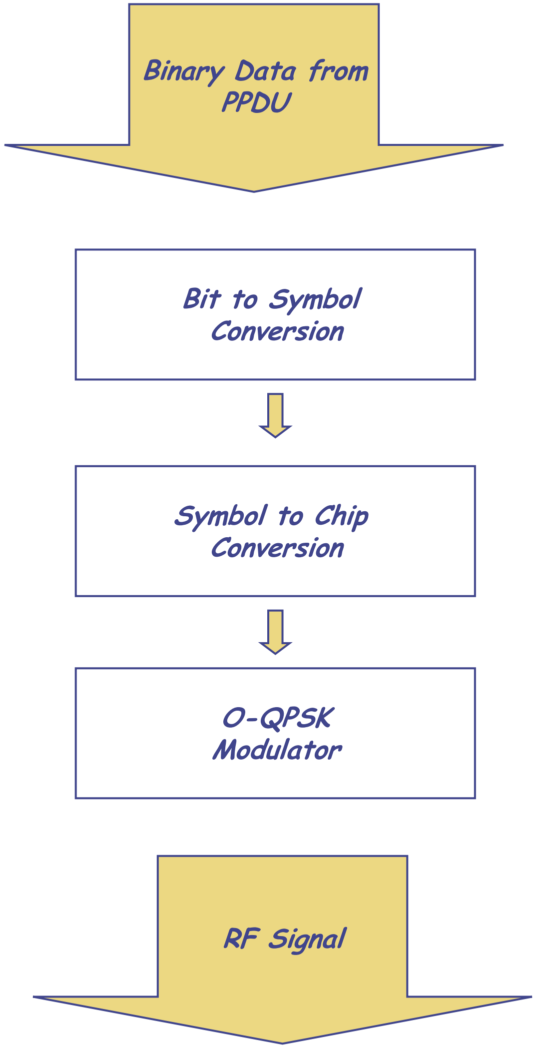
WSN :Physical Layer

Computer Networks Group
Universität Paderborn

Physical Layer Transmission Process



Binary Data from PPDU

Bit to Symbol Conversion

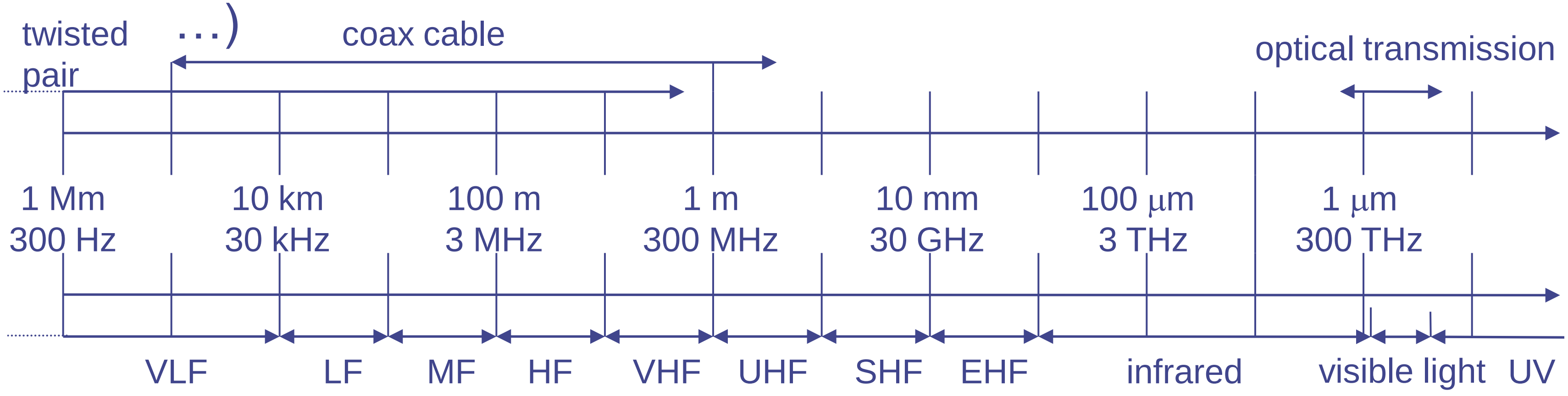
Symbol to Chip Conversion

O-QPSK Modulator

RF Signal

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, …)



- VLF = Very Low Frequency
- LF = Low Frequency
- MF = Medium Frequency
- HF = High Frequency
- VHF = Very High Frequency

UHF = Ultra High Frequency

SHF = Super High Frequency

EHF = Extra High Frequency

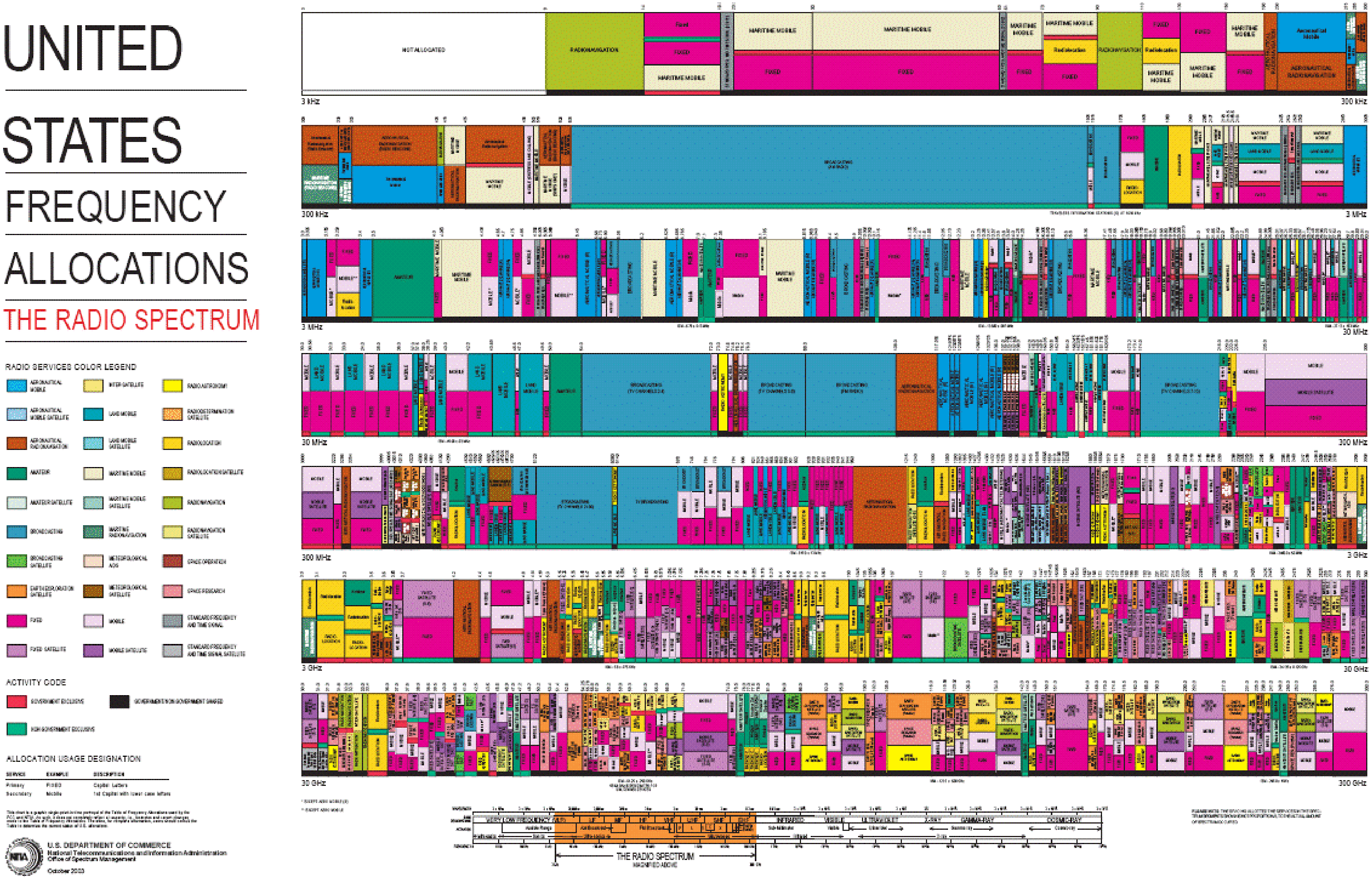
UV = Ultraviolet Light

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



Overview

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

Transmitting data using radio waves

- Basics: Transmit can send a radio wave, receive can detect whether such a wave is present and also its parameters
- Parameters of a wave = sine function:

$$s(t) = A(t)\,\mathsf{sin}(2\pi f(t)t + \phi(t))$$

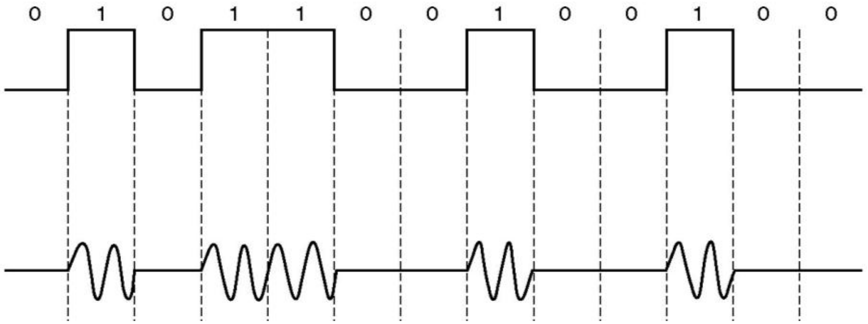
  - Parameters: amplitude $A(t)$, frequency $f(t)$, phase $\phi(t)$
- Manipulating these three parameters allows the sender to express data; receiver reconstructs data from signal
- Simplification: Receiver “sees” the same signal that the sender generated – not true, see later!

Modulation and keying

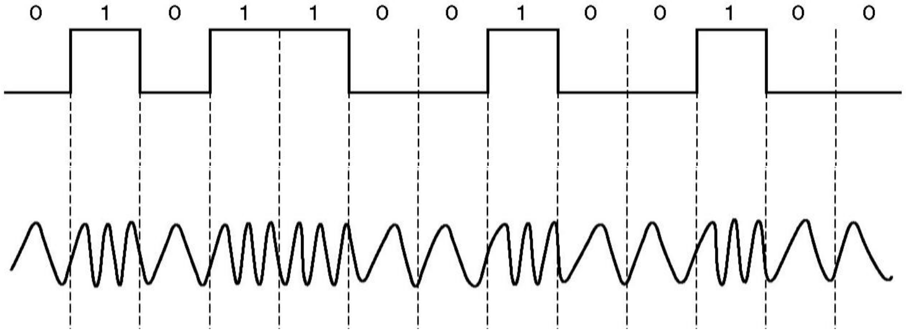
- How to manipulate a given signal parameter?
    - Set the parameter to an arbitrary value: ***analog modulation***
    - Choose parameter values from a finite set of legal values: ***digital keying***
    - Simplification: When the context is clear, ***modulation*** is used in either case
- Modulation?
    - Data to be transmitted is used 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

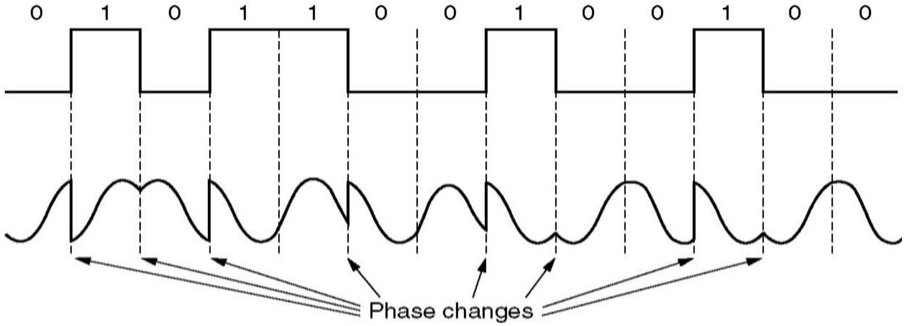
- Use data to modify the amplitude of a carrier frequency ! ***Amplitude Shift Keying***



- Use data to modify the ***frequency*** of a carrier frequency ! ***Frequency Shift Keying***



- Use data to modify the ***phase*** of a carrier frequency ! ***Phase Shift Keying***



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Receiver: Demodulation

- The receiver looks at the received wave form and matches it with the data bit that caused the transmitter to generate this wave form
  - Necessary: one-to-one mapping between data and wave form
  - Because of channel imperfections, this is at best possible for digital signals, but not for analog signals
- Problems caused by
  - Carrier synchronization: frequency can vary between sender and receiver (drift, temperature changes, aging, …)
  - Bit synchronization (actually: symbol 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!

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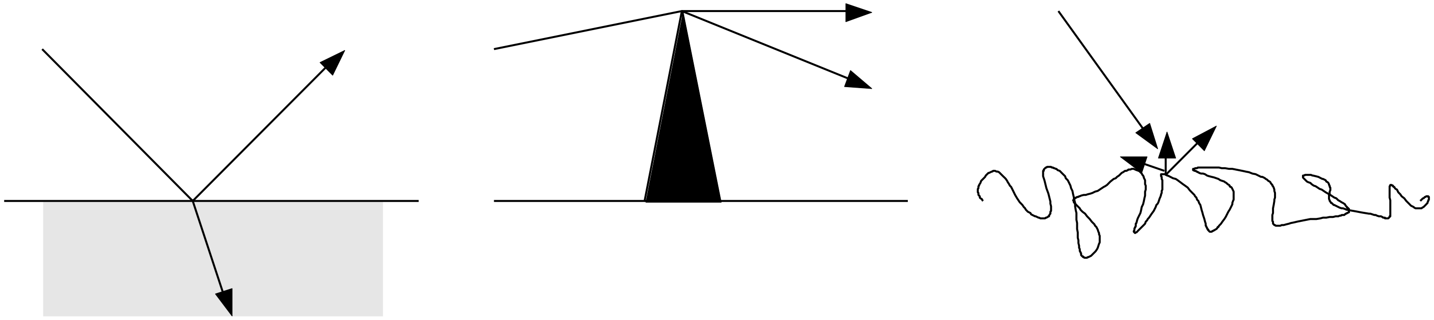
Transmitted signal <> received signal!

- Wireless transmission ***distorts*** any transmitted signal
  - Received <> transmitted signal; results in ***uncertainty at receiver*** about which bit sequence originally caused the transmitted signal
  - Abstraction: ***Wireless channel*** describes these distortion effects
- Sources of distortion
  - Attenuation – energy is distributed to larger areas with increasing distance
  - Reflection/refraction – bounce of a surface; enter material
  - Diffraction – start "new wave" from a sharp edge
  - Scattering – multiple reflections at rough surfaces
  - Doppler fading – shift in frequencies (loss of center)



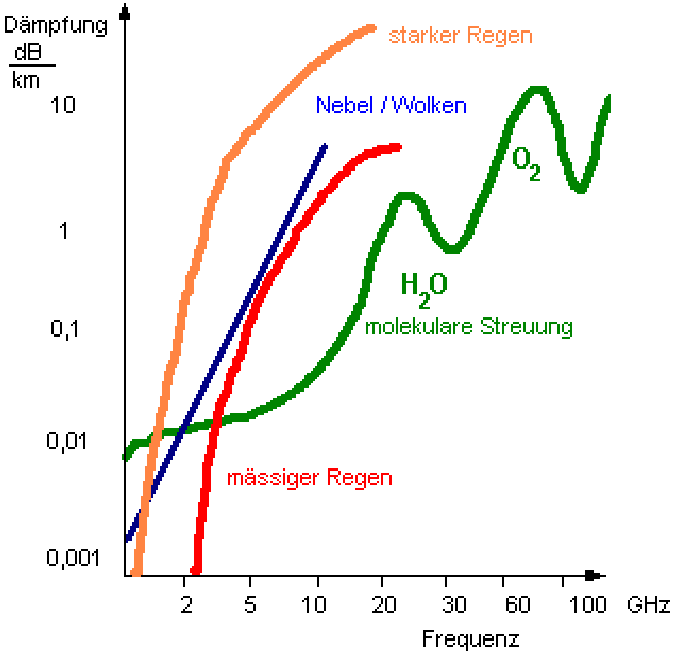
Attenuation results in path loss

- Effect of attenuation: received signal strength is a function of the distance *d* between sender and transmitter
- Captured by ***Friis free-space equation***
  - Describes 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

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

Suitability of different frequencies – Attenuation

- Attenuation depends on the used frequency
- Can result in a ***frequency-selective channel***
    - If bandwidth spans frequency ranges with different attenuation properties



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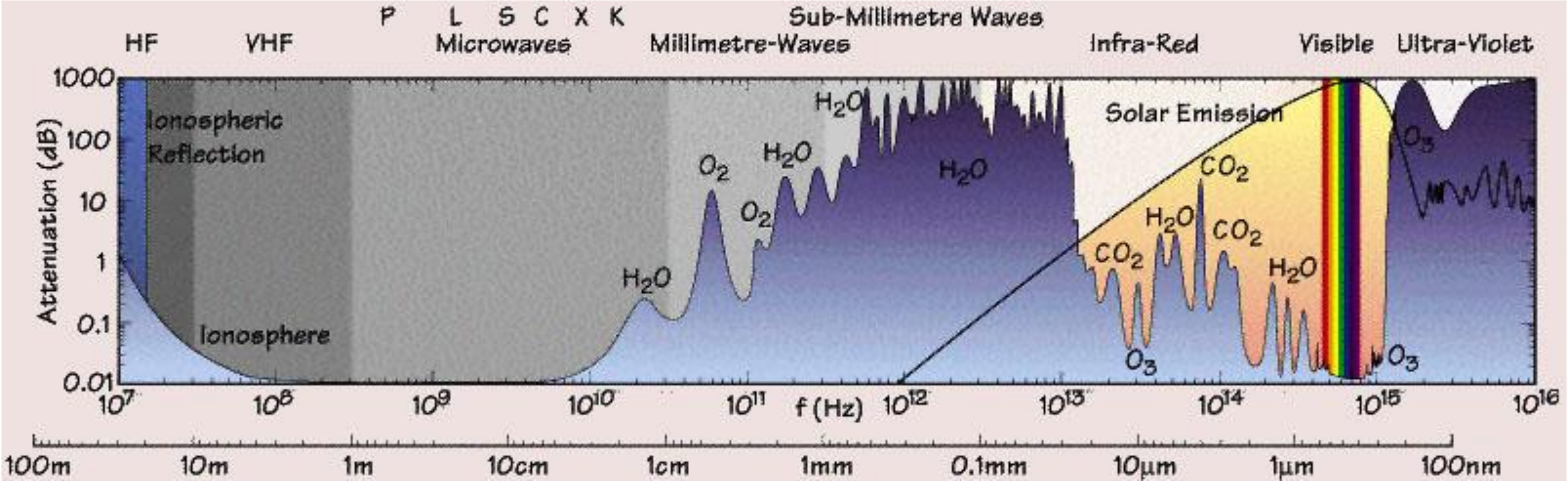

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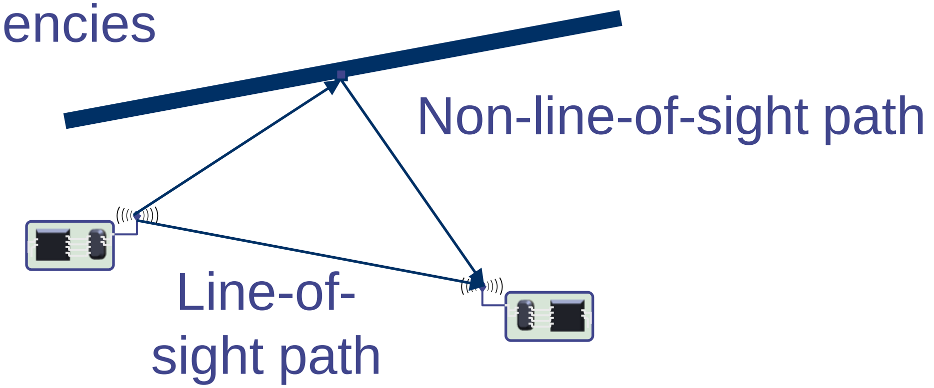
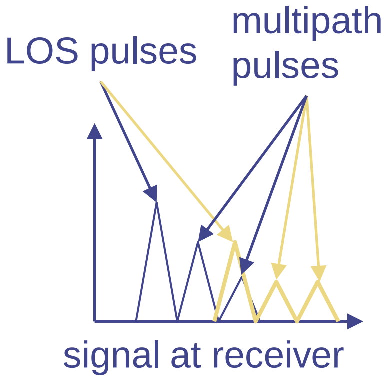
Distortion effects: Non-line-of-sight paths

- 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



- Different paths have different lengths = propagation time
  - Results in ***delay spread*** of the wireless channel
  - Closely related to frequency-selective fading properties of the channel
  - With movement: ***fast fading***



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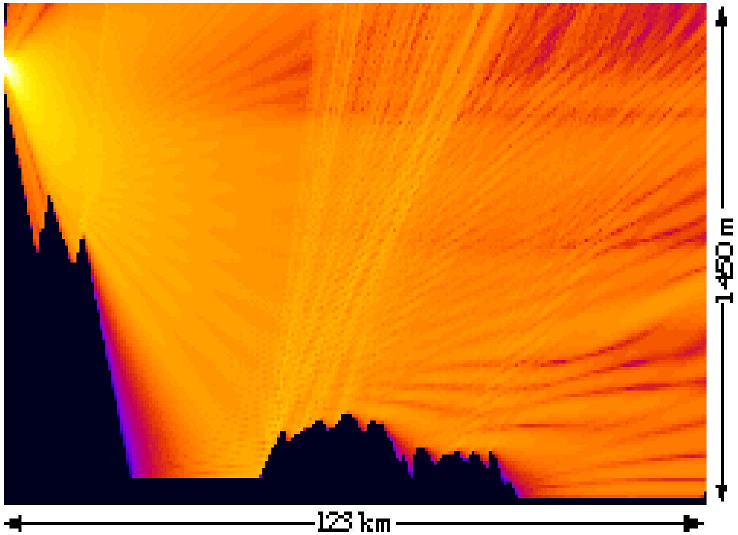
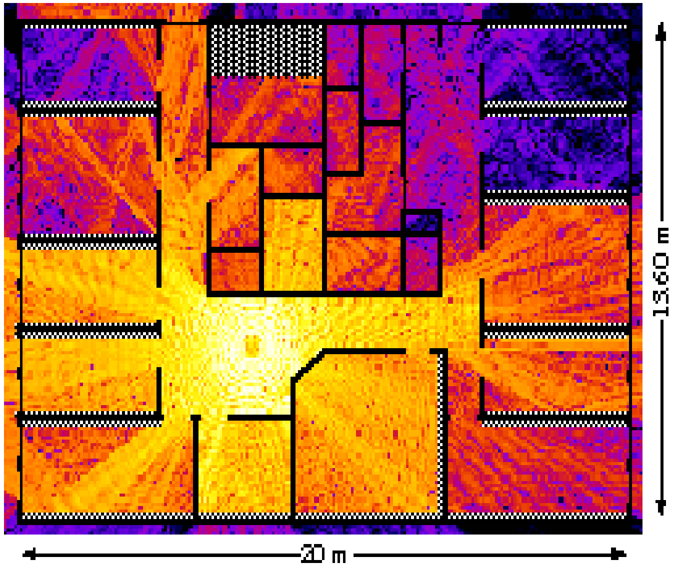
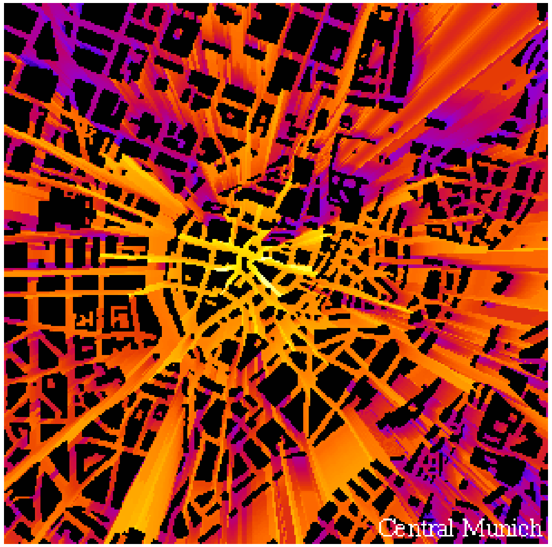
Wireless signal strength in a multi-path environment

- Brighter color = stronger signal
- Obviously, 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***

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

  - Rewrite in logarithmic form (in dB):

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

- Take obstacles into account by a random variation
  - Add a Gaussian random variable with 0 mean, variance σ^2 to dB representation
  - Equivalent to multiplying with a lognormal distributed r.v. in metric units ! ***lognormal fading***

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

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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
    - Typical model: an additive Gaussian variable, mean 0, no correlation in time
  - ***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
- Effect: Received signal is distorted by channel, corrupted by noise and interference
  - What is the result on the received bits?

Symbols and bit errors

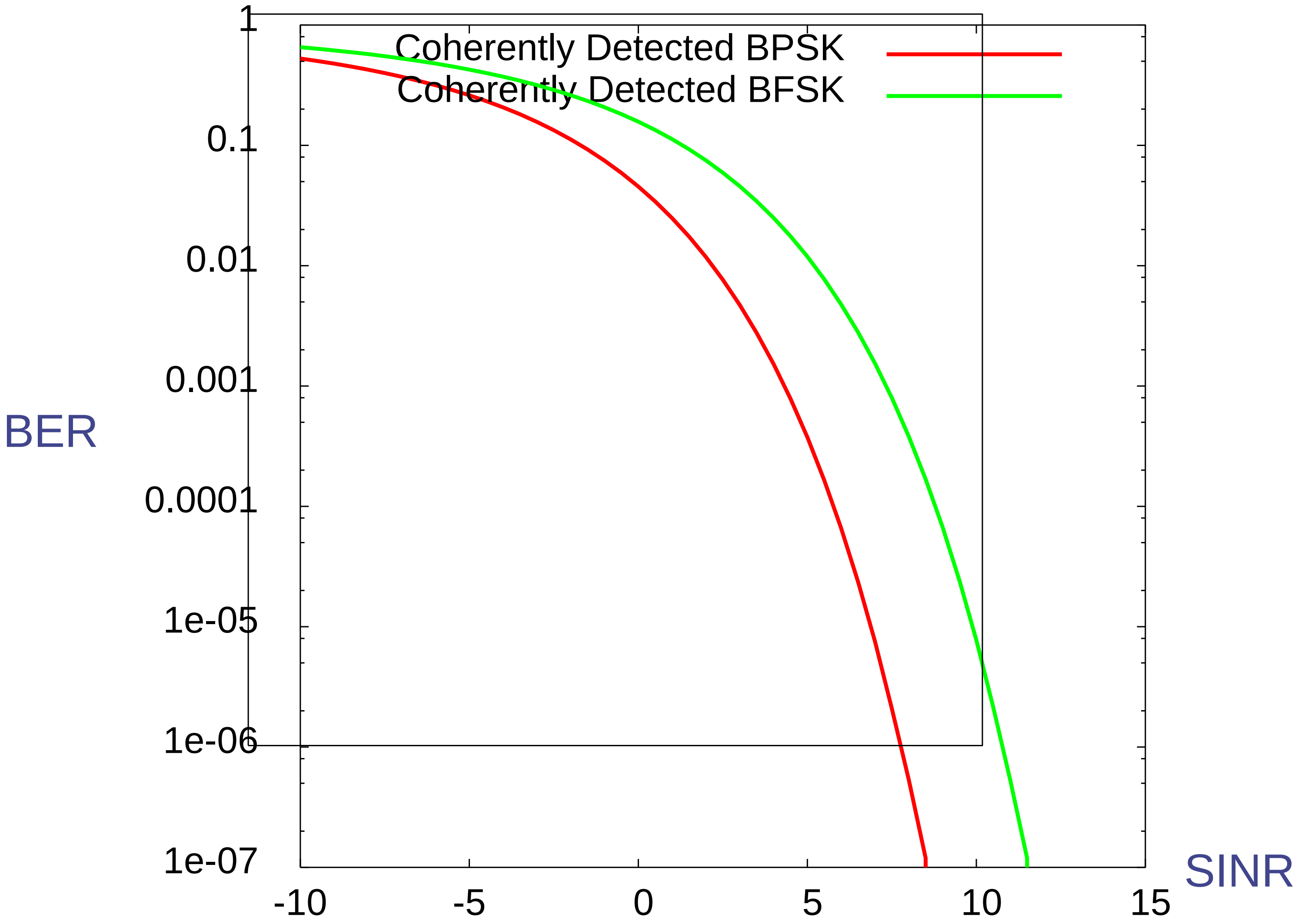
- Extracting symbols out of a distorted/corrupted wave form is fraught with errors
  - Depends essentially on strength of the received signal compared to the corruption
  - Captured by ***signal to noise and interference ratio (SINR)***

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

- SINR allows to compute ***bit error rate*** (***BER***) for a given modulation
  - Also depends on data rate (# bits/symbol) of modulation
  - E.g., for simple DPSK, data rate corresponding to bandwidth:

$$\mathrm{BER}(\mathrm{SINR}) = 0.5 e^{-\frac{E_b}{N_0}}$$
$$E_b/N_0 = \mathrm{SINR} \cdot \frac{1}{R}$$

Examples for SINR ! BER mappings



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Some transceiver design considerations

- Strive for good power efficiency at low transmission power
  - Some amplifiers are optimized for efficiency at high output power
  - To radiate 1 mW, typical designs need 30-100 mW to operate the transmitter
    - WSN nodes: 20 mW (mica motes)
  - Receiver can use as much or more power as transmitter at these power levels

    ! Sleep state is important
- Startup energy/time penalty can be high
  - Examples take 0.5 ms and ¼ 60 mW to wake up
- Exploit communication/computation tradeoffs
  - Might payoff to invest in rather complicated coding/compression schemes

Going from Watts to dBm

$$\mathrm{P(in\ dBm)} = 10\log\frac{\mathrm{P(in\ mW)}}{1\mathrm{mW}}$$

+20dBm=100mW

+10dBm=10mW

+7dBm=5mW

+6dBm = 4mW

+4dBm=2.5mW

+3dBm=2mW

0dBm=1mW

-3dBm=.5mW

-10dBm=.1mW

Friss Free Space Propagation Model

$$\frac{P_R}{P_T} = G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2 = G_T G_R \left(\frac{c}{4\pi d}\right)^2$$

P_T and P_R power values at the receiving and transmitting antennas (in watts)

G_T and G_R are the power gains for the transmitting and receiving antenna

λ - wavelength in meters

c - speed of light

d - distance between receiver and transmitter

Same formula in dB path loss form (with Gain constants filled in):

$$L_B(dB) = 32.44 + 20\log_{10} f_{MHz} + 20\log_{10} d_{km}$$

How much is the range for a 0dBm transmitter 2.4 GHz band transmitter and pathloss of 92dBm?

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G_T and G_R are the power gains for the transmitting and receiving antenna

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d - distance between receiver and transmitter

Highly idealized model. It assumes:

- *Free space, Isotropic antennas*
- *Perfect power match & no interference*
- *Represent the theoretical max transmission range*

Same formula in dB path loss form (with Gain constants filled in):

$$L_B(dB) = 32.44 + 20\log_{10} f_{MHz} + 20\log_{10} d_{km}$$

How much is the range for a 0dBm transmitter 2.4 GHz band transmitter and pathloss of 92dBm?

A more realistic model: Log-Normal Shadowing Model

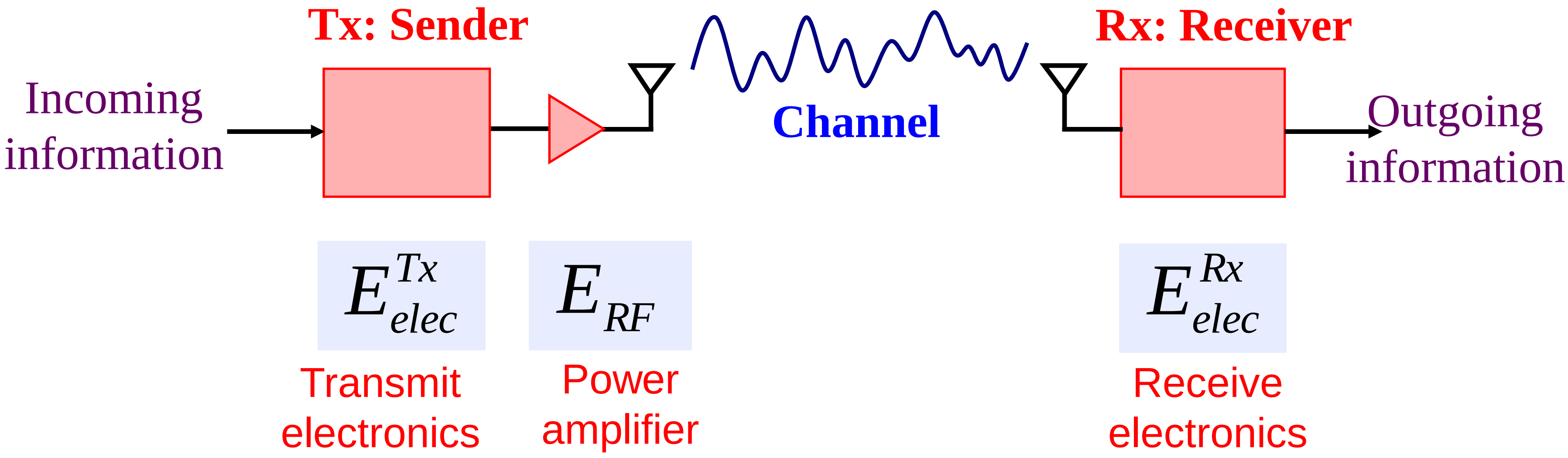
- Model typically derived from measurements

$$L_B(dB) = 32.44 + 10n\log_{10} f_{MHz} + 10n\log_{10} d_{km} + X_\sigma$$

X_σ is zero-mean Gaussian r.v (in dB) with standard deviation σ (in dB)

- Statistically describes random shadowing effects
  - values of n and σ are computed from measured data using linear regression
- Log normal model found to be valid in indoor environments!!!

Radio Energy Model: the Deeper Story….



Tx: Sender

Incoming information

Channel

Rx: Receiver

Outgoing information

E^{Tx}_{elec} Transmit electronics

E_{RF} Power amplifier

E^{Rx}_{elec} Receive electronics

- Wireless communication subsystem consists of three components with substantially different characteristics
- Their relative importance depends on the **transmission range** of the radio

Radio Energy Cost for Transmitting 1-bit of Information in a Packet

The choice of modulation scheme is important for energy vs. fidelity and energy tradeoff

$$E_{bit} = \frac{E_{start}}{L} + \frac{P_{elec} + P_{RF}(M)}{R_S * \log_2 M} * \left(1 + \frac{H}{L}\right)$$

$$E_{start} = \text{energy asssociated with radio startup}$$

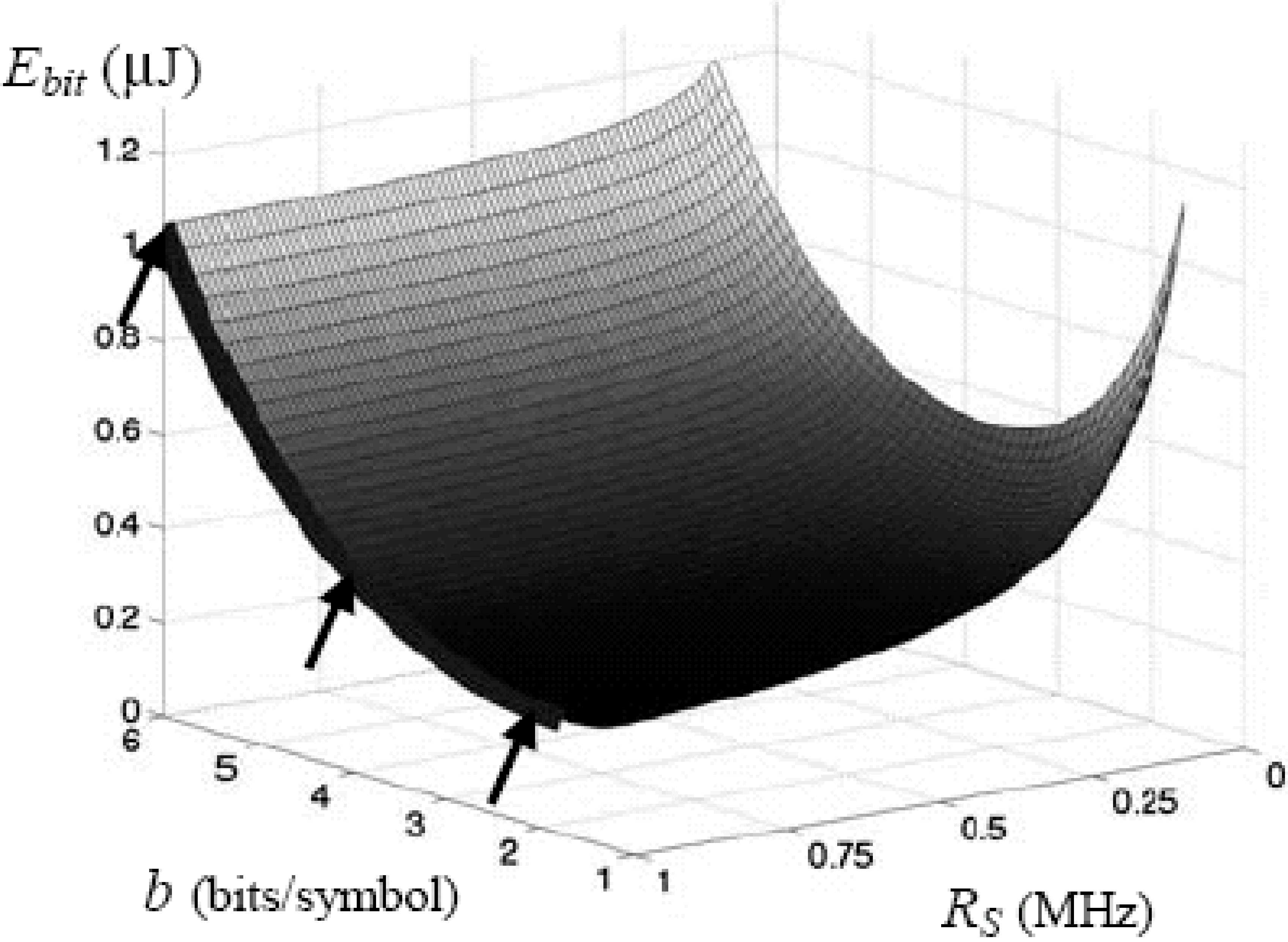
$$L = \text{packet payload length}$$

$$H = \text{packet header length}$$

$$P_{elec} = \text{power consumption of electronic circuitry}$$
$$\text{for frequency synthesis}$$

$$R_s = \text{Symbol rate for an M-ary modulation scheme}$$

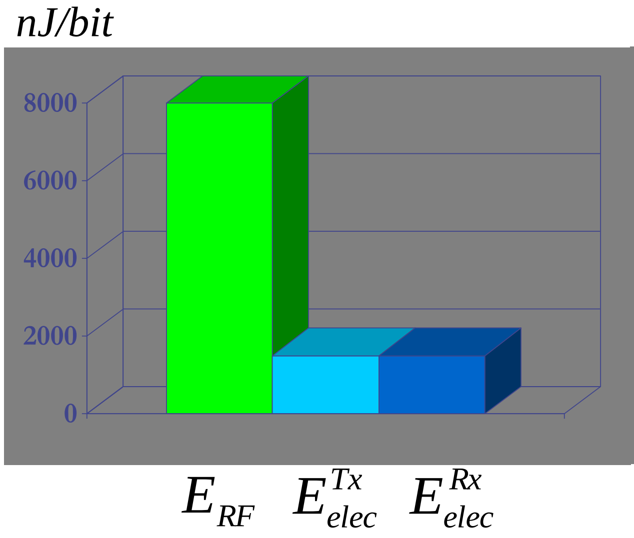
$$M = \text{Modulation level}$$



E_{bit} (μJ)
1.2
1
0.8
0.6
0.4
0.2
0
6
5
4
3
2
1
b (bits/symbol)
1
0.75
0.5
0.25
0
R_S (MHz)

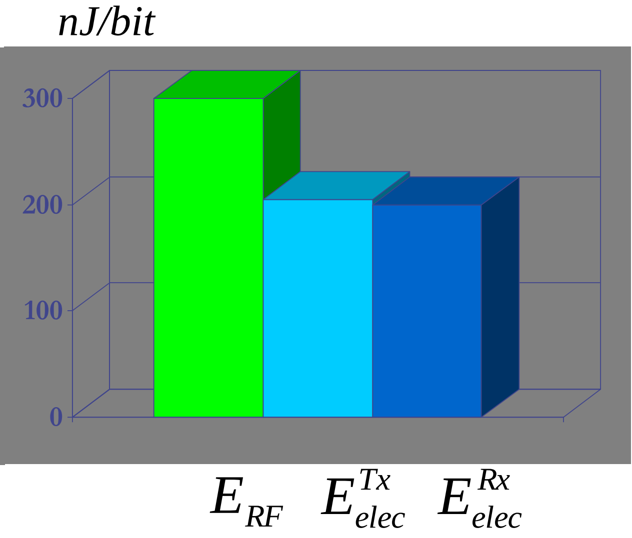
Examples

GSM



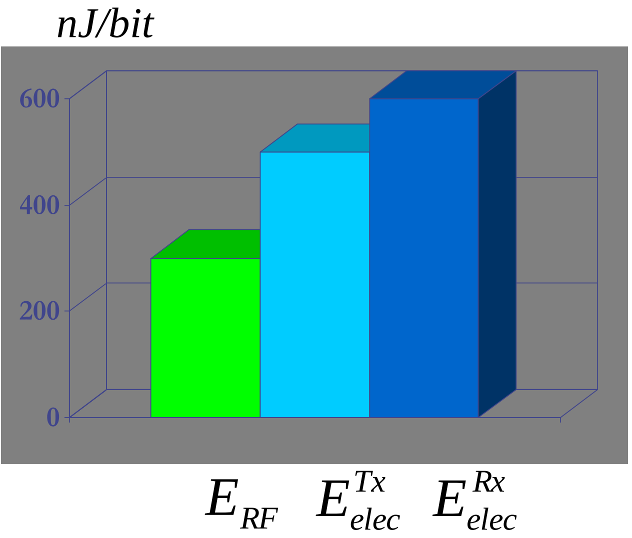
~ 1 km

Nokia C021 Wireless LAN



~ 50 m

Medusa Sensor Node (UCLA)



~ 10 m

- The RF energy increases with transmission range
- The electronics energy for transmit and receive are typically comparable

Where Does The Power Go?