Non-LOS Propagation and Link Budget Analysis

WIRELESS SHORT COURSE

PROF. SUNDEEP RANGAN

Learning Objectives

- Perform simple noise and interference calculations
- Define key communication requirements
  - BER, BLER, information rate, spectral efficiency, bandwidth
  - SNR: Energy per bit and energy per symbol
- Estimate rate based on simple models or from link curves
- Perform simple link budget calculations
- Qualitatively describe various propagation mechanisms in real world settings
- Compute reflected power from the radar equation
- Generate samples from a statistical path loss model
- Compute rate and SNR distributions using a statistical path loss model

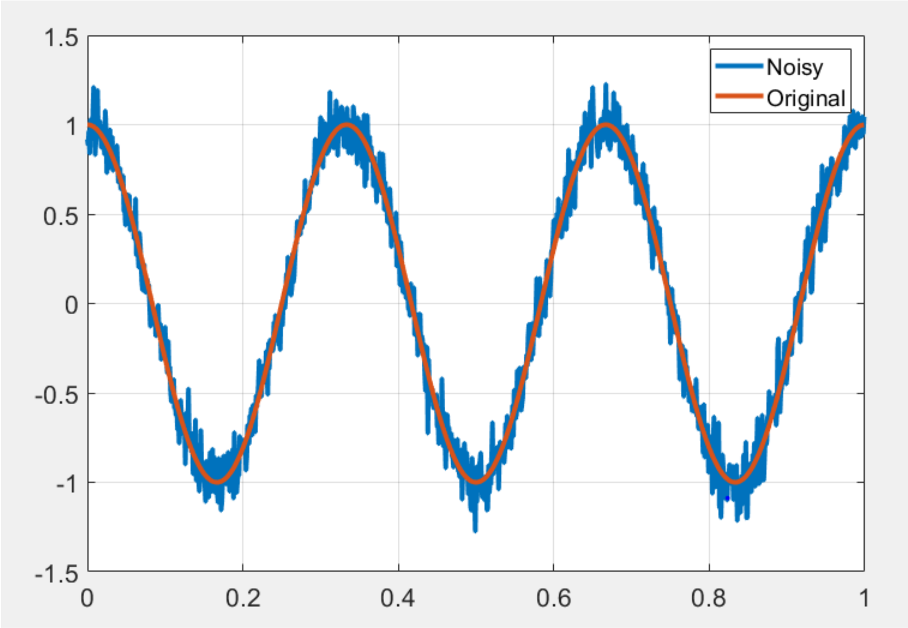
Outline

- Noise and Interference
- Communication Requirements and Link Budget Analysis
- Non-LOS Propagation
- Statistical Models for Path Loss
- Demo: Estimating Rates with a 3GPP model

What is Noise?

- ❑ Noise: Any unwanted component of the signal

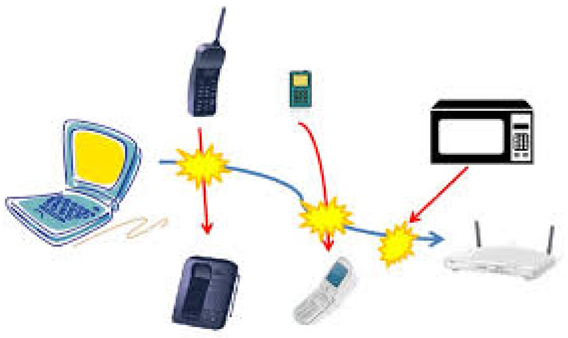
- ❑ Key challenge in communication:
  - Estimate the transmitted signal in the presence of noise



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



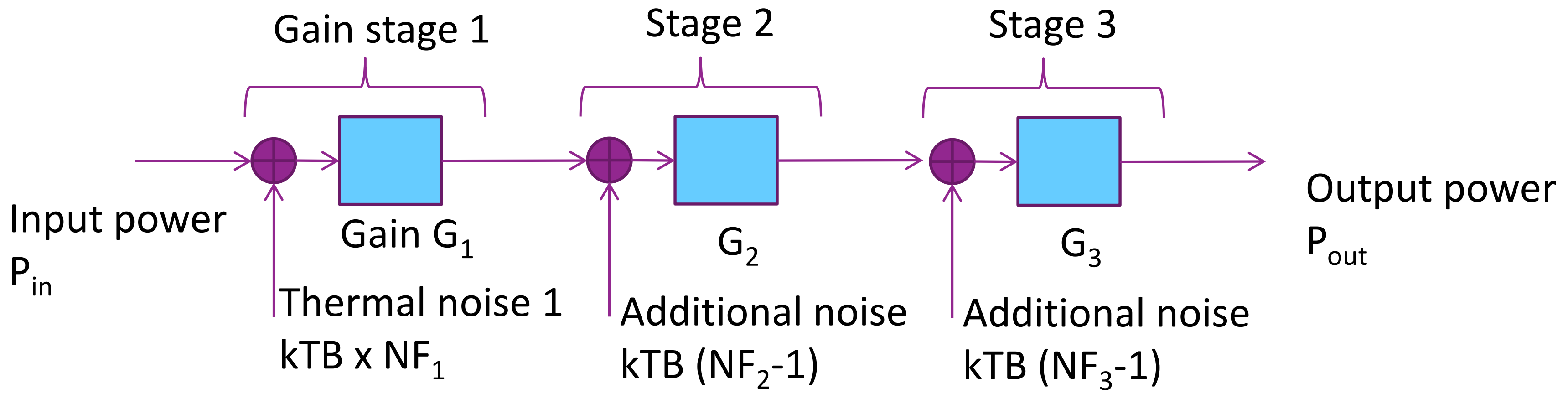
Thermal Noise

- 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 orthogonal 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

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

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

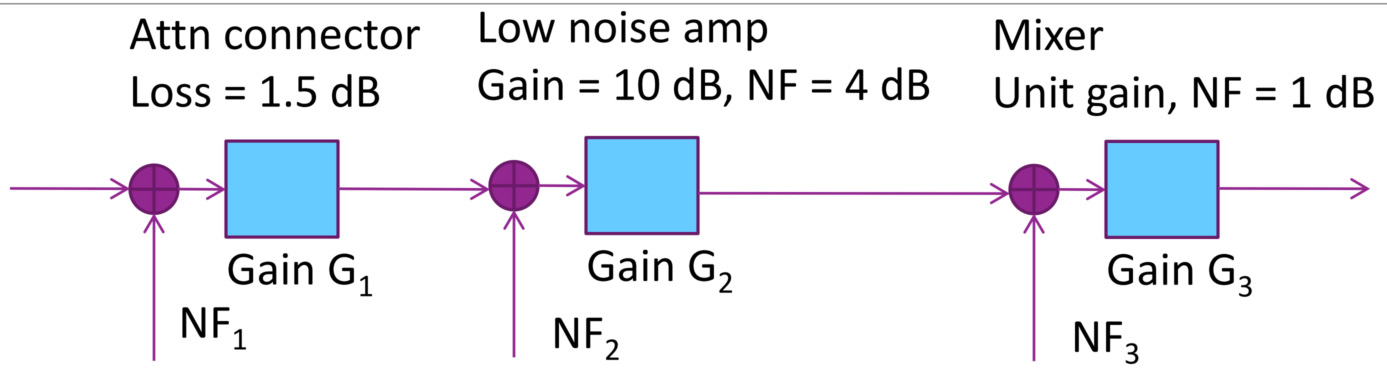
NF for Cascade of Elements



- 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

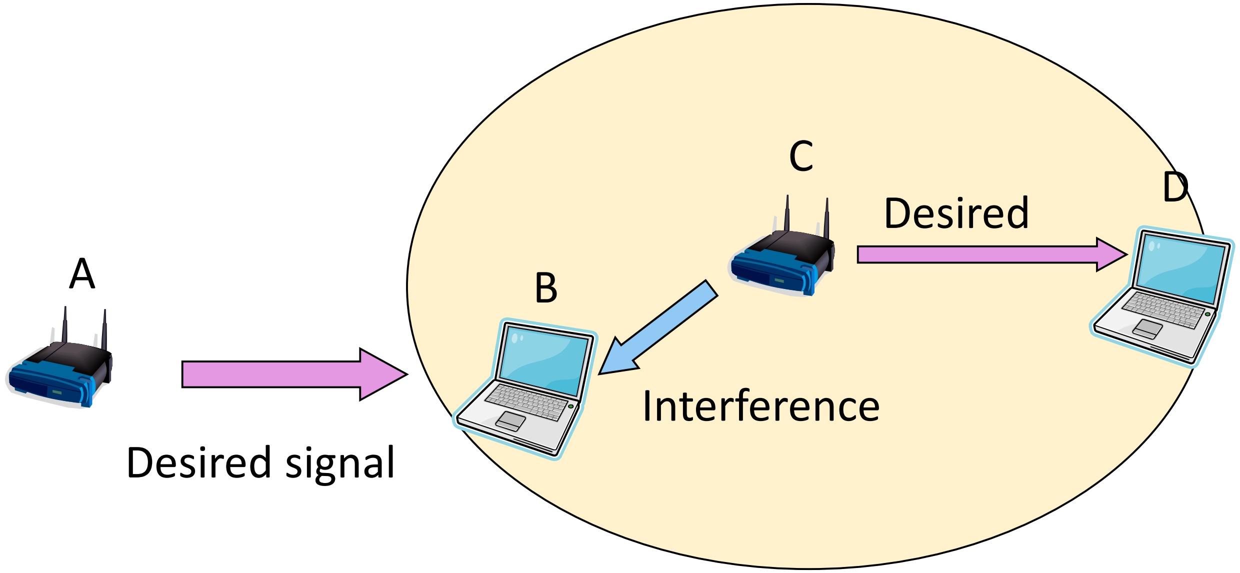
Molisch 3.1



- 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 $NF_{tot} = NF_1 + \frac{NF_2-1}{G_1} + \frac{NF_3-1}{G_1G_2} = 1 + \frac{2.51-1}{0.707} + \frac{1.25-1}{(0.707)(10)} = 3.15 \approx 5.0$ dB

Interference

- Signals from other transmitters using same band and same time.
- Fundamental to the broadcast nature of the wireless medium.
- Adds to total noise seen at receiver
- Example:
  - A transmits to B (desired signal)
  - C transmits to D (desired signal)
  - But B gets interference from A



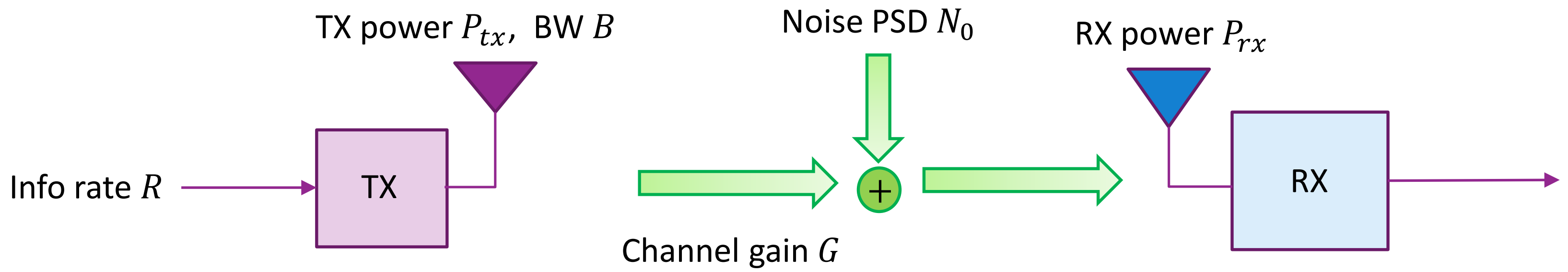
Interference Calculations

- Remember: Noise and interference powers add in linear scale (not in dB)!
- Example:
  - NF = 4 dB, B = 20 MHz
  - Interference power = -95 dBm, RX signal power = -80 dBm
  - Find the SNR=signal to noise and SINR = signal to interference + noise
- Solution:
  - Thermal noise density $N_0 = -174 + 4 = -170$ dBm/Hz
  - Noise power $P_N = N_0 B$. In dBm: $P_N = -170 + 10\log_{10}(2(10)^7) = -97$ dBm
  - SNR = -80 – (-97) = 17 dB
  - Noise + interference power, $P_{NI} = 10^{-9.7} + 10^{-9.5} = 5.2(10)^{-9} = -92.9$ dBm
  - Note: You add in linear scale first before converting to dB!!
  - SINR = -80 – (-92.9) = 12.9 dB

Outline

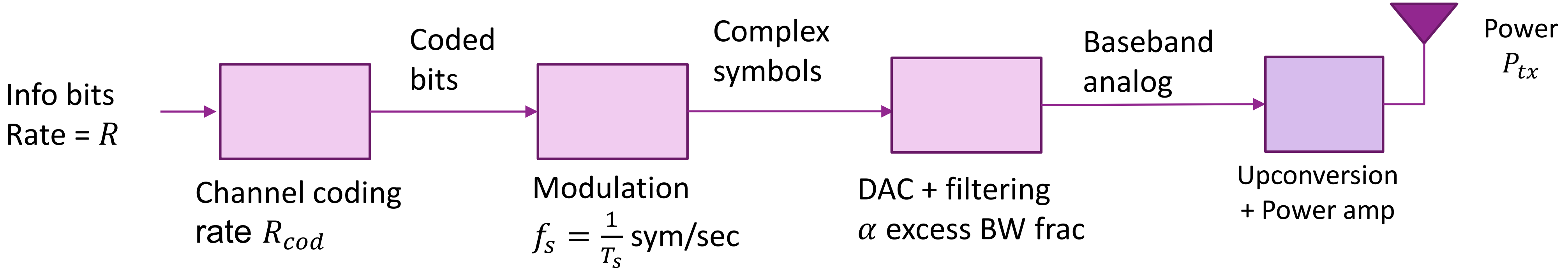
- ❑Noise and Interference
- ❑Communication Requirements and Link Budget Analysis
- ❑Non-LOS Propagation
- ❑Statistical Models for Path Loss
- ❑Demo: Estimating Rates with a 3GPP model

Communication Requirements



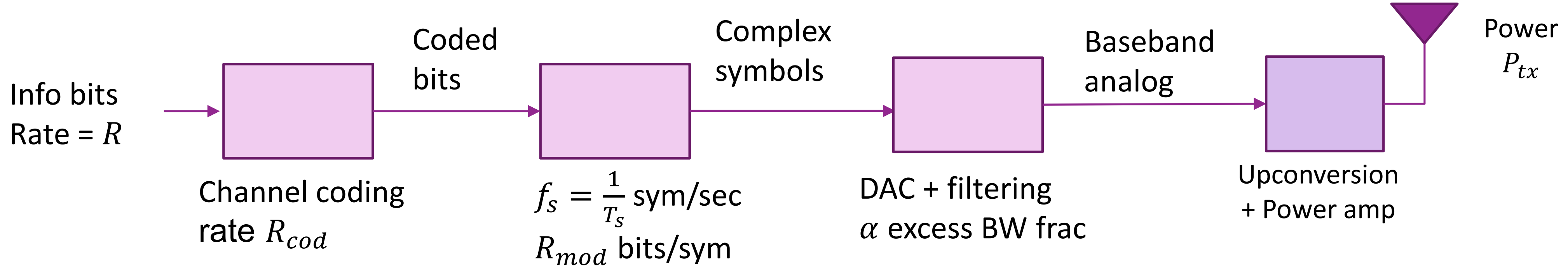
- Basic tradeoff in all communication systems:
  - Information rate: Amount of information we try to send
  - Bandwidth: Spectrum the signal occupies
  - Reliability: The probability it is received correctly
  - Channel quality: Typically measured by the signal to noise ratio
- Will review some basic concepts from digital communication:
  - How are these exactly measured?
  - What is the tradeoff in practical communication systems?

Review: Typical Transmitter Steps



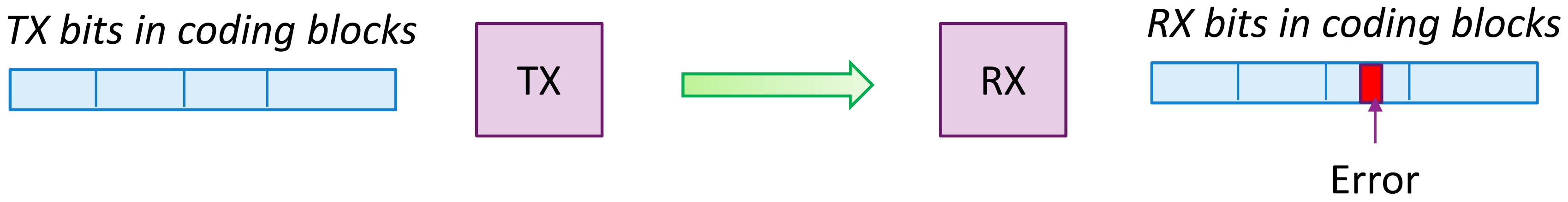
- Communication systems typically use three stages
  - Channel coding: ex. Convolutional, turbo, LDPC
  - Modulation: QPSK, 16-QAM, 64-QAM, …
  - Pulse shaping
- Determines modulation + coding scheme (MCS)

Information Rate and Bandwidth



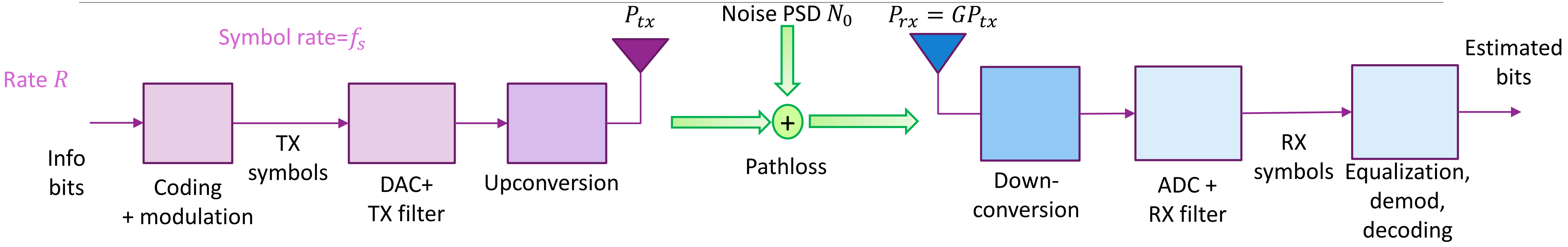
- Information rate: $R = R_{cod} R_{mod} f_s$ [bits/sec]
- Signal bandwidth: f_s [Hz]
- Occupied bandwidth: $B = (1+\alpha) f_s$ [Hz]
- Spectral efficiency $\frac{R}{B}$ (Units are bps/Hz or bits/DOF)
- Ex: A system transmits with rate ½ coding, 16-QAM, 10 Msym/s and excess BW 10%
  - Data states: $R_{cod} = \frac{1}{2}$; $R_{mod} = 4$ (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

Reliability: BER and BLER



- Most communication system TX data into blocks
  - Framing may be used for coding, MAC layer transport blocks or IP layer
  - Range in size from 100s to > 10000 bits per blocks
- Measure reliability by either:
  - BER: Bit error rate = fraction of bits in error (useful when there is no blocks)
  - BLER: Block error rate = fraction of blocks that have at least one error
- Errors typically need to be corrected at some higher layer
  - Retransmissions / ARQ at MAC or transport layer (A lot more on this later!)
  - Corrected by application (e.g. voice masking in audio)
- Acceptable level for BER and BLER depend on many MAC and application layer factors

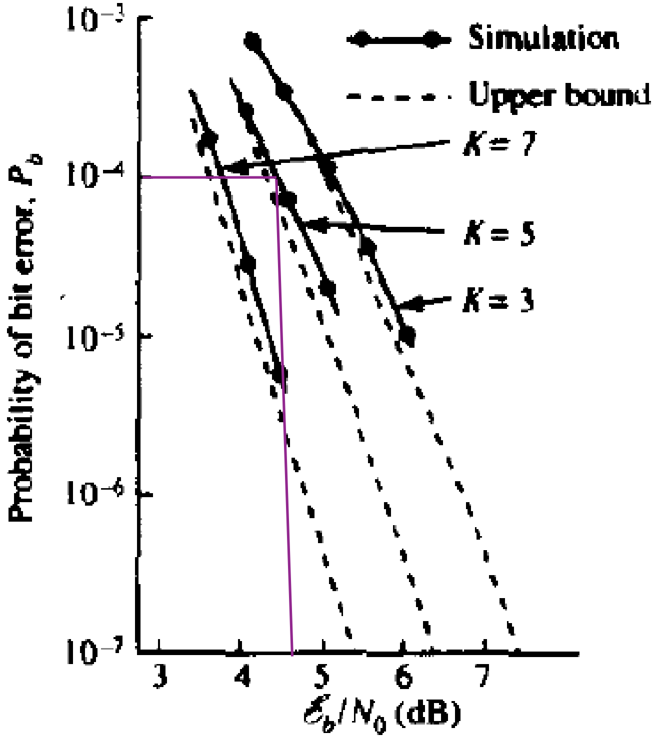
SNR and Power Relations



- Power relations
  - Power at receiver is $P_{rx} = GP_{tx}$
  - Noise energy per degree of freedom = Noise PSD: N_0
- Channel quality is measured by SNR = signal to noise ratio
  - SNR per bit $\frac{E_b}{N_0} = \frac{P_{rx}}{N_0 R}$ (pronounced “ebb-no”)
  - SNR per symbol: $\frac{E_b}{N_0} = \frac{P_{rx} T_S}{N_0}$
- Requirement will depend on the MCS used and the quality of the receiver

Example Problem

- A system uses:
  - Convolutional code shown ($K = 5$) 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 $L = P_{tx} - P_{rx} = 23 - (-82.5) = 105.5$ dB



From Proakis

Shannon Capacity

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

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

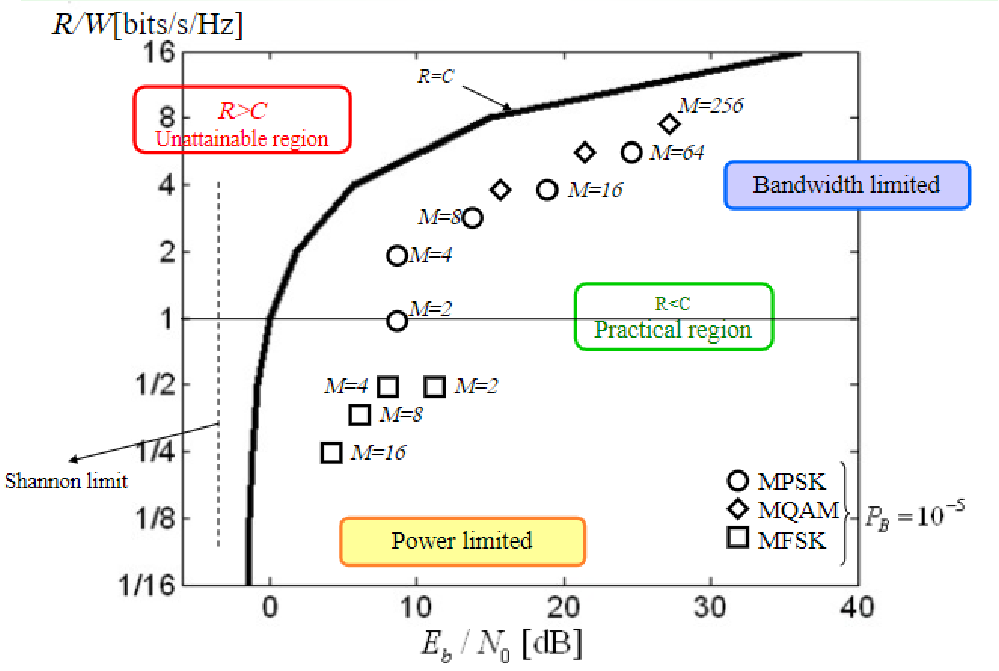
- Capacity relates theoretical rate to two key parameters:
  - B = bandwidth in Hz
  - SNR in linear scale (not dB!!!)
- Mathematical result from classic paper in 1948.

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

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

Example: Rate in Free Space

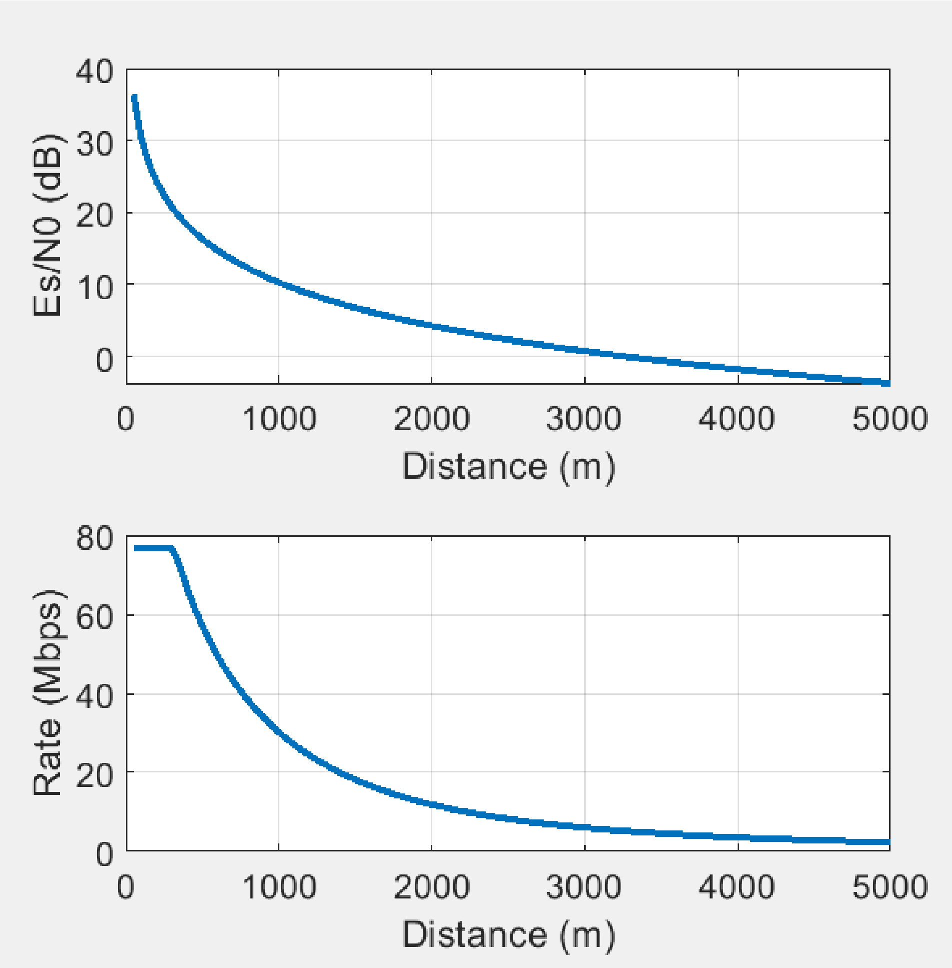
- Parameters similar to small cell transmission
- Can get data rate of 5 km!
- Since we assume free-space
  - Will be much worse in reality

```
% Parameters
B = 20e6;    % bandwidth
fc = 2.3e9;  % carrier
NF = 6;      % noise figure
snrLoss = 6; % loss from Shannon capacity
maxSE = 4.8;
bwLoss = 0.2;
Ptx = 15;  % Power in dBm
dist = linspace(50,5000,100)';  % distance

% Compute the FS path loss
vp = physconst('lightspeed');  % speed of light
lambda = vp/fc;   % wavelength
pl = fspl(dist, lambda);

% Compute SNR
kT = -174;
EsN0 = Ptx - pl - kT - NF - 10*log10(B);

% Compute rate
snrEff = 10.^(0.1*(EsN0-snrLoss));
rateMbps = B*(1-bwLoss)*min(log2(1 + snrEff), maxSE)/1e6;
```



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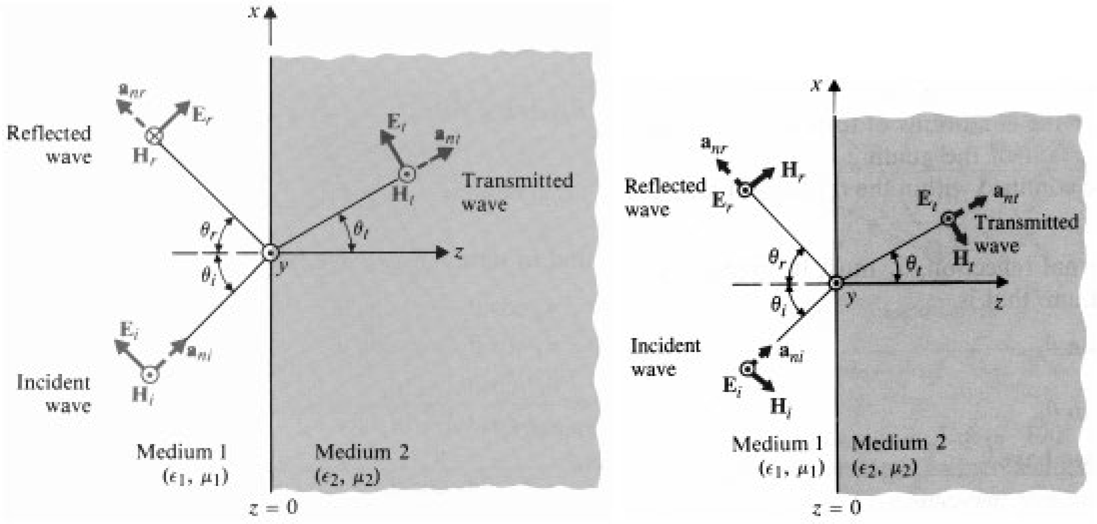
Reflections and Refractions

Sean Hum, Lecture Notes, U of Toronto



(a) Parallel polarization

(b) Perpendicular polarization

$$\Gamma_{\parallel} = \frac{\eta_2 \cos\theta_t - \eta_1 \cos\theta_i}{\eta_2 \cos\theta_t + \eta_1 \cos\theta_i}$$

$$T_{\parallel} = \frac{2\eta_2 \cos\theta_i}{\eta_2 \cos\theta_t + \eta_1 \cos\theta_i}$$

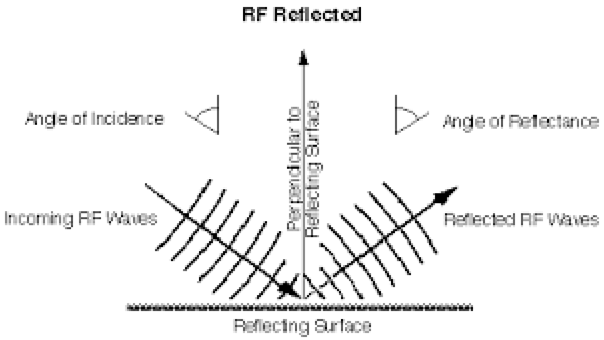
$$\Gamma_{\perp} = \frac{\eta_2 \cos\theta_i - \eta_1 \cos\theta_t}{\eta_2 \cos\theta_i + \eta_1 \cos\theta_t}$$

$$T_{\perp} = \frac{2\eta_2 \cos\theta_i}{\eta_2 \cos\theta_i + \eta_1 \cos\theta_t}$$

- Occur at any dielectric interface
  - Change in characteristic impedance η
- Consider two separate polarizations
  - Parallel and perpendicular
- Reflected components
  - $\theta_r = \theta_i$: Reflects in opposite angle
- Refracted / transmission component:
  - $\sqrt{\mu_1 \epsilon_1} \sin\theta_i = \sqrt{\mu_2 \epsilon_2} \sin\theta_t$
  - May be no components
- Complex gains on each component
  - Γ, T
- Polarization may in general change

Metal Reflectors

Sean Hum, [Lecture Notes](), U of Toronto



$$\Gamma_{\|} = \frac{\eta_2 \cos\theta_t - \eta_1 \cos\theta_i}{\eta_2 \cos\theta_t + \eta_1 \cos\theta_i} \qquad \Gamma_{\perp} = \frac{\eta_2 \cos\theta_i - \eta_1 \cos\theta_t}{\eta_2 \cos\theta_i + \eta_1 \cos\theta_t}$$

$$T_{\|} = \frac{2\eta_2 \cos\theta_i}{\eta_2 \cos\theta_t + \eta_1 \cos\theta_i} \qquad T_{\perp} = \frac{2\eta_2 \cos\theta_i}{\eta_2 \cos\theta_i + \eta_1 \cos\theta_t}$$

- Special case of a perfect conductor:
  - $\eta_2 = 0$
- All signal is reflected back:
  - $\Gamma_{||} = \Gamma_{\perp} = -1$
- No transmission component:
  - $T_{||} = T_{\perp} = 0$
- Polarization direction is unchanged

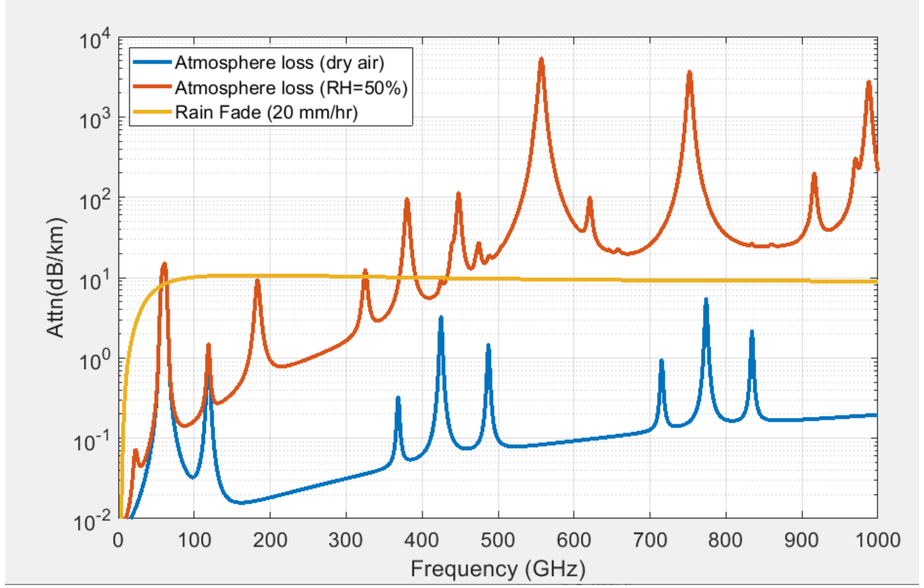
Transmission Through Typical Materials

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: Water absorption is particularly important to model for mmWave!

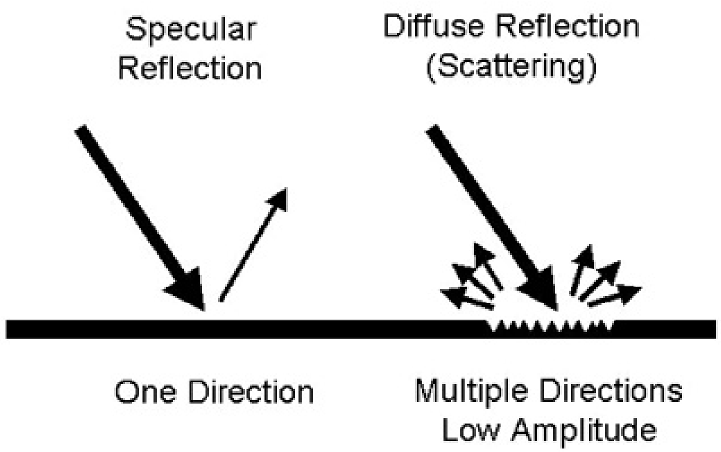



```
% Frequencies to test
freq = linspace(1,1000,1000)'*1e9;
range = 1000;  % Compute attenuation at 1 km
rr = 20;       % Rain rate

T = 15;       % temperature in C
P = 101300.0;  % atmospheric pressure
Wsat = 4.8;  % vapor density at saturation (g/m^3)
RH = 0.5;    % relative humidity
W = RH*Wsat;  % vapor density

% Compute attenuations
attn_dry = gaspl(range,freq,T,P,0)';
attn_humid = gaspl(range,freq,T,P,W)';
attn_rain = rainpl(range, freq, rr)';
```

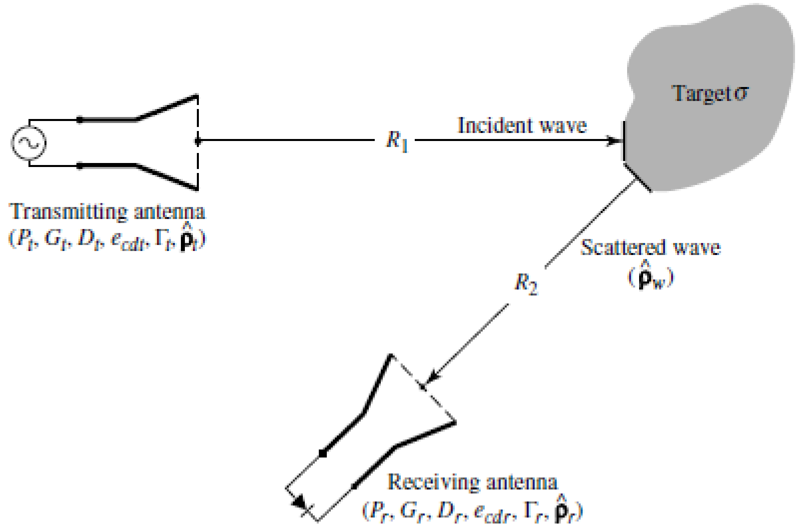
Specular Reflections & Scattering



- 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.

Radar Cross Section

- Intuition:
  - Let W_i = incident radiation density
  - Reflect total power = σW_i
  - σ = effective area captured for reflection
  - Scattered density is: $W_s = \frac{\sigma W_i}{4\pi R_2^2}$
- Define radar cross section:
  - $\sigma = \lim_{R_2 \to \infty} \left[4\pi R_2^2 \frac{W_s}{W_i} \right]$
- Defines effective area of receiving target
- Generally depends on angle

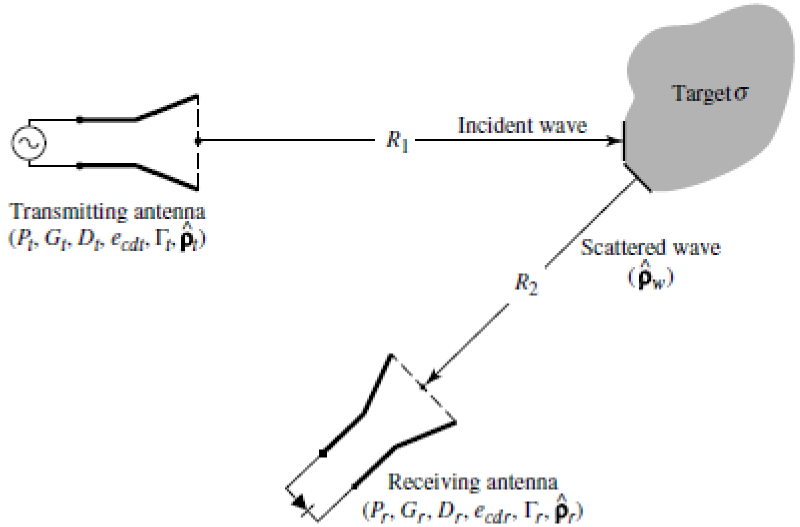


Radar Equation

- Radar Equation: Ratio of RX to TX power

$$\frac{P_r}{P_t} = \frac{\sigma D_r D_t}{4\pi}\left(\frac{\lambda}{4\pi R_1 R_2}\right)^2$$

  - Proof: Next slide
- Provides basic equation for radar link budgets
- Key points:
  - Power decays as $\frac{1}{R^4}$
  - Much faster than LOS free-space $\frac{1}{R^2}$
  - Remember directivity and RCS depend on angle



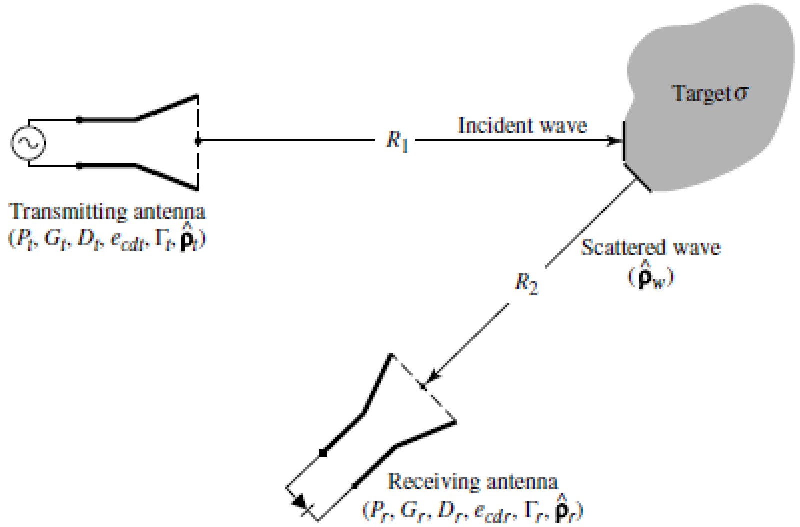
Proof of the Radar Equation

- Incident density: $W_i = \frac{P_t D_t}{4\pi R_1^2}$
- Reflected density:

$$W_s = \frac{\sigma W_i}{4\pi R_2^2} = \frac{\sigma P_t D_t}{(4\pi R_1 R_2)^2}$$

- Received power $P_r = A_r W_s$
- Using antenna-directivity relation: $A_r = \frac{D_r \lambda^2}{4\pi}$
- Therefore:

$$P_r = \frac{\sigma \lambda^2 D_r D_t}{4\pi (4\pi R_1 R_2)^2} P_t$$



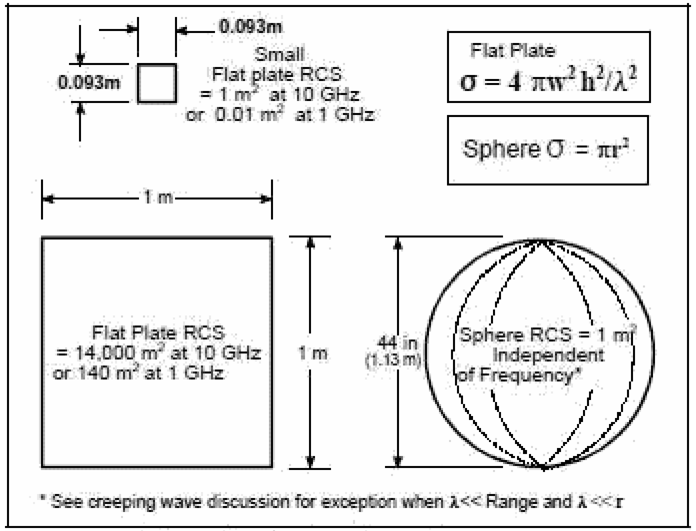
Typical RCS Values

TABLE 2.2 RCS of Some Typical Targets

	Typical RCSs [22]	
Object	**RCS (m^2)**	**RCS (dBsm)**
Pickup truck	200	23
Automobile	100	20
Jumbo jet airliner	100	20
Large bomber *or* commercial jet	40	16
Cabin cruiser boat	10	10
Large fighter aircraft	6	7.78
Small fighter aircraft *or* four-passenger jet	2	3
Adult male	1	0
Conventional winged missile	0.5	−3
Bird	0.01	−20
Insect	0.00001	−50
Advanced tactical fighter	0.000001	−60

From Balanis

- Values are often quoted in dBsm
  - $\sigma[dBsm] = 10\log_{10}\left(\frac{\sigma}{1\ m^2}\right)$

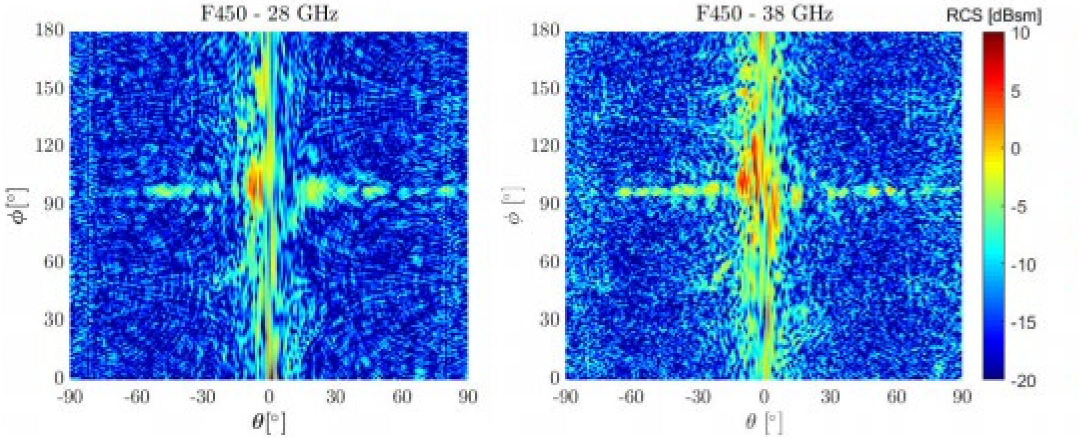


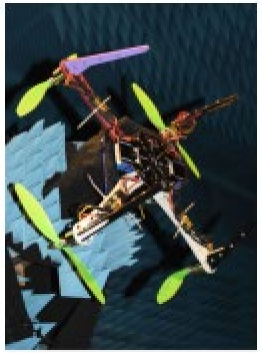
From RFCafe

Note formulas only true valid in optical range:

- Range $\gg \lambda$
- Area $\gg \lambda^2$

Example: RCS of a UAV





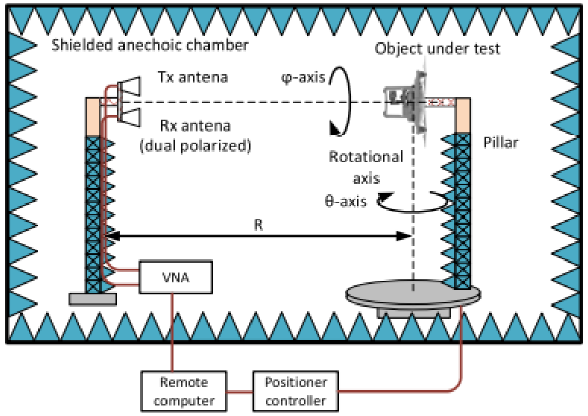
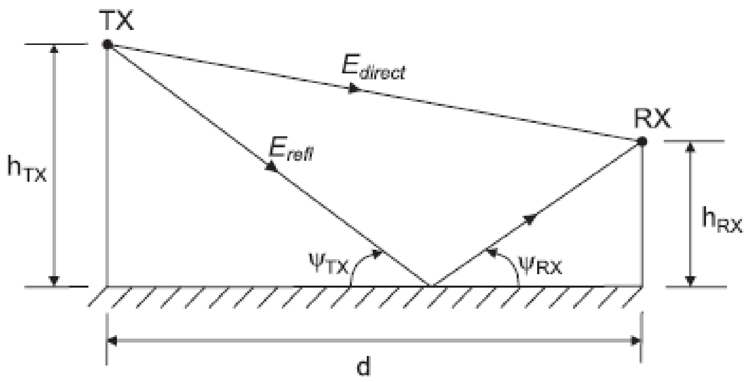


FIGURE 1. The schematic view of the measurement setup.

- Measurements of RCS of commercial UAVs
  - Use an anechoic chamber (removes reflections)
- Notice RCS is much larger when facing the drone
- Very small when seeing drone from side

From Semkin, Vasilii, et al. "Analyzing Radar Cross Section signatures of diverse drone models at mmWave frequencies." *IEEE Access* (2020).

Propagation Loss with Reflections



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

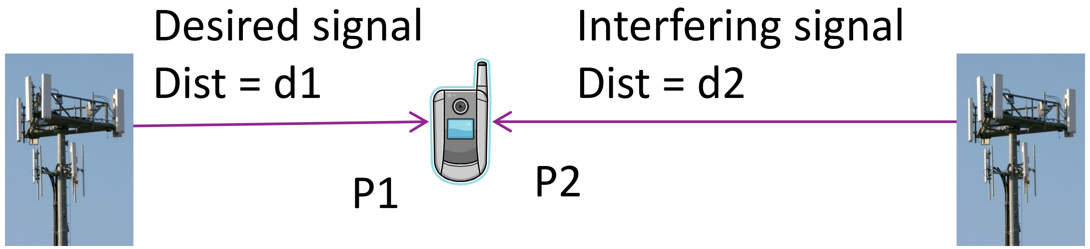
- In free space, we saw power density decays as d^2
- Due to ground reflections, power decays faster than d^2
- For d large, decays as d^α, α= path loss exponent.
  - α has been observed from 1.5 to 5.5, but usu. btw 3 and 5.
- For single ground reflection, can show α=4.
  - Based on reflected wave canceling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

Path Loss Exponent, Coverage & Interference

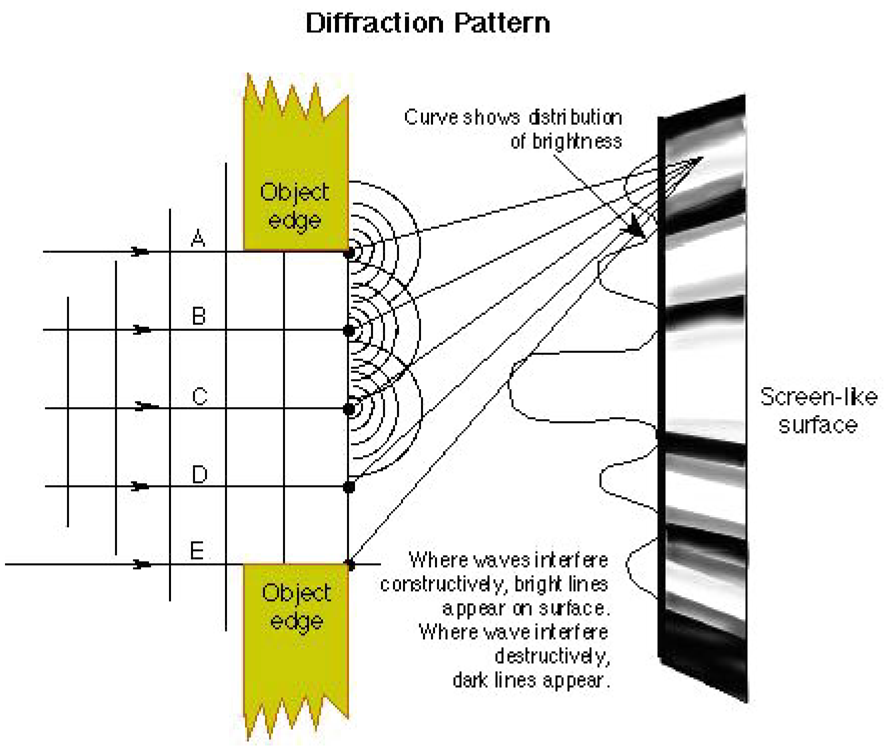
- For coverage-limited systems, low α is good
  - Power decays slower => signals have greater range

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

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

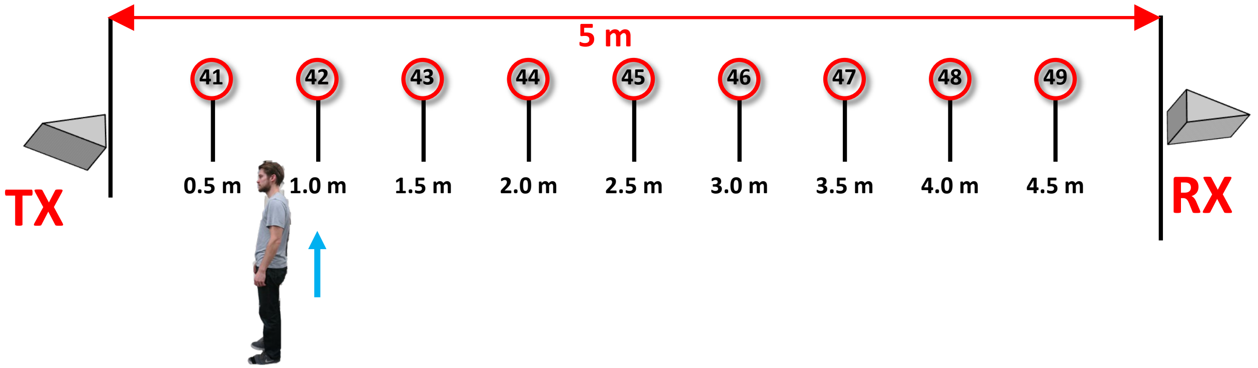


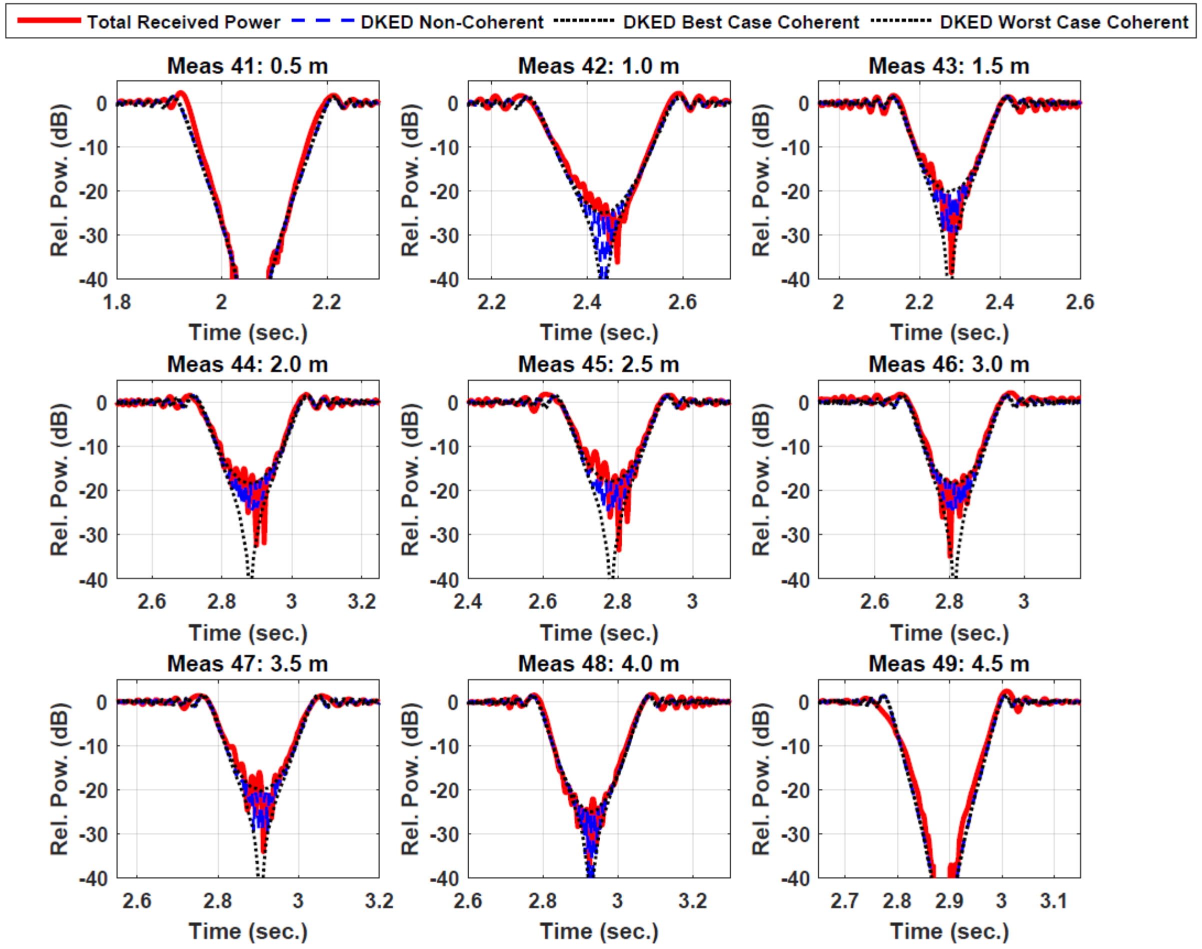
Diffraction



- 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

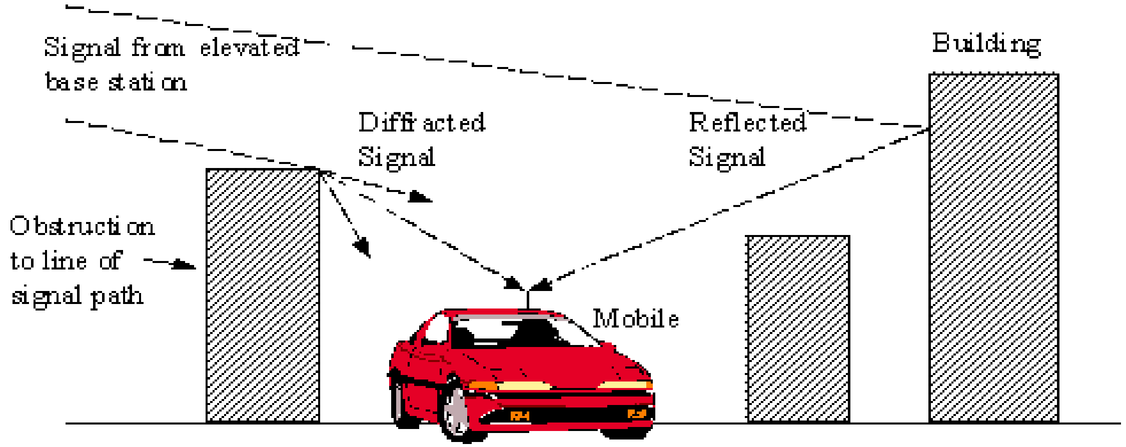


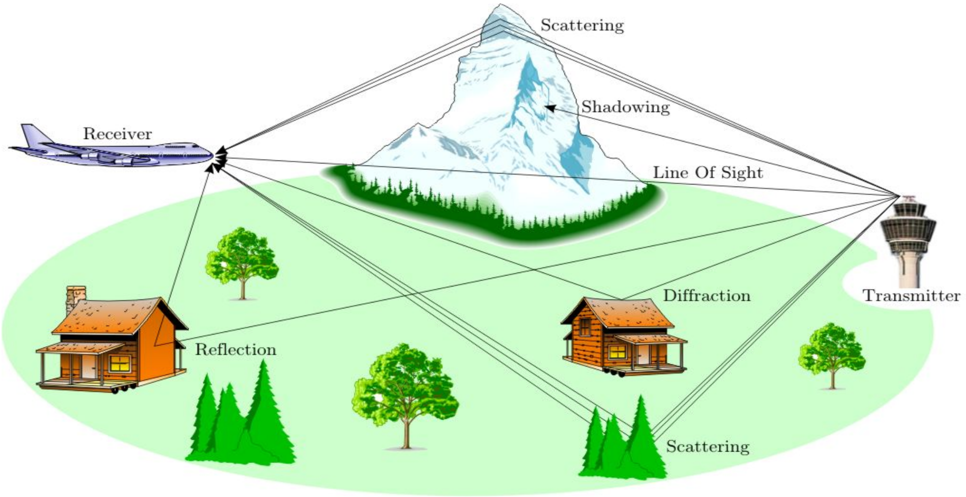


- Between 25 and 40 dB blockage
  - Depends on distance
- Total power predicted by knife edge diffraction
- Piecewise linear model used by 3GPP

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

Radio Waves Have Many Paths



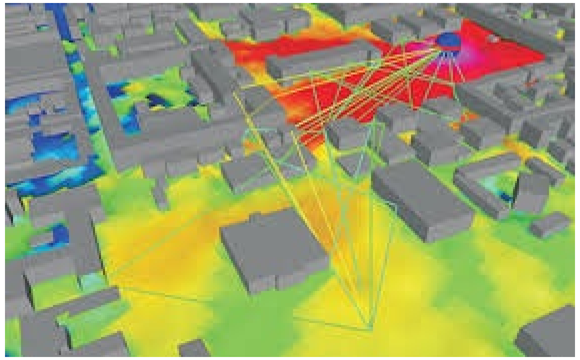


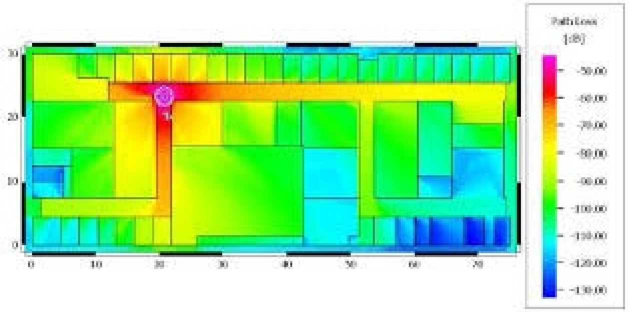
Outline

- ❑Noise and Interference
- ❑Communication Requirements and Link Budget Analysis
- ❑Non-LOS Propagation
- ❑Statistical Models for Path Loss
- ❑Demo: Estimating Rates with a 3GPP model

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

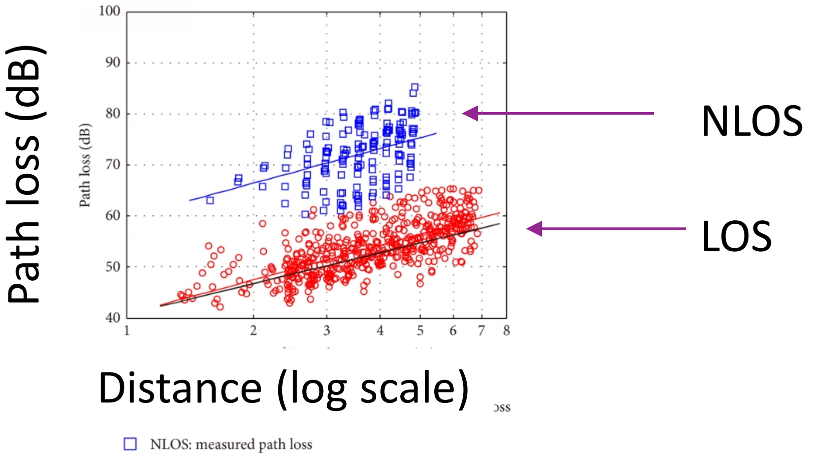
- Floating intercept model:

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

  - 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:

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

Outline

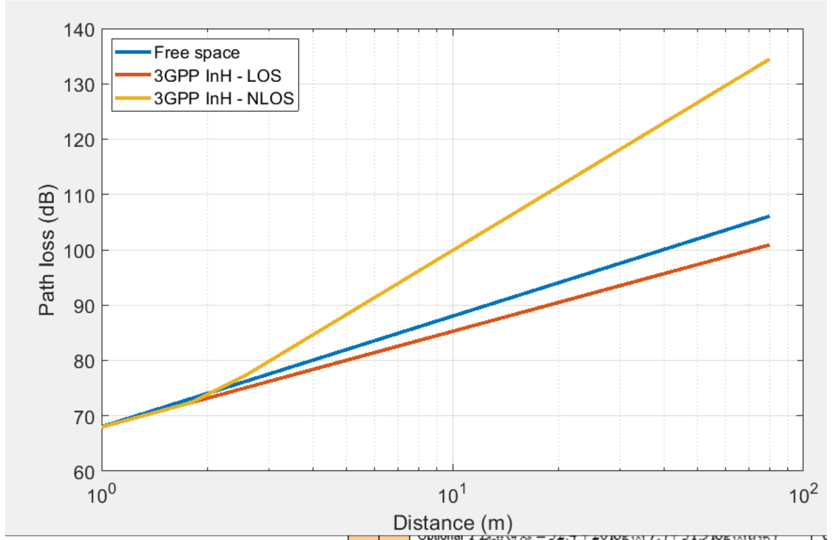
- Noise and Interference
- Communication Requirements and Link Budget Analysis
- Non-LOS Propagation
- Statistical Models for Path Loss
- Demo: Estimating Rates with a 3GPP model

Ex: 3GPP Indoor Home Office Model

- 3GPP has models for many statistical models
  - 38.900: Path loss models for above 6 GHz
- Example: Indoor home office
  - Separate models for LOS and NLOS
  - Plotted is the median path loss vs. distance

```
% Parameters
fc = 60e9;   % Frequency
vp = physconst('lightspeed');  % speed of light
lambda = vp/fc;    % wavelength

% Compute LOS and NLOS path loss
dist = linspace(1,80,100)';
pllos = 32.4 + 17.3*log10(dist) + 20*log10(fc/1e9);
plnlos = 17.3 + 38.3*log10(dist) + 24.9*log10(fc/1e9);
plnlos = max(pllos, plnlos);
plfs = fspl(dist,lambda);
```

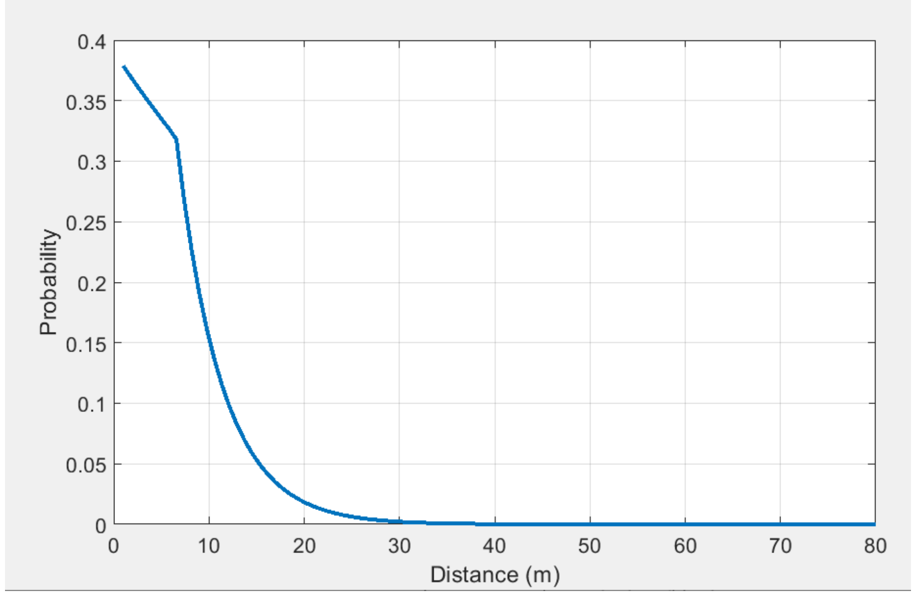


InH - Office	LOS	$PL_{\text{InH-LOS}} = 32.4 + 17.3\log_{10}(d_{3D}) + 20\log_{10}(f_c)$	$\sigma_{SF} = 3$	$1\text{m} \le d_{3D} \le 100\text{m}$
	NLOS	$PL_{\text{InH-NLOS}} = \max(PL_{\text{InH-LOS}}, PL'_{\text{InH-NLOS}})$ $PL'_{\text{InH-NLOS}} = 38.3\log_{10}(d_{3D}) + 17.30 + 24.9\log_{10}(f_c)$	$\sigma_{SF} = 8.03$	$1\text{m} \le d_{3D} \le 86\text{m}$
		Optional $PL'_{\text{InH-NLOS}} = 32.4 + 20\log_{10}(f_c) + 31.9\log_{10}(d_{3D})$	$\sigma_{SF} = 8.29$	$1\text{m} \le d_{3D} \le 86\text{m}$

Ex: Probability of LOS

- Model has a probability of LOS
- Function of distance
  - As distance is larger, probability of LOS is smaller

```
%% Plot the probability of LOS
plosl = min( exp(-(dist-1.2)/4.7), 1);
plos = min( 0.32*exp(-(dist-6.5)/32.6), plosl);
plot(dist, plos, 'Linewidth', 3);
```



Indoor - Mixed office	$P_{LOS} = \begin{cases} 1 & , d_{2D} \le 1.2\text{m} \\ \exp\left(-\frac{d_{2D}-1.2}{4.7}\right) & , 1.2\text{m} < d_{2D} < 6.5\text{m} \\ \exp\left(-\frac{d_{2D}-6.5}{32.6}\right) \cdot 0.32 & , 6.5\text{m} \le d_{2D} \end{cases}$

Ex: Generating Random Samples

- The full model generate random path loss
  - Path loss is a function of distance
  - Samples from the conditional distribution $P(L|d)$
- Steps:
  - Compute median LOS and NLOS path loss
  - Add shadowing
  - Randomly select between LOS and NLOS
  - Use PLOS probability

```
function pl = pathLoss3GPPInH(dist,fc)
    % pathLoss3GPPInH:  Generates random path loss
    %
    % Samples the path loss using the 3GPP-InH model

    % Compute the median path losses for LOS and NLOS
    pllos = 32.4 + 17.3*log10(dist) + 20*log10(fc/1e9);
    plnlos = 17.3 + 38.3*log10(dist) + 24.9*log10(fc/1e9);

    % Add shadowing
    w = randn(size(dist));
    pllos = pllos + 3*w;
    plnlos = plnlos + 8.03*w;

    % Compute probability of being LOS or NLOS
    plos = min( exp(-(dist-1.2)/4.7), 1);
    plos = min( 0.32*exp(-(dist-6.5)/32.6), plos);

    % Select randomly between LOS and NLOS path loss
    u = (rand(size(dist)) < plos);
    pl = u.*pllos + (1-u).*plnlos;

end
```

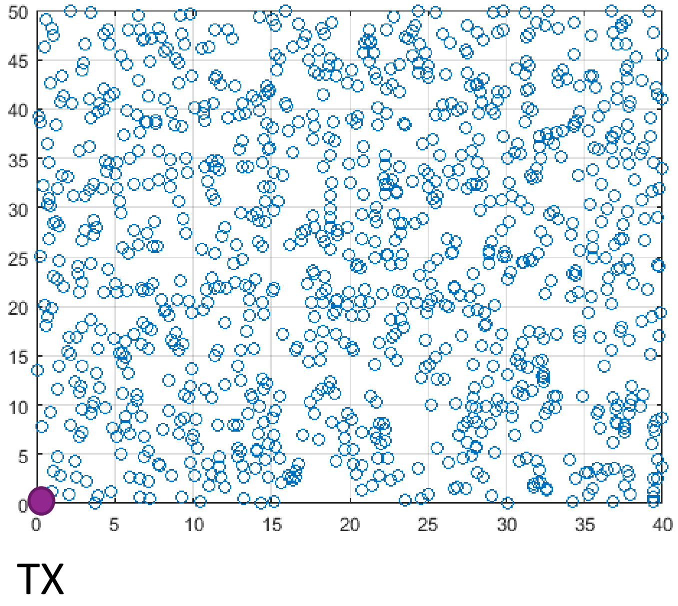
Example Simple Simulation

- Simulations: Often used to estimate distribution of rates
  - Assume some statistical distribution on locations and propagation
- Illustrate with a simple simulation
  - RX is randomly located in a square region.
  - TX is located at origin
- 3GPP has much more realistic deployment models

```
% Parameters
len = 40;  % length of region in m
wid = 50;  % width in m
nx = 1000;  % number of random points

% Generate random points in a square
x = rand(nx,2).*[len wid];

% Plot the random points
plot(x(:,1), x(:,2), 'o');
grid on;
```



Generate Random Path Loss

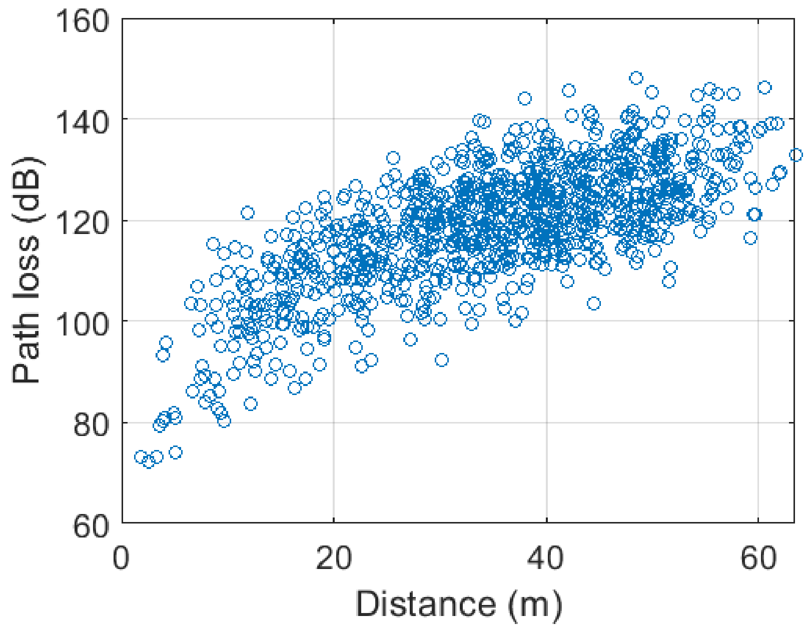
- Generate random path losses based on distances

```
% We will make some simple assumptions for a wifi-like system
fc = 60e9;

% Compute the distances
dh = 1;  % Distances in height
dist = sqrt(sum(x.^2,2) + dh^2);

% We next generate random path losses to each
pl = pathLoss3GPPInH(dist, fc);

% Plot a scatter plot of the PL vs. distance
plot(dist, pl, 'o');
grid on;
xlabel('Distance (m)');
ylabel('Path loss (dB)');
set(gca, 'Fontsize', 16);
```



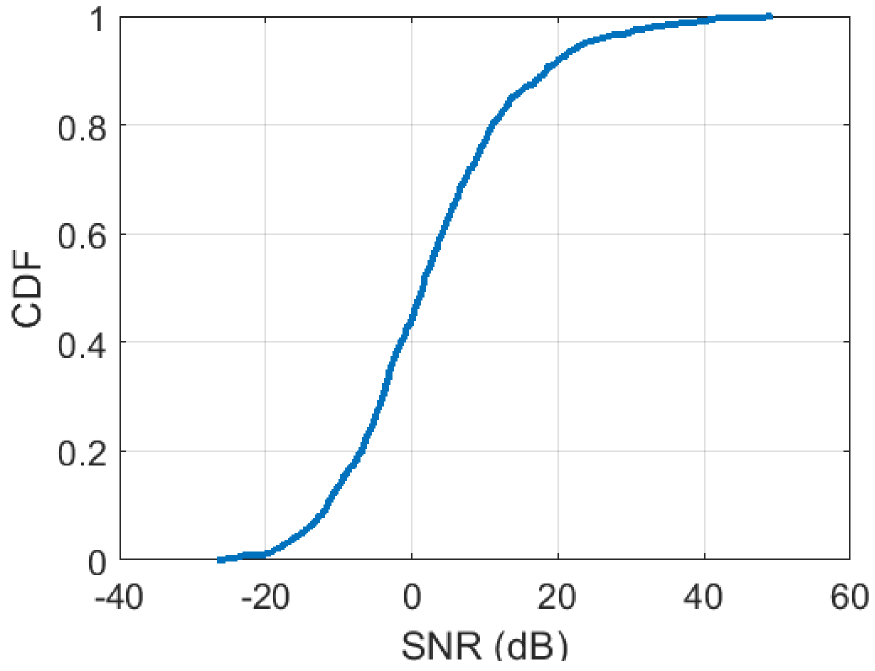
Compute SNR Distribution

- Make assumptions similar to an 802.11ad-like system
  - We assume very directive antennas
  - Later we show how to do this with beamforming

```
% Parameters
ptx = 20;      % transmit power
bw = 1.76e9;   % sample rate
nf = 6;        % noise figure
kt = -174;     % thermal noise
gaintx = 16;   % antenna gain
gainrx = 10;

% Compute SNR
snr = ptx - pl - nf - 10*log10(bw) - kt + gainrx + gaintx;

% Plot the SNR CDF
p = (1:nx)/nx;
plot(sort(snr), p,'Linewidth', 3);
grid on;
xlabel('SNR (dB)');
ylabel('CDF');
set(gca, 'Fontsize', 16);
```



Compute Rate Distribution

- Compute rate distribution assuming simple backoff from Shannon capacity
  - More realistic models are possible
- Note the large range of rates in this region

```
% Finally we compute the rate based on some simple simulatins
snrLoss = 6;
bwLoss = 0.2;
maxSE = 4.8;
rate = bw*(1-bwLoss)*min(log2(1 + 10.^(0.1*(snr-snrLoss))), maxSE);
rate = rate/1e6;

p = (1:nx)/nx;
semilogx(sort(rate), p,'Linewidth', 3);
grid on;
xlabel('Rate (Mbps)');
ylabel('CDF');
set(gca, 'Fontsize', 16);
```