Ad hoc and Sensor Networks
Chapter 4: Physical layer

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Goals of this chapter

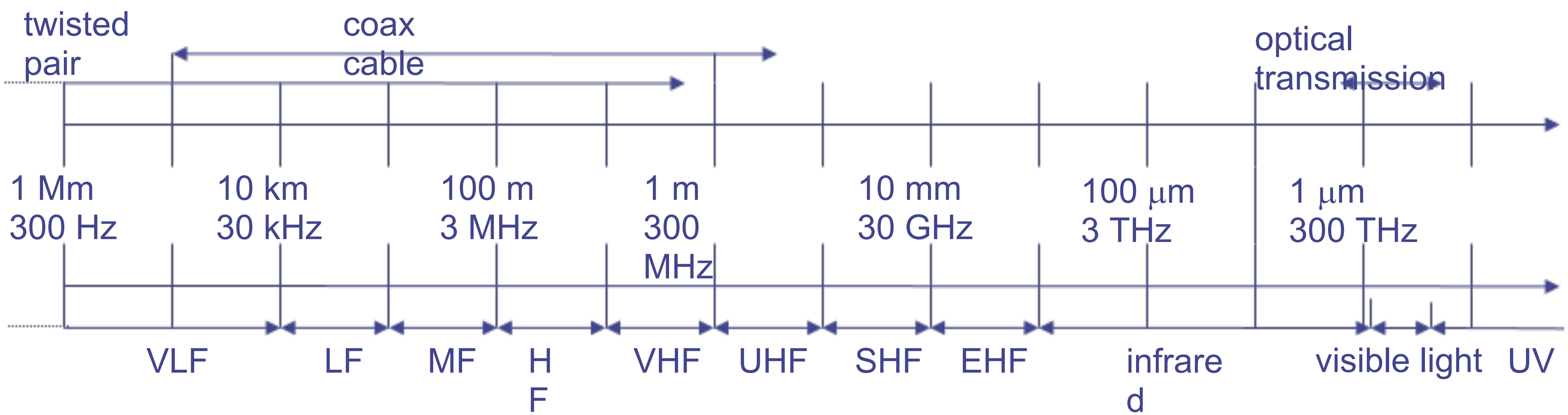
- Get an understanding of the peculiarities of wireless communication
  - "Wireless channel" as abstraction of these properties – e.g., bit error patterns
  - Focus is on radio communication
- Impact of different factors on communication performance
  - Frequency band, transmission power, modulation scheme, etc.
- Understanding of energy consumption for radio communication
- Here, differences between ad hoc and sensor networks mostly in the required performance
  - Larger bandwidth/sophisticated modulation for higher data rate/range

Overview

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

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, …)



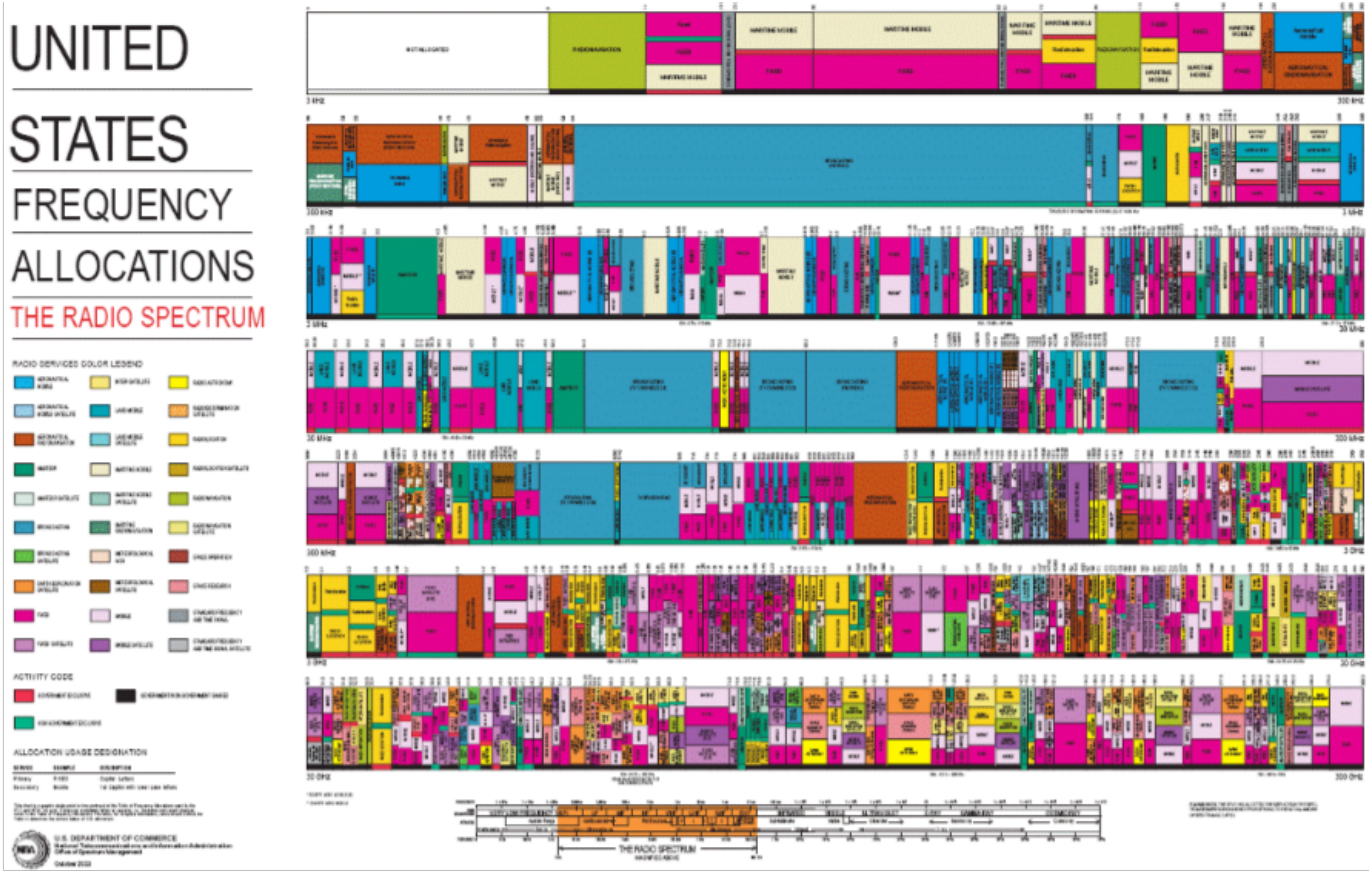
- VLF = Very Low Frequency UHF = Ultra High Frequency
- LF = Low Frequency SHF = Super High Frequency
- MF = Medium Frequency EHF = Extra High Frequency
- HF = High Frequency UV = Ultraviolet Light
- VHF = Very High Frequency

Frequency allocation

- Some frequencies are allocated to specific uses
  - Cellular phones, analog television/radio broadcasting, 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



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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:

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

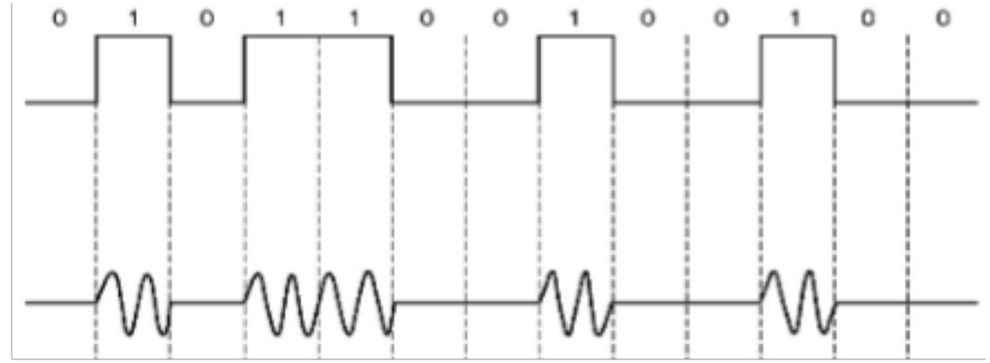
- Parameters: amplitude $A(t)$, frequency $f(t)$, phase $\varphi(t)$
- Manipulating these three parameters allows the sender to express data; receiver reconstructs data from signal
- Simplification: Receiver "sees" the same signal that the sender generated – not true, see later!

Modulation and keying

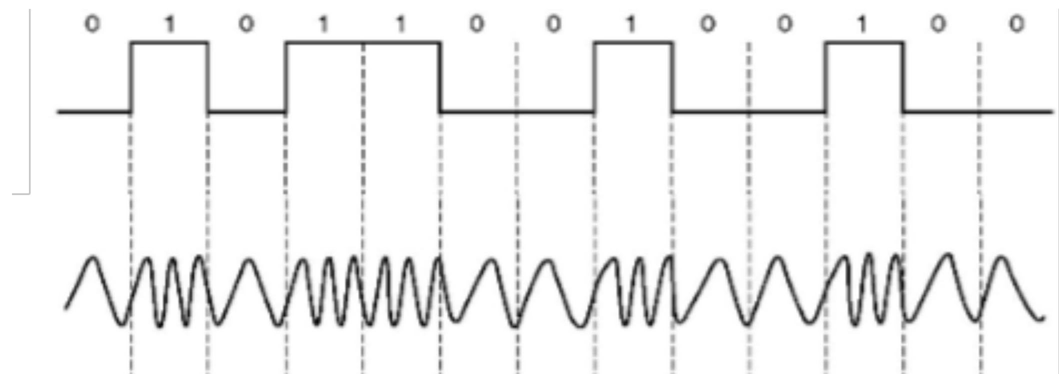
- How to manipulate a given signal parameter?
  - Set the parameter to an arbitrary value: ***analog modulation***
  - Choose parameter values from a finite set of legal values: ***digital keying***
  - Simplification: When the context is clear, ***modulation*** is used in either case
- Modulation?
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

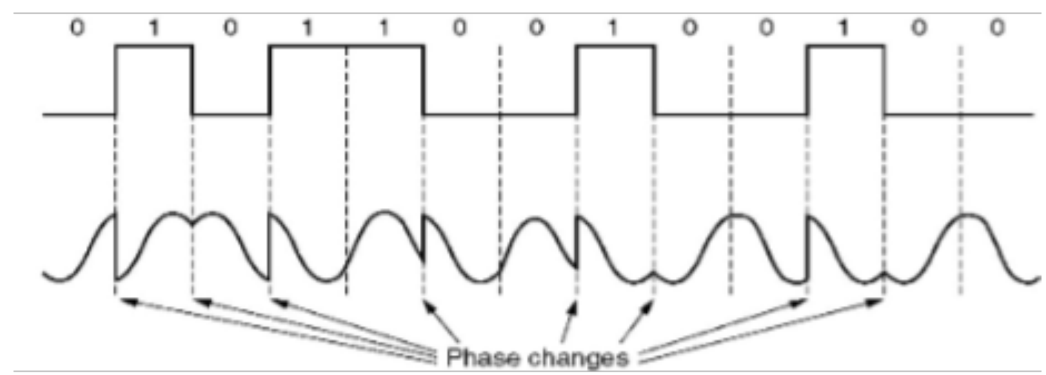
- Use data to modify the amplitude of a carrier frequency ! ***Amplitude Shift Keying***



- 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***



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
- 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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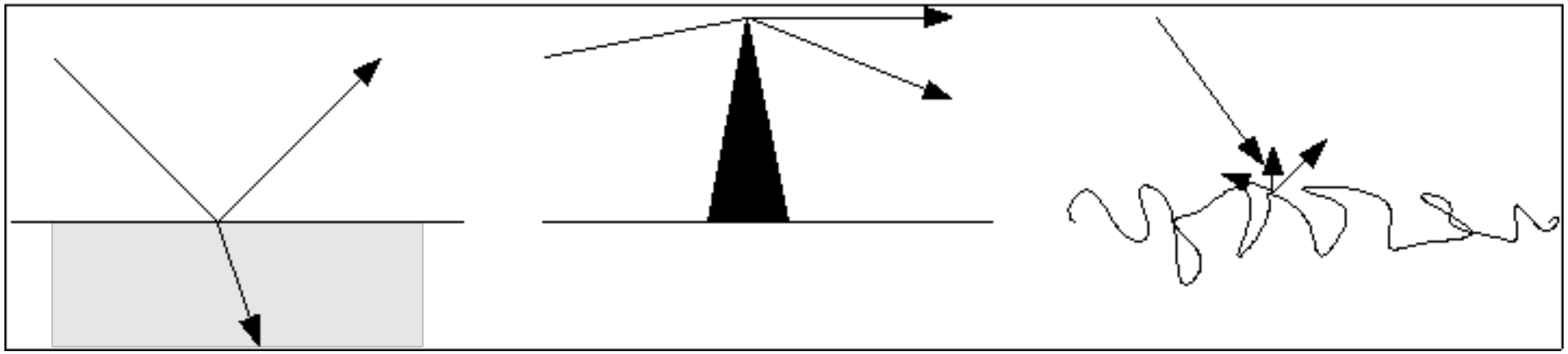
Transmitted signal <> received signal!

- 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)



What is a Decibel- dB

- Decibel is a unit used to express relative differences in signal strength
- It is expressed as the base 10 logarithm of the ratio of the **powers** of two signals:
  - dB = 10 log (P1/P2)
- Logarithms are useful as the unit of measurement
  - **signal power tends to span several orders of magnitude**
  - **signal attenuation losses and gains can be expressed in terms of subtraction and addition**

For Example

- Suppose that a signal passes through two channels is first attenuated in the ratio of 20 and 7 on the second. The total signal degradation is the ratio of 140 to 1. Expressed in dB, this become $10 \log 20 + 10 \log 7 = 13.01 + 8.45 = 21.46$ dB

The order of dB

- The following table helps to indicate the order of magnitude associated with dB:
  - 1 dB attenuation means that 0.79 of the input power survives.
  - 3 dB attenuation means that 0.5 of the input power survives.
  - 10 dB attenuation means that 0.1 of the input power survives.
  - 20 dB attenuation means that 0.01 of the input power survives.
  - 30 dB attenuation means that 0.001 of the input power survives.
  - 40 dB attenuation means that 0.0001 of the input power survives.

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

$$P_{\text{recv}}(d) = \frac{P_{\text{tx}} \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi)^2 \cdot d^2 \cdot L}$$

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

Slow fading: signal variations at timescales of (tens of) seconds to minutes

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***

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

- Rewrite in logarithmic form (in dB):

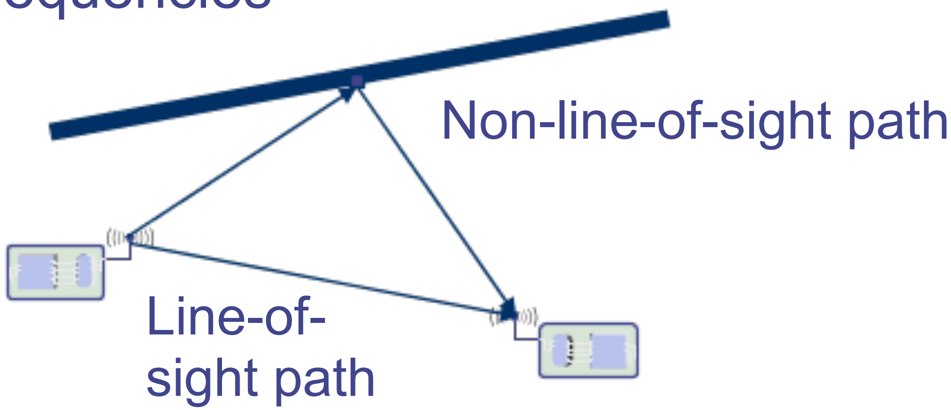
$$\text{PL}(d)[\text{dB}] = \text{PL}(d_0)[\text{dB}] + 10\gamma \log_{10}\left(\frac{d}{d_0}\right)$$

- 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***

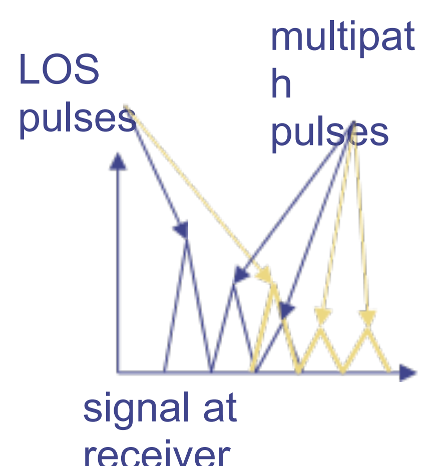
$$\text{PL}(d)[\text{dB}] = \text{PL}(d_0)[\text{dB}] + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma[\text{dB}]$$

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
  - With movement: ***fast fading***



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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)***

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

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

$$\text{BER}(\text{SINR}) = 0.5 e^{-\frac{E_b}{N_0}}$$

$$E_b/N_0 = \text{SINR} \cdot \frac{1}{R}$$

Examples for SINR ! BER mappings

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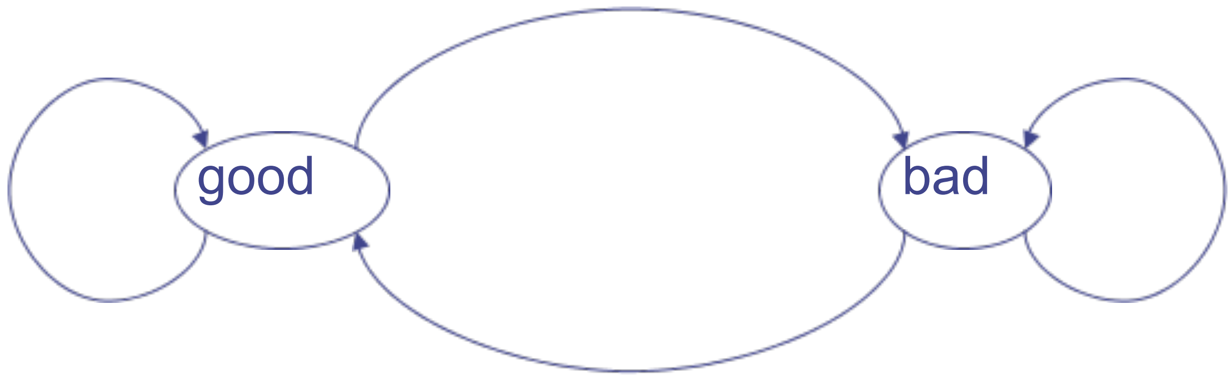
Channel models – analog

- How to stochastically capture the behavior of a wireless channel
  - Main options: model the SNR or directly the bit errors
- Signal models
  - Simplest model: assume transmission power and attenuation are constant, noise an uncorrelated Gaussian variable
    - ***Additive White Gaussian Noise*** model, results in constant SNR
    - $r(t) = s(t) + n(t)$
  - Situation with no line-of-sight path, but many indirect paths: 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 models – digital

- Directly model the resulting bit error behavior
  - Each bit is erroneous with constant probability, independent of the other bits ! ***binary symmetric channel (BSC)***
  - Capture fading models' property that channel be 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



Wireless channel quality – summary

- Wireless channels are substantially worse than wired channels
  - In throughput, bit error characteristics, energy consumption, …
- Wireless channels are extremely diverse
  - There is no such thing as THE typical wireless channel
- Various schemes for quality improvement exist
  - Some of them geared towards high-performance wireless communication – not necessarily suitable for WSN, ok for MANET
  - Some of them general-purpose ARQ (automatic repeat request) and FEC(forward error correction)
  - Energy issues need to be taken into account!

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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

Direct Sequence Spread Spectrum (DSSS)

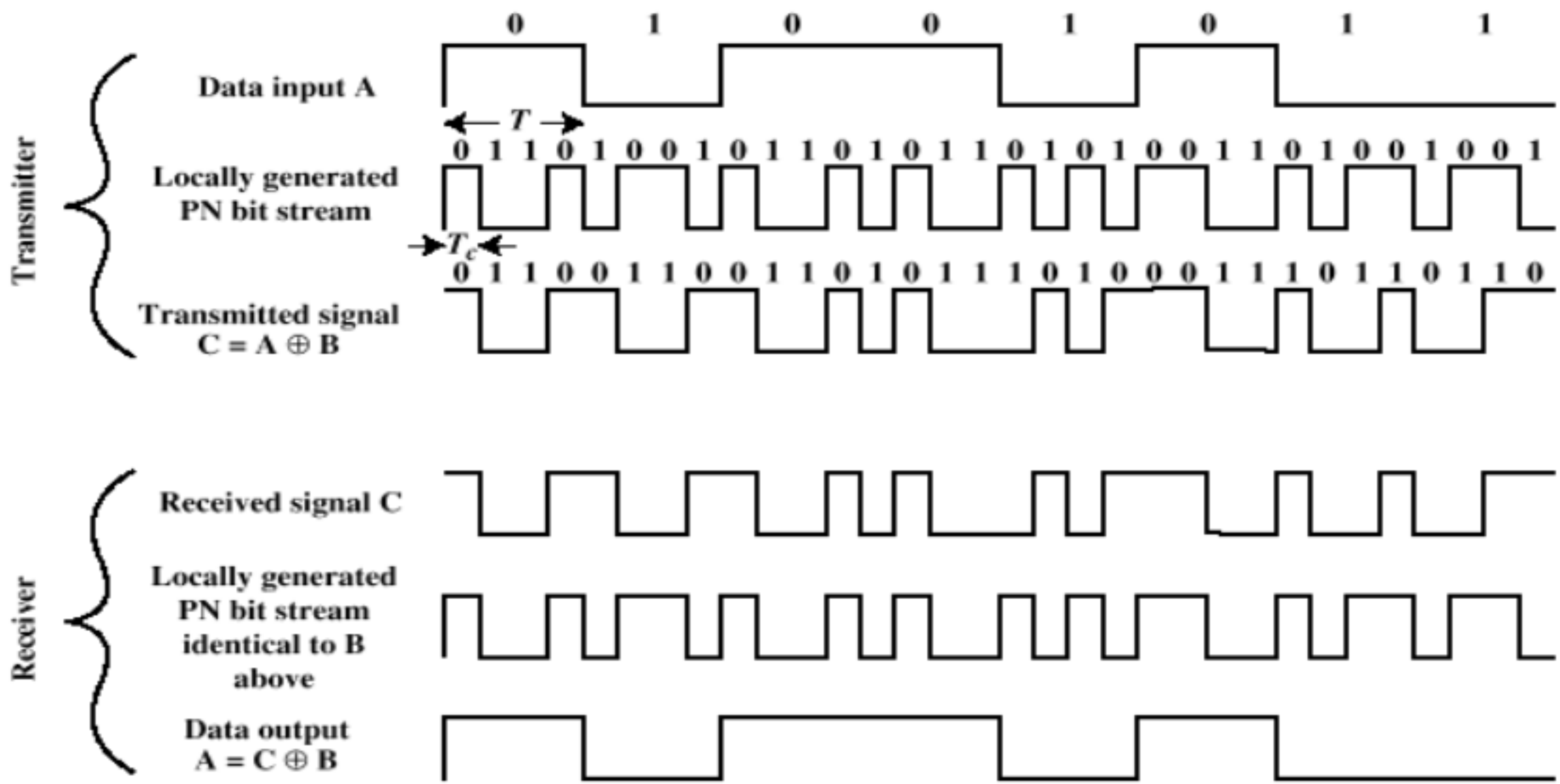

Figure 7.6 Example of Direct Sequence Spread Spectrum

Frequency Hoping Spread Spectrum (FHSS)

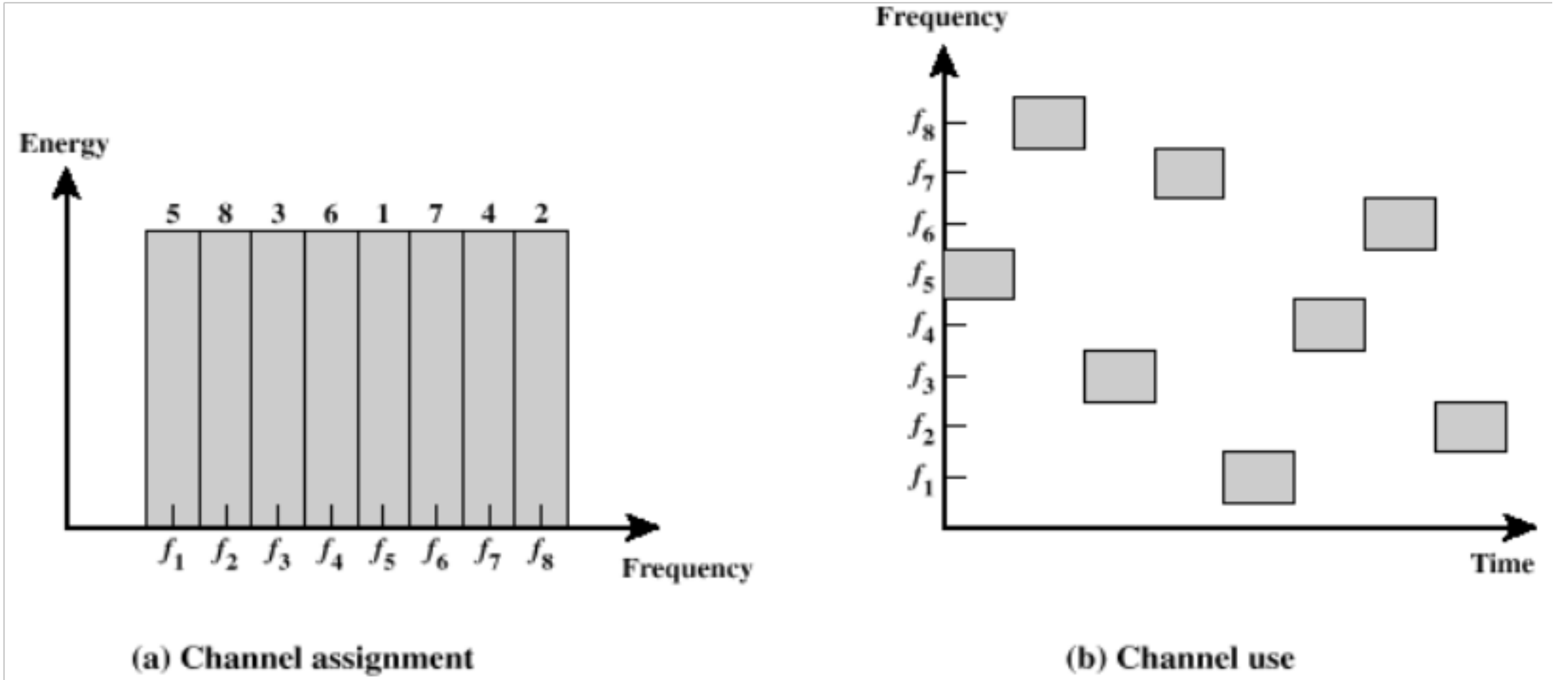

Figure 7.2 Frequency Hopping Example

CDMA Example

- Each station has its own unique chip sequence (CS)
- All CSs are pairwise orthogonal
- For example :(codes A, B, C and D are pairwise orthogonal)
    - A: 00011011 => (-1-1-1+1+1-1+1+1)
    - B: 00101110 => (-1-1+1-1+1+1+1-1)
    - C: 01011100 => (-1+1-1+1+1+1-1-1)
    - D: 01000010 => (-1+1-1 - 1-1-1+1-1)

CDMA Example

- A·B = (1+1-1-1+1-1+1-1) = 0
- B·C = (1-1-1-1+1+1-1+1) = 0
- Ex: If station C transmits 1 to station E, station B transmits 0 and station A transmits 1 simultaneously then the signal received by station E will become
  - S_E = (-1+1-1+1+1+1-1-1) + (+1+1-1+1-1-1-1+1) + (-1-1-1+1+1-1+1+1) = (-1+1-3+3-1-1-1+1)
  - E can convert the signal S_E to $S_E C = S_E$(-1+1-1+1+1+1-1-1) = (1+1+3+3+1-1+1-1)/8 = 1

Summary

- Wireless radio communication introduces many uncertainties and vagaries into a communication system
- Handling the unavoidable errors will be a major challenge for the communication protocols
- Dealing with limited bandwidth in an energy-efficient manner is the main challenge
- MANET and WSN are pretty similar here
  - Main differences are in required data rates and resulting transceiver complexities (higher bandwidth, spread spectrum techniques)