Embedded Internet and the Internet of Things WS 12/13

3. Physical Layer

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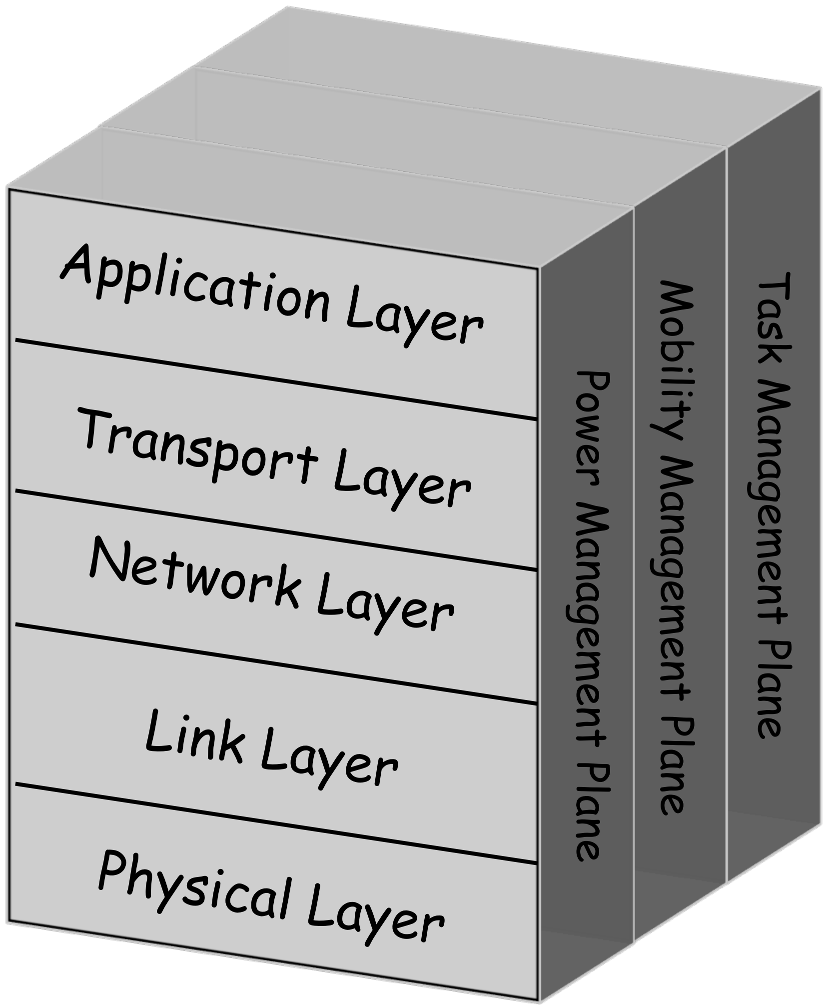
Overview

- Overview of wireless communications
- Wireless channel
- Channel models

Overview of wireless communications

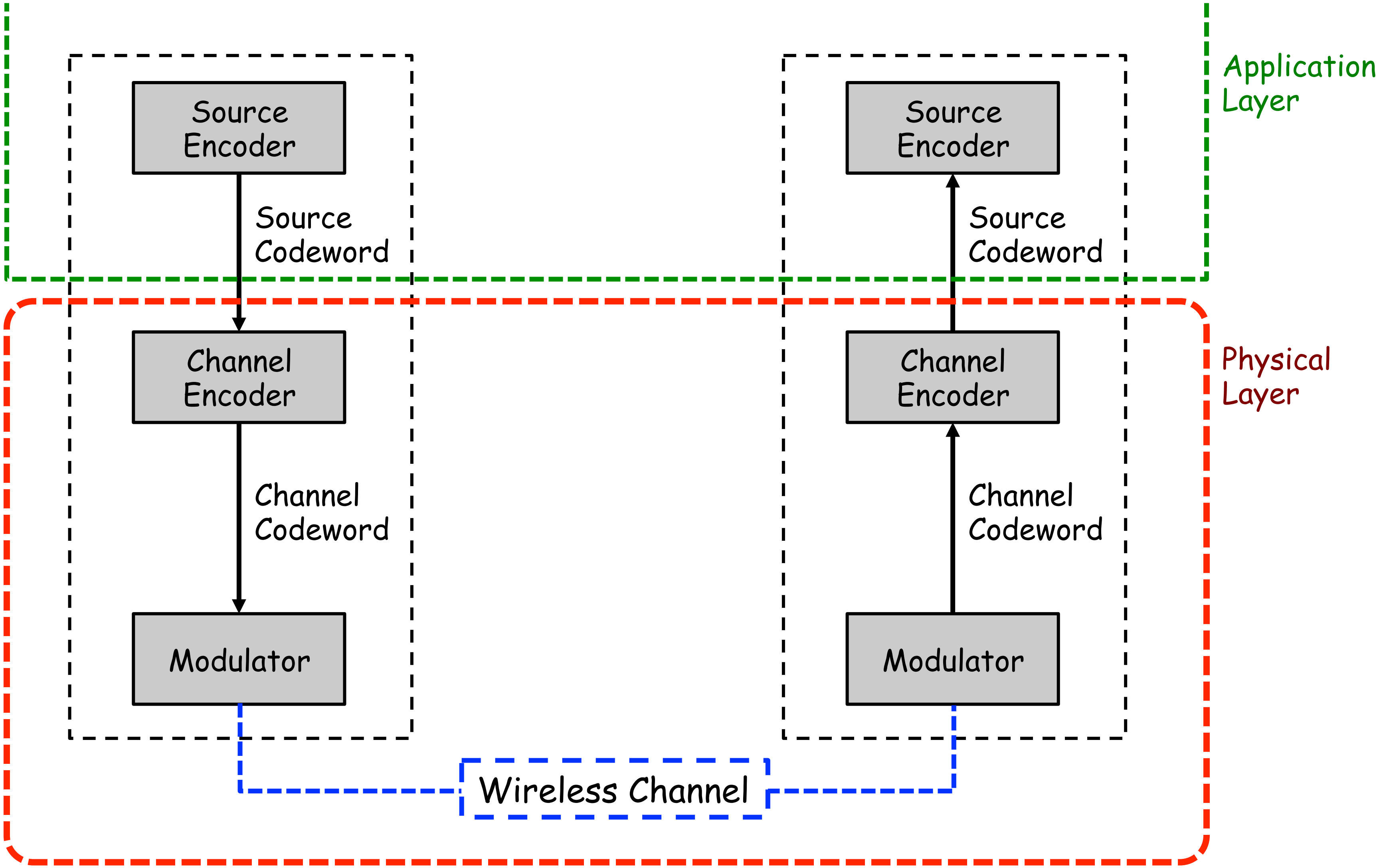
Protocol stack



Elements of robust communication

- Application layer: feasible workload
  - Packet rates, pattern, timing
- Network layer: finding and using good paths
  - Topology discovery and route selection
  - Route cost determination, selection
  - Forwarding
- Link layer: Framing, Media Management Protocol
  - On to receive during transmission
  - Frame structure, error detection, acknowledgement
  - Avoiding contention (MAC, CCA, Hidden Terminal)
  - Link quality estimation
- **Physical layer: Signal to Noise Ratio**
  - Device Transmission Power / Receive Sensitivity
  - Antenna design and orientation, obstructions, attenuation
  - Receive signal vs interference, noise, multipath
  - Modulation, channel coding

Protocol stack: Details

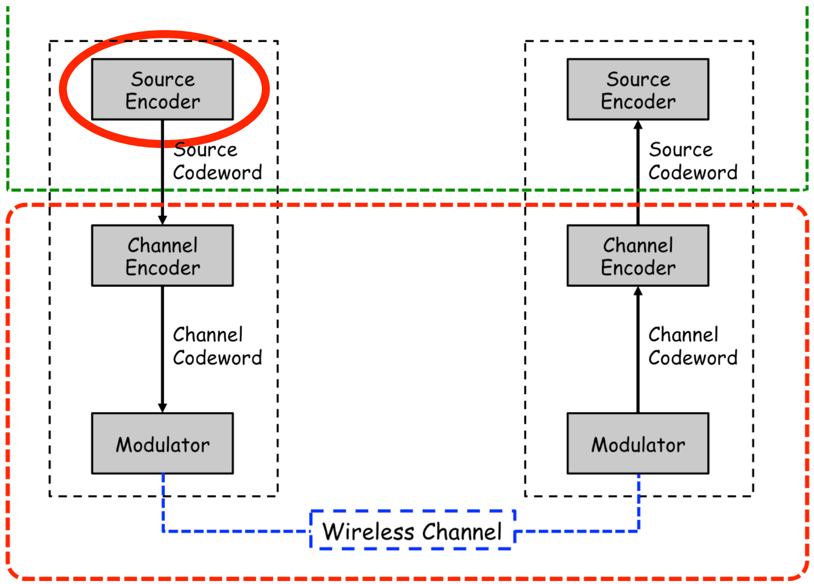


Source coding (data compression)

- At the transmitter end, the information source is first encoded with a source encoder
  - Exploit the information statistics
  - Represent the source with fewer number of bits

  -> source codeword

- Performed at the application layer

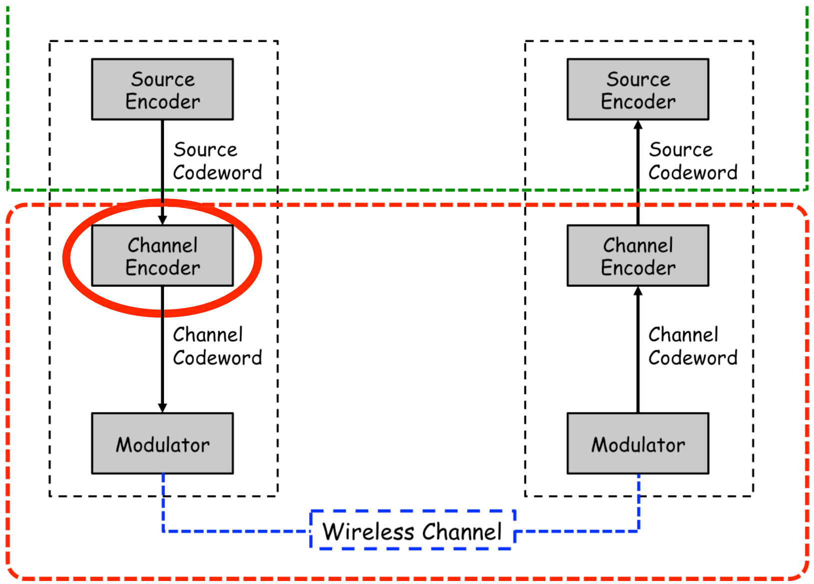


Channel coding (error control coding)

- Source codeword is then encoded by the channel encoder

-> channel codeword

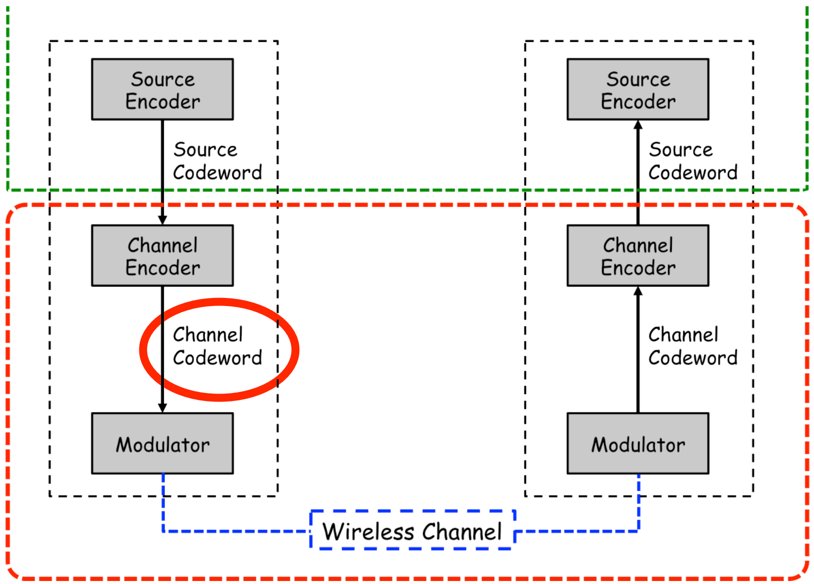
- Goal: address the wireless channel errors that affect the transmitted information



Interleaving and modulation

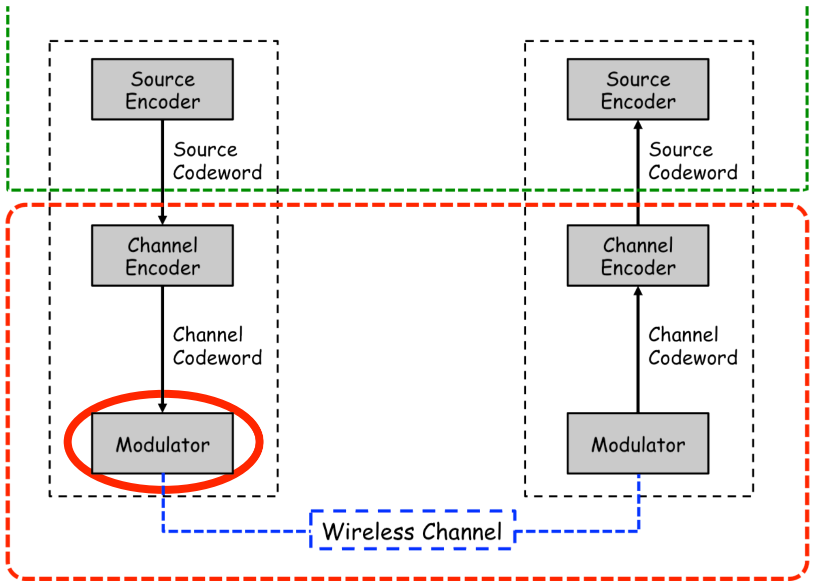
- The encoded channel codeword is then interleaved to combat the bursty errors

- Channel coding and the interleaving mechanism help the receiver either to
  - identify bit errors to initiate retransmission (ARQ)
  - correct a limited number of bits in case of errors (FEC)



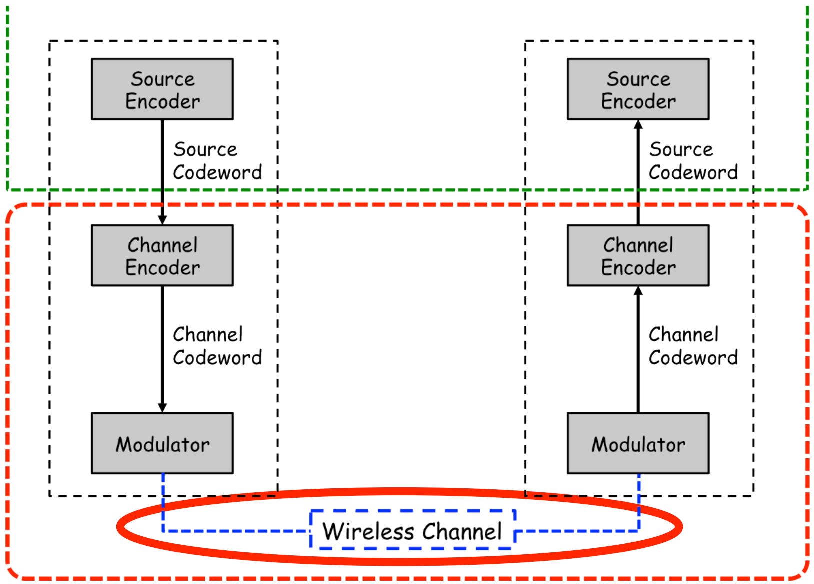
Interleaving and modulation

- Then, an analog signal (or a set thereof) is modulated by the digital information to create the waveform that will be sent over the channel
- Finally, the waveforms are transmitted through the antenna to the receiver

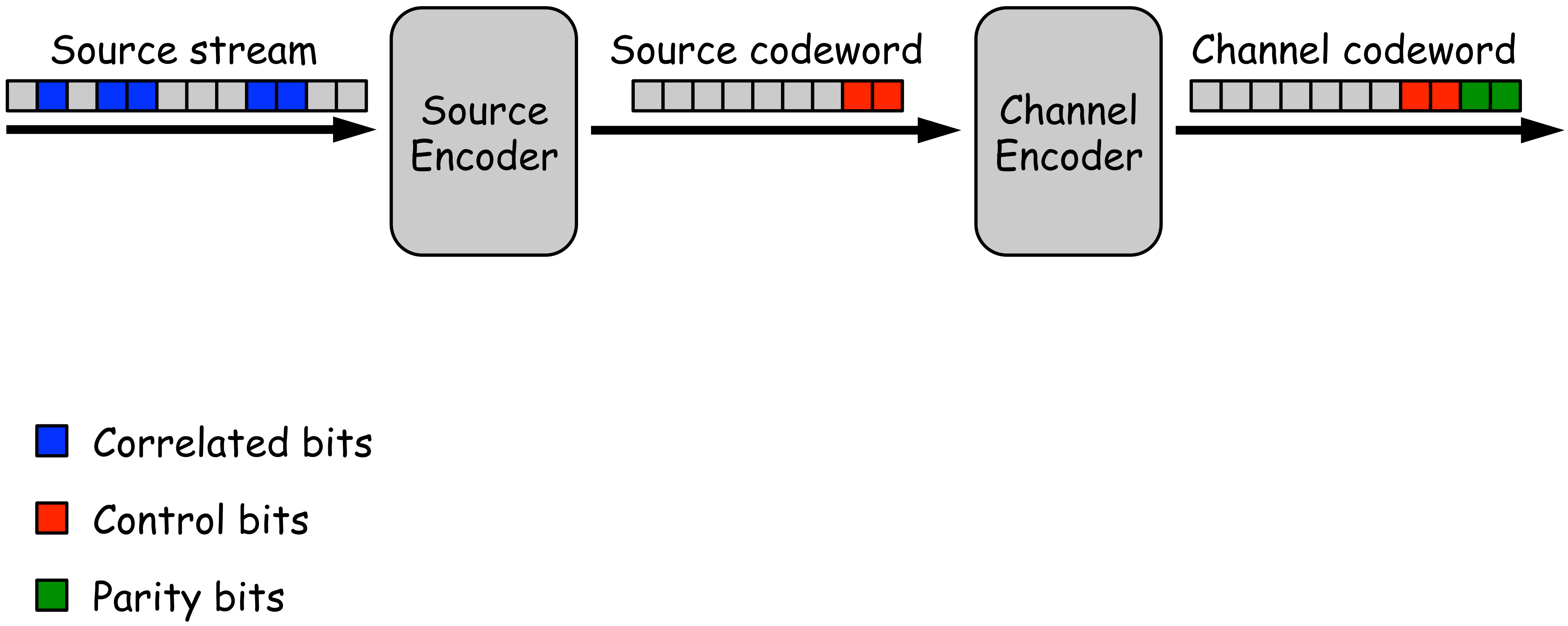


Wireless transmission

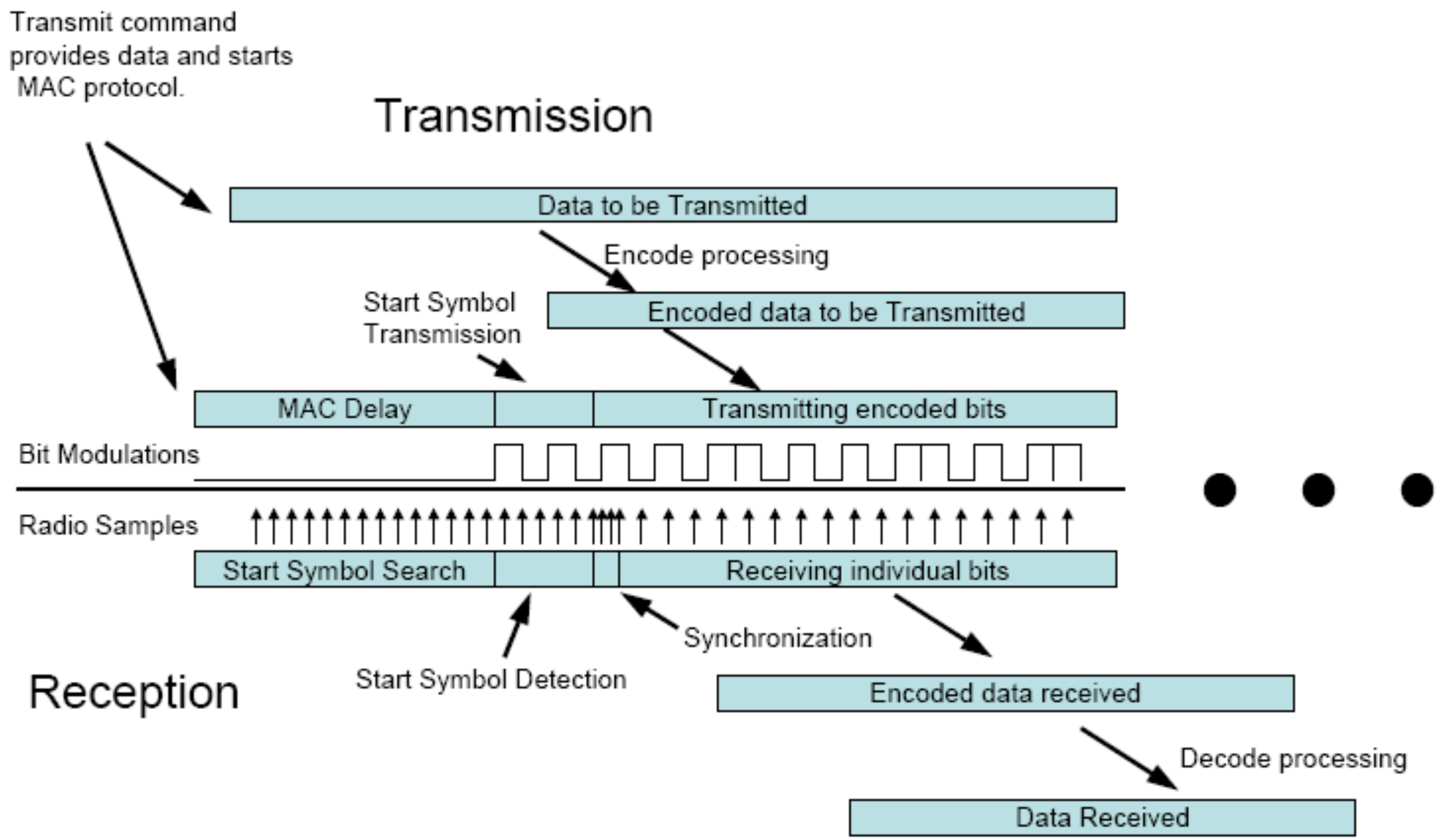
- The transmitted waveform travels through the channel
- Meanwhile, the waveform is attenuated and distorted by several wireless channel effects



Information Processing



Wireless Communication Basics



Wireless Communication Basics

Frequency bands

Radio spectrum for communication

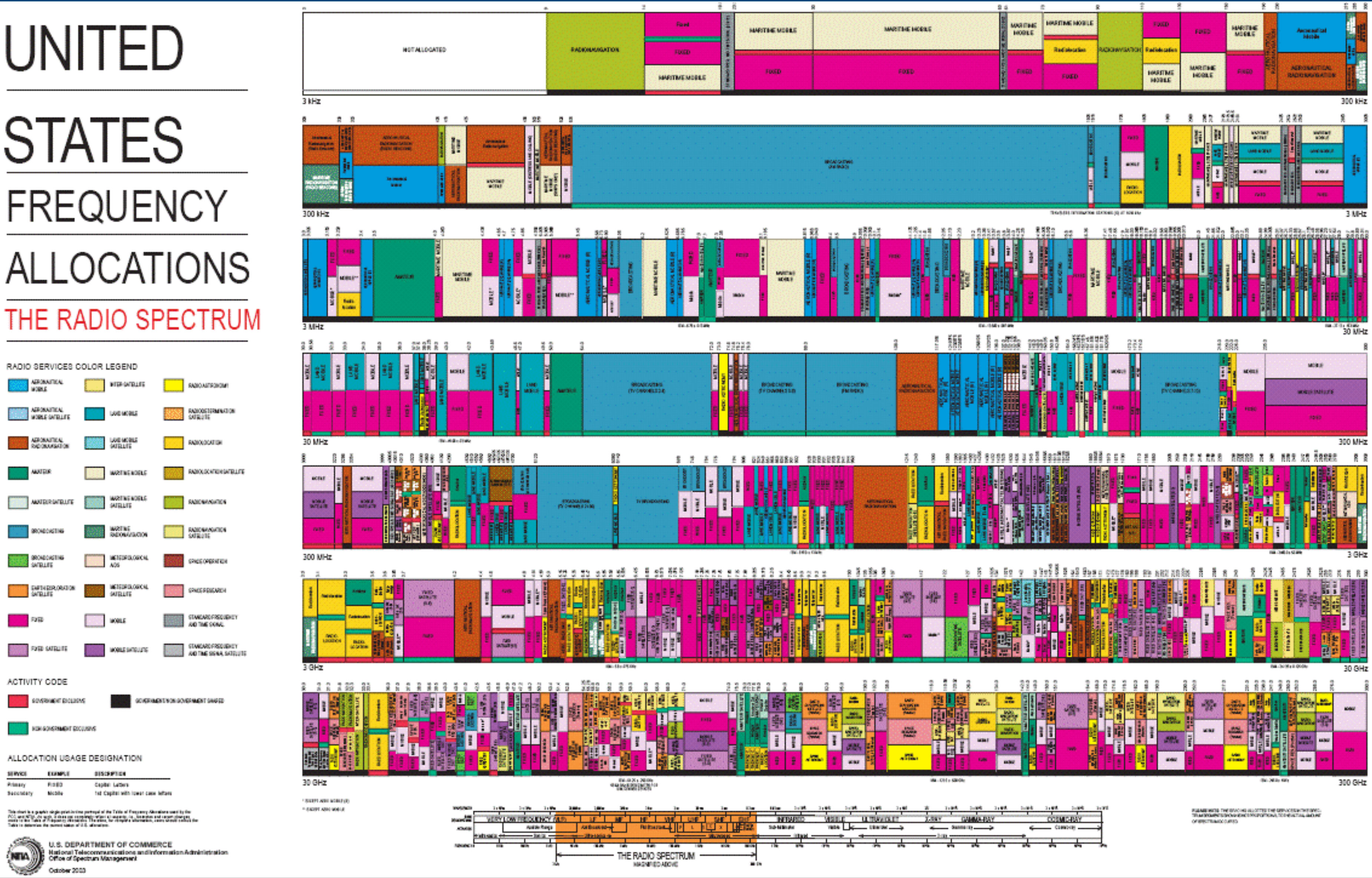
- Which part of the electromagnetic spectrum is used for communication
- Not all frequencies are equally suitable for all tasks, e.g.,
  - wall penetration
  - different atmospheric attenuation (oxygen resonances, …)

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, medicine") – license-free operation

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	

Example: US frequency allocation



Wireless Communication Basics

Modulation

Transmitting Data Using Radio Waves

- Basics: Wireless communication is performed through radio waves
  - Transmitter can send a radio wave
  - Receiver can detect the wave and its parameters
- Typical radio wave = sine function:

$$s(t) = A \cdot \sin(2\pi ft + \phi)$$

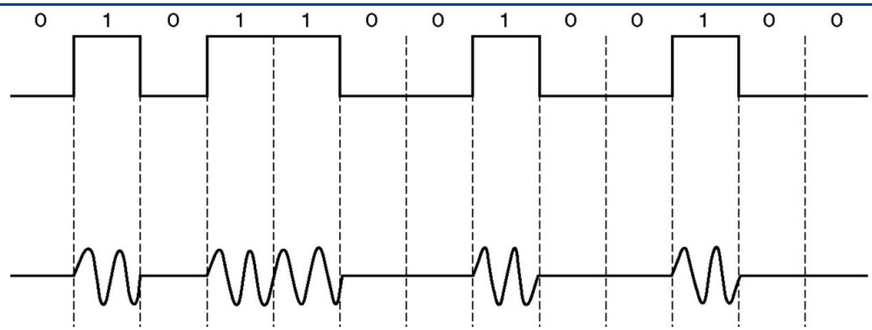
  - Parameters: amplitude A, frequency f, phase ϕ
- Modulation: Manipulate these parameters

Modulation

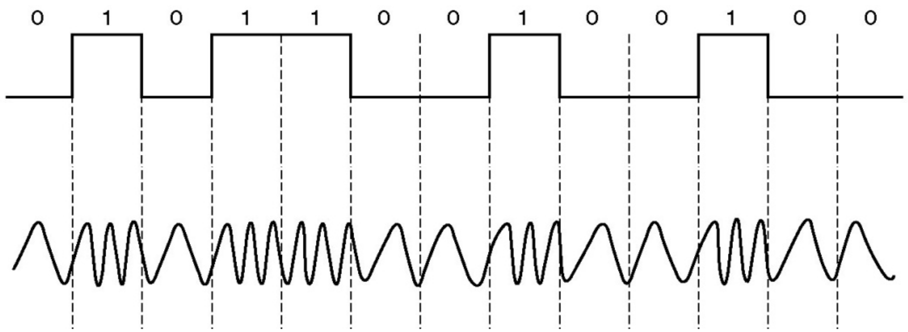
- Data to be transmitted is used to select transmission parameters as a function of time
- These parameters modify a basic sine wave, which serves as a starting point for modulating the signal onto it
- This basic sine wave has a center frequency f_c
- The resulting signal requires a certain bandwidth to be transmitted (centered around center frequency)

Modulation (Keying) examples

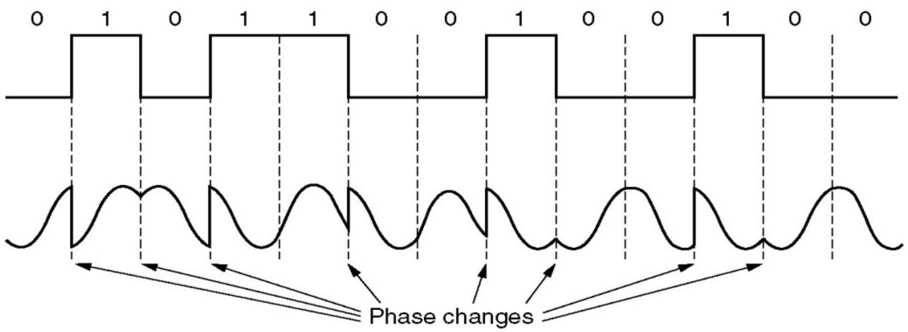
- (ASK)
  Amplitude Shift Keying



- (FSK)
  Frequency Shift Keying



- (PSK)
  Phase Shift Keying



Receiver: Demodulation

- Receiver tries to match the received waveform with the transmitted data bit
  - Necessary: one-to-one mapping between data and waveform

- Problems (Wireless Channel Errors)
  - Carrier synchronization: Frequency can vary between sender and receiver (drift, temperature changes, aging, …)
  - Bit synchronization: When does symbol representing a certain bit start/end?
  - Frame synchronization: When does a packet start/end?

- Biggest problem: Received signal is not the transmitted signal!

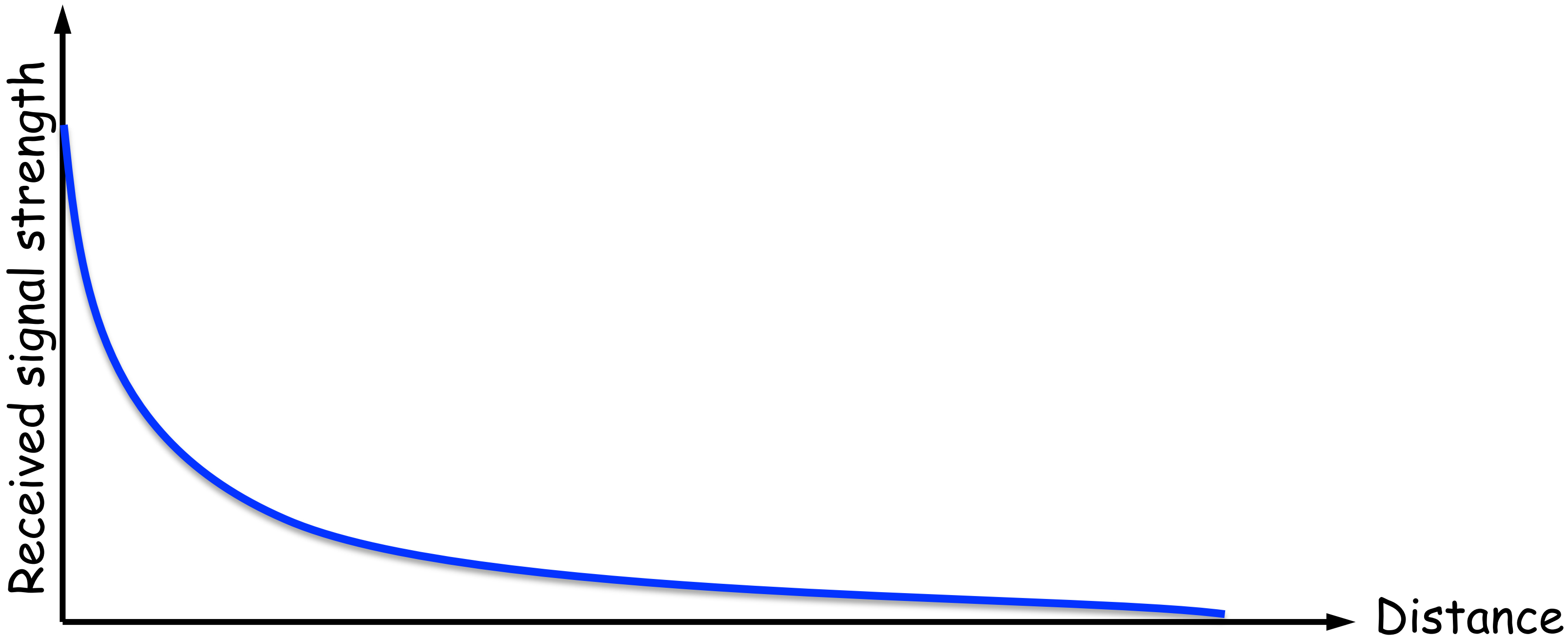
Wireless channel

Wireless Channel

- Path-loss
- Multi-path effects
- Channel errors
- Signals-to-bits
- Bits-to-packets

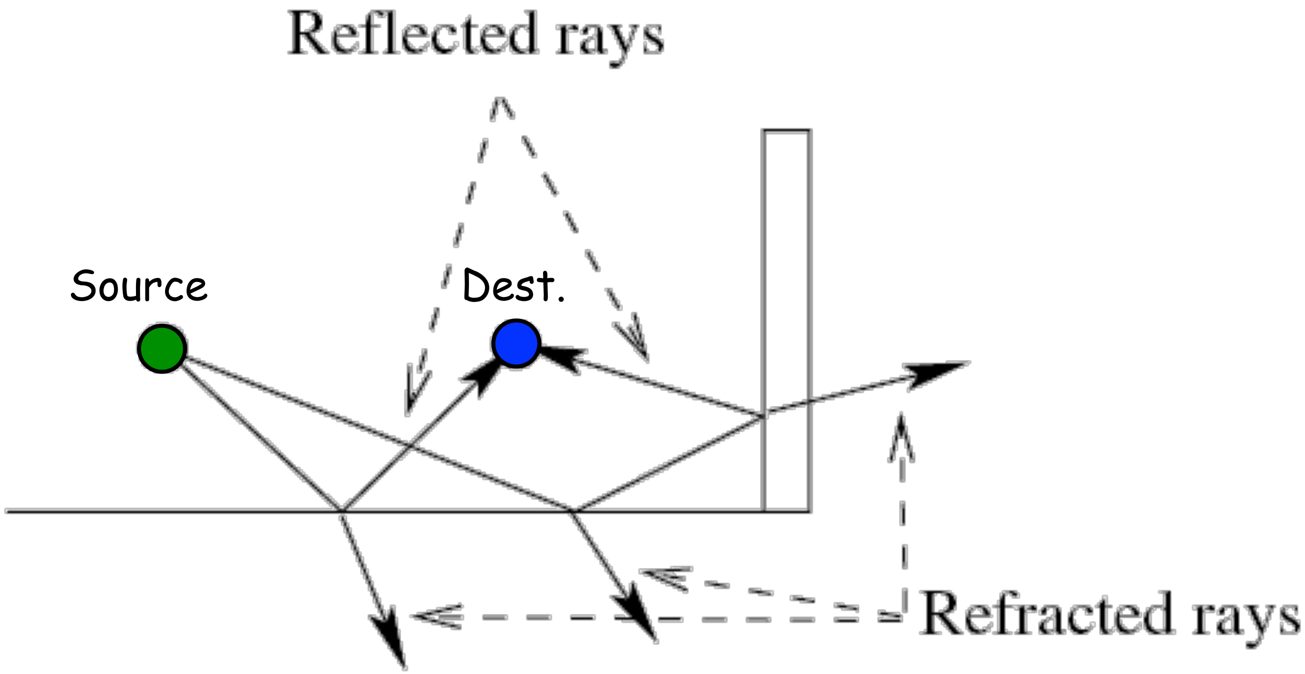
Radio propagation

- Attenuation: As the signal wave propagates through air, the signal strength is attenuated.
  - Proportional to the distance traveled over the air
  - Results in path loss for radio waves



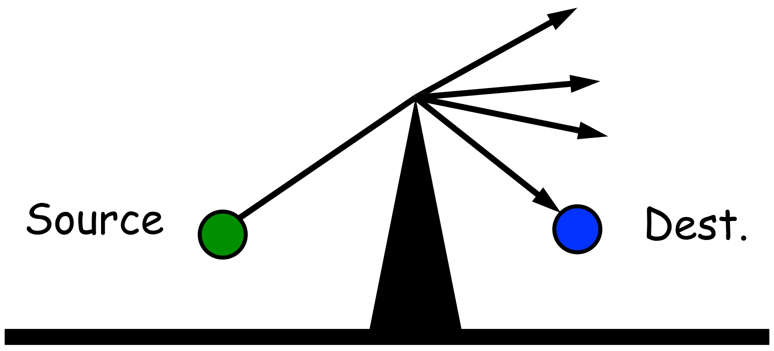
Radio propagation

- Reflection and refraction: When a signal wave is incident at a boundary between two different types of material
  - fraction of the wave bounces off the surface -> reflection
  - fraction of the wave propagates through the boundary->refraction

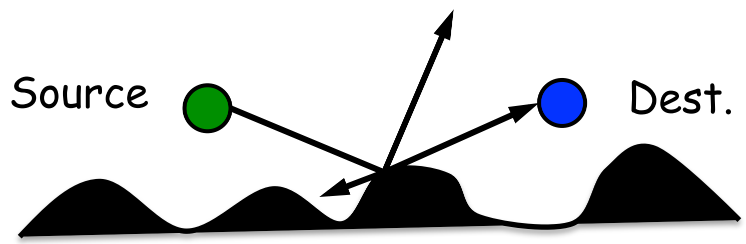


Radio propagation

- Diffraction: When signal wave propagates through sharp edges such as the tip of a mountain or a building, the sharp edge acts as a source
  - New waves are generated
  - Signal strength is distributed to the new generated waves

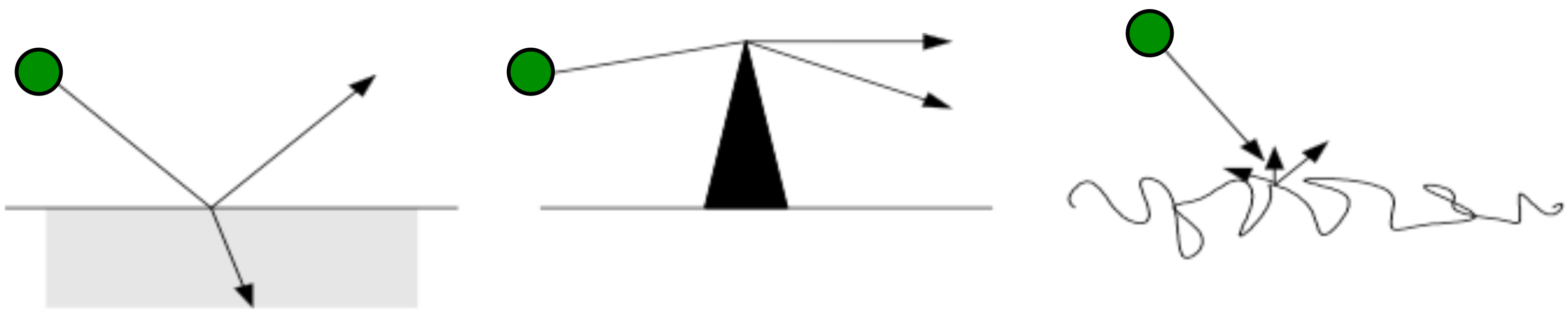


- Scattering: In reality, no perfect boundaries. When a signal wave is incident at a rough surface, it scatters in different directions



Wireless Channel

- Wireless transmission distorts any transmitted signal
  - Wireless channel describes these distortion effects
- Sources of distortion
  - Attenuation: Signal strength decreases with increasing distance
  - Reflection/refraction: Signal bounces of a surface; enter material
  - Diffraction: start "new wave" from a sharp edge
  - Scattering: multiple reflections at rough surfaces



Attenuation

- Results in path loss
- Received signal strength is a function of the distance d between sender and transmitter
- Friis free-space model
  - Signal strength at distance d relative to some reference distance $d_0 < d$ for which strength is known
  - d_0 is far-field distance, depends on antenna technology

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

- Pr, Pt — Receive, transmit power
- Gr, Gt — Receive, transmit antenna gain
- d — Distance between transmitter-receiver
- L — System loss no related to propagation

Attenuation

- Friis free-space model

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

$$= \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_0^2 L}\left(\frac{d_0}{d}\right)^2$$

$$= P_r(d_0)\left(\frac{d_0}{d}\right)^2$$

$P_r(d_0)$ Received power at reference distance d_0

Attenuation

- Friis free-space model is only valid for d in far-field distance of the transmitting antenna
  - Far-field region is also called Fraunhofer region
- Far-field distance is given by

$$d_f = \frac{2D^2}{\lambda}$$

- Additionally the following must be true

$$d_f >> D \qquad\qquad d_f >> \lambda$$

  - D   largest physical linear dimension of the antenna
  - λ wavelength

Attenuation

- Example: Find the far-field distance for an antenna with max. dimension of 1m and f=900 MHz

- Solution:
  - D = 1m
  - F = 900MHz -> $\lambda = \frac{c}{f} = \frac{3 \times 10^8 \frac{m}{s}}{900 \times 10^6 Hz} = \frac{1}{3} m$

  - Far-field distance $d_f = \frac{2(1)^2}{\frac{1}{3}} = 6m$

-> d_0 needs to be in the far-field distance!

Attenuation

What is the path loss (PL)?

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

$$\frac{P_t}{\mathrm{P_r}(d)} = \left(\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \right)^{-1}$$

$$PL[dB] = 10\log\left(\frac{P_t}{\mathrm{P_r}(d)} \right) = -10\log\left(\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \right)$$

Path loss at distance d in dB

Attenuation

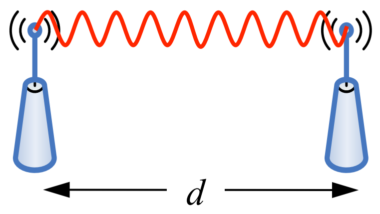
$$PL[dB] = 10\log\left(\frac{P_t}{\mathrm{P_r}(d)}\right) = -10\log\left(\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2 L}\right)$$

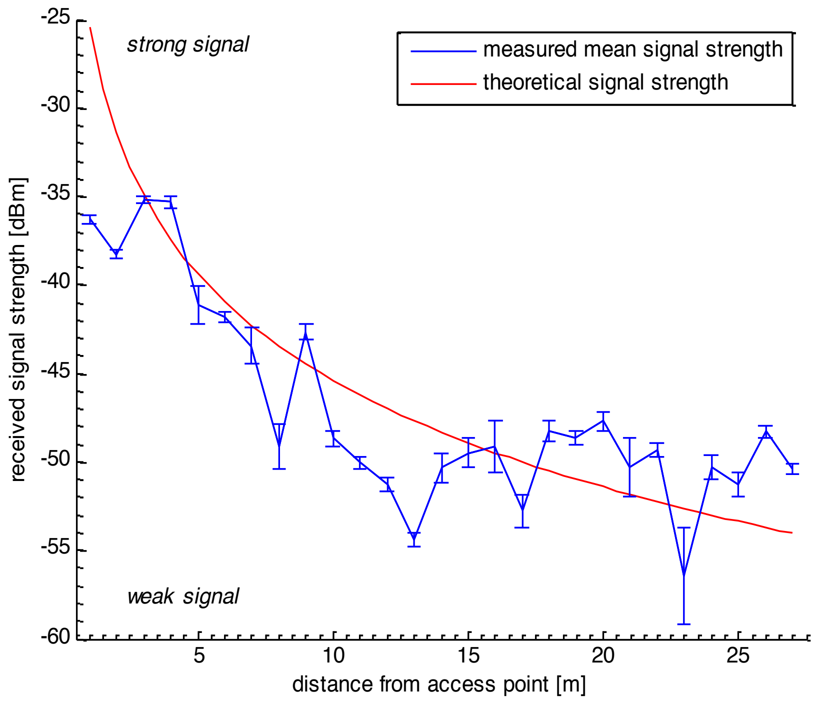
Set $G_t = G_r = L = 1$

$$PL(d)[dB] = -10\log\left(\frac{\lambda^2}{(4\pi)^2 d^2}\right)$$

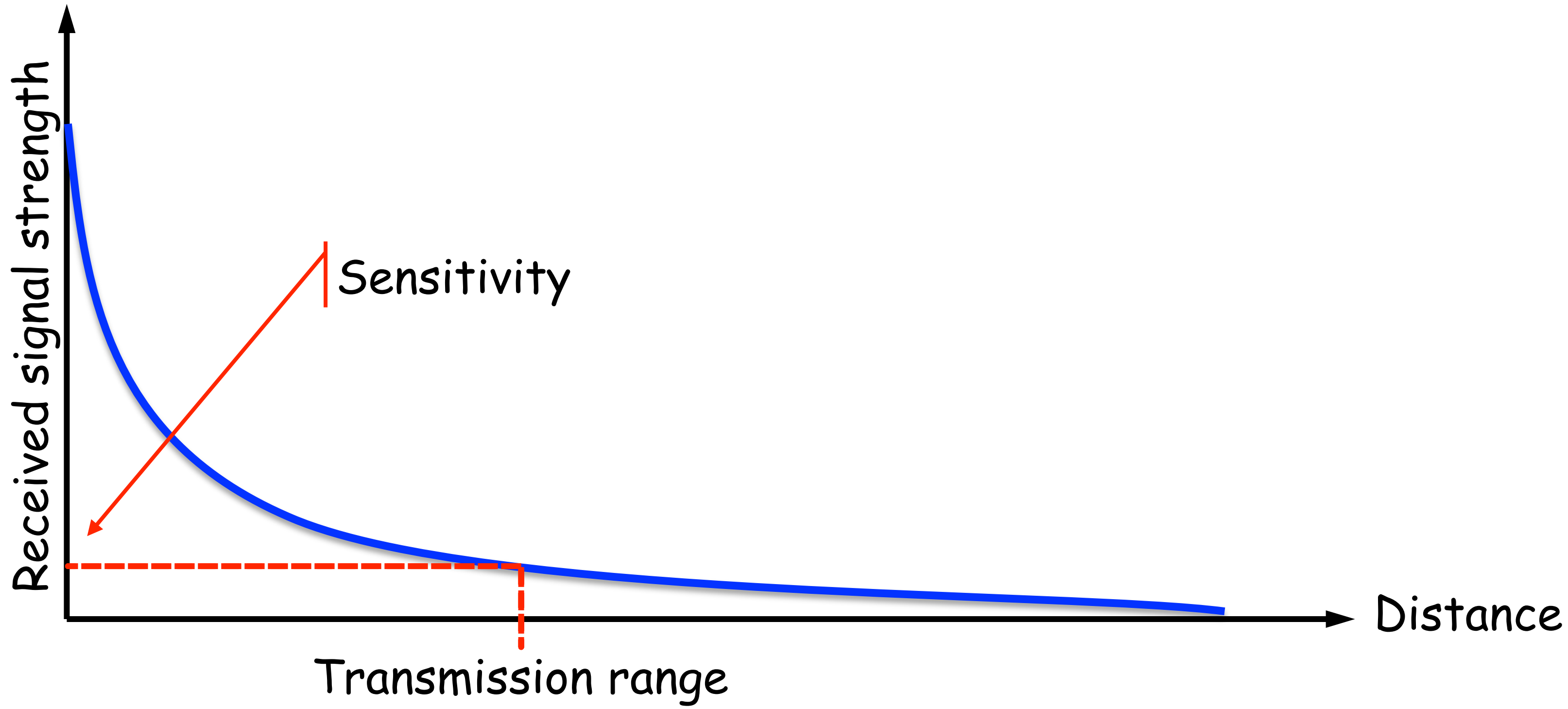
Attenuation

- Radio signal propagation
  - Free-Space-Model
  - Model: $PL_{dB}(d) = -10\log\left(\frac{\lambda^2}{(4\pi)^2 d^2}\right)$
- Assumptions:
  - Direct line of sight (LOS) between communication peers
  - No obstacles
- Advantages:
  - Simple asymptotic formulae for open space
- Disadvantages:
  - Not really useful for indoor and city environments



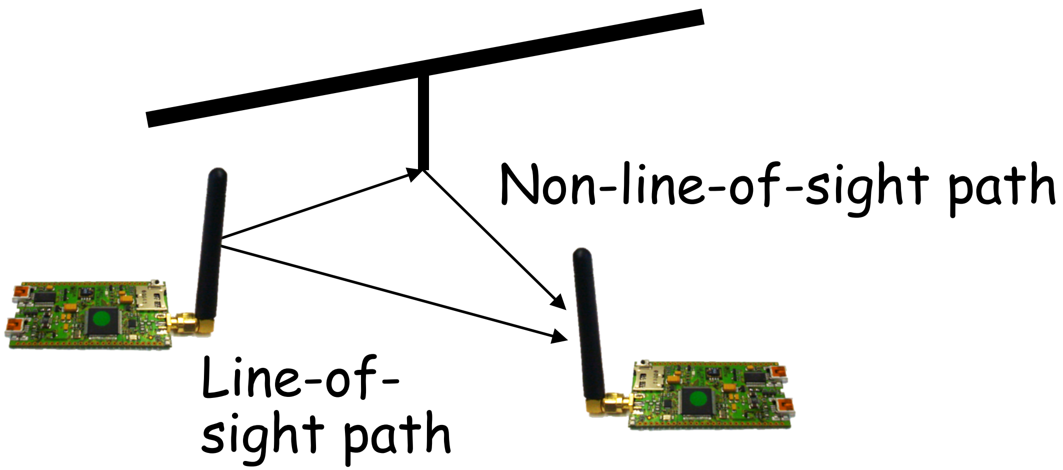


Radio propagation



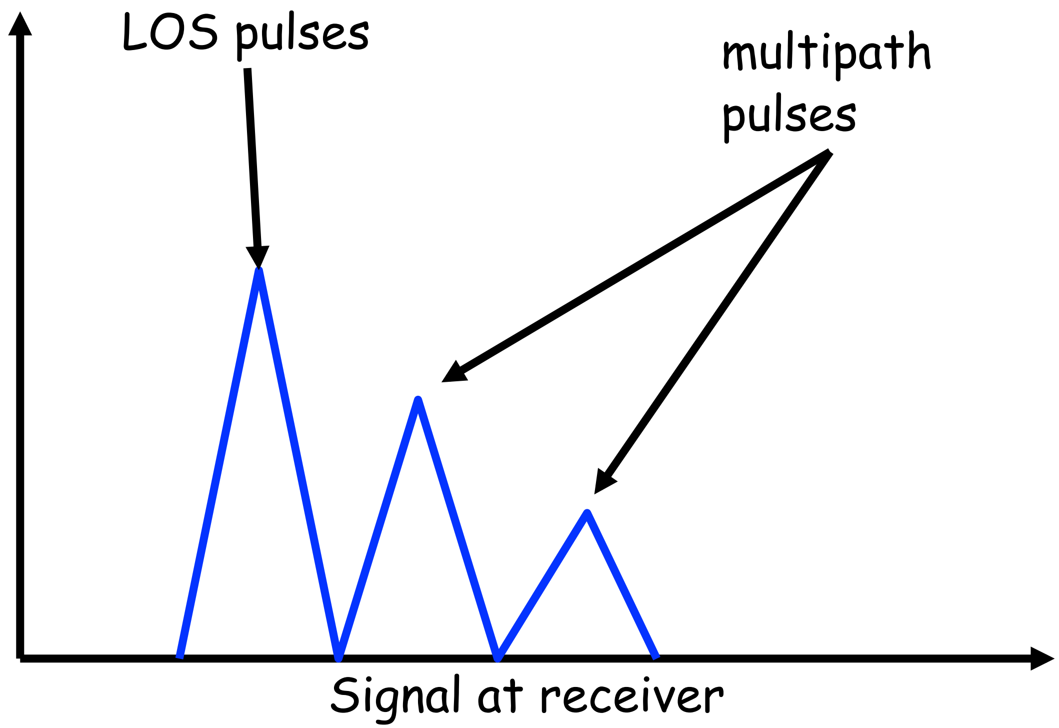
Non-line-of-sight

- Because of reflection, scattering, …, radio communication is not limited to direct line of sight communication
  - Effects depend strongly on frequency, thus different behavior at higher frequencies



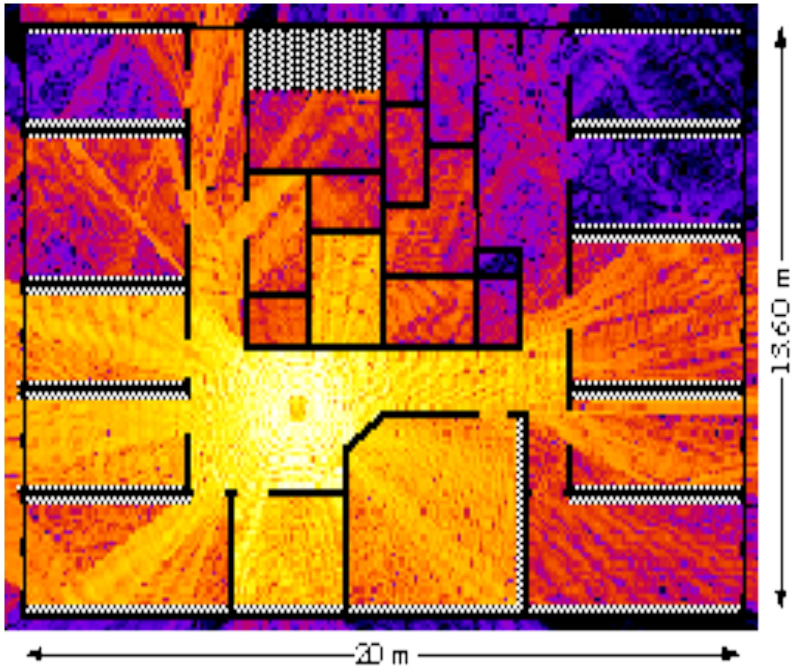
Non-line-of-sight

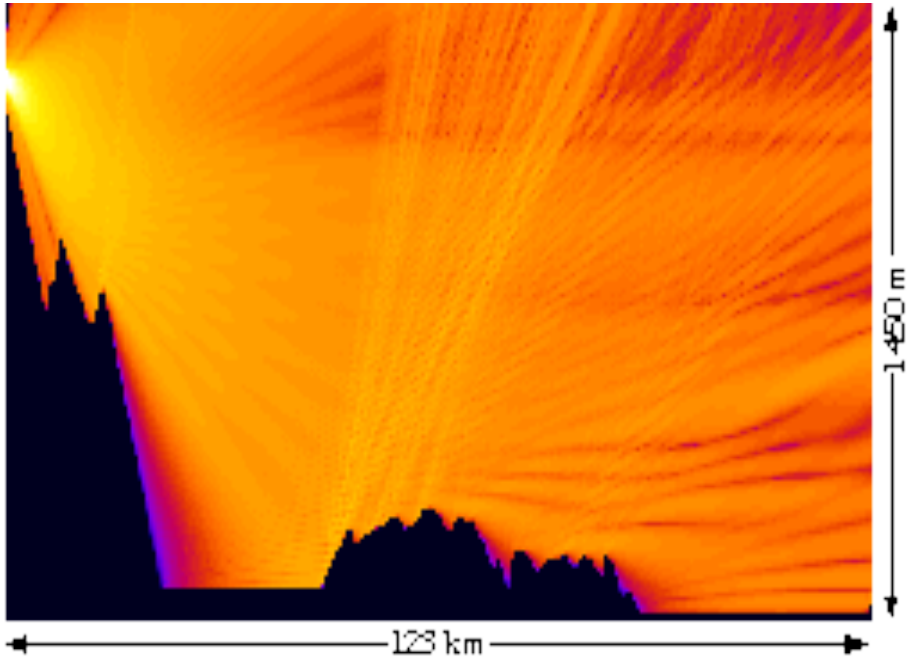
- Different paths have different lengths = propagation time
  - Results in delay spread of the wireless channel



Multi-path

- Brighter color = stronger signal
- Simple (quadratic) free space attenuation formula is not sufficient to capture these effects

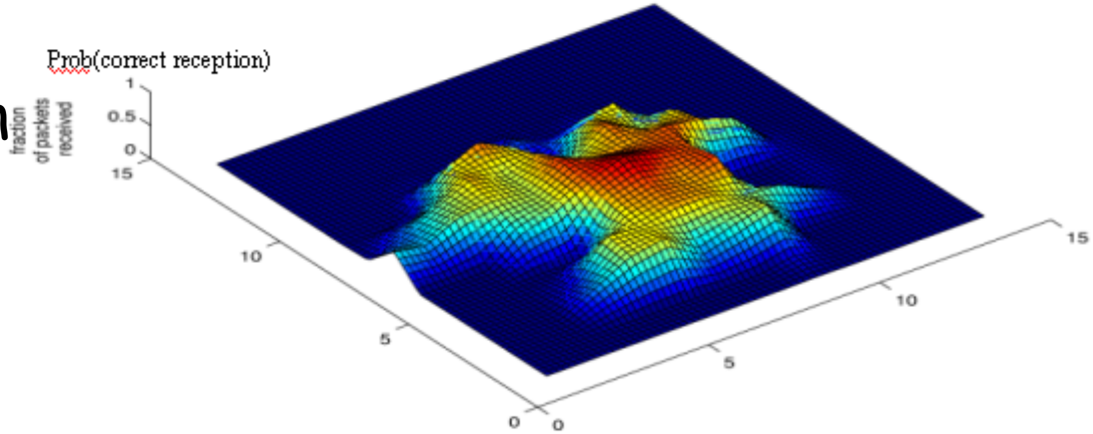


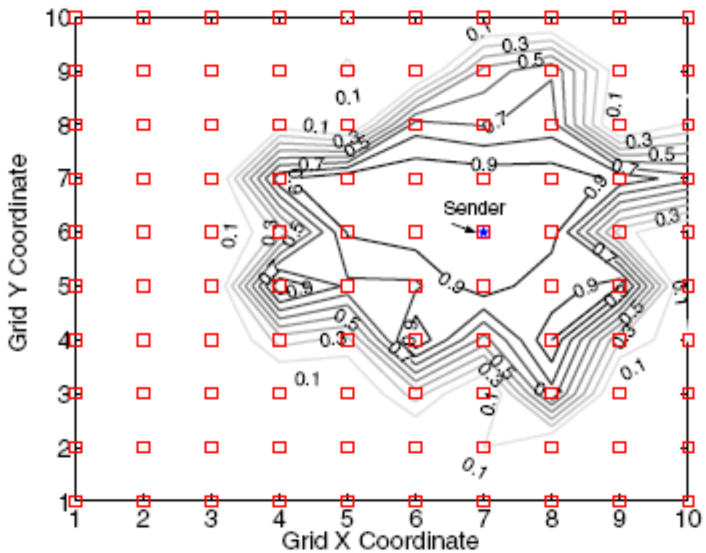


World example: Open surface

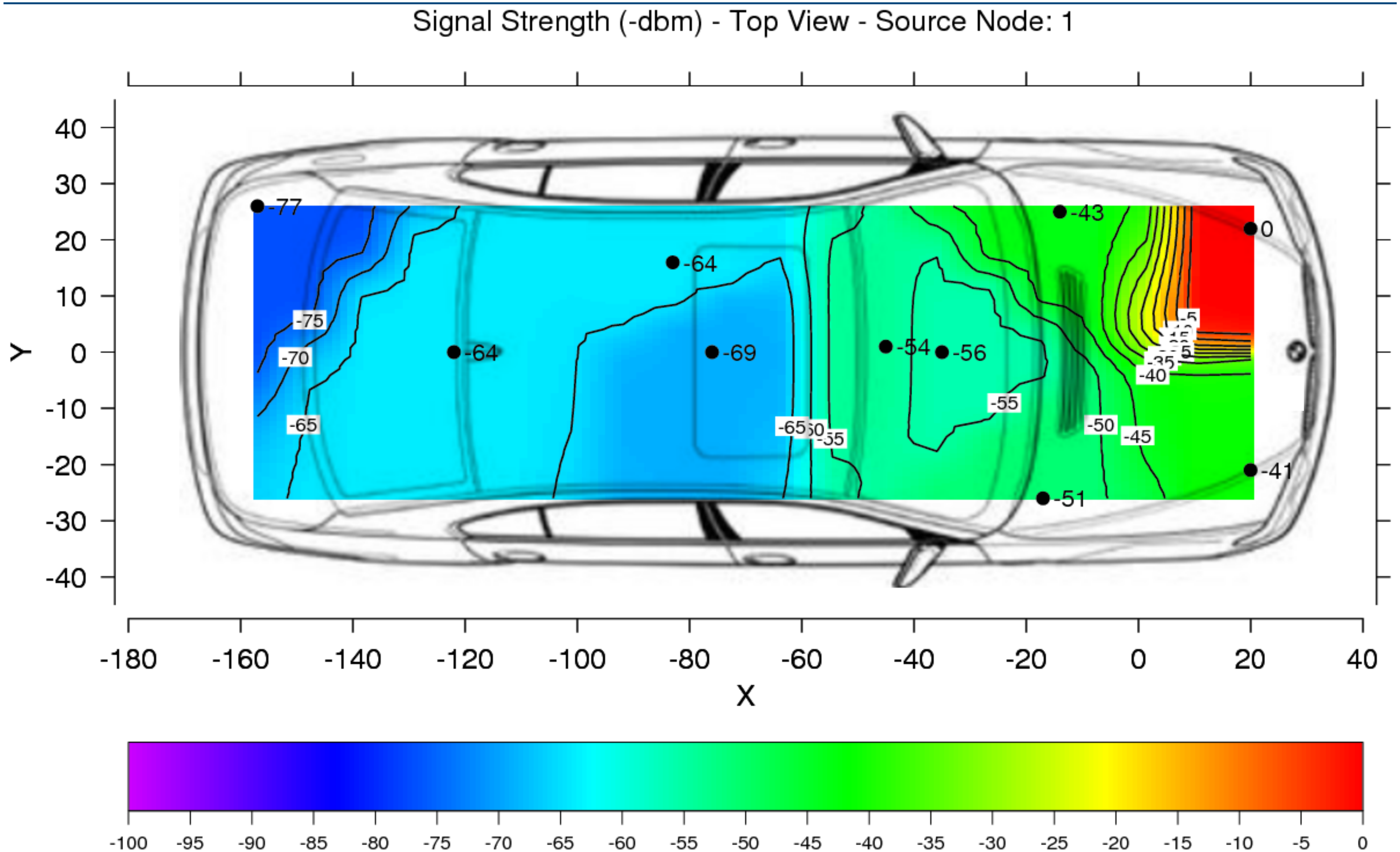
[Woo]
[Ganesan]

- 2003 study of 100-200 first generation motes placed in regular grid in open tennis court.
- RFM 916 MHz ASK RF transceivers with simple whip antenna.
- Variation in Packet Receive Rate (PRR) from each transmitter.

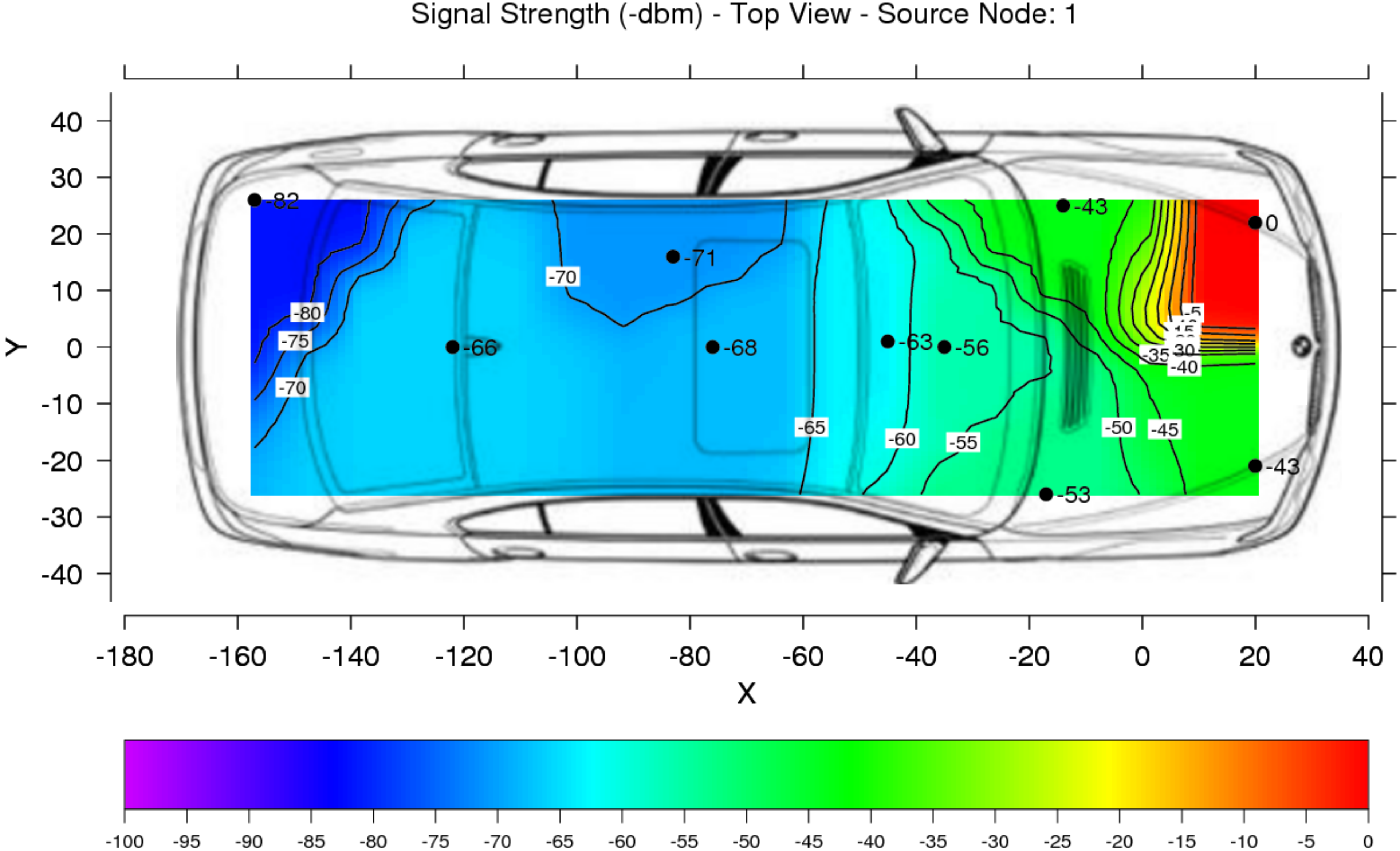




RSSI: Stationary



RSSI: Driving



Generalizing the Attenuation Formula

- To take into account stronger attenuation than only caused by distance (e.g., walls) use a larger exponent γ>2

  - γ is the path-loss exponent

$$\overline{\mathrm{PL}}(d) \propto \left(\frac{d}{d_0}\right)^{\gamma}$$

  - Rewrite in logarithmic form (in dB):

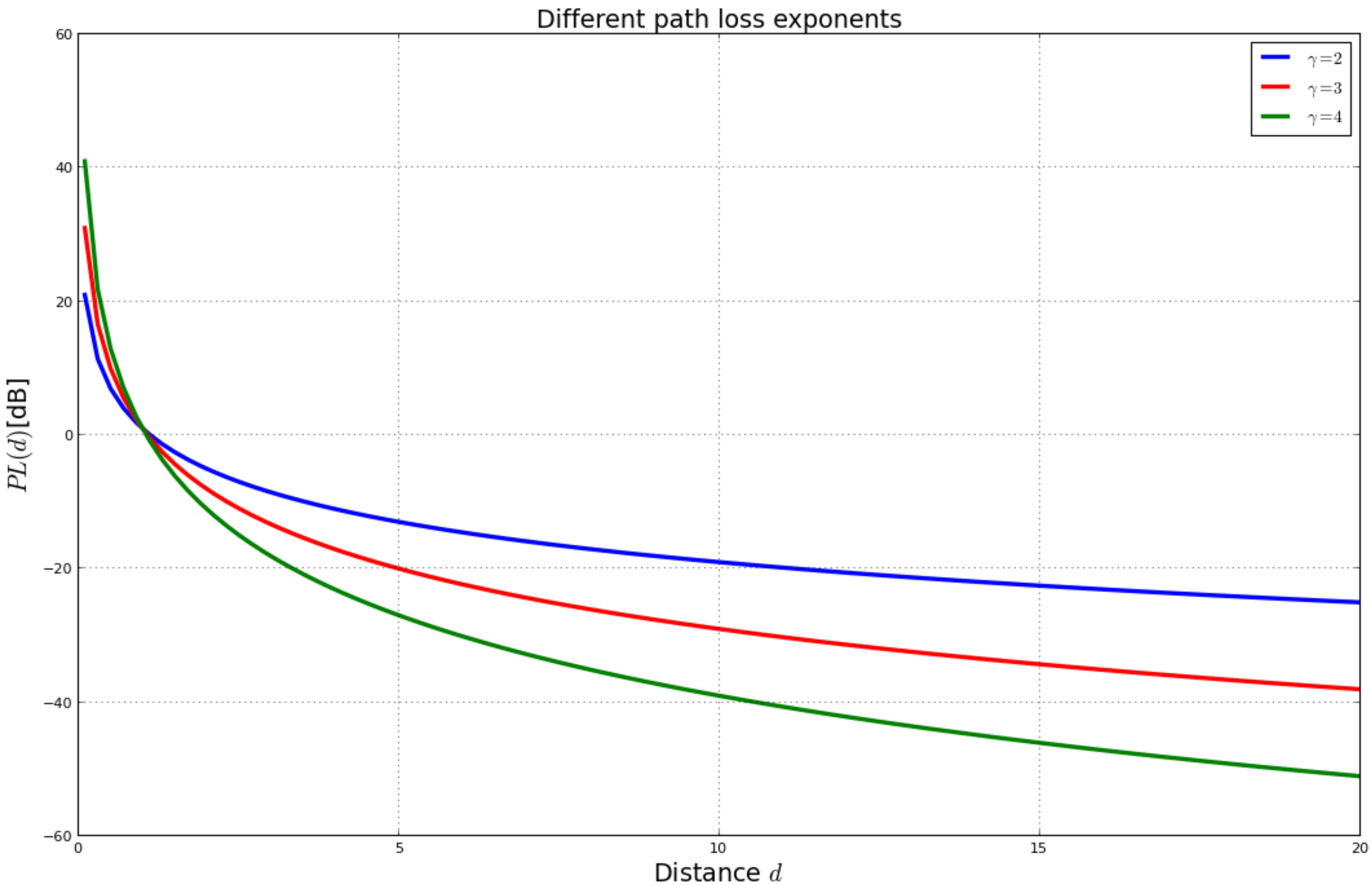
$$\overline{\mathrm{PL}}(d)[\mathrm{dB}] = \overline{\mathrm{PL}}(d_0)[\mathrm{dB}] + 10\gamma \log_{10}\left(\frac{d}{d_0}\right)$$

Generalizing the Attenuation Formula [Rappaport]

- Path loss exponents for different environments

Environment	Path loss exponent γ
Free space	2
Urban area cellular radio	2.7 – 3.5
Shadowed urban cellular radio	3 - 5
In building line-of-sight	1.6 – 1.8
Obstructed in building	4 - 6
Obstructed in factories	2 - 3

Generalizing the Attenuation Formula



Generalizing the Attenuation Formula

- Obstacles, multi-path, etc.?
- Experiments show that these can be represented by a random variable
  - Equivalent to multiplying with a lognormal distributed random variable in metric units !

-> Lognormal fading

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

Log-normal Fading Channel model

$$P_r(d) = P_t - PL(d_0) - 10\gamma\log\left(\frac{d}{d_0}\right) + X_\sigma$$

Received Power

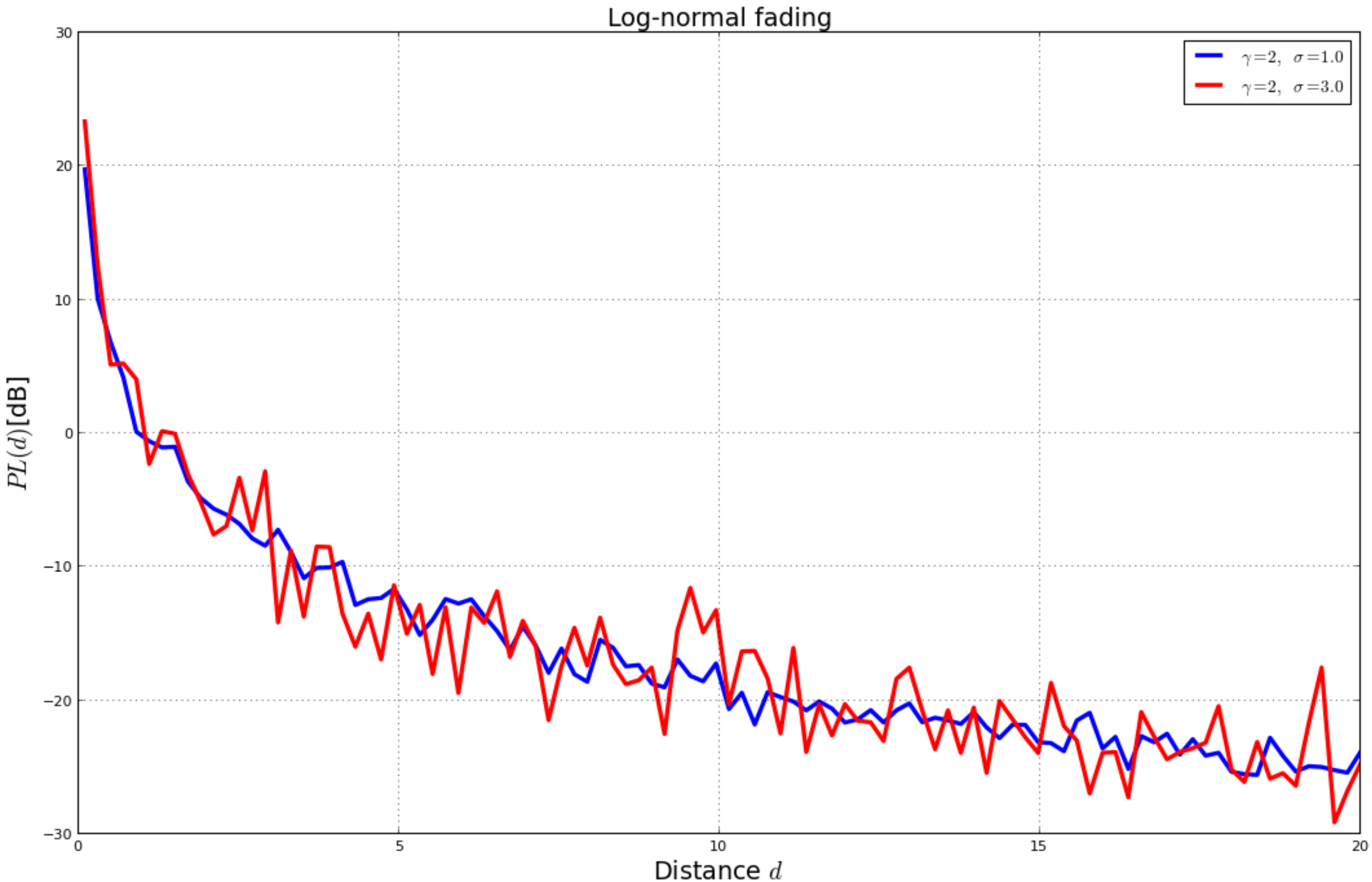
Transmit Power

Path loss

Path loss exponent

Log-normal Shadow fading

Log-normal Fading Channel model



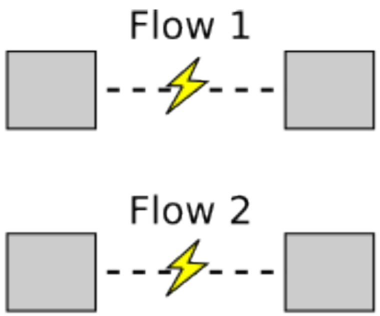
Noise and interference

- So far: only a single transmitter assumed
  - Only disturbance: self-interference of a signal with multi-path "copies" of itself
- In reality, two further disturbances
  - Noise: due to effects in receiver electronics, depends on temperature
  - Interference from 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

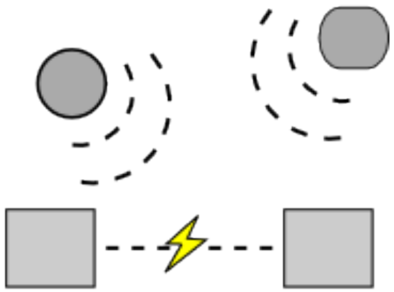
Sources of interference

- Intra-path
  - Two links on the same path utilize the same channel

- Inter-path
  - Two links of two disjoint flows interfere
  - Spatial proximity



- External interferences
  - Co-deployed networks and devices operate on the same channels



Symbols and bit errors

- Extracting symbols out of a distorted/corrupted wave form is fraught with errors
  - Depends essentially on strength of the received signal compared to the corruption
  - Captured by signal-to-noise and interference ratio (SNIR)

$$\mathrm{SNIR} = 10\log_{10}\left(\frac{\mathrm{P_r}}{N_0 + \sum_{j=1}^{k} I_j}\right)$$

- P_r Receive power (signal strength)
- N_0 Noise power
- I_j Interferer j
- k Number of neighbors that contribute to noise

Symbols and bit errors

- MAC limits the simultaneous communication
  - Interference is low
- Simplified definition of SNIR ~ SNR

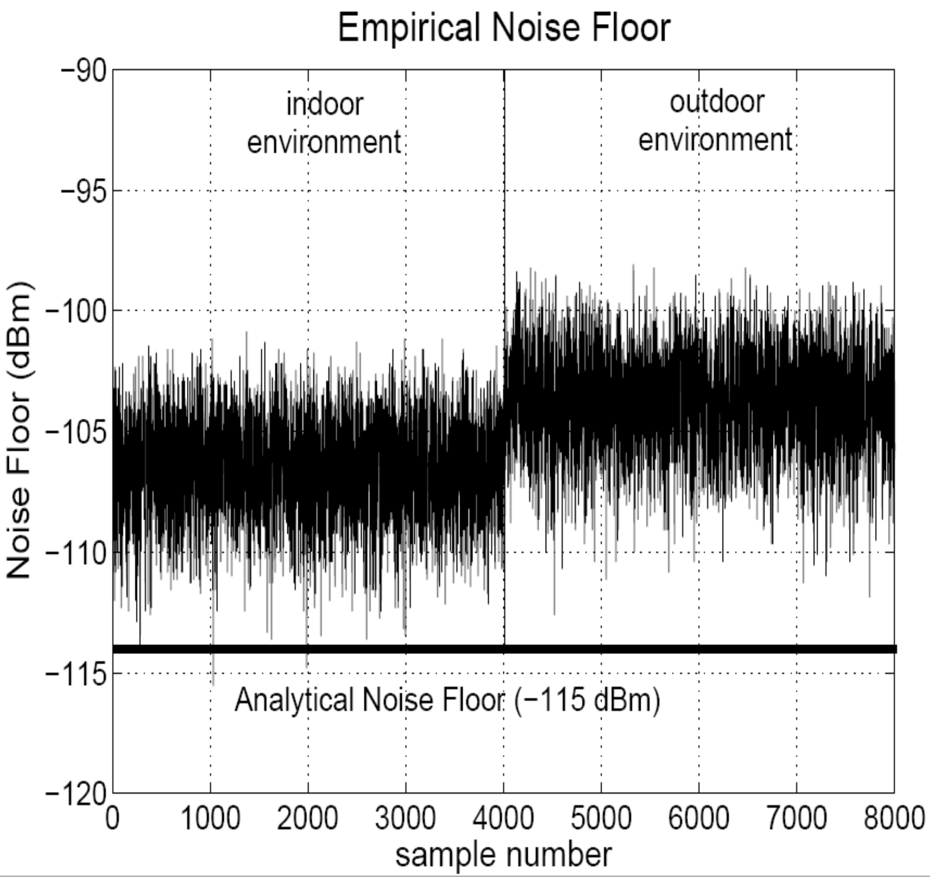
$$\mathrm{SNR} = \Psi(d) = P_t - PL(d) - P_n$$

- $\Psi(d)$ Simplified SNR
- P_t Transmit power
- $PL(d)$ Path loss at distance d
- P_n Noise power (noise floor)

Noise Floor

[Zuniga]

- Changes with time
- Varies according to location (indoor vs. outdoor)
- Even if received power is the same, SNR varies with time!



Bit Error Rate (BER)

- p_b = Probability that a received bit will be in error
  - 1 sent → 0 received
- p_b is proportional to SNR (channel quality)
  - Exact relation depends on modulation scheme
- Bit error rate depends on ratio of energy per bit to noise spectral density

$$\frac{E_b}{N_0}$$

- can be expressed also as

Noise bandwidth

$$\frac{E_b}{N_0} = \Psi \frac{B_N}{R}$$

Data rate

Received SNR

Bit Error Rate (BER)

- Example for FSK (e.g., Mica2)

$$p_b^{FSK} = \frac{1}{2} e^{-\frac{E_b}{2N_0}}$$

Bit Error Rate

- CC2420 (MicaZ, Tmote, SunSPOT) use offset quadrature phase shift keying (O-QPSK) with direct sequence spread spectrum (DSSS)

$$p_b^{OQPSK} = Q\left(\sqrt{(Eb/No)_{DS}}\right)$$

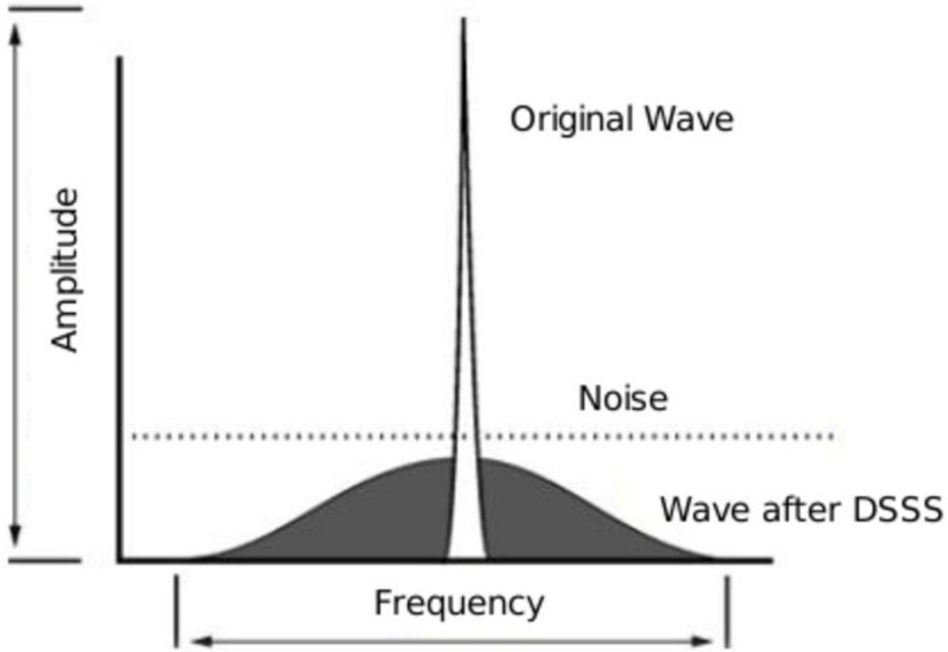
$$(Eb/No)_{DS} = \frac{2N(Eb/No)}{N + \frac{4}{3}Eb/No(K-1)}$$

# of chips per bit (16)

=2 for MicaZ

Bit Error Rate

- CC2420 (MicaZ, Tmote, SunSPOT) use offset quadrature phase shift keying (O-QPSK) with direct sequence spread spectrum (DSSS)



Packet Error Rate (PER)

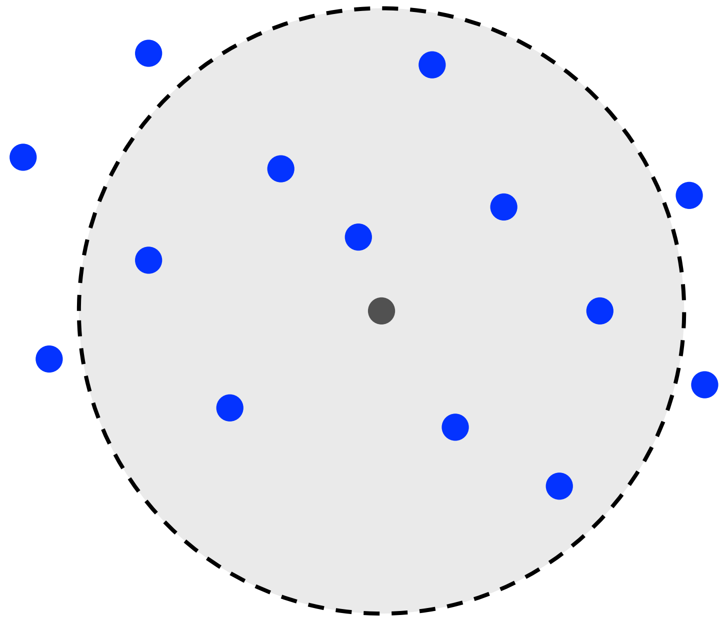
- Packet error rate (PER) can be given based on BER
  - Depends on channel coding scheme
- Assume all errors in a packet can be detected
- PER of a single transmission with a payload of k bits when CRC is used is given by

$$PER^{CRC}(k) = 1 - \left(1 - p_b\right)^k$$

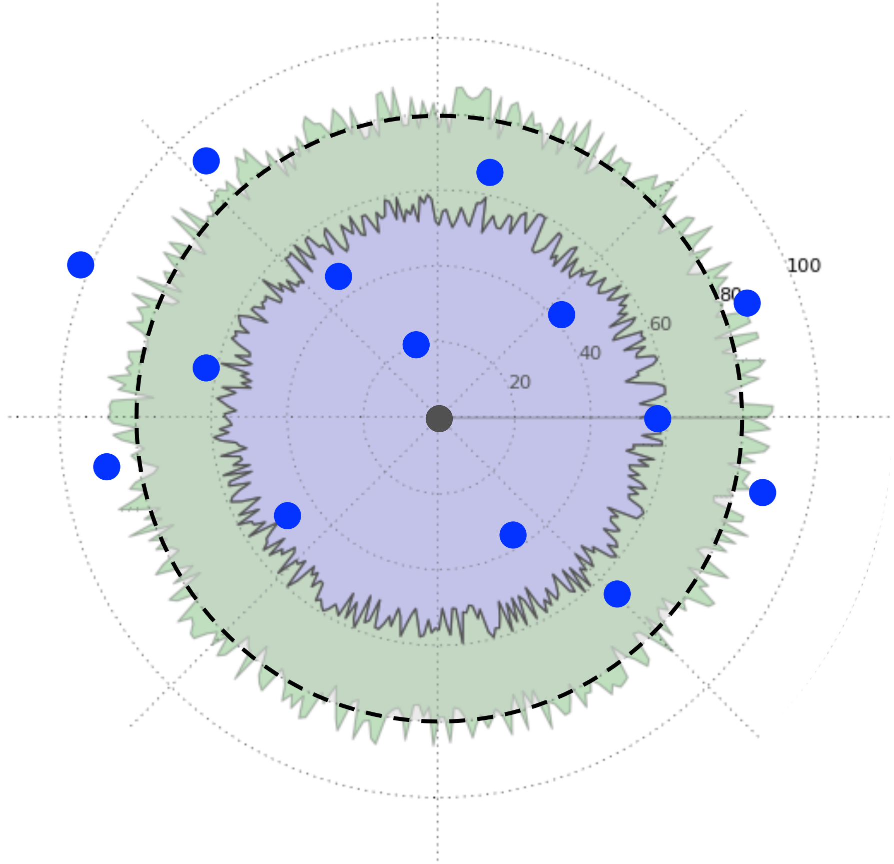
Wireless channel models

Channel Models

Unit disc graph model

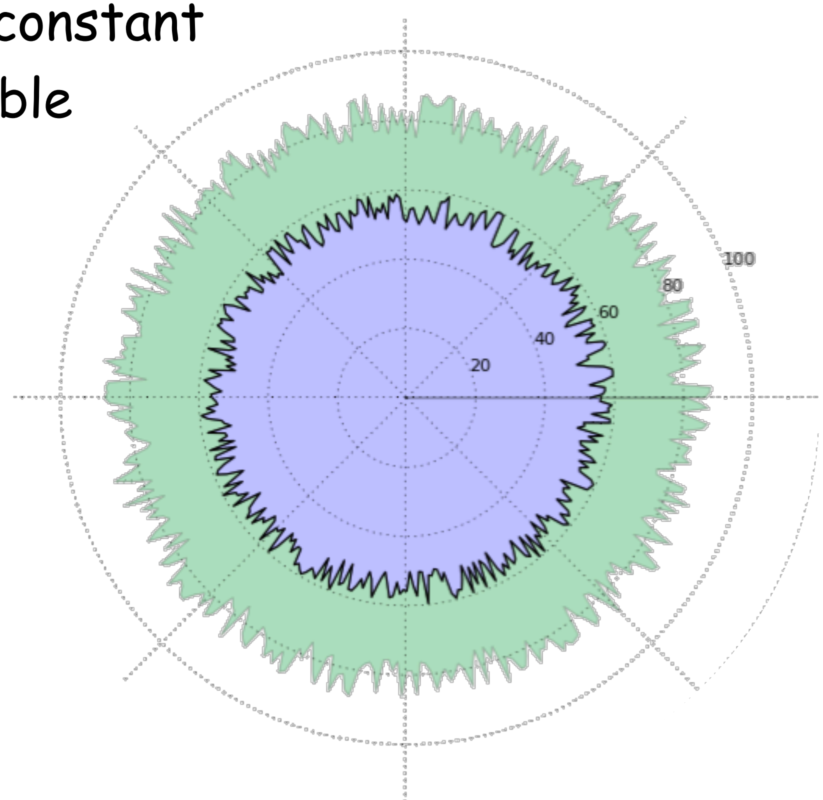


Statistical channel model



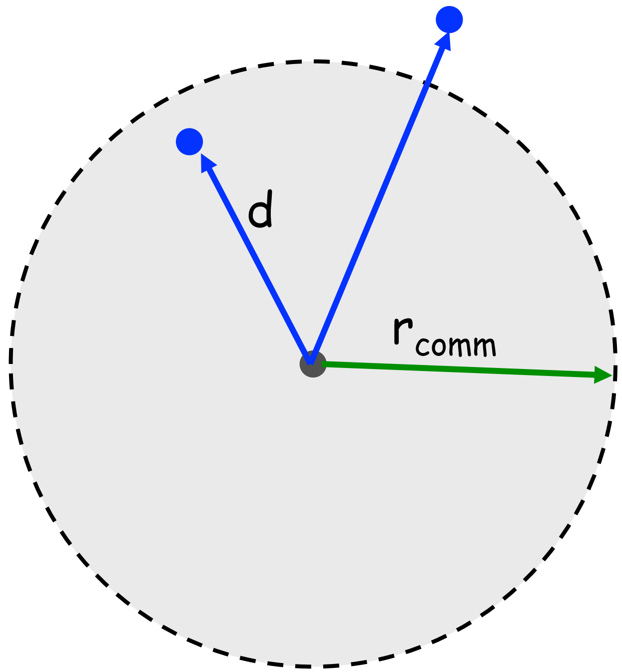
Channel Models

- Goal: Capture the behavior of a wireless channel
  - Model the SNR
  - Model directly the bit errors
- Simplest model
  - Transmission power and attenuation constant
  - Noise an uncorrelated Gaussian variable
    - Additive White Gaussian Noise model
    - Results in constant SNR



Channel Models: Unit disc graph (UDG)

- Unit disc graph (UDG) model
  - Based on graph theory
  - Very simple
  - Communication range r_{comm}
- Pro
  - Useful for simplifying the analysis of protocols
- Contra
  - Unrealistic

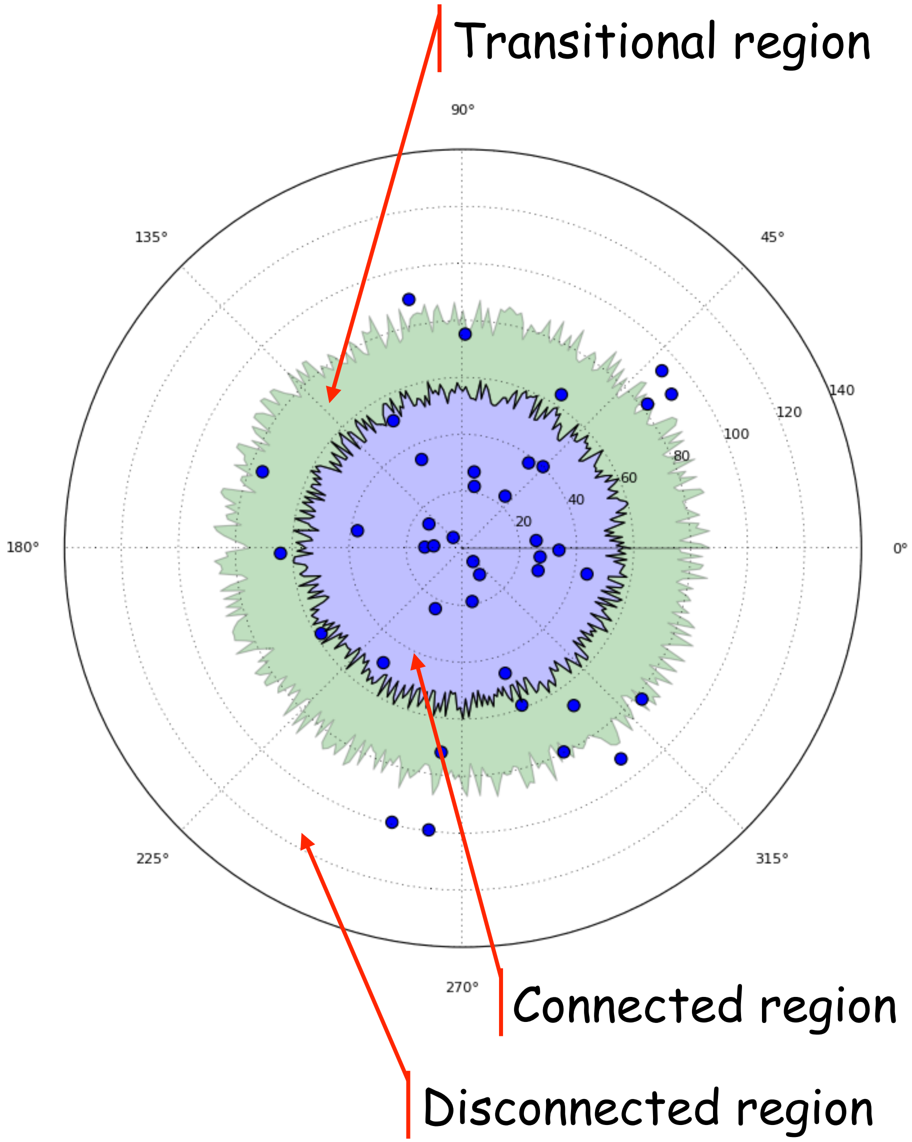


$$p_b = \begin{cases} 0 & \text{if } d \leq r_{comm} \\ 1 & \text{if } d > r_{comm} \end{cases}$$

Channel Models: Statistical channel model

- Non-deterministic characteristics
  - Random multi-path effects
- More accurate than UDG model
- SNR can be modeled as a Gaussian random variable

$$\Psi(d) = P_t - PL(d_0) - 10\gamma \log\left(\frac{d}{d_0}\right) - P_n + X_\sigma$$



Channel Models: Statistical channel model

$$\Psi(d) = \underbrace{P_t - PL(d_0) - 10\gamma\log\left(\frac{d}{d_0}\right) - P_n}_{\beta(d,\gamma)} + X_\sigma$$

$$\Psi(d) = N(\beta(d,\gamma),\sigma)$$

Channel Models

- Non-line-of-sight path
  - Amplitude of resulting signal has a Rayleigh distribution (Rayleigh fading)
- One dominant line-of-sight plus many indirect paths
  - Signal has a Rice distribution (Rice fading)

Channel Model for WSN

- Typical WSN properties
  - Low power communication
  - Small transmission range
  - Implies small delay spread (nanoseconds, compared to micro/milliseconds for symbol duration)
  - Frequency-non-selective fading, low to negligible inter-symbol interference
    - Coherence bandwidth often > 50 MHz

Channel Model for WSN

[Zuniga]

- Some example measurements
  - γ path loss exponent
  - Shadowing variance σ^2

environment	γ (95% conf. bounds)	σ (95% conf. bounds)
outdoor	4.7 (4.30 - 5.10)	4.6 (2.80 - 6.40)
indoor	3.0 (2.67 - 3.23)	3.8 (2.60 - 5.00)

Wireless channel models

An example: the wireless channel of wireless sensor networks

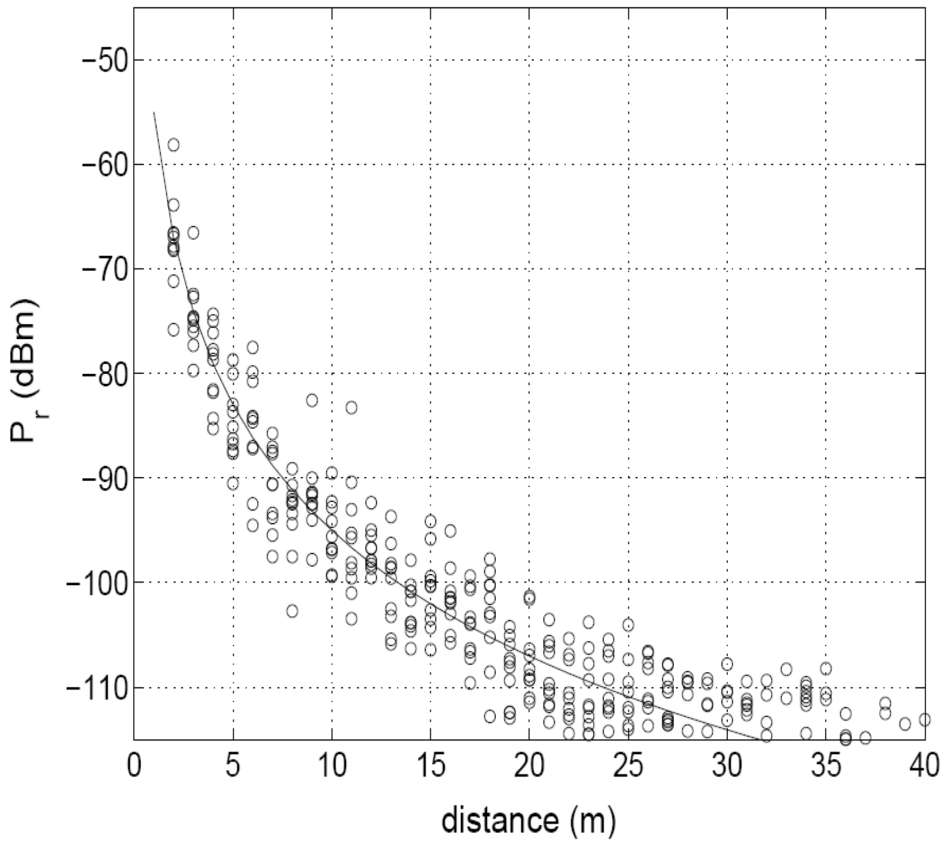
Channel Model for WSN

[Zuniga]

- Log-normal fading channel best characterizes WSN channels

$$P_r(d) = P_t - PL(d_0) - 10\gamma \log\left(\frac{d}{d_0}\right) + X_\sigma$$

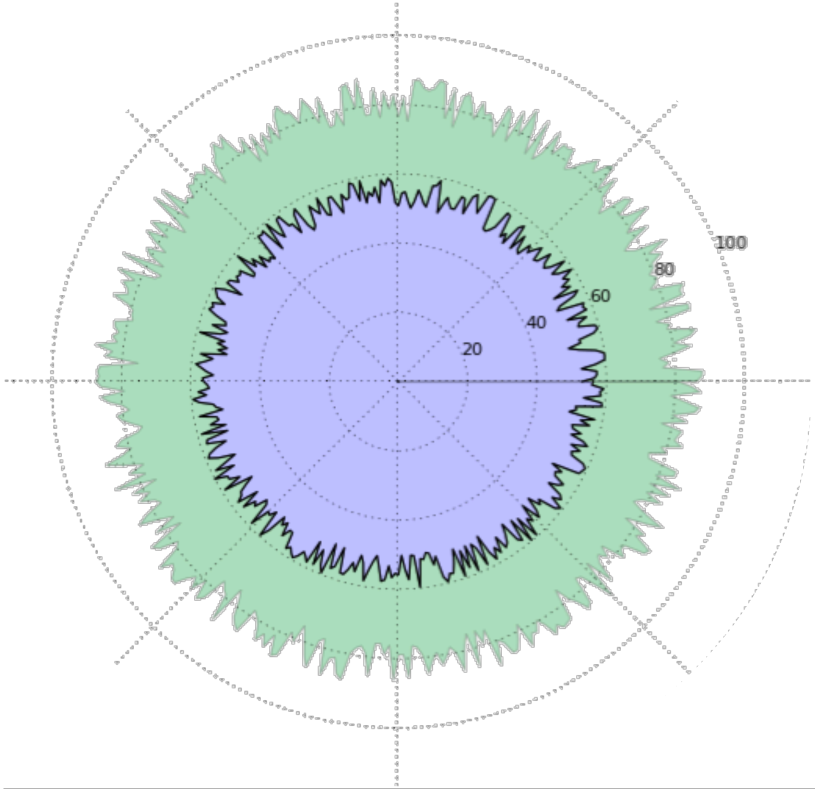
- Empirical evaluations for Mica2

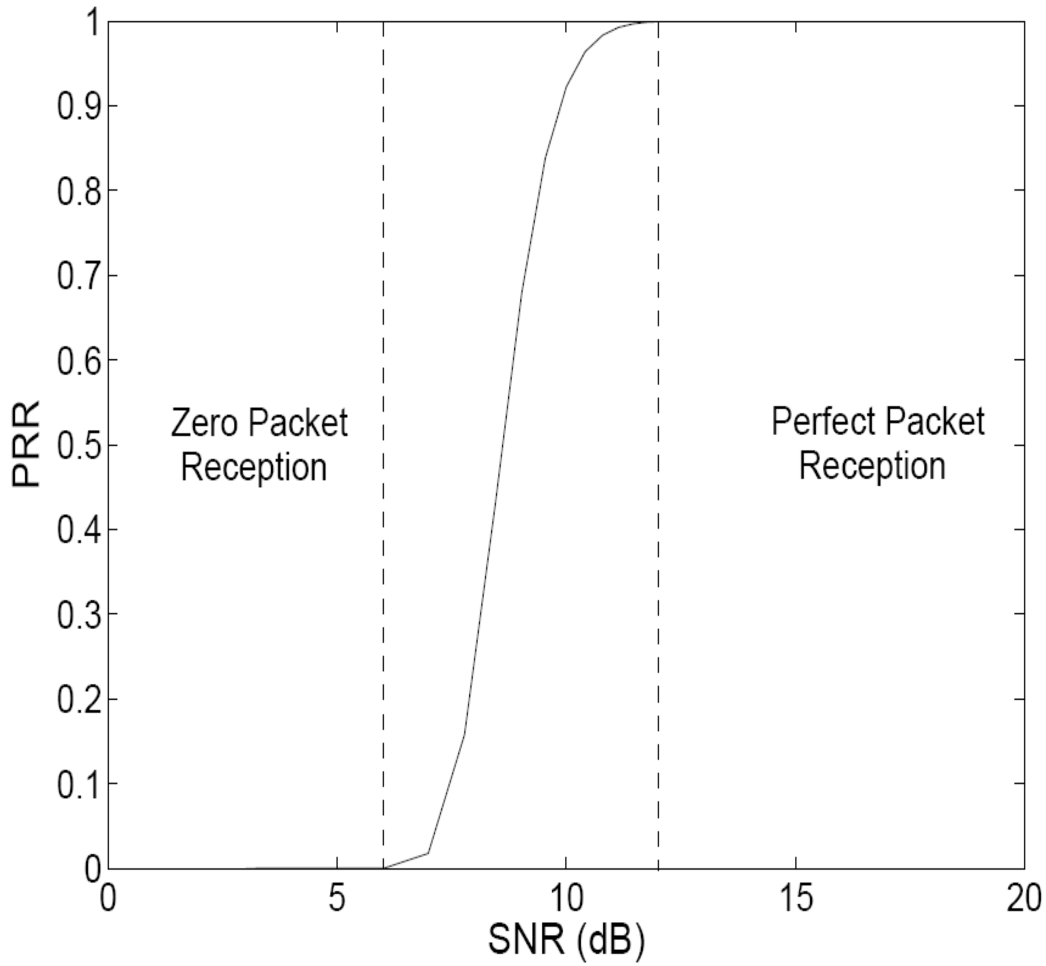


Channel Model for WSN

[Zuniga]

- PRR: Packet reception rate $(1-p_b)^k$
- Transitional region for packet reception
  - Not too good, not too bad





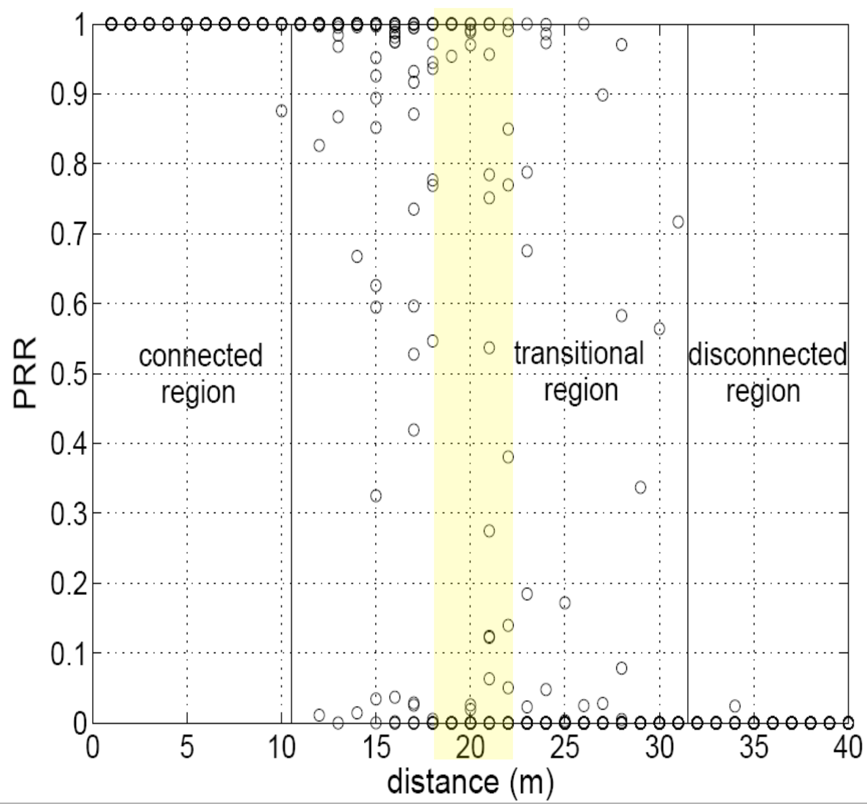
Channel Model for WSN

[Zuniga]

- PRR significantly varies in the transitional region
- Example: d = 20m -> PRR = [0,1]

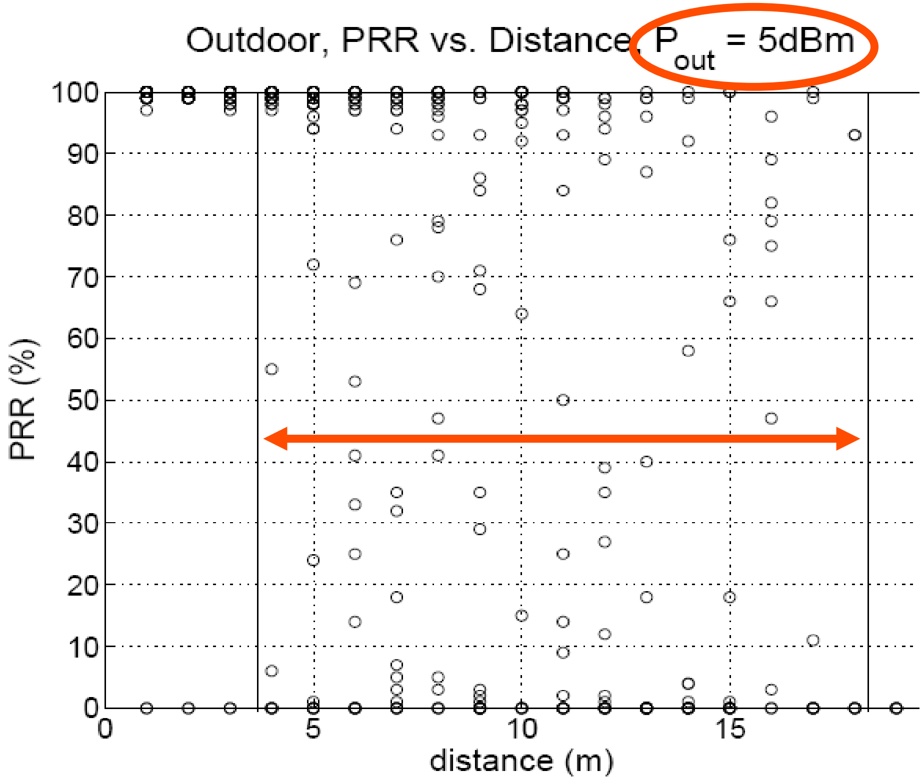
-> We cannot operate solely in the connected region

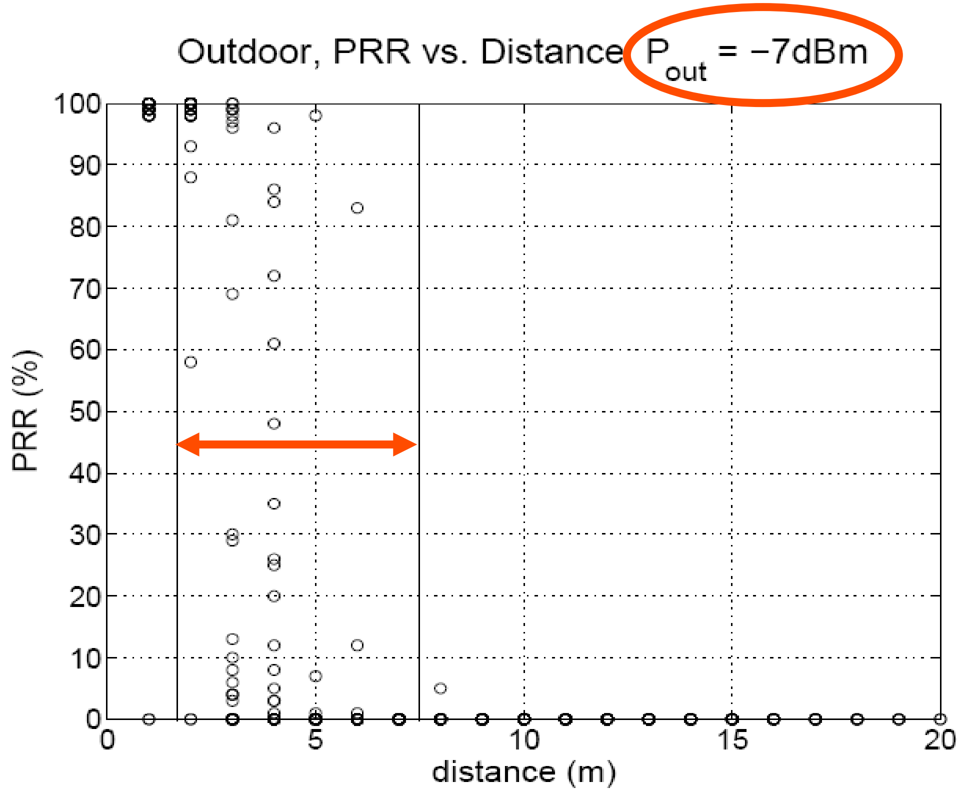
  - Communication distance too short



Channel Model for WSN

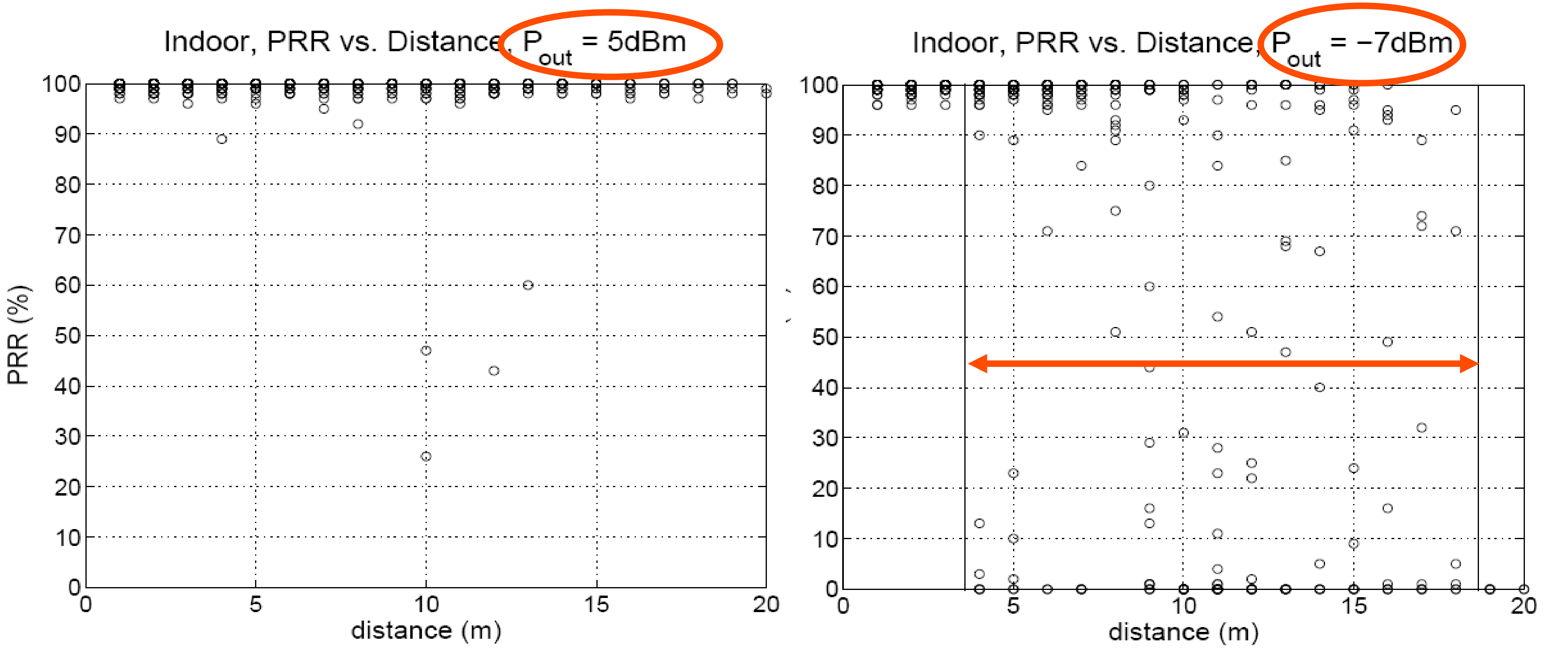
[Zuniga]





Channel Model for WSN

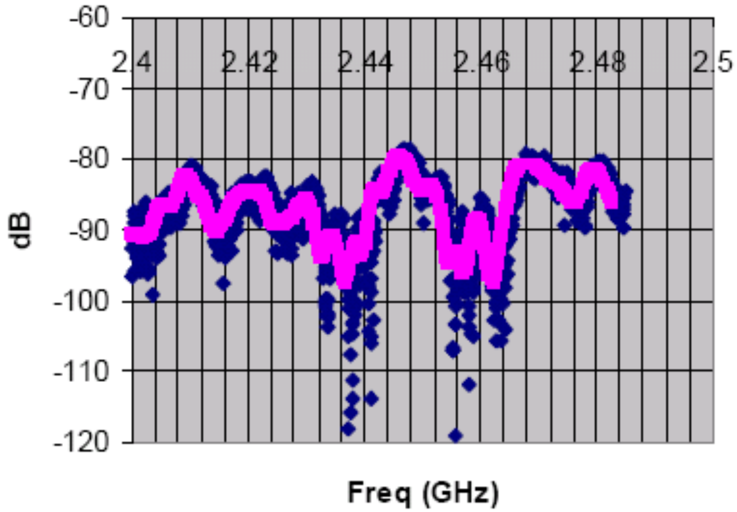
[Zuniga]

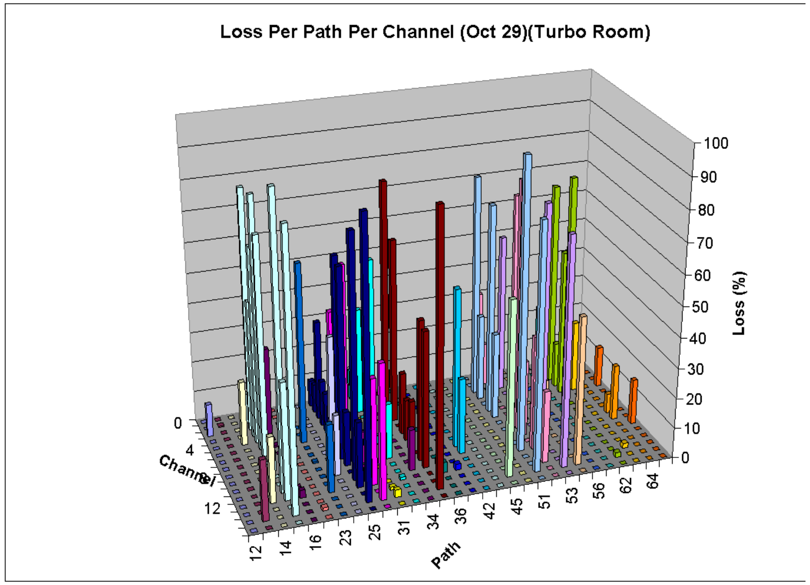


Channel Fading

[Sexton]

- Multipath effects
  - Varies by position
  - Varies by frequency
  - Varies over time
- Overcome with diversity
  - Time diversity
    - Retransmission
  - Spatial diversity
    - Multiple antennas
  - Path diversity
    - Alternative receivers
  - Frequency diversity
    - Spreading, Multiple channels





Channel models

Digital

Channel Models: Digital

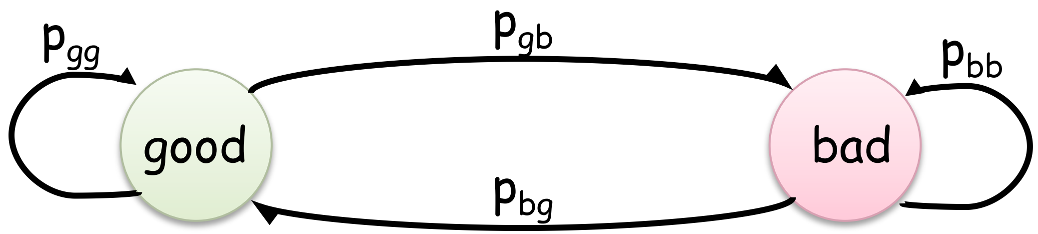
- Directly model the resulting bit error behavior (p_b)
- Each bit is erroneous with constant probability, independent of the other bits
  - Binary symmetric channel (BSC)

- Capture property of fading models that channel is in different states!

-> Markov models – states with different BERs

Channel Models: Digital

- Markov models -> states with different BERs
- Example: Gilbert-Elliot model with
  - bad state: high bit error rate
  - good state: low bit error rate



Popular wireless interfaces

Radio	RFM TR1000	Infineon TDA5250	TI CC1000	TI CC2420	Zeevo ZV4002
Platforms	WeC, Rene Dot, Mica	eyesIFX	Mica2Dot, Mica2 BTNode	MicaZ, TelosB SunSPOT, Imote2	Imote BTNode
Standard	N/A	N/A	N/A	IEEE 802.15.4	Bluetooth
Data Rate (kbps)	2.4-115.2	19.2	38.5	250	723.2
Modulation	OOK/ASK	ASK/FSK	FSK	OQPSK	FHSS-GFSK
Radio Frequency (MHz)	916	868	315/433/868/915	2.4GHz	2.4GHz
Supply Voltage (V)	2.7-3.5	2.1-5.5	2.1-3.6	2.1-3.6	0.85-3.3
TX Max (mA/dBm)	12 / -1	11.9 / 9	26.7 / 10	17.4 / 0	32 / 4
TX Min (mA/dBm)	N/A	4.9 / -22	5.3 / -20	8.5 / -25	N/A
RX (mA)	1.8-4.5	8.6-9.5	7.4-9.6	18.8	32
Sleep (μA)	5	9	0.2-1	0.02	3.3mA
Startup Time (ms)	12	0.77-1.43	1.5-5	0.3-0.6	N/A

Summary

- Packet loss will always disturb communication
- Asymmetric links are common
- Link quality varies over time
- What is a good link metric?

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