements and Link Budget Analysis
- ❑Non-LOS Propagation
- ❑Statistical Models for Path Loss

Real Path Loss

- ❑Path loss is a complex function of environment
- ❑Varies with distance, obstacles, reflections …
- ❑Site specific path loss can be predicted with ray tracing





Outputs of commercial WinProp ray tracer

Statistical Path Loss Models

- Model path loss as a random variable
- Environmental effects are modeled as random
- Model fit for a type of environment
  - Eg. Urban, suburban, indoor, … Not site-specific
- Based on data
- Used for evaluation of performance statistics
  - Coverage, rate distribution, …

Linear Models

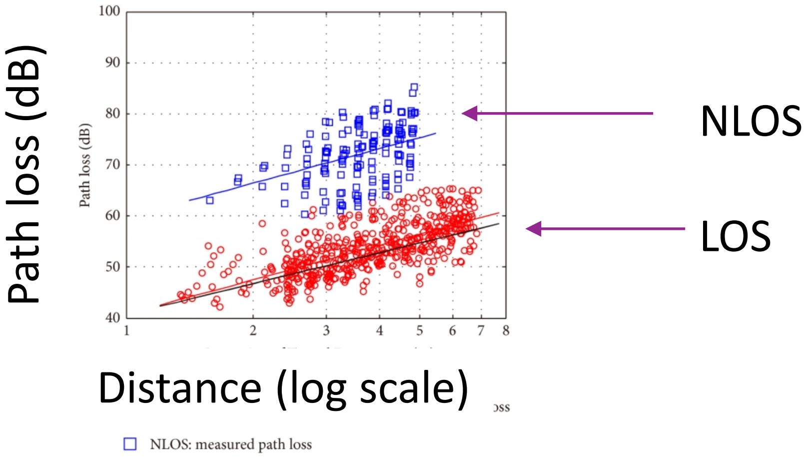
- Floating intercept model:

$$PL(d) = 10\alpha \log_{10} d + \beta + \xi, \qquad \xi \sim N(0, \sigma^2)$$

  - Parameters α, β, σ^2 fit from data

- Used widely in 3GPP, IEEE
  - Different models for different scenarios

- Caution in any fit model:
  - Do not use outside distances, frequencies it was derived



Related Models

- Close in (CI) model
  - Match free space at some fixed reference distance d_0

$$PL(d) = FSPL(d_0) + 10\alpha \log_{10} \frac{d}{d_0} + \xi$$

  - One less parameter to fit
  - Matches true path loss at d_0

- Hata model, ….
- Multi-slope models
- 3GPP NLOS / LOS hybrid models

Outage Probability

- Consider transmission with fixed MCS with rate R
  - No adaptation!
- Requires $SNR \geq SNR_{min}$
  - Outage: Event that $SNR < SNR_{min}$
  - Results in zero rate
- With variable path loss, SNR, is a random variable
- Outage probability:

$$\begin{aligned} P_{out} &= P(SNR < SNR_{min}) \\ &= P(P_{TX} - PL(d) - P_{noise} < SNR_{min}) \end{aligned}$$