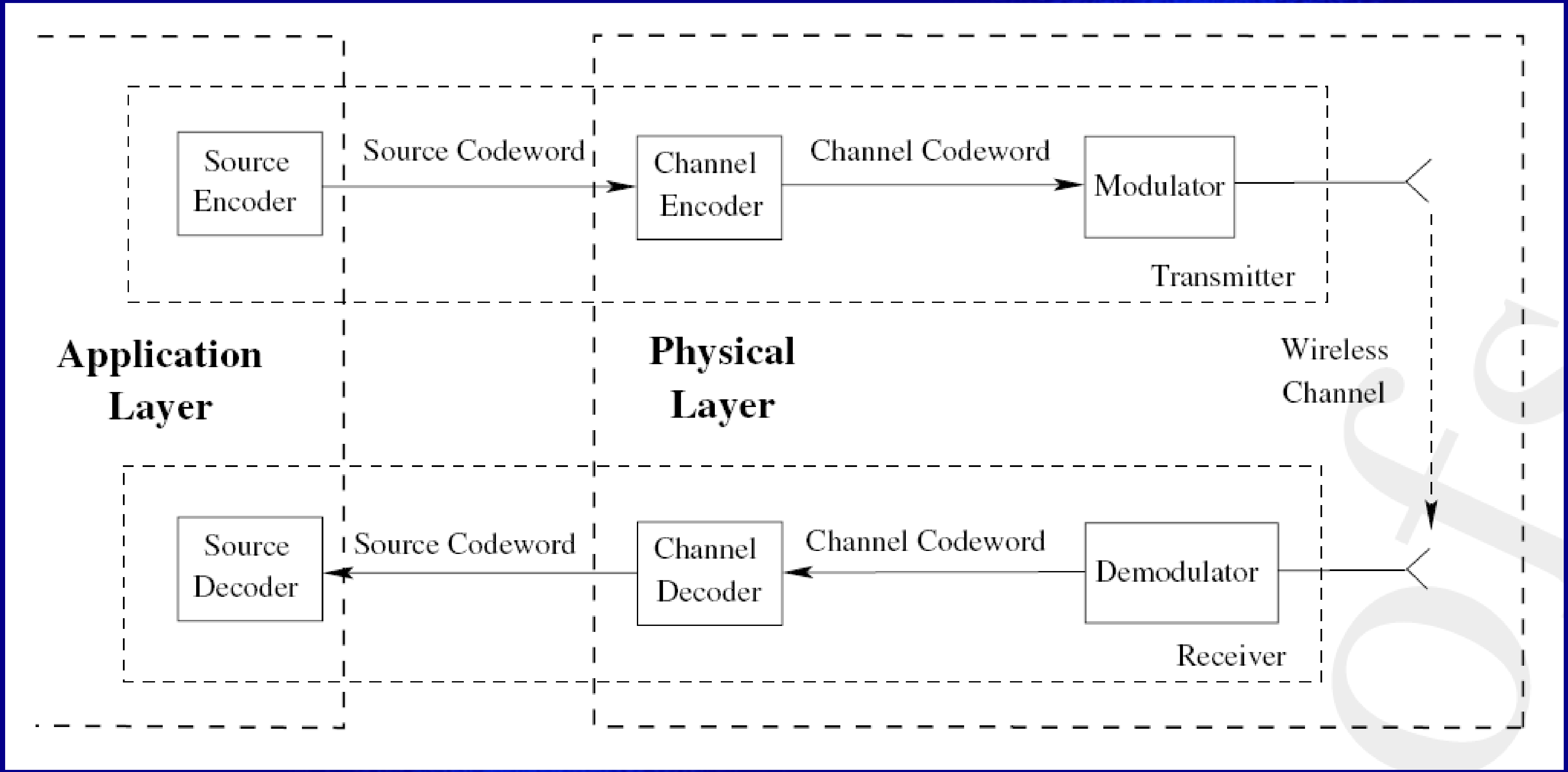
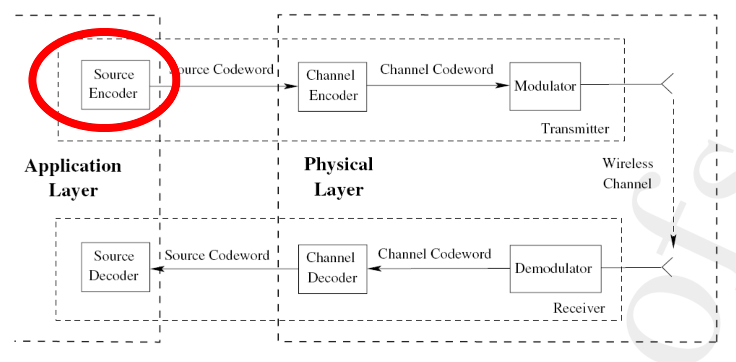
Chapter 4:
Physical Layer

PHYSICAL LAYER

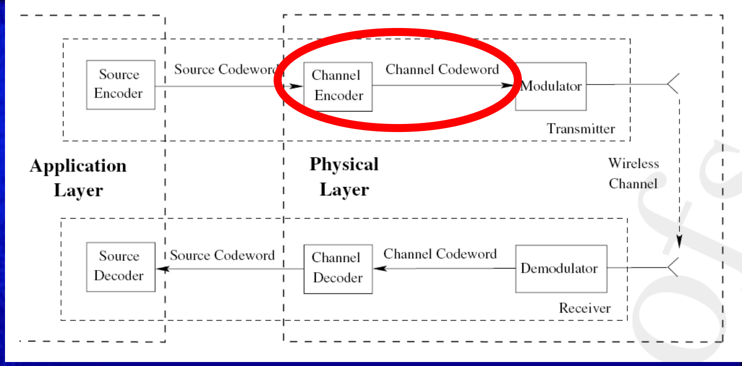


Source coding (data compression)



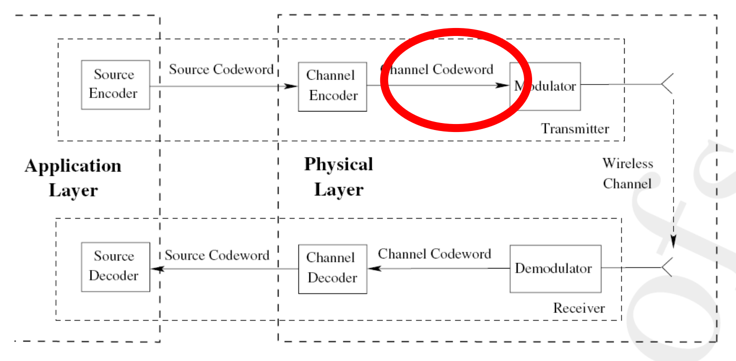
- At the transmitter end, the information source is first encoded with a source encoder
  - Exploit the information statistics
  - Represent the source with a fewer number of bits,
  - → source codeword
- Performed at the application layer

Channel coding (error control coding)



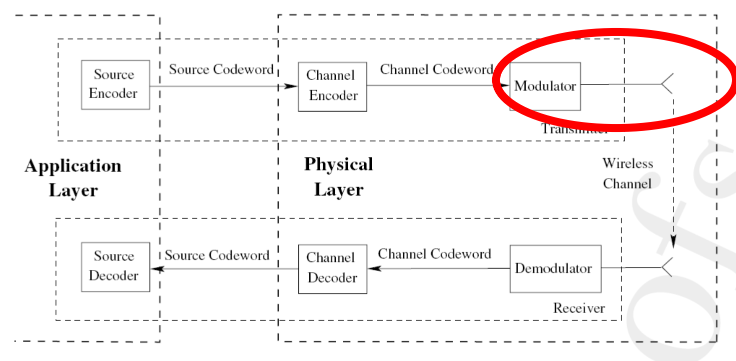
- Source codeword is then encoded by the channel encoder
- → channel codeword
  - Goal: address the wireless channel errors that affect the transmitted information

Interleaving and modulation



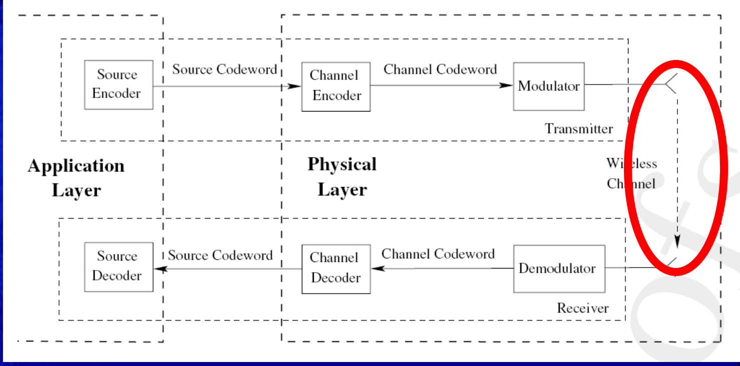
- The encoded channel codeword is then **interleaved** to combat the bursty errors
- Channel coding and the interleaving mechanism help the receiver either to
  - Identify bit errors to initiate retransmission
  - Correct a limited number of bits in case of errors.

Interleaving and modulation



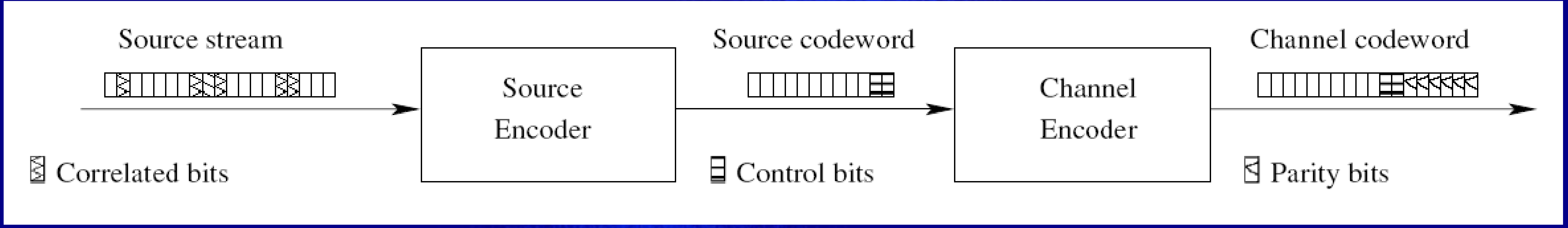
- Then, an analog signal (or a set thereof) is modulated by the digital information to create the waveform that will be sent over the channel
- Finally, the waveforms are transmitted through the antenna to the receiver

Wireless channel propagation



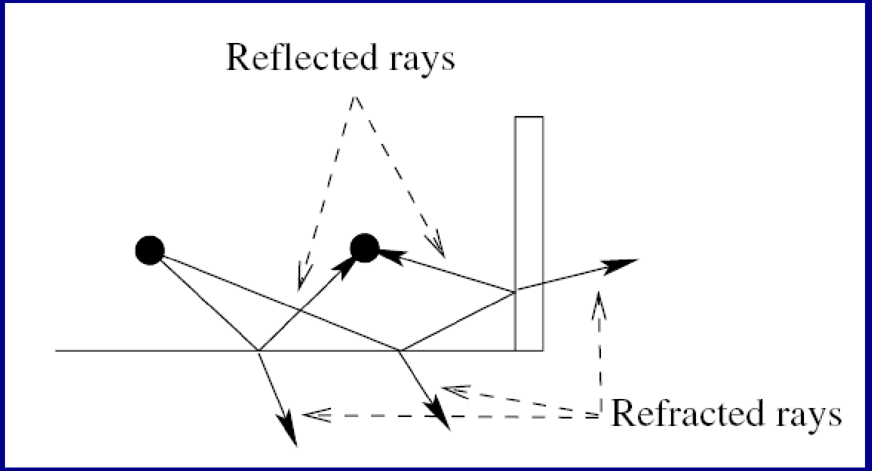
- The transmitted waveform travels through the channel
- Meanwhile, the waveform is attenuated and distorted by several wireless channel effects

Information Processing



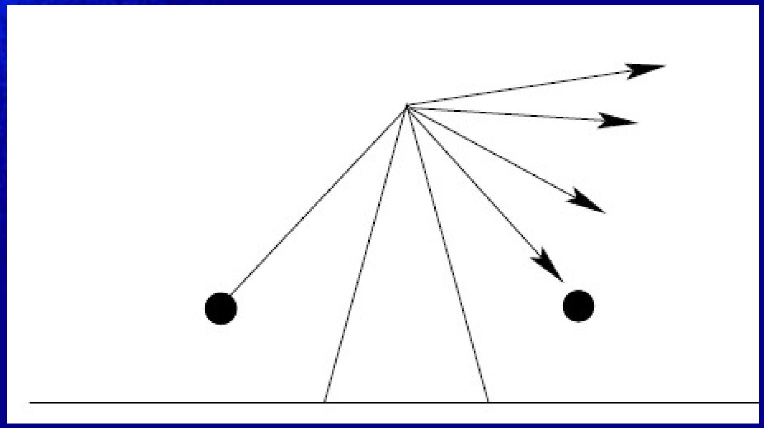
Wireless channel propagation

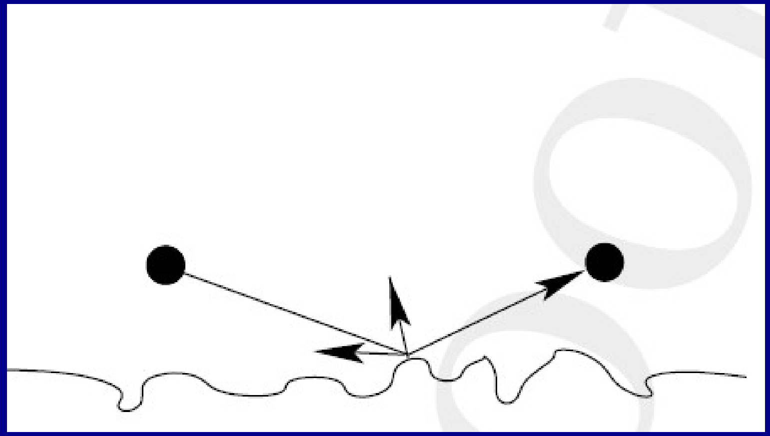
- **Attenuation:** As the signal wave propagates through air, the signal strength is attenuated.
  - Proportional to the distance traveled over the air
  - Results in **path loss** for radio waves
- **Reflection and refraction:** When a signal wave is incident at a boundary between two different types of material
  - a certain fraction of the wave bounces off the surface, ***reflection***.
  - a certain fraction of the wave propagates through the boundary, ***refraction***.



Wireless channel 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 Model

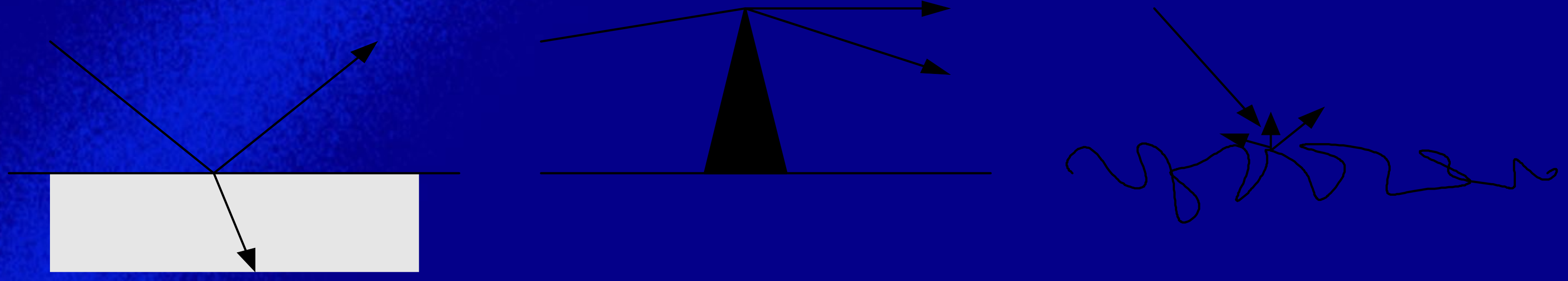
- Path-loss
- Multi-path effects
- Channel errors
- Signals-to-bits
- Bits-to-packets

Overview

- Frequency bands
- Modulation
- *Signal Distortion – Wireless Channel Errors*
- From waves to bits
- Channel models
- Transceiver design

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

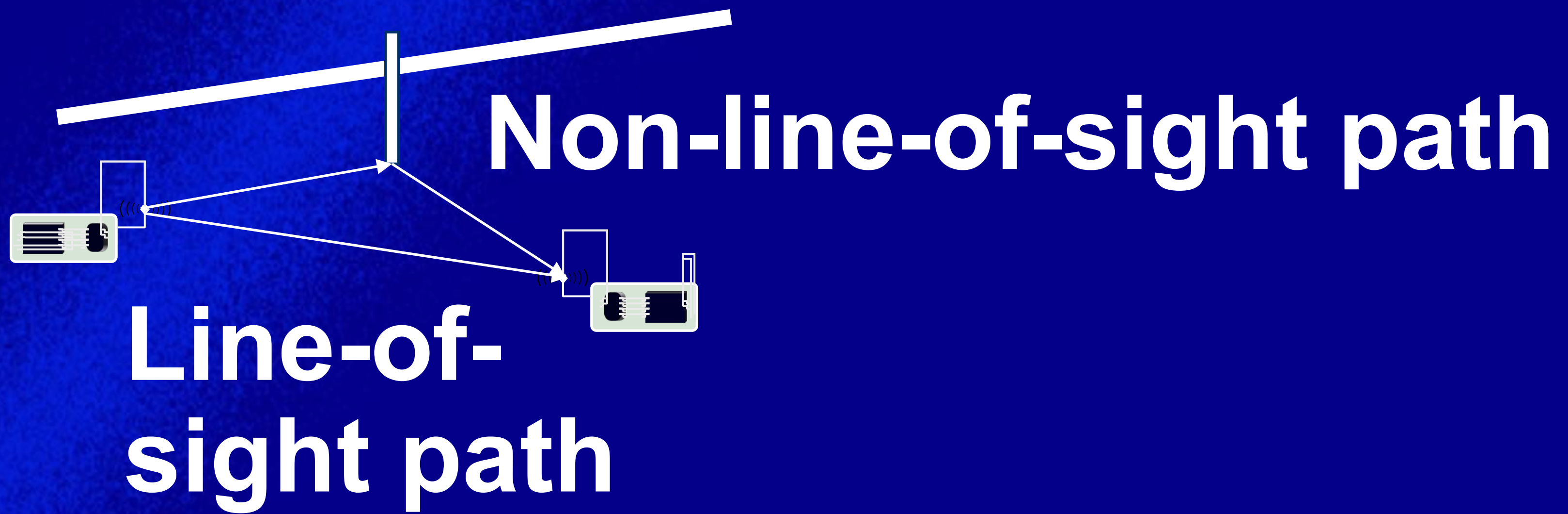
Attenuation

- ***Friis free-space model***

$$
\begin{aligned}
P_{\mathrm{recv}}(d) &= \frac{P_{\mathrm{tx}} \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi)^2 \cdot d^2 \cdot L} \\
&= \frac{P_{\mathrm{tx}} \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi)^2 \cdot d_0^2 \cdot L} \cdot \left(\frac{d_0}{d}\right)^2 = P_{\mathrm{recv}}(d_0) \cdot \left(\frac{d_0}{d}\right)^2
\end{aligned}
$$

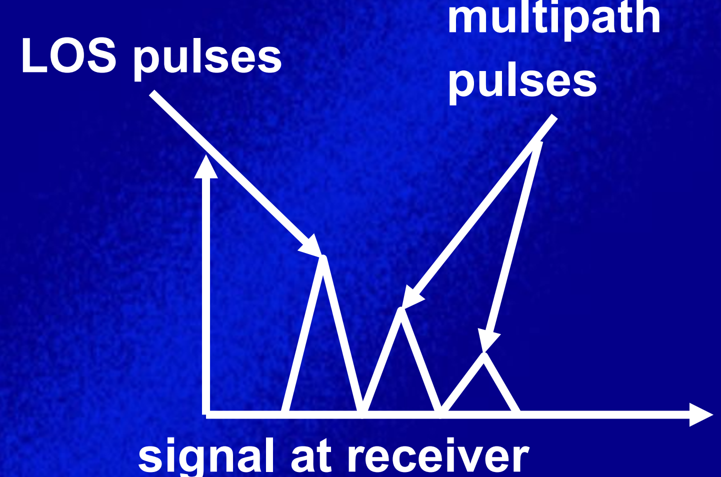
Non-line-of-sight

- 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



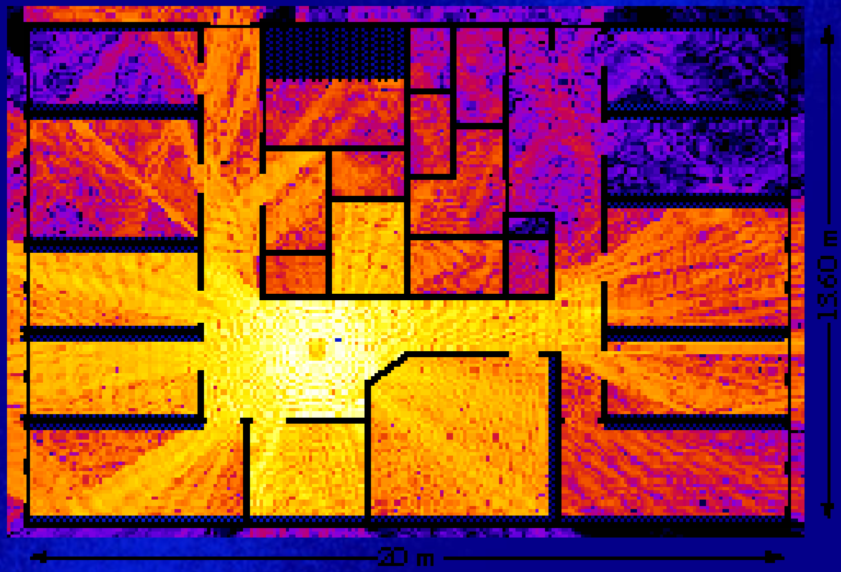
Non-line-of-sight

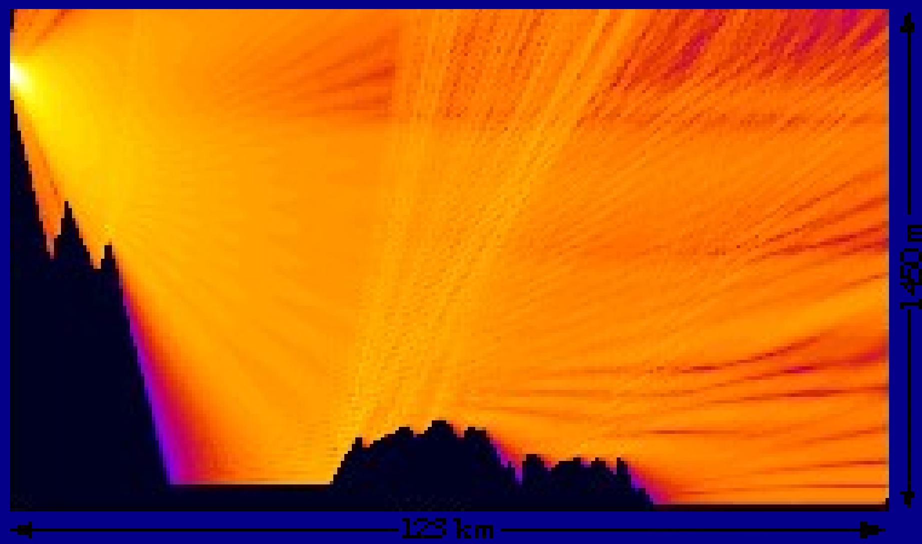
- Different paths have different lengths = propagation time
  - Results in *delay spread* of the wireless channel



Multi-path

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





Generalizing the Attenuation Formula

- To take into account stronger attenuation than only caused by distance (e.g., walls, …), use a larger exponent $\gamma > 2$
  - γ is the *path-loss exponent*

$$P_{\mathrm{recv}}(d) = P_{\mathrm{recv}}(d_0) \cdot \left(\frac{d_0}{d}\right)^{\gamma}$$

  - Rewrite in logarithmic form (in dB):

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

Generalizing the Attenuation Formula

- Obstacles, multi-path, etc?
- Experiments show can be represented by a random variable
  - Equivalent to multiplying with a lognormal distributed r.v. 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

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

Received Power

Transmit Power

Path loss

Path loss exponent

Log-normal Shadow fading

Overview

- Frequency bands
- Modulation
- Signal distortion – wireless channels
- *From waves to bits*
- Channel models
- Transceiver design

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

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 (SINR)***

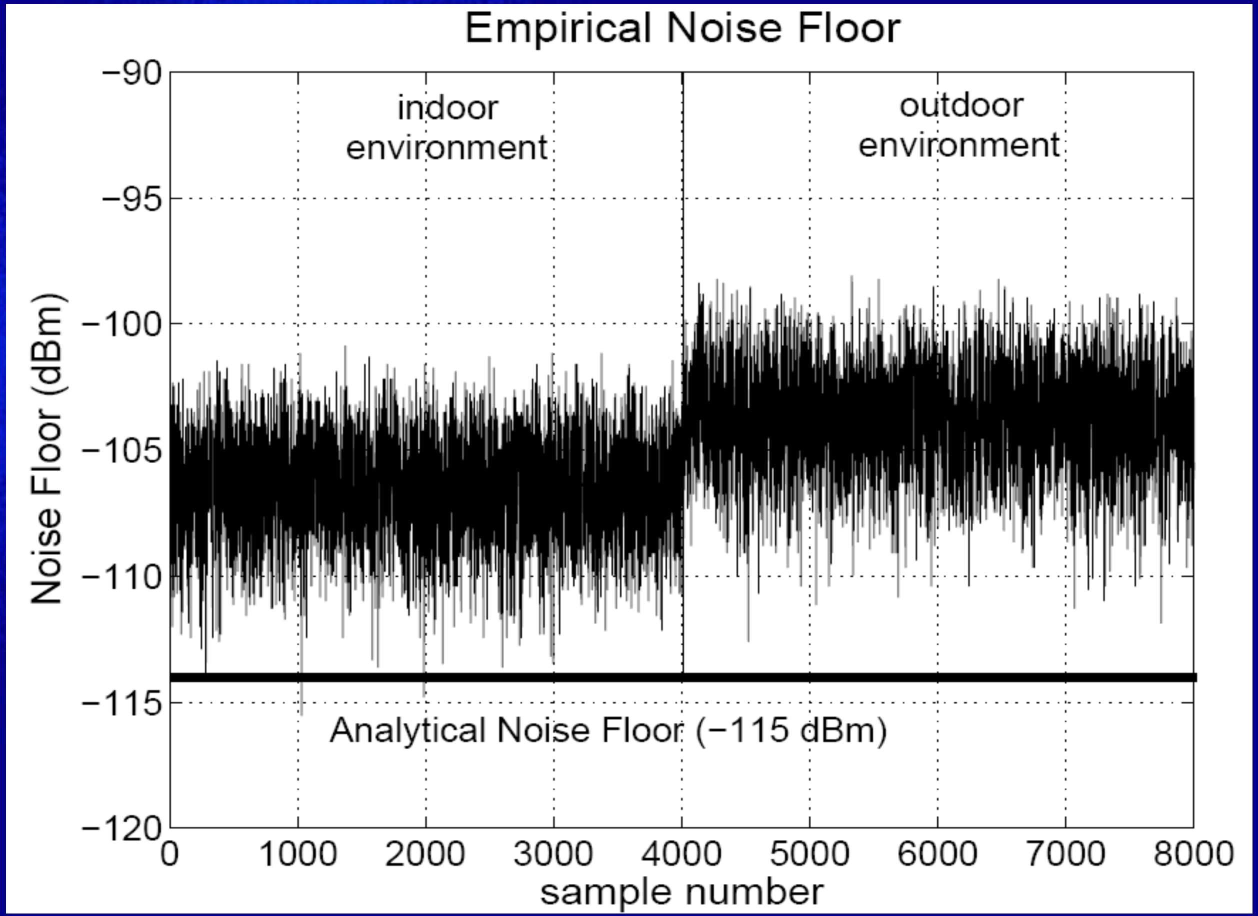
$$\mathrm{SINR} = 10\log_{10}\left(\frac{P_{\mathrm{recv}}}{N_0 + \sum_{i=1}^{k} I_i}\right)$$

Symbols and Bit Errors

- For WSN
  - Interference is usually low → MAC protocols
  - SINR ~ SNR
  - SNR = $P_r - P_n$ (in dB)
- P_n – Noise power (noise floor)

Noise Floor

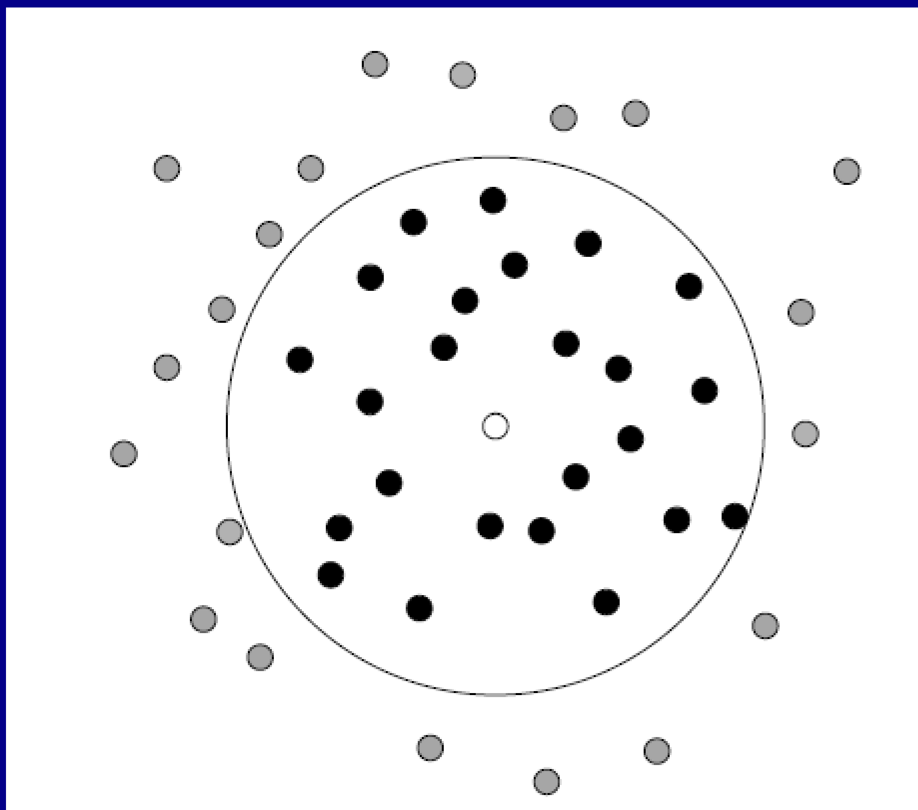
- Changes with time
- Varies according to location (indoor vs. outdoor)
- Even if received power is the same, SNR varies with time!

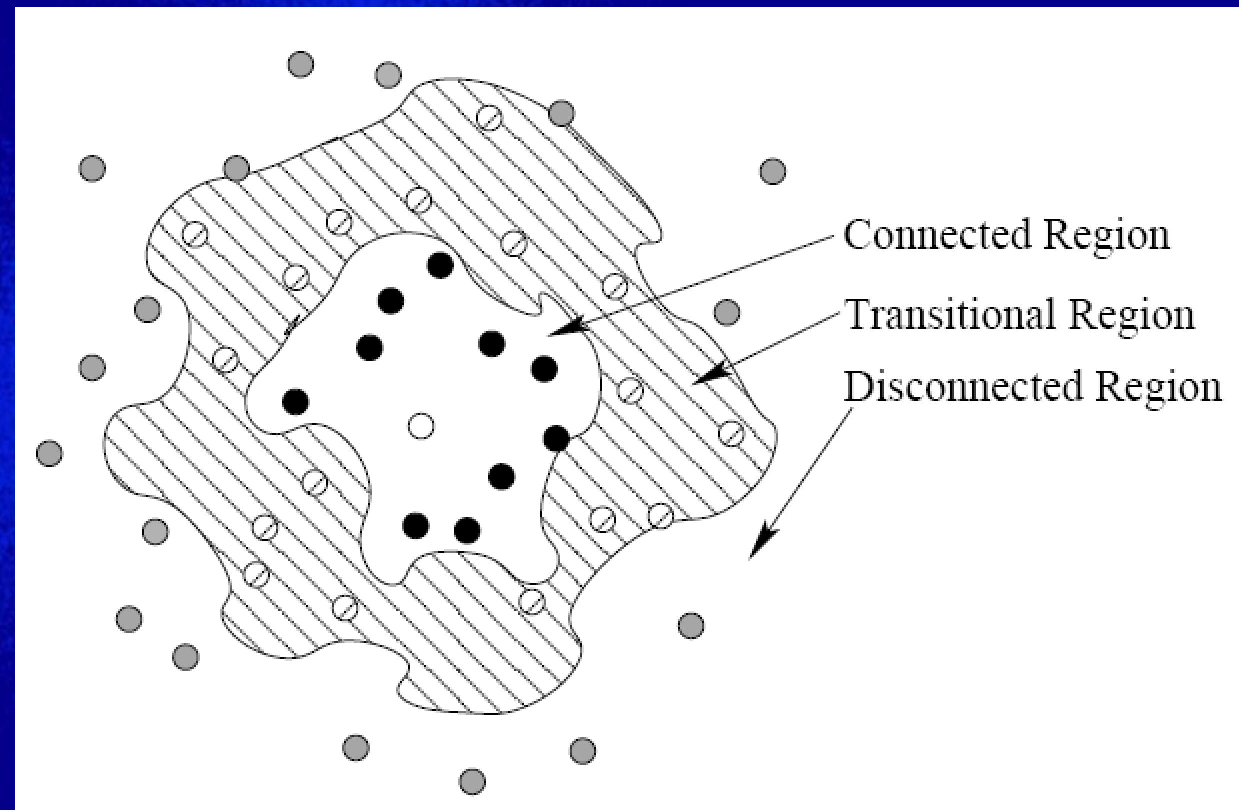


Bit Error Rate

- 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

Channel Models





Channel Models

- Main goal: Stochastically capture the behavior of a wireless channel
  - Main options: model the SNR or 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

- 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

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

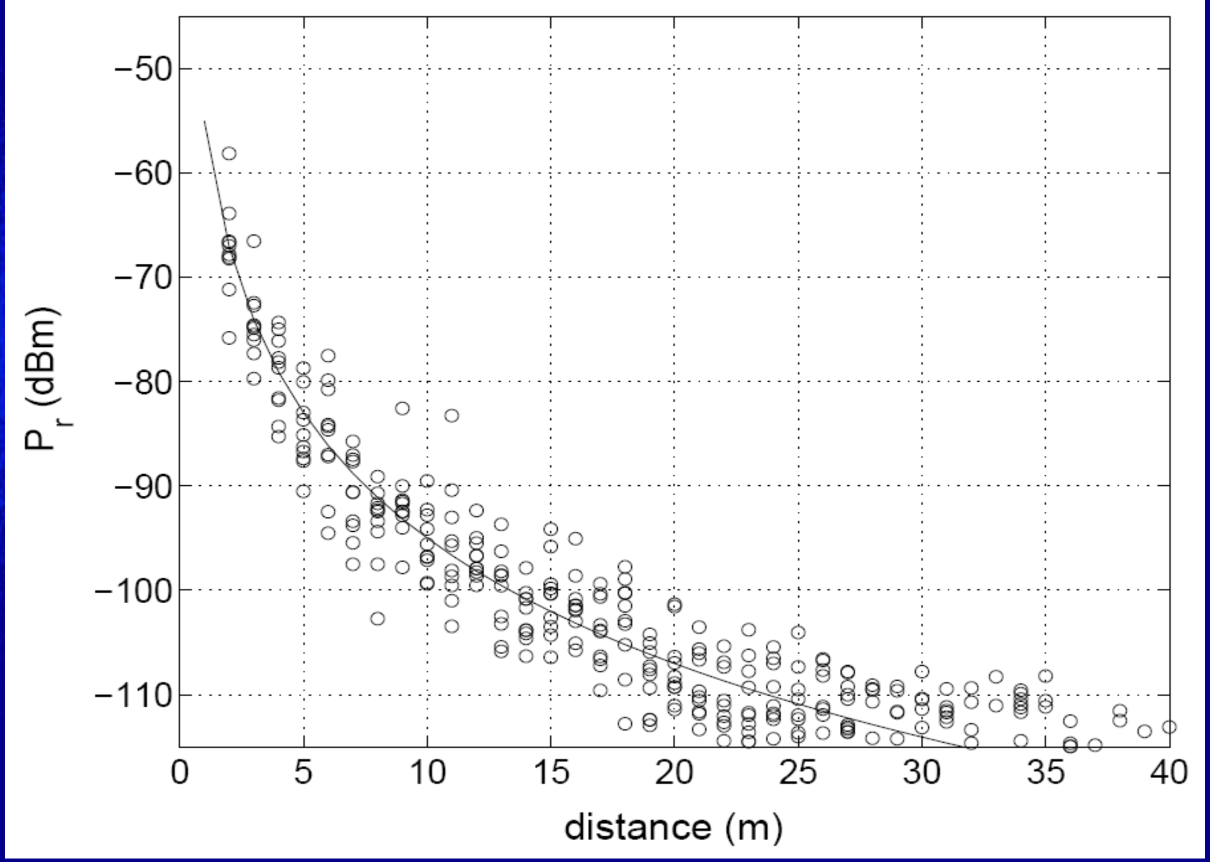
environment	γ (95% conf. bounds)	σ (95% conf. bounds)
outdoor	4.7 (4.30 - 5.10)	4.6 (2.80 - 6.40)
indoor	3.0 (2.67 - 3.23)	3.8 (2.60 - 5.00)

Channel Model for WSN

Marco Zuniga, Bhaskar Krishnamachari, "An Analysis of Unreliability and Asymmetry in Low-Power Wireless Links", ACM Transactions on Sensor Networks, Vol 3, No. 2, June 2007. (Conference version: "Analyzing the Transitional Region in Low Power Wireless Links", IEEE SECON 2004)

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

- Log-normal fading channel best characterizes WSN channels
- Empirical evaluations for Mica2



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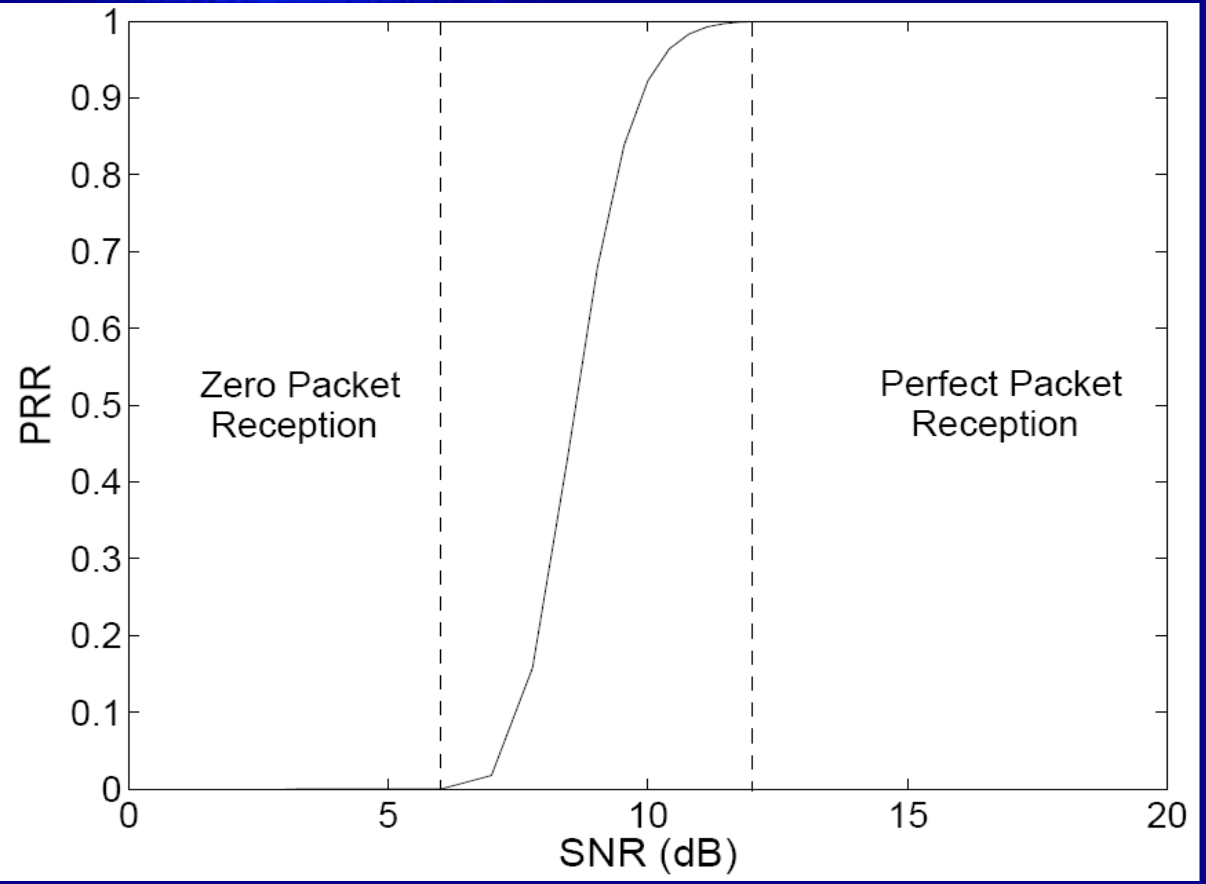
- PRR – Packet reception rate $(1\text{-}p_b)^k$
- Transitional region for packet reception
  - Not too good, not too bad



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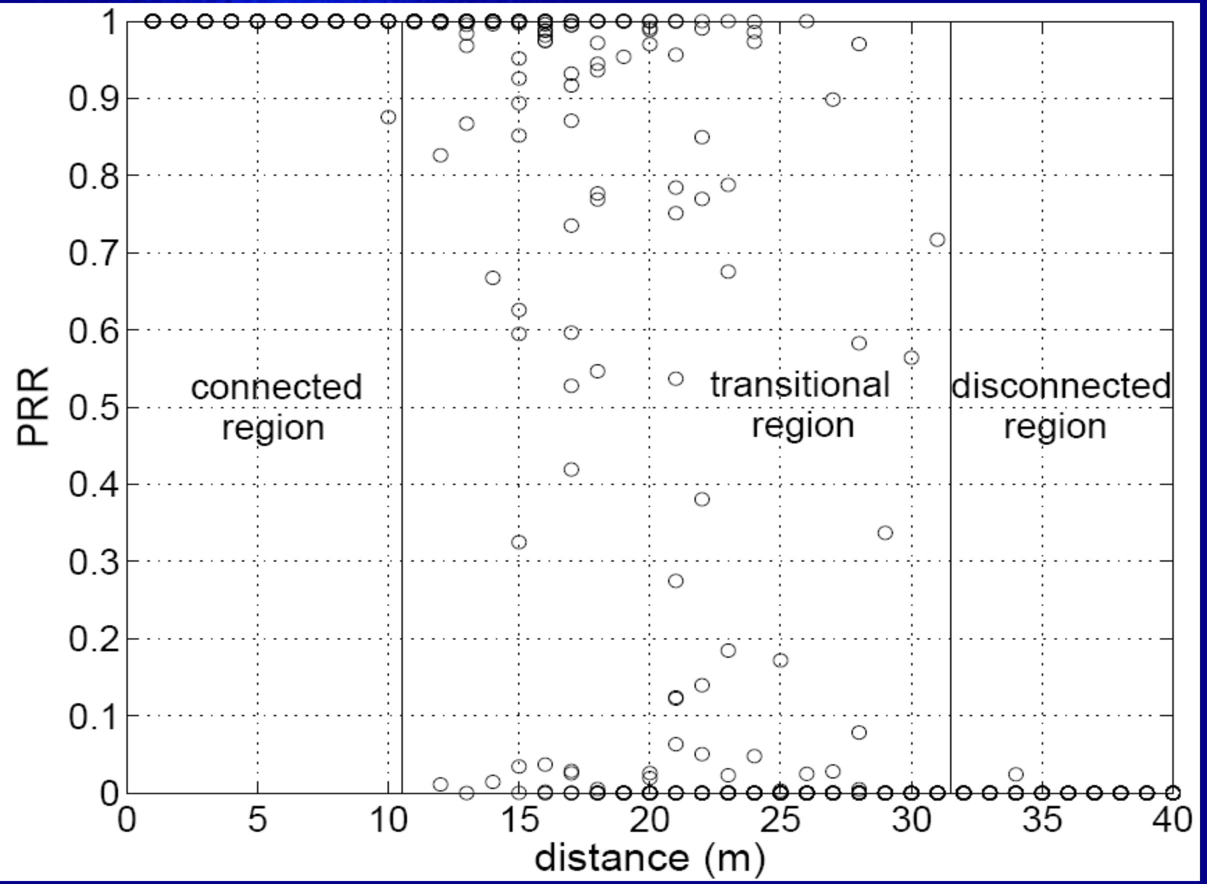
- PRR significantly varies in the transitional region
- d = 20m
  - PRR = [0,1]
- We cannot operate solely in the connected region
  - Communication distance too short



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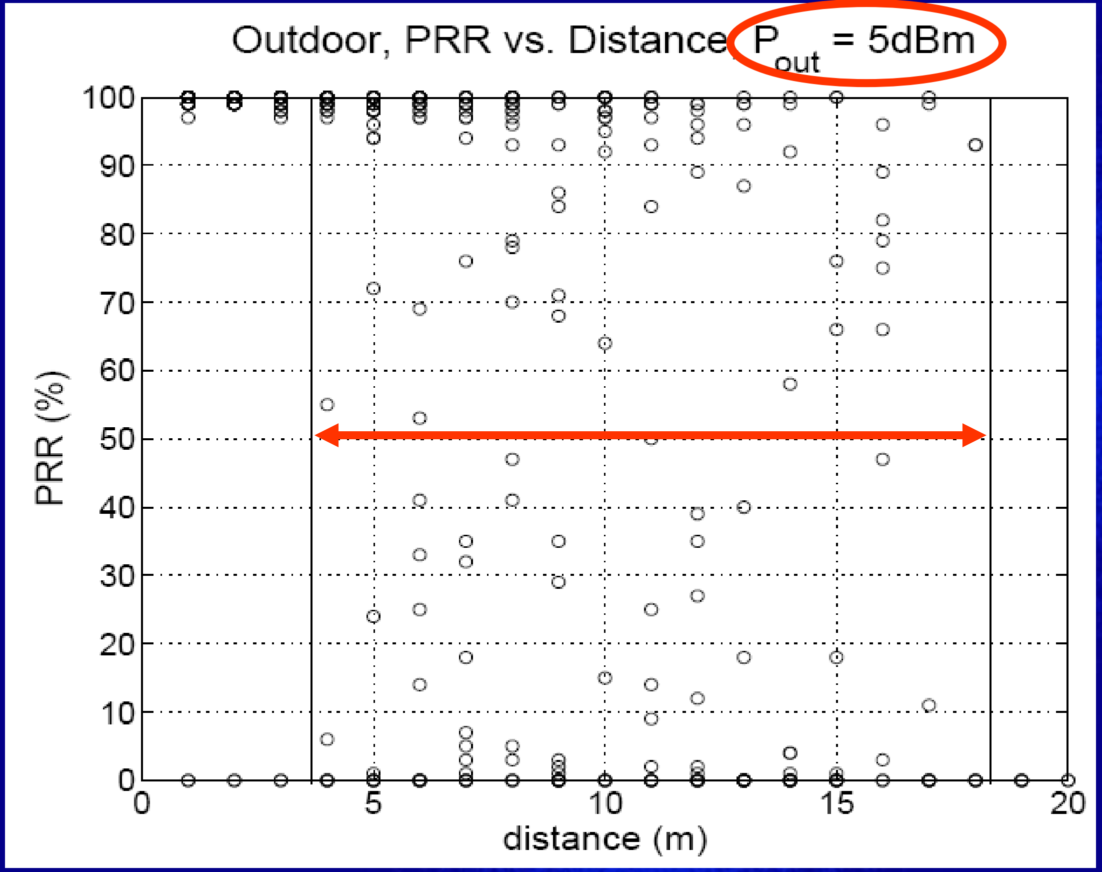

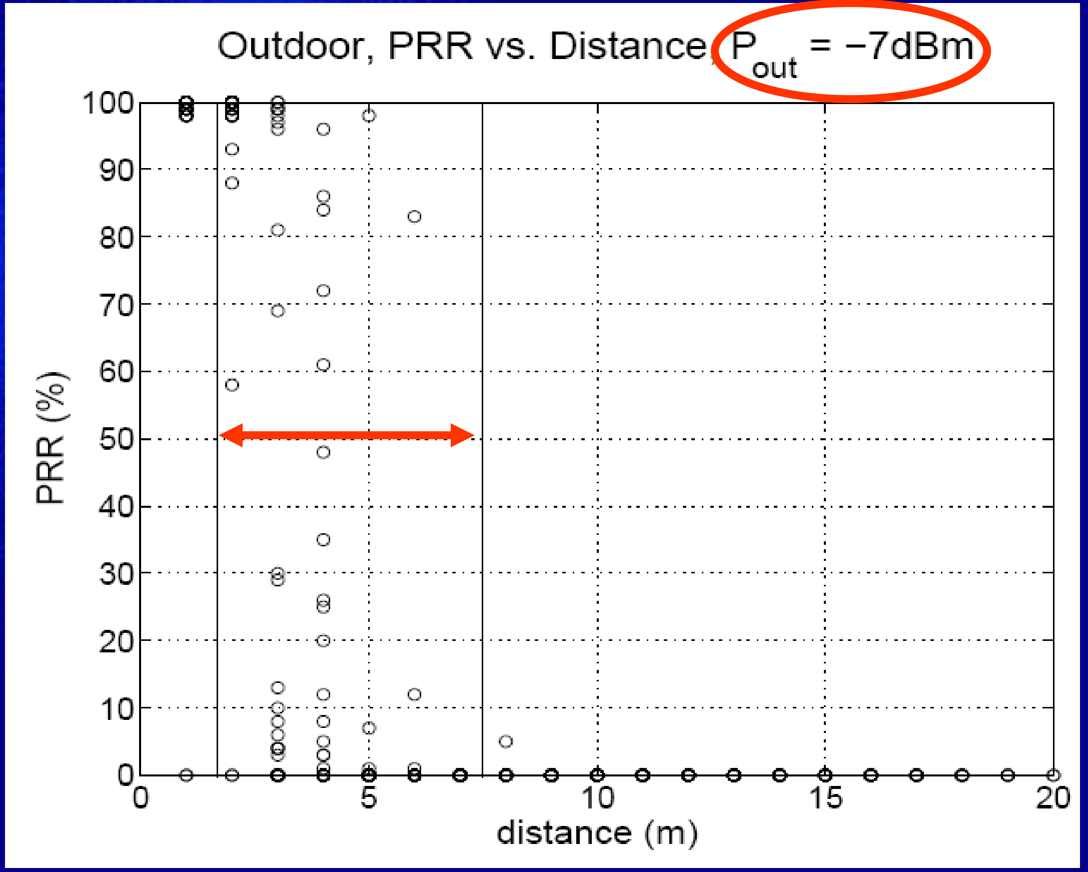

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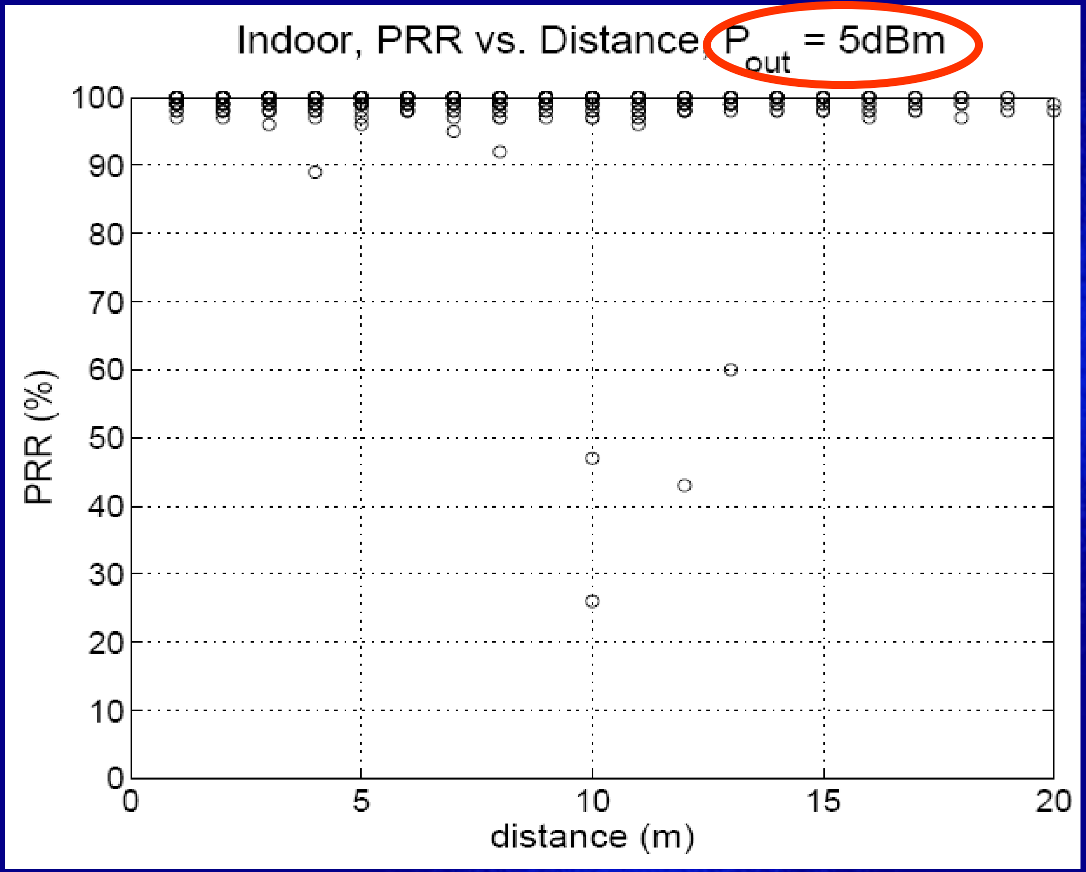
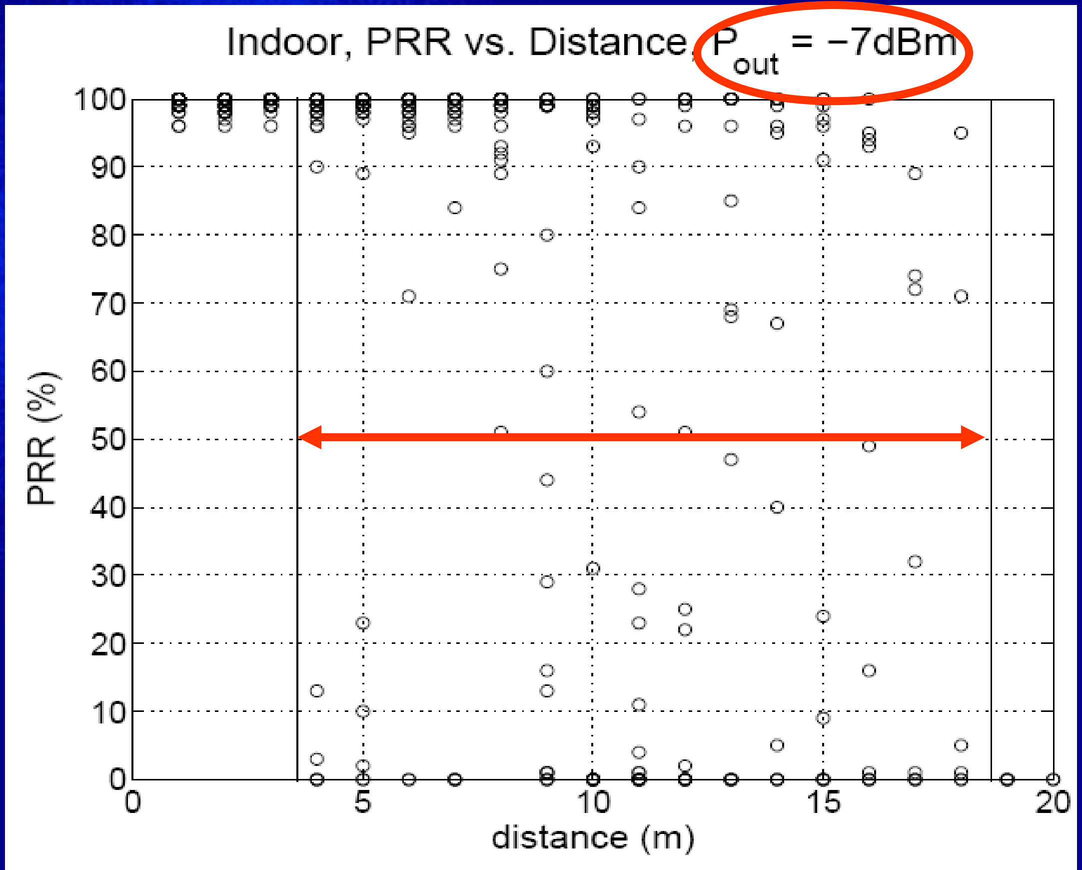
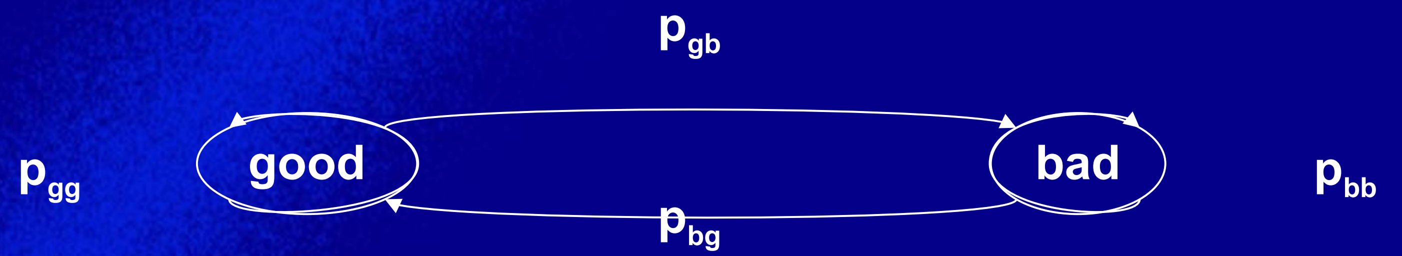




Channel Models – Digital

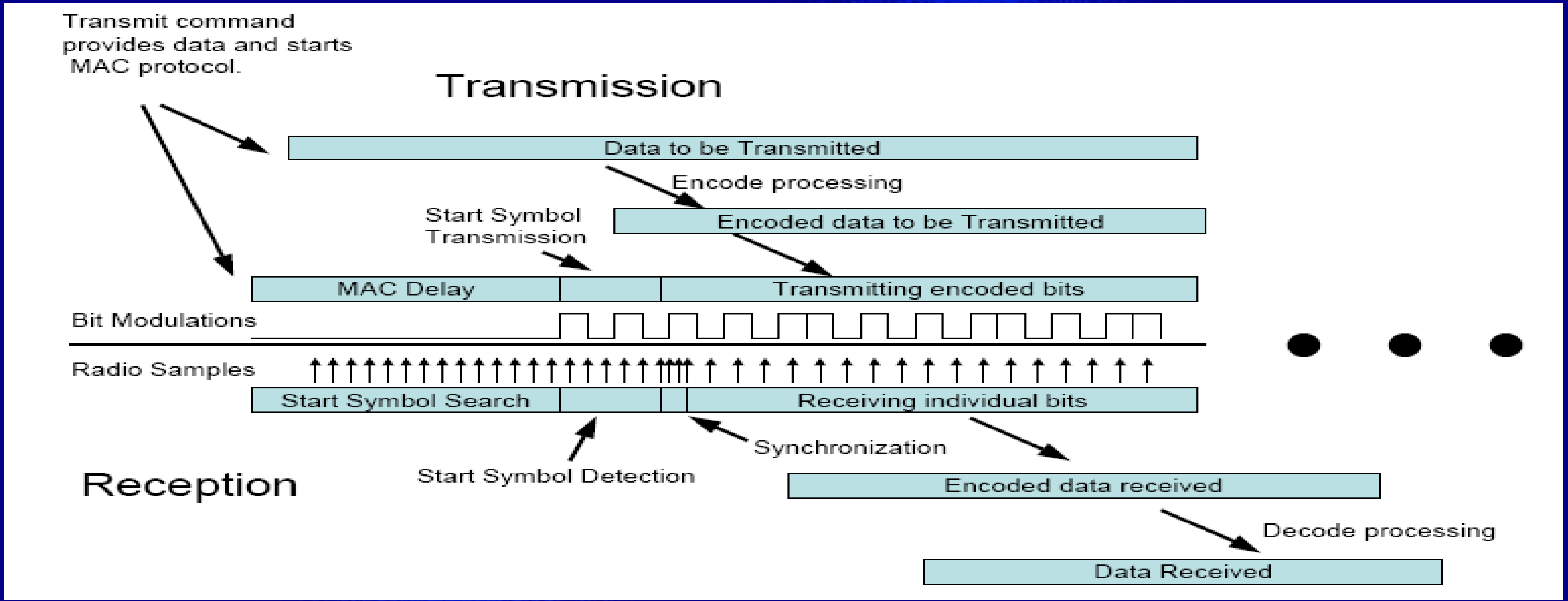
- Directly model the resulting bit error behavior (p_b)
- Each bit is erroneous with constant probability, independent of the other bits
  - *Binary symmetric channel (BSC)*
- Capture fading models' property that channel is in different states! Markov models – states with different BERs
  - Example: Gilbert-Elliot model with "bad" and "good" channel states and high/low bit error rates



Channel Models – Digital

- Fractal channel models describe number of (in-)correct bits in a row by a heavy-tailed distribution
  - Burst errors (bit errors are NOT independent)

Wireless Communication Basics



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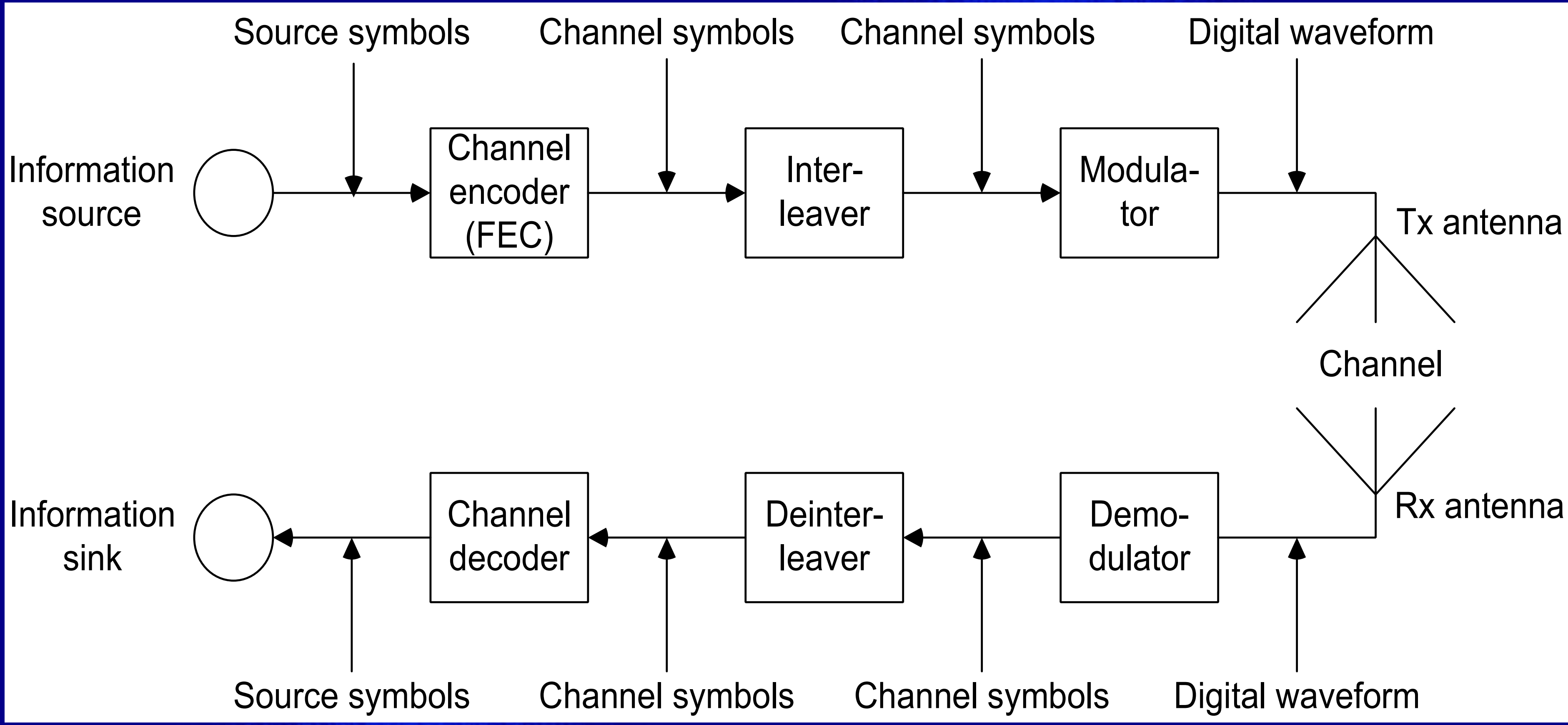


Wireless Communication Basics

- Frequency bands
- Modulation
- Signal distortion – wireless channels
- From waves to bits
- Channel models

Wireless Communication Basics

- *Frequency bands*
- **Modulation**
- Signal distortion – wireless channels
- From waves to bits
- Channel models

Radio spectrum for communication

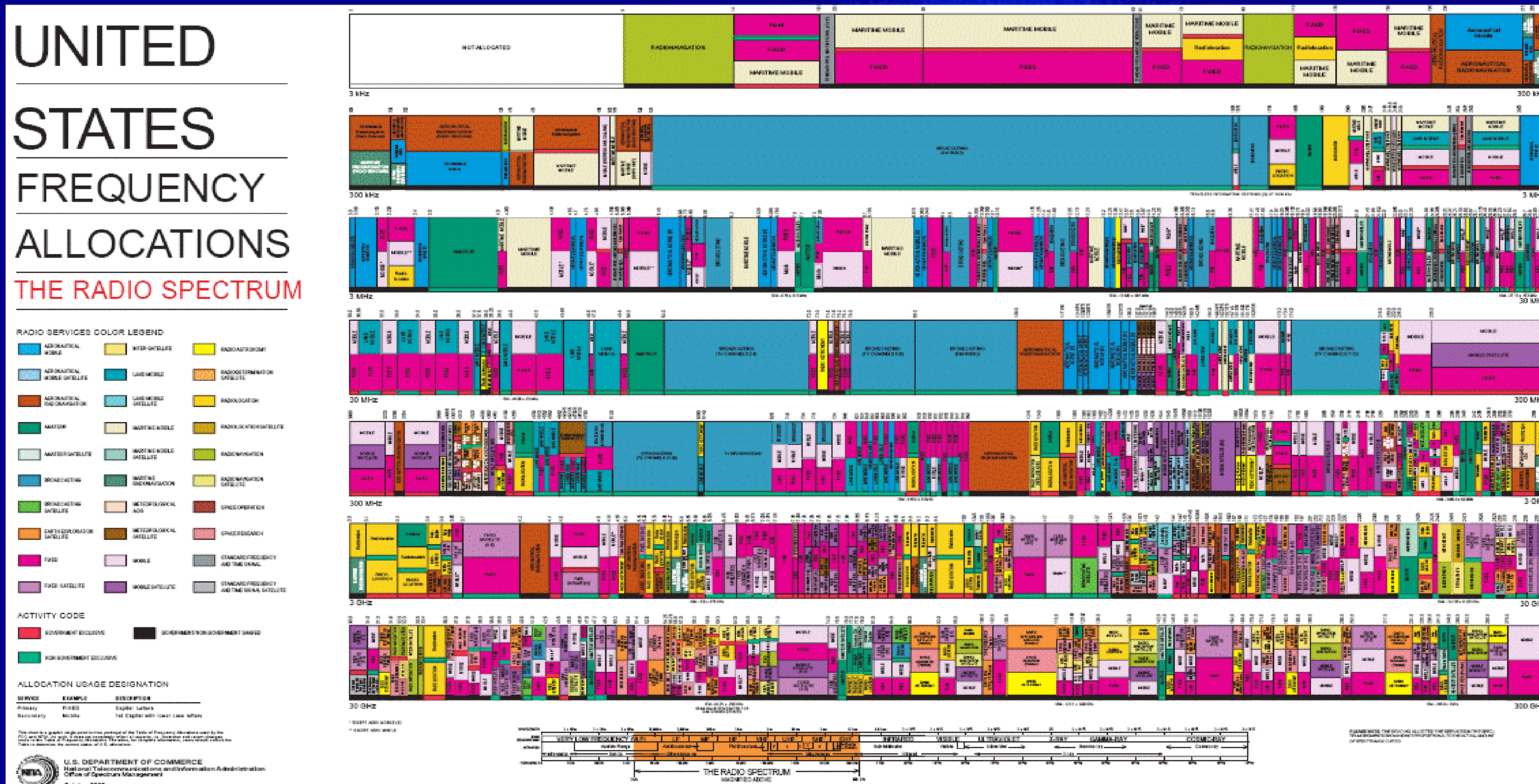
- Which part of the electromagnetic spectrum is used for communication
  - Not all frequencies are equally suitable for all tasks – e.g., wall penetration, different atmospheric attenuation (oxygen resonances, …)

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

- Frequency bands
- *Modulation*
- Signal distortion – wireless channels
- From waves to bits
- Channel models

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:

$$s(t) = A(t)\sin\left(2\pi f(t)t + \phi(t)\right)$$

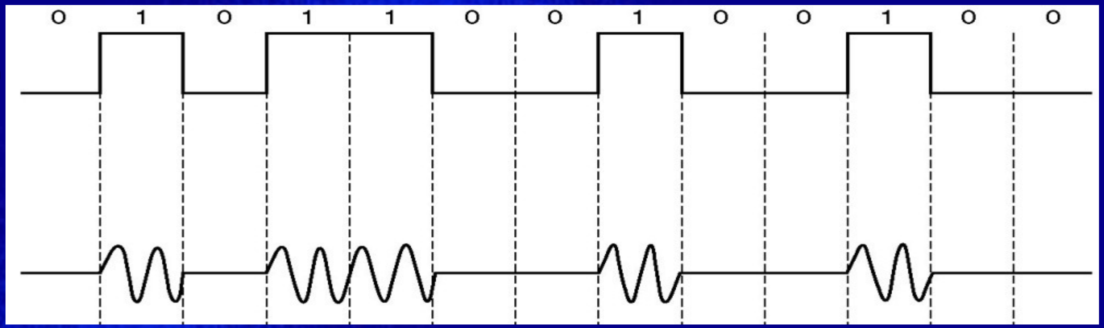
  - Parameters: amplitude A(t), frequency f(t), phase ϕ(t)
- Modulation: Manipulate these parameters

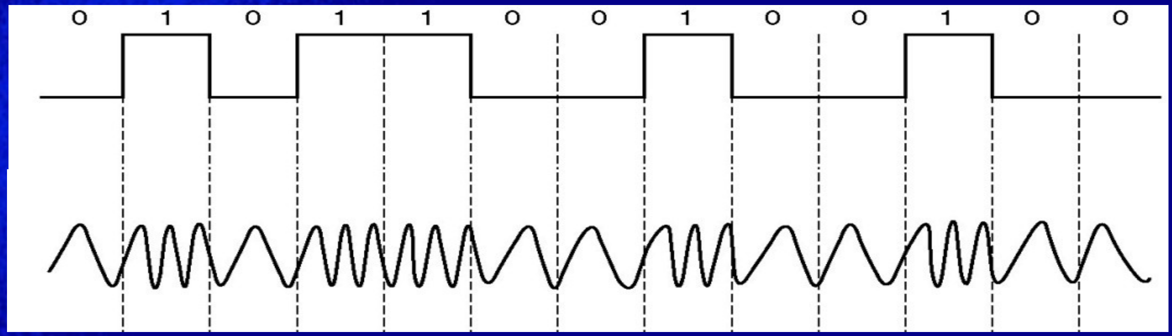
Modulation

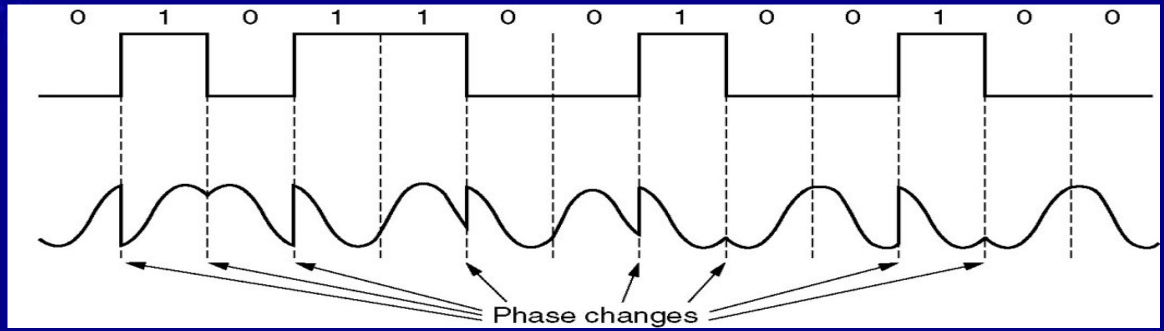
- Data to be transmitted is used to select transmission parameters as a function of time
- These parameters modify a basic sine wave, which serves as a starting point for ***modulating*** the signal onto it
- This basic sine wave has a ***center frequency*** f_c
- The resulting ***signal*** requires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

Modulation (Keying)

- Use data to modify
  - Amplitude - ***Amplitude Shift Keying (ASK)***
  - Frequency - ***Frequency Shift Keying (FSK)***
  - *Phase* - ***Phase Shift Keying (PSK)***







Receiver: Demodulation

- Receiver tries to match the received waveform with the tx'ed 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!

Bit Error Rate

- Mica2 nodes use **frequency shift keying (FSK)**

$$p_b^{FSK} = \frac{1}{2} e^{-\frac{Eb/No}{2}} \; ; Eb/No = SNR \frac{B_N}{R}$$

Bandwidth

Bit rate

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

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