

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.
 - Some brief remarks on transceiver design
- 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



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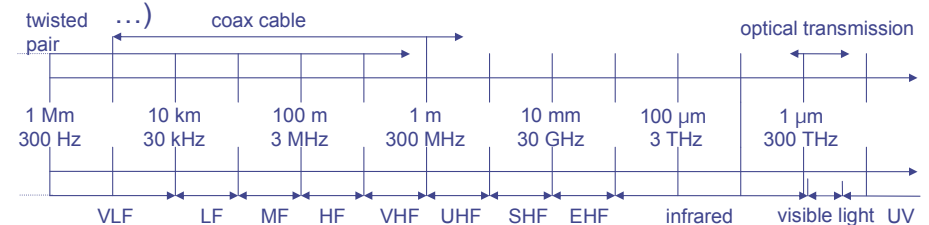
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Overview

- **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
- 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

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Frequency allocation

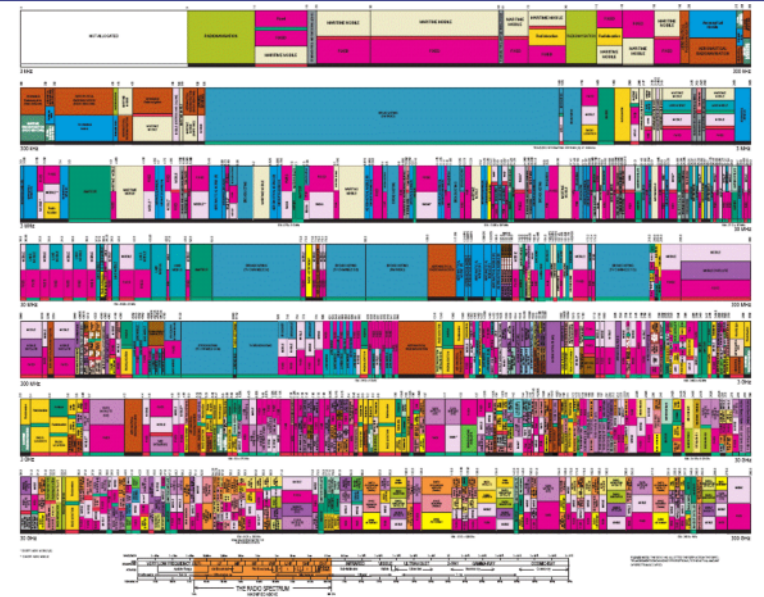
- Some frequencies are allocated to specific uses
 - Cellular phones, analog television/radio broadcasting, DVB-T, radar, emergency services, radio astronomy, ...
- Particularly interesting: ISM bands (“Industrial, scientific, medicine”) – license-free operation

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

UNITED STATES FREQUENCY ALLOCATIONS THE RADIO SPECTRUM



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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 $\phi(t)$
- 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!



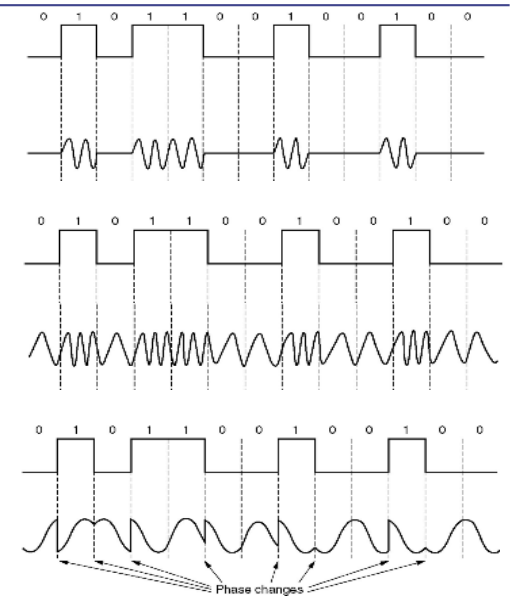
Modulation and keying

- 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**



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!



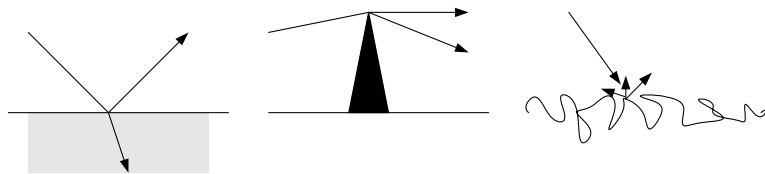
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Transmitted signal <> received signal!

- 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

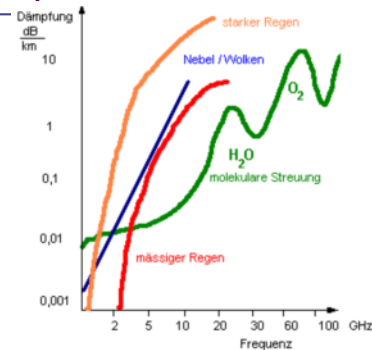
$$P_{\text{recv}}(d) = \frac{P_{\text{tx}} \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi)^2 \cdot d^2 \cdot L}$$

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

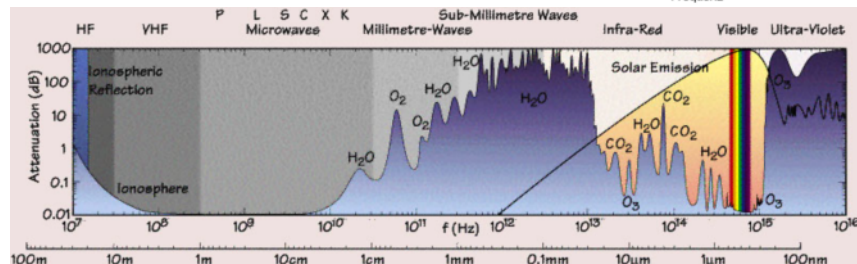


Suitability of different frequencies – Attenuation

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

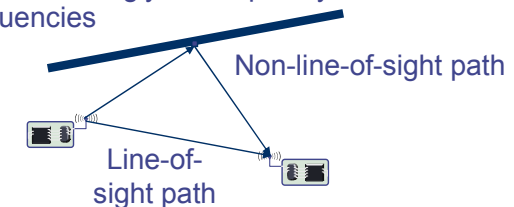


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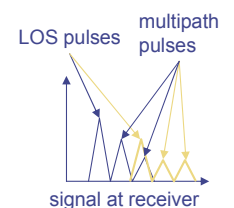


Distortion effects: Non-line-of-sight paths

- 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**

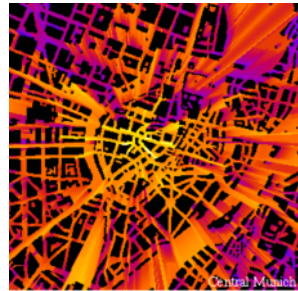
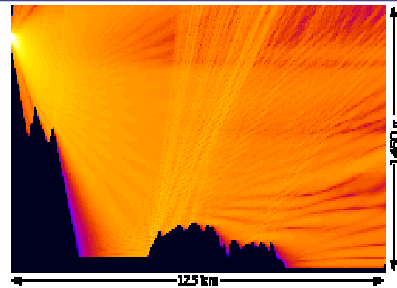
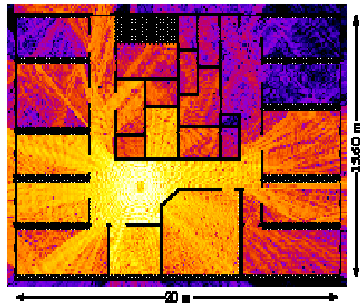


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Wireless signal strength in a multi-path environment

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



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

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



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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?



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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)**

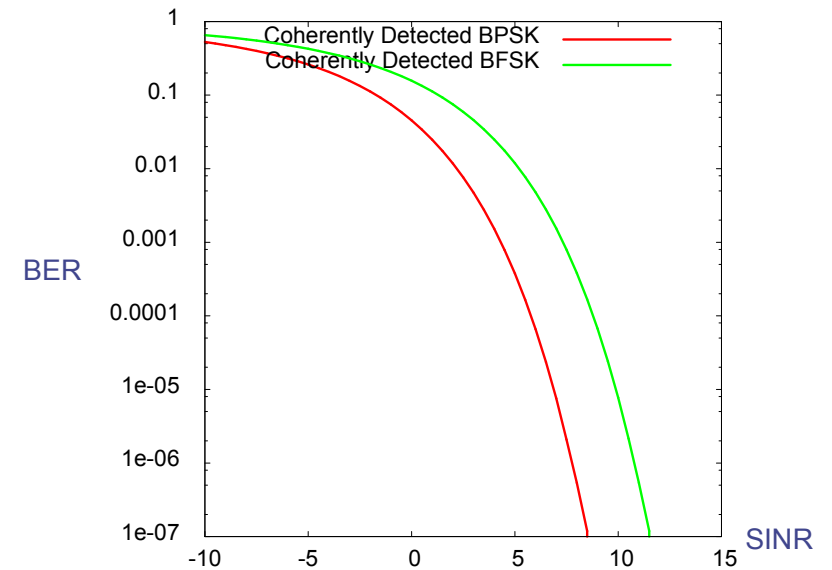
$$\text{SINR} = 10 \log_{10} \left(\frac{P_{\text{recv}}}{N_0 + \sum_{i=1}^k I_i} \right)$$

- SINR 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:

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



Examples for SINR ! BER mappings



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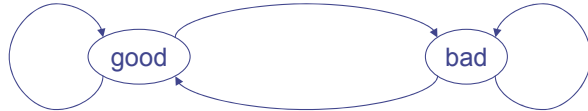
Channel models – analog

- 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
 - 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



- Fractal channel models describe number of (in-)correct bits in a row by a heavy-tailed distribution



WSN-specific channel models

- Typical WSN properties
 - 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

- Some example measurements

- γ path loss exponent
- Shadowing variance σ^2
- Reference path loss at 1 m

Location	Average of γ	Average of σ^2 [dB]	Range of PL(1m)[dB]
Engineering Building	1.9	5.7	[-50.5, -39.0]
Apartment Hallway	2.0	8.0	[-38.2, -35.0]
Parking Structure	3.0	7.9	[-36.0, -32.7]
One-sided Corridor	1.9	8.0	[-44.2, -33.5]
One-sided patio	3.2	3.7	[-39.0, -34.2]
Concrete canyon	2.7	10.2	[-48.7, -44.0]
Plant fence	4.9	9.4	[-38.2, -34.5]
Small boulders	3.5	12.8	[-41.5, -37.2]
Sandy flat beach	4.2	4.0	[-40.8, -37.5]
Dense bamboo	5.0	11.6	[-38.2, -35.2]
Dry tall underbrush	3.6	8.4	[-36.4, -33.2]



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
 - Diversity, equalization, ...
 - Some of them general-purpose (ARQ, FEC)
 - 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 $\frac{1}{4}$ 60 mW to wake up
- Exploit communication/computation tradeoffs
 - Might payoff to invest in rather complicated coding/compression schemes



Choice of modulation

- One exemplary design point: which modulation to use?
 - Consider: required data rate, available symbol rate, implementation complexity, required BER, channel characteristics, ...
 - Tradeoffs: the faster one sends, the longer one can sleep
 - Power consumption can depend on modulation scheme
 - Tradeoffs: symbol rate (high?) versus data rate (low)
 - Use m-ary transmission to get a transmission over with ASAP
 - But: startup costs can easily void any time saving effects
 - For details: see example in exercise!
- Adapt modulation choice to operation conditions
 - Akin to dynamic voltage scaling, introduce **Dynamic Modulation Scaling**



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)

