Wireless Physical Layers for Ad-Hoc Networks

CSE-561
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Adapted from Holger Karl and Jan Rabaey

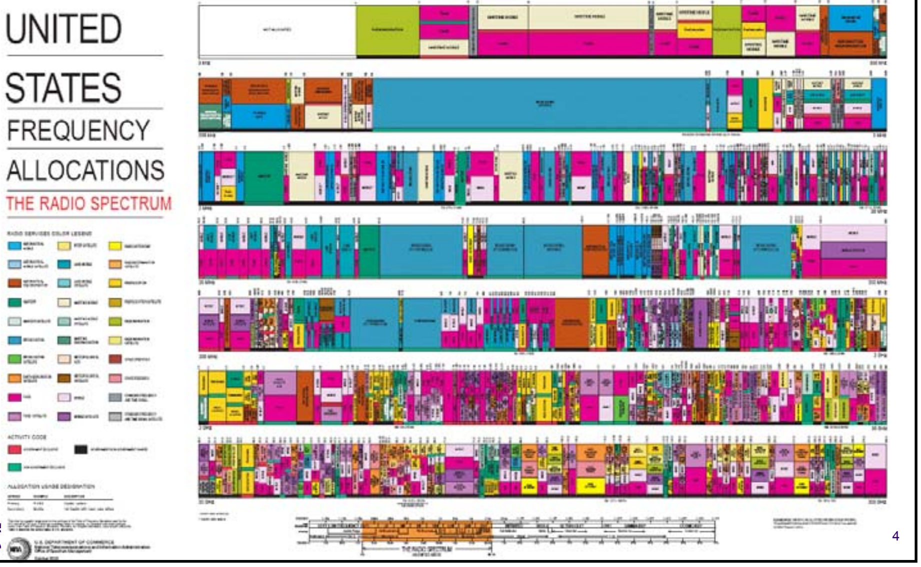
Goals of this chapter

- 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

Overview

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

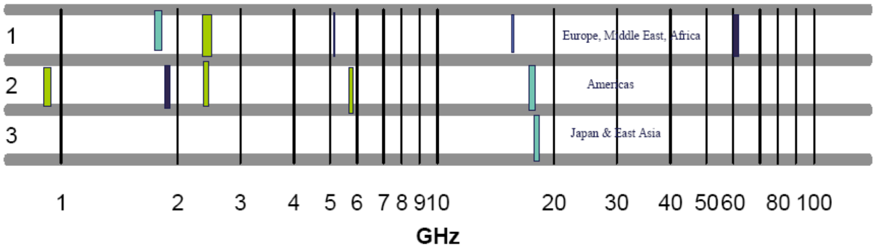
Example: US Frequency Allocation



ISM Bands

- The majority of frequency bands are assigned through regulation
  - (By technology, By operator) => In some area
- ISM bands: No license needed, open for everybody
  - The good news: you can just use it
  - The bad news: you neighbor can as well... and you might interfere...
- Some constraints are necessary, as for the shape of signal, the strength of signal: regulatory body
- This sharing rules pertain both to the physical layer as well as to the procedures of usage.
  - Etiquette rather than protocol
- Regional differences ...

ISM Frequency Bands: Examples!



- 902 - 928 MHz (US only; used for GSM in Europe)
- 1.910 – 1.920 (US only; unlicensed PCS data band)
- 2.400 – 2.4835 GHz (US ISM, Japan)
- 2.400 – 2.500 GHz (European unlicensed band)
- 5.150 – 5.250 GHz (European HIPERLAN)
- 5.725 – 5.875 GHz (US ISM)
- 61 – 61.5 GHz (Europe)

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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:

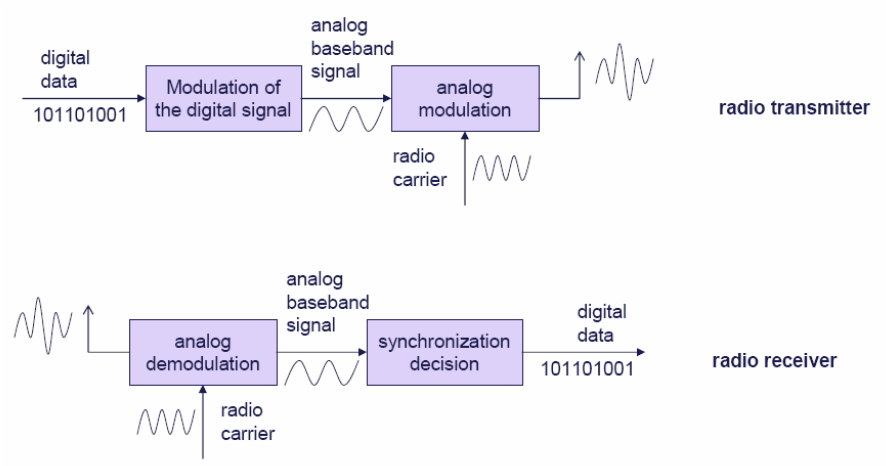
$$s(t) = A(t)\,\mathrm{sin}(2\pi f(t)t + \phi(t))$$

  - Parameters: amplitude A(t), frequency f(t), phase ϕ(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 and Demodulation



digital data

101101001

Modulation of the digital signal

analog baseband signal

analog modulation

radio carrier

radio transmitter

analog demodulation

analog baseband signal

synchronization decision

radio carrier

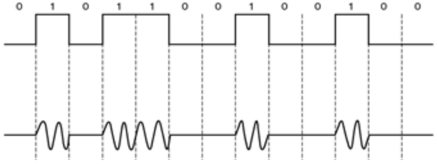
digital data

101101001

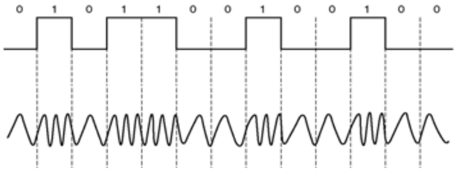
radio receiver

Modulation/Keying Examples

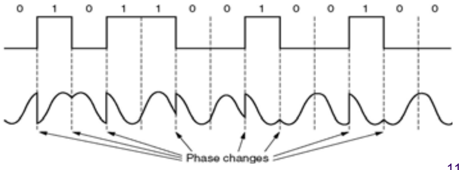
- Use data to modify the amplitude of a carrier frequency
  - ***Amplitude Shift Keying***



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

Overview

- Frequency bands
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- ***Signal distortion – wireless channels***
- From waves to bits
- Channel models
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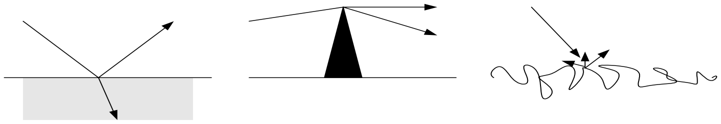
Transmitted signal <> received signal!

- 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)

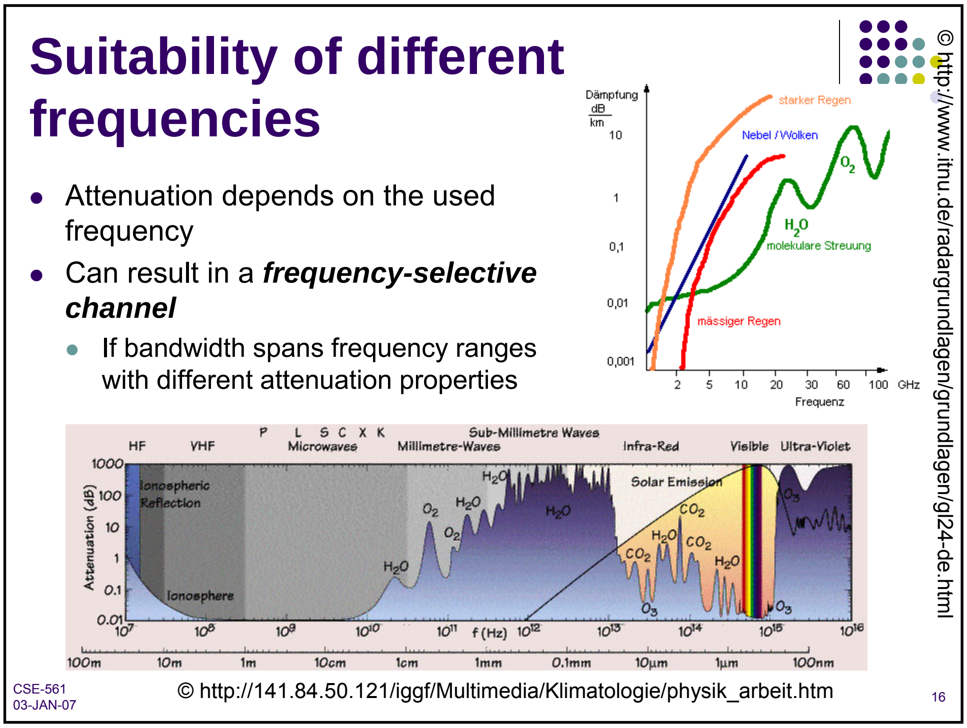


Attenuation results in path loss

- 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 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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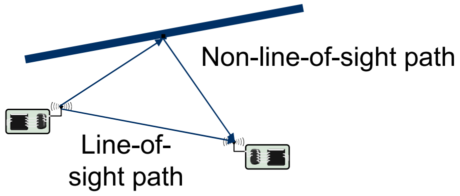
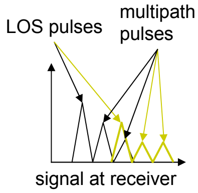
Distortion effects: Non-line-of-sight paths

- 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


Non-line-of-sight path

Line-of-sight path

- 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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Propagation Mechanisms

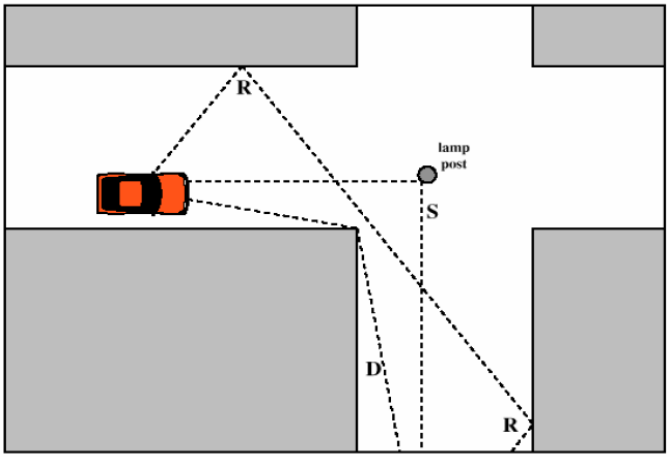
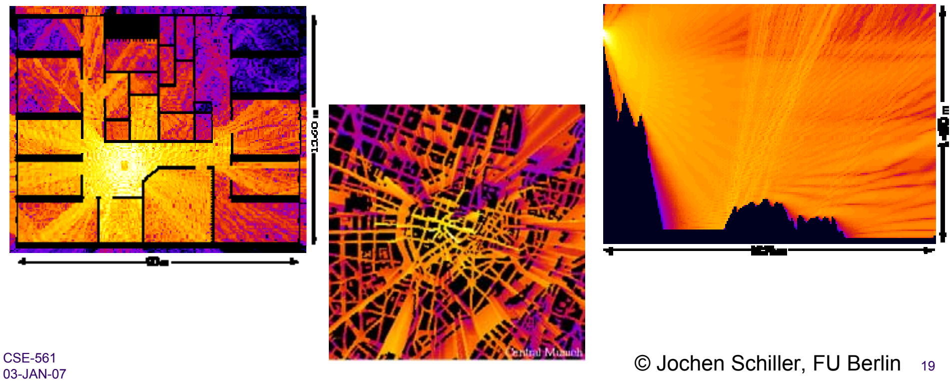


Figure 5.10 Sketch of Three Important Propagation Mechanisms: Reflection (R), Scattering (S), Diffraction (D) [ANDE95]

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***

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

  - Rewrite in logarithmic form (in dB):

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

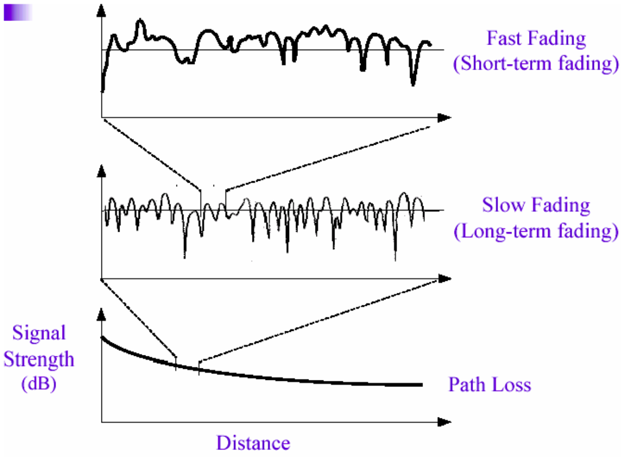
- Take obstacles into account by a random variation
  - Add a Gaussian random variable $N(0,\sigma^2)$ to dB representation

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

  - Equivalent to multiplying with a lognormal distributed r.v. in metric units -> ***lognormal fading***

Fading

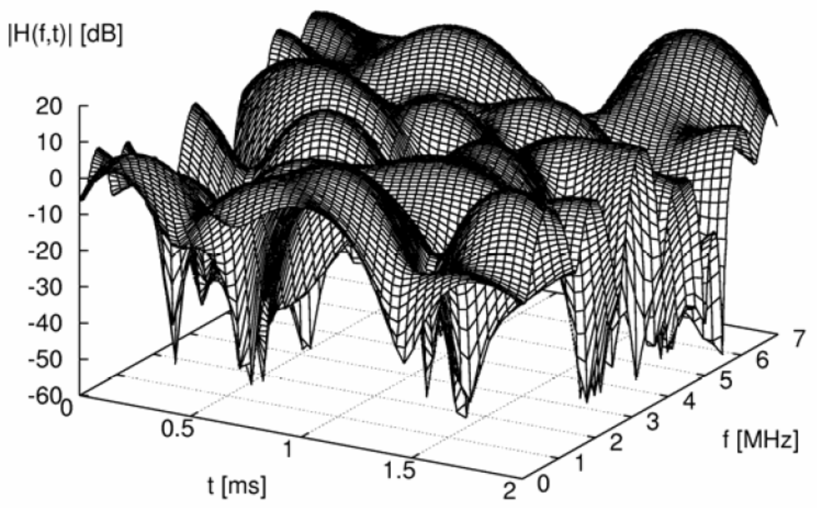
- Variation of mean level of the received signal over time



Fading

- Slow fading (in the order of tens of s)
  - Caused by shadowing
  - Log-normal distribution is used for modeling
- Fast fading (in the order of ms)
  - Caused by multipath: several waves arrive at the same time at the receiver from different propagation paths.
  - Amplitude of received signal in general Rician distributed
  - Rayleigh distribution when no direct path (no line of sight) available; worst case scenario!
  - Gaussian distribution when received signal power >> noise (SNRavg >> 0 dB)

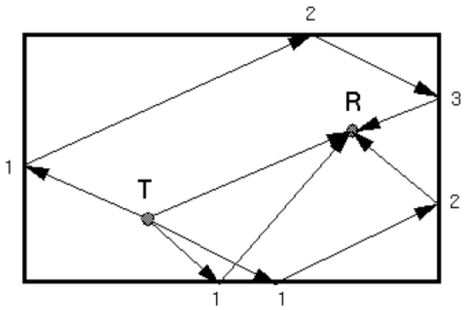
Fading and Bandwidth Coherence



Coherence Bandwidth

- Coherence bandwidth B_C:
  - Represents correlation between 2 fading signal envelopes at frequencies f_1 and f_2
  - Is a function of delay spread
  - Two frequencies whose spread is larger than the coherence bandwidth fade independently
  - Concept useful in diversity reception
    - Multiple copies of same message are sent using different frequencies

Multipath Fading

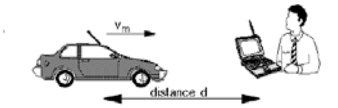


Reflections in a rectangular room

- The received signal is the vector sum of the signals arriving along different paths,
  - Except for the LOS path all paths are the result of reflection and diffraction,
  - Phase and amplitude of individual signals are different ...
  - Countermeasures: Equalization, Diversity

Doppler Shift

- As the transmitter moves towards the receiver, the propagation time τ will change with time t as (1)
  - The original frequency fc changes to fc+fd (2)
  - fd is a shift in the frequency observed at the receiver ***(Doppler frequency shift)***
  - fd is positive if the receiver and sender move towards each other, else negative
  - The Doppler effect constitutes a source of signal fading.



Mobile and fixed terminal communicating radio

$$\tau(t) = \frac{d(t)}{c} = \frac{d_0 - v_m t}{c} \qquad (1)$$

$$f_d = \frac{v_m}{c} f_c \qquad (2)$$

Impairments Beyond the Channel

- 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?
- ‘channel’ not just from TX antenna to RX antenna
  - include impairments in TX and RX front-ends

Total Channel Impairments

- 4 main parameters:
  - Timing
    - offset and drift in the TX/RX clocks
    - unknown time of flight from TX antenna to RX antenna
  - Frequency
    - offset and drift of TX/RX carrier references
    - Doppler shift - in high-speed mobility situations
  - Phase and Amplitude
    - respective changes by TX/RX front-ends and wireless channel
    - In presence of multipath - amplitude and phase are frequency dependent, and must be estimated and corrected as a function of frequency using equalization
- Measure of goodness: variance of the estimate
  - Increased estimation variance directly result in SNR degradation -> higher BER!

Total Channel Impairments (cont.)

- 2 other parameters
  - carrier detection
    - determines the presence of a packet
  - start of frame (SOF) detection
    - determines the demarcation between preamble bits and actual data bits
- Measure of goodness: false-positive/false-negative rate
  - Increased errors in these two parameters result in dropped packets and higher energy consumption rather than decreased SNR

Parameter Estimation

- There are three methods of parameter estimation, the choice of which is very important to preamble length reduction.
- *Data-aided* (DA) <- most widely used
  - use known preamble bits pre-pended to each packet for synchronization.
- *Non-data-aided* (NDA, also known as blind)
  - use the unknown incoming data bits for synchronization
- *Decision-directed* (DD)
  - use detected symbols to determine estimation errors
- DA and NDA synchronization may be feed-forward or feedback, whereas DD synchronization may only be feedback

Parameter Estimation: How To

- Main idea
  - Correlate received waveform with known transmitted preamble bits
    - At different timing offsets
    - For different frequency offsets
    - Correlation tells amplitude and phase
  - A big search space!
- More sophisticated algorithms limit search space or estimate parameters directly

Dynamic Channel Impairments

- Two categories of parameters:
  - static parameters – can be estimated only once per packet and
  - dynamic parameters - require continuous re-estimation or tracking
- Generally, all parameters are dynamic, but depending on the observation period and the tolerable change, they can appear static.
- Re-estimation or tracking using DA algorithms requires additional synchronization bits in the middle of the packet. Therefore, NDA or DD algorithms are typically used for parameter tracking
- For simplicity, keep packets short so that parameters don’t have to be re-estimated

Synchronization Requirements

- *Synchronization requirements*
  - which parameters need to be estimated, to what accuracy
  - whether they are static or dynamic
  - how much implementation loss can be tolerated
- Synchronization requirements are dictated by system parameters such as packet length, data rate, clock accuracy, and modulation scheme; and channel parameters such as multipath delay spread and channel coherence time.
- These tradeoffs can directly affect the preamble length

Modulation and Synchronization

- Different modulation schemes -> different sync requirements
- Coherent (M-PSK and M-QAM)
  - Frequency, phase, timing
  - Equalization in multipath environments
  - Amplitude estimation for M-QAM where M>4.
- Differentially coherent (D-BPSK and D-QPSK)
  - Frequency, timing
  - Equalization in multipath environments
- Non-coherent (OOK and FSK)
  - Timing estimation
  - For OOK: amplitude estimation, and equalization in multipath environments
- Coherent modulation schemes: least transmitted power for given BER, but more synchronization

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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)***

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

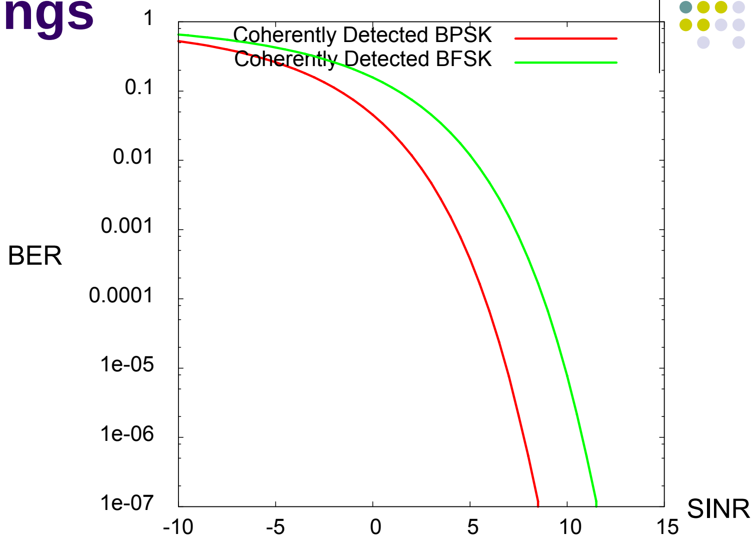
- SINR allows to compute ***bit error rate*** (***BER***) for a given modulation

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

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

  - Also depends on data rate (# bits/symbol) of modulation
  - E.g., for simple DPSK, data rate corresponding to bandwidth

Examples for SINR : BER mappings



How to Influence the Quality

- Transmission power might be increased
  - But: interference area will increase as well
- Modulation/coding might be changed
  - More bits/symbol (higher bit rate), reduces TX power needs, but makes receiver more complex
  - Coding means DECREASING the number of information bits/second (redundancy is increased), but might lead to INCREASING the GOODPUT
  - ARQ might be used…
- To influence the packet loss rate, packet length might be adjusted

Assuming independence of bit errors, the packet error rate P (i.e. the probability by which a packet is received erroneously) is given by:

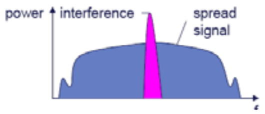
$$P(p) = 1 - (1 - p)^n$$

Selecting a Radio

Narrowband	**Wideband**
Low bit rate (< 250kbps)	High bit rate (100kbps+)
Lower frequencies ->higher range	High frequencies -> Global ISM band at 2.4GHz
Simple channel modulation	Complex channel modulation
Susceptible to interference and Fading (narrow frequency use)	Less sensitive to noise (using spreading codes)
Low power consumption (<15mA)	High power consumption (>20mA)
Fast wakeup times (some may be clocked by MCU)	Slow wakeup times (must start external oscillators)
Examples: RFM TR1000, Chipcon CC1020	Examples: IEEE 802.15.4, Bluetooth

Spread Spectrum

- Problem of radio transmission: frequency dependent fading can wipe out narrow band
- signals for duration of the interference
- Solution: spread the narrow band signal into a broad band signal using a special code
- Protection against narrow band interference



Alternatives:
- Direct Sequence,
- Frequency Hopping

- **Side effects:**
  - coexistence of several signals without dynamic coordination
  - Improved security
- **Disadvantages:**
  - Increased system complexity
  - The frequency band to transmit a baseband signal is large

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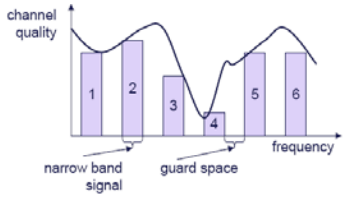
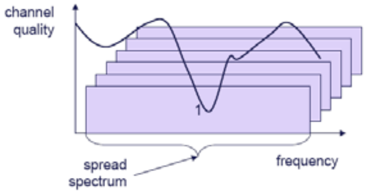
Spreading and Frequency Selective Fading



narrowband channels



spread spectrum channels

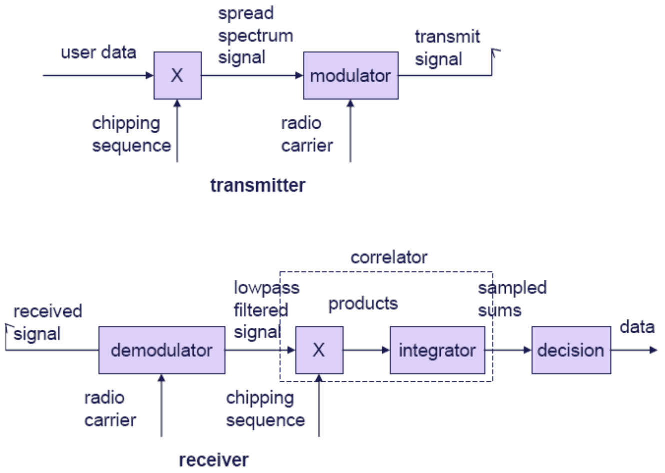
Direct Sequence Spread Spectrum (DSSS)

- Every bit (duration Tb) is convolved with a sequence of narrower pulses (chips) with time duration Tc
- Spreading factor $N = \frac{T_b}{T_c}$
- Chip sequence is coded to appear random, (pseudonoise= PN)
- Disadvantage: wider bandwidth than conventional communication,
- Potential for a special use: CDMA: several users can share the same bandwidth using spreading codes which are orthogonal to one another (CDMA).

DSSS in Detail

- **XOR the signal with pseudo-random number (chipping sequence)**
  - many chips per bit (e.g., 128) result in higher bandwidth of the signal
- Advantages
  - reduces frequency selective fading
  - in cellular networks
    - base stations can use the same frequency range
    - several base stations can detect and recover the signal
    - soft handover
      - a WT communicates with two BS at the same time
- Disadvantages
  - precise power control necessary

DSSS: Processing Steps



user data
X
spread spectrum signal
modulator
transmit signal
chipping sequence
radio carrier
transmitter

correlator
received signal
demodulator
lowpass filtered signal
X
products
integrator
sampled sums
decision
data
radio carrier
chipping sequence
receiver

FHSS: Frequency Hopping Spread Spectrum

- **Discrete changes of carrier frequency**
  - sequence of frequency changes determined via pseudo random number sequence
- **Two versions**
  - Fast Hopping: several frequencies per user bit
  - Slow Hopping: several user bits per frequency
- **Advantages**
  - frequency selective fading and interference limited to short period
  - simple implementation
  - uses only small portion of spectrum at any time
- **Disadvantages**
  - not as robust as DSSS
  - simpler to detect

FHSS: Illustrated

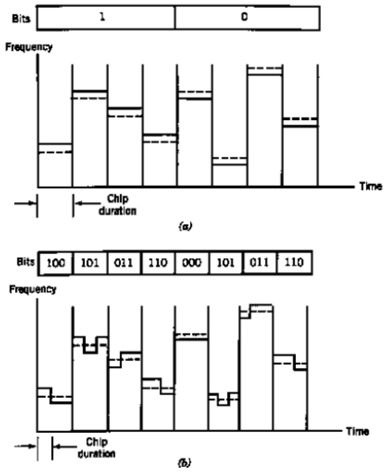
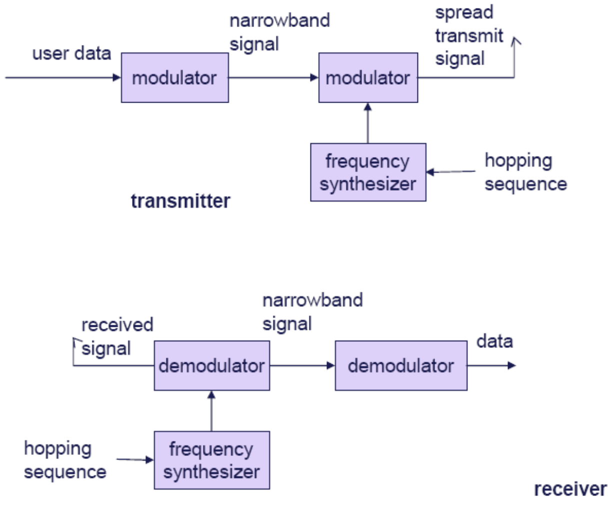


Figure 9.14 Simplified description of fast and slow frequency hopping. (*a*) Fast hopping with 4 hops per bit. (*b*) Show hopping with 3 bits per hop. (From [Skl88] © Prentice-Hall.)

FHSS – System Overview



user data

modulator

narrowband
signal

modulator

spread
transmit
signal

frequency
synthesizer

hopping
sequence

transmitter

received
signal

demodulator

narrowband
signal

demodulator

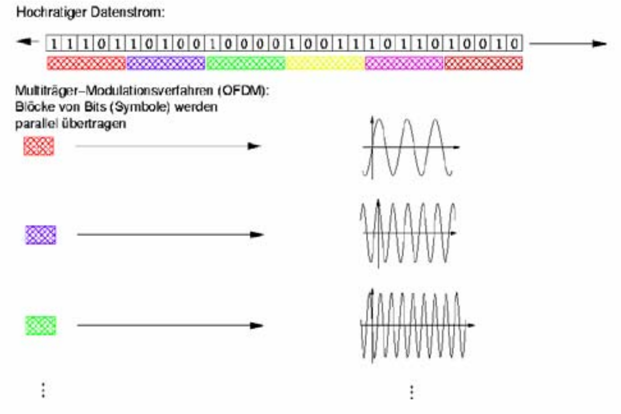
data

hopping
sequence

frequency
synthesizer

receiver

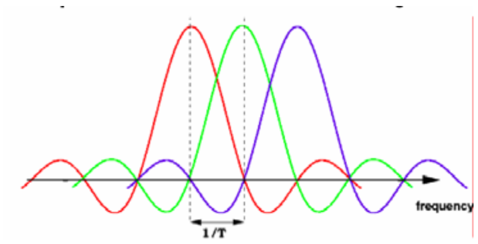
OFDM – Transmission Scheme



Multiträger–Modulationsverfahren (OFDM):
Blöcke von Bits (Symbole) werden
parallel übertragen

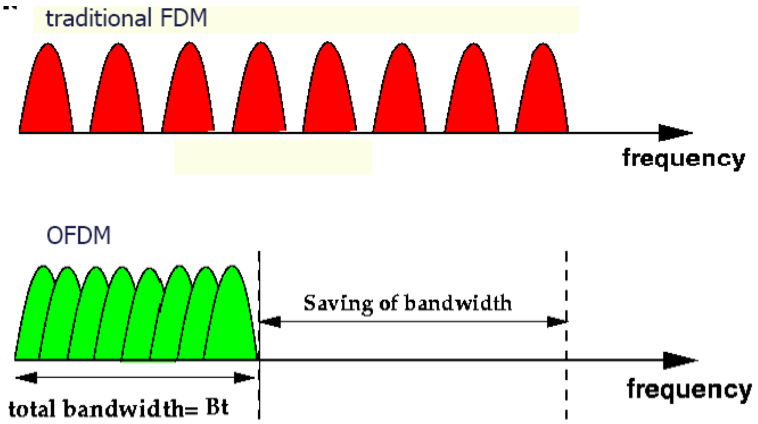
OFDM: Orthogonal FDM

- Fixed spacing between each adjacent subcarrier, related to the symbol duration of each subcarrier
  - Spectral nulls at each subcarriers‘ center frequency, no interchannel interference (ICI)
- Symbol rate per subcarrier is reduced -> ISI mitigation



OFDM – Spectral Efficiency

- Increased spectral efficiencies, the frequencies can overlap



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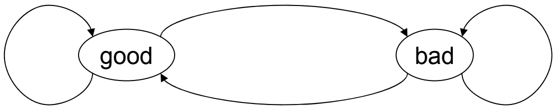
- ***Channel models***
- Transceiver design

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!

Overview

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

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

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

- 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