EEC173B/ECS152C, Winter 2006

Fundamentals of Wireless Communications

- #1: Frequencies
- #2: Radio Propagation Model
- #3: Modulation

Acknowledgment: Selected slides from Prof. Schiller & Prof. Goldsmith

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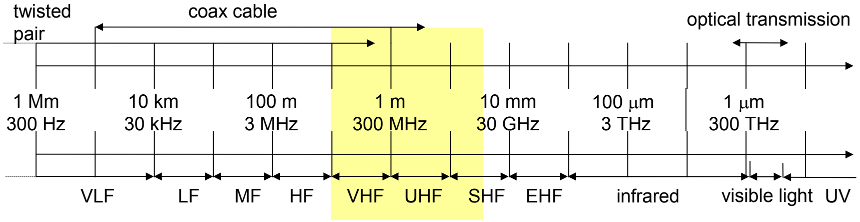
Characteristics of Wireless Medium

- Comparison to wired media
  - Unguided link
  - Unreliable
  - Low bandwidth
  - Untethered: supports mobility
  - Broadcast nature
  - Shared medium
  - Capacity limitation
- Frequency of operation and legality of access differentiates a variety of alternatives for wireless networking

Frequencies for Communication



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 and wave length: $\lambda = c/f$

- Wave length λ, speed of light $c \cong 3\times10^8$m/s, frequency f

Frequencies for Mobile Communication

- VHF-/UHF-ranges for mobile radio
  - Simple, small antenna for cars
  - Deterministic propagation characteristics, reliable connections
- SHF and higher for directed radio links, satellite communication
  - Small antenna, focusing
  - Large bandwidth available
- Wireless LANs use frequencies in UHF to SHF spectrum
  - Some systems planned up to EHF
  - Limitations due to absorption by water and oxygen molecules (resonance frequencies)
    - Weather dependent fading, signal loss caused by heavy rainfall etc.

Operational Ranges

- 1 GHz (cellular)
- 2 GHz (PCS and WLAN)
- 5 GHz (WLANs)
- 28-60 GHz (local multipoint distribution services (LMDS) and point-to-point base-station connections)
- IR frequencies for optical communications

Licensed and Unlicensed Bands

- Licensed:
  - Cellular/PCS
  - Expensive (PCS bands in US were sold for around $20B)
  - Time consuming to deploy new applications rapidly at low costs
- Unlicensed:
  - Industrial, Medical, and Scientific (ISM) Bands
  - Free, component costs are also low
  - New applications such as WLAN, Bluetooth are easily developed
- With the increase in frequency and data rate, the hardware cost increases, and the ability to penetrate walls also decreases

Frequencies and regulations

	Europe	USA	Japan
Cellular Phones	**GSM** 450-457, 479-486/460-467,489-496, 890-915/935-960, 1710-1785/1805-1880 **UMTS** (FDD) 1920-1980, 2110-2190 **UMTS** (TDD) 1900-1920, 2020-2025	**AMPS**, **TDMA**, **CDMA** 824-849, 869-894 **TDMA**, **CDMA**, **GSM** 1850-1910, 1930-1990	**PDC** 810-826, 940-956, 1429-1465, 1477-1513
Cordless Phones	**CT1+** 885-887, 930-932 **CT2** 864-868 **DECT** 1880-1900	**PACS** 1850-1910, 1930-1990 **PACS-UB** 1910-1930	**PHS** 1895-1918 **JCT** 254-380
Wireless LANs	**IEEE 802.11** 2400-2483 **HIPERLAN 2** 5150-5350, 5470-5725	902-928 **IEEE 802.11** 2400-2483 5150-5350, 5725-5825	**IEEE 802.11** 2471-2497 5150-5250
Others	**RF-Control** 27, 128, 418, 433, 868	**RF-Control** 315, 915	**RF-Control** 426, 868

Radio Propagation

- Three most important radio propagation characteristics used in the design, analysis, and installation of wireless networks are:
  - Achievable signal coverage
  - Maximum data rate that can be supported by the channel
  - Rate of fluctuations in the channel

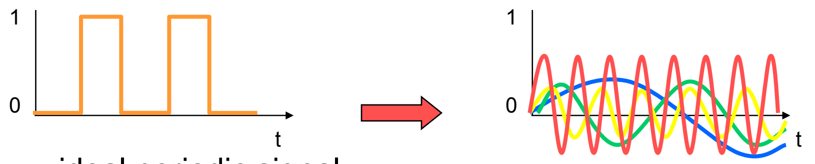
Signals - 1

- Physical representation of data
- Function of time and location
- Signal parameters: parameters representing the value of data
- Classification
  - Continuous time/discrete time
  - Continuous values/discrete values
  - Analog signal = continuous time and continuous values
  - Digital signal = discrete time and discrete values
- Signal parameters of periodic signals:
  period T, frequency f=1/T, amplitude A, phase shift φ
  - sine wave as special periodic signal for a carrier:

$$s(t) = A_t \sin(2 \pi f_t t + \varphi_t)$$

Fourier representation of periodic signals

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)$$

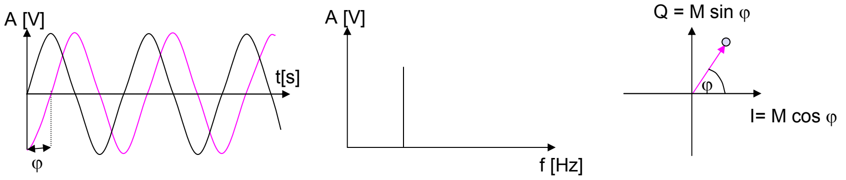


ideal periodic signal

real composition
(based on harmonics)

Signals - 2

- Different representations of signals
  - Amplitude (amplitude domain)
  - Frequency spectrum (frequency domain)
  - Phase state diagram (amplitude M and phase φ in polar coordinates)

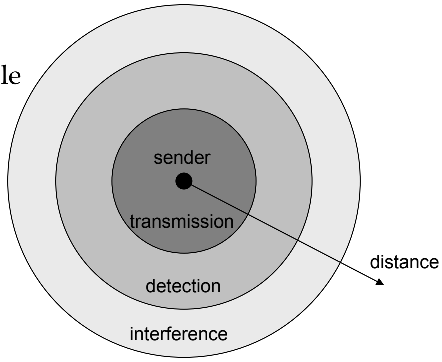


Signal - 3

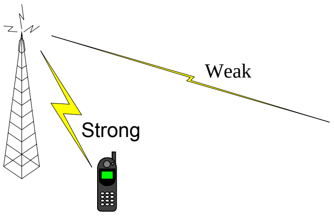
- Composed signals transferred into frequency domain using Fourier transformation
- Digital signals need
  - infinite frequencies for perfect transmission
  - modulation with a carrier frequency for transmission (analog signal!)

Signal propagation ranges

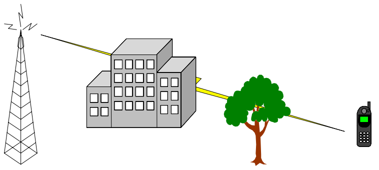
- Transmission range
  - Communication possible
  - Low error rate
- Detection range
  - Detection of the signal possible
  - No communication possible
- Interference range
  - Signal may not be detected
  - Signal adds to the background noise



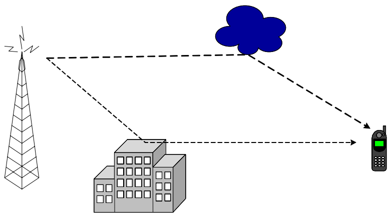
Radio Environment



Path Loss



Shadowing

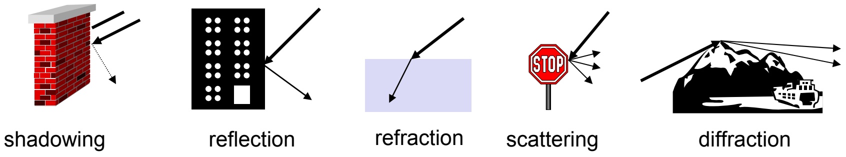


Multi-path Fading

Limit the Bit Rate
and/or Coverage

A. Path Loss of Radio Signal

- Signal propagation in free space always like light (straight line)
- Receiving power proportional to 1/d²
  (d = distance between sender and receiver)
- Receiving power additionally influenced by
  - Fading (frequency dependent)
  - Shadowing
  - Reflection at large obstacles
  - Refraction depending on the density of a medium
  - Scattering at small obstacles
  - Diffraction at edges



Path Loss Model (1)

- Many path loss models
  - Analytical, empirical (fitting curves to measured data), or combination.
- A general model for path loss (or sometimes referred to as path gain), *L*, is:

$$L = \frac{\overline{P}_r}{P_t} = G_t G_r \frac{1}{k(4\pi)^2 f^2 d^\alpha}$$

where P_r is the local mean received signal power

P_t is the transmitted power
d is the transmitter-receiver distance,
f is frequency
G_t, G_r are transmitter and receiver antennae gains
k is a loss factor not related to propagation

The path loss exponent: $2 \le \alpha \le 4$ ($\alpha = 2$ in free space)

Path Loss Model (2)

- We can simplify things by lumping the constant together:

$$L = K(\frac{1}{f^2 d^\alpha})$$

- In practice, one can measure the power received at a reference point, d_o from the transmitted and estimate P_r as:

$$P_r = P_o \left(\frac{d}{d_o} \right)^{-\alpha}$$

$$P_r(dBm) = P_o(dBm) - 10\alpha \log\left(\frac{d}{d_o} \right)$$

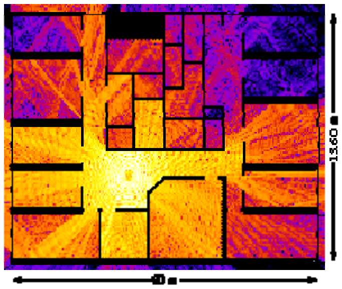
  - Free space propagation model: α = 2
    - Used when transmitter and receiver has clear, unobstructed, line-of-sight (LOS) path
  - For shadow urban, α = 4

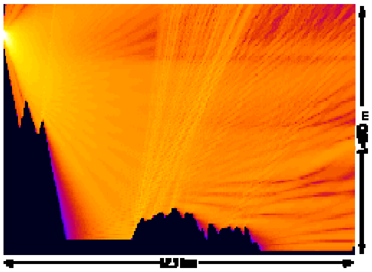
(Example link budget calculation: slides # 35-36)

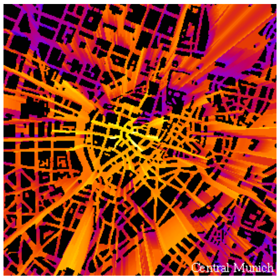
Radio Propagation Mechanisms

- Reflection and Transmission:
  - Upon reflection or transmission, the radio signals attenuates by factors that depend on the frequency, angle of incidence, and the nature of medium
- Diffraction:
  - Diffracted fields are generated by secondary wave sources formed at the edges of the buildings, walls, and other large objects. Diffraction facilitates the reachability of signals that are not in line of sight of the transmitter. However, the losses are more than that of reflection and transmission
- Scattering:
  - Irregular surfaces scatter signals in all directions in the form of spherical waves. Propagation in many directions results in reduced power levels.

Real World Example







B. Shadow fading

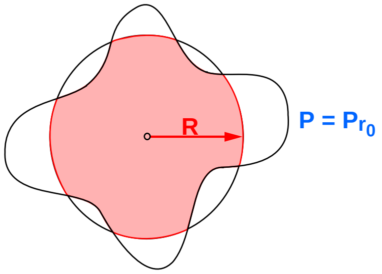
- Received signal is shadowed by obstructions such as hills and buildings.
- Depending on the environment and the surroundings, and the location of objects, the received signal strength for the same distance from the transmitter will be different. This variation of signal strength due to location is referred to as shadow fading
- This results in variations in the local mean received signal power

$$P_r \text{ (dB)}\_ = P_r \text{ (dB)} + G_S$$

$$\text{where } G_S \sim N(0, \sigma_S^2), 4 \le \sigma_S \le 10 \text{ dB.}$$

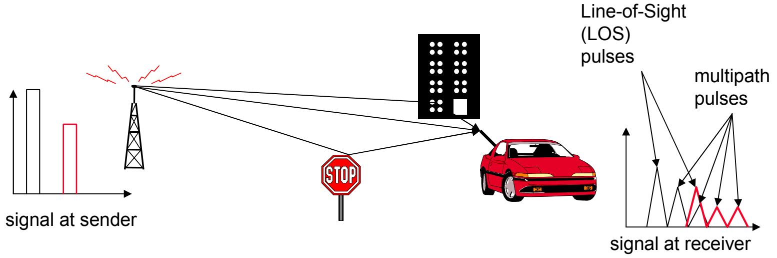
B. Shadow Fading - Implications

- Non-uniform coverage
- Increases the required transmit power
  - To overcome the shadow fading effects, a fade margin is added to the path loss or received signal strength. The fade margin is the additional signal power that can provide a certain fraction of the locations with the required signal strength



C. Multipath propagation

- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction



Multipath propagation – Cont'd

- Time dispersion: signal is dispersed over time
  ➔ Interference with "neighbor" symbols
  ➔ Inter Symbol Interference (ISI)
- The signal reaches a receiver directly and phase shifted
  ➔ Distorted signal depending on the phases of the different parts

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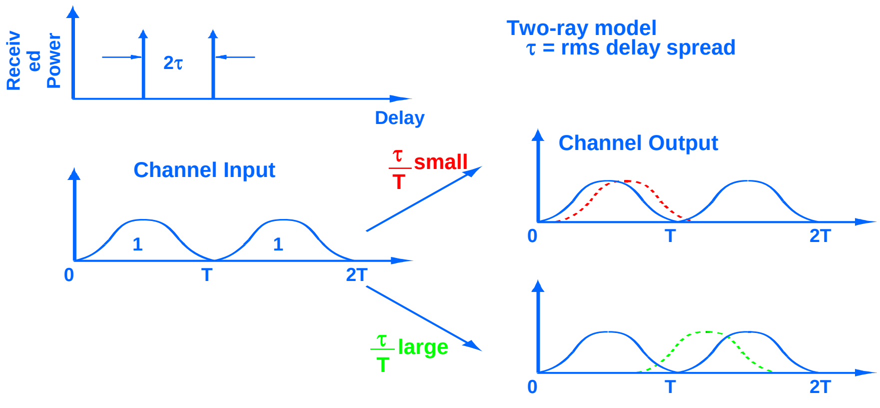
Delay Spread

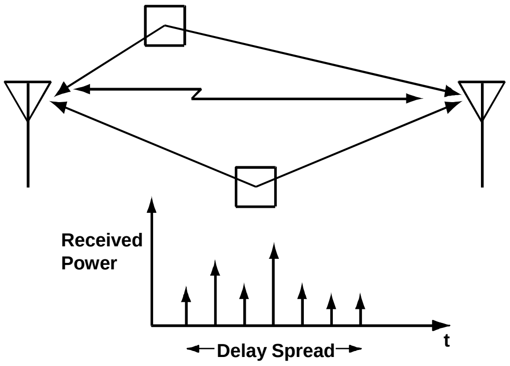


Two-ray model
τ = rms delay spread

$\frac{\tau}{T}$ small ⟹ negligible intersymbol interference

$\frac{\tau}{T}$ large ⟹ significant intersymbol interference, which causes an irreducible error floor

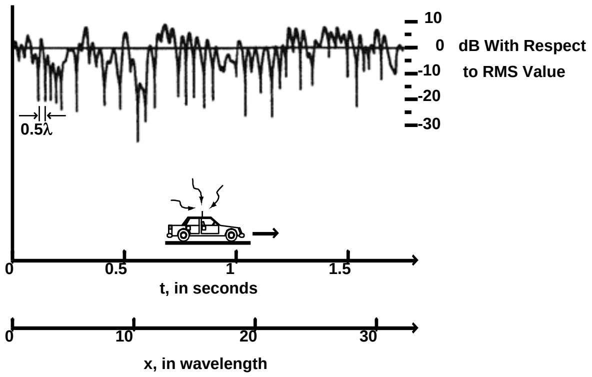
Multipath Propagation – Cont'd



$$h(t) = \sum_i a_i e^{j\theta_i} \delta(t-t_i)$$

Multipath - Example

Constructive and destructive interference of arriving rays



Multipath Fading

- Fluctuations of the signal amplitude because of the addition of signals arriving in different phases (paths) is called multipath fading
- Multipath fading results in high BER, and can be mitigated by FEC, diversity schemes, and using directional antennae

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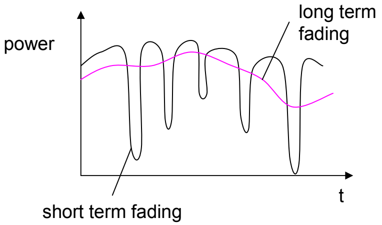
Effects of Mobility

- Channel characteristics change over time and location
  - Signal paths change
  - Different delay variations of different signal parts
  - Different phases of signal parts

➔ Quick changes in the power received (short term fading)

- Additional changes in
  - Distance to sender
  - Obstacles further away

➔ Slow changes in the average power received (long term fading)

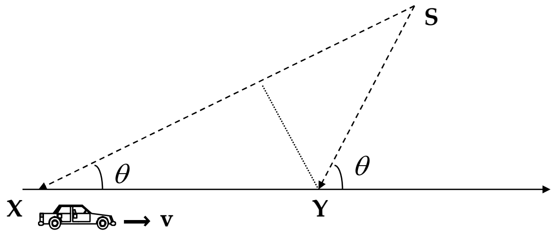


Doppler Shift

- Doppler Shift, f_d
  - Apparent change in frequency due to movement

$$f_d = \frac{1}{2\pi} \cdot \frac{\Delta\phi}{\Delta t} = \frac{v}{\lambda} \cdot \cos\theta$$

  - If mobile is moving toward the direction of arrival of the wave, the Doppler shift is positive
  - If the mobile is moving away, the Doppler shift is negative
  - Max shift when angle = 0 (moving directly toward/away transmitter)



Time-varying Channel Conditions

- Due to users' mobility and variability in the propagation environment, both desired signal and interference are time-varying and location-dependent
- A measure of channel quality:

SNR (Signal to Noise Ratio)

$$SNR = \frac{\text{Desired Signal Power}}{\text{Noise power}} = \frac{P_r}{N}$$

- Desired signal power = received power = P_r
  - We know how to estimate this from slide #17
- Background noise, e.g., thermal noise
  - Simple model: Noise power = ηW, where η is the average power per Hertz of the thermal noise, and W is the signal bandwidth

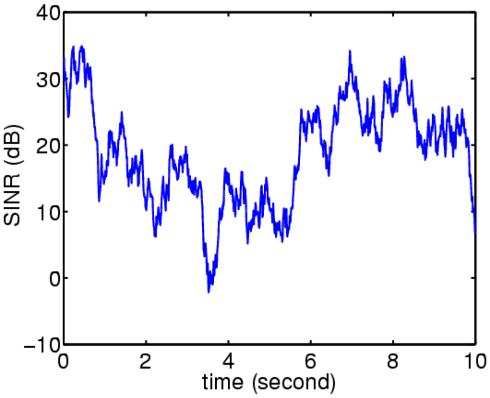
Time-varying Channel Conditions

- A more complete measure of channel quality:
  SINR (Signal to Interference plus Noise Ratio)

$$\text{SINR} = \frac{\text{desired signal power}}{\text{interference power} + \text{background noise power}}$$

- In the impact of interference is much more than noise, another measure is carrier-to-interference (C/I) ratio, i.e., assuming noise power is close to zero
- We will talk about how to estimate ‘Interference’ in the next lecture

Illustration of Channel Conditions



Physical Layer Issues

- Practical Link Performance Measures
  - Probability of Bit Error (BER)
  - Efficiency
- Modulation Tradeoffs
- Flat Fading Countermeasures
- Delay Spread Countermeasures

EEC165, EEC166
EEC265, EEC266

Link Performance Measure (1): BER

- The probability of bit error, P_b, in a radio environment is a random variable
  - **Average P_b ($\overline{P}_b$)**
  - **$P_r [P_b > P_{b_{target}}] \triangleq$ outage (P_{out})**
- Bit-error-rate is a function of SNR (signal-to-noise-ratio), or C/I (carrier-to-interference ratio), at the receiver
  - The function itself depends on the modulation

Calculate 'Link Budget' using Path Loss Models

- Link budget calculation requires
  - Estimate of power received from transmitted at a receiver
  - Estimate of noise & power received from "interferers"
  - For example, SNR (dB) = P_r (in dBm) – N (in dBm)
- Recall on slide #17,

$$P_r = P_o\left(\frac{d}{d_o}\right)^{-\alpha} \Rightarrow P_r(dBm) = P_o(dBm) - 10\alpha\log\left(\frac{d}{d_o}\right)$$

- Typical approximation
  - d is the distance between transmitted and receiver measured relative to the reference point d_0
  - α is the path-loss exponent
  - P_0 is a constant that accounts for antenna gains, carrier frequency, and reference point d_0

Example Link Budget calculation

- Maximum separation distance vs. transmitted power (with fixed BW)

  Given:
  - Cellular phone with 0.6 W transmit power
  - Unity gain antenna, 900 MHz carrier frequency
  - SNR must be at least 25dB for proper reception
  - Noise = -119 dBm
  - Assume path loss constant, α=2, and P_0 (at d_0 =1km) = -63.5 dBm

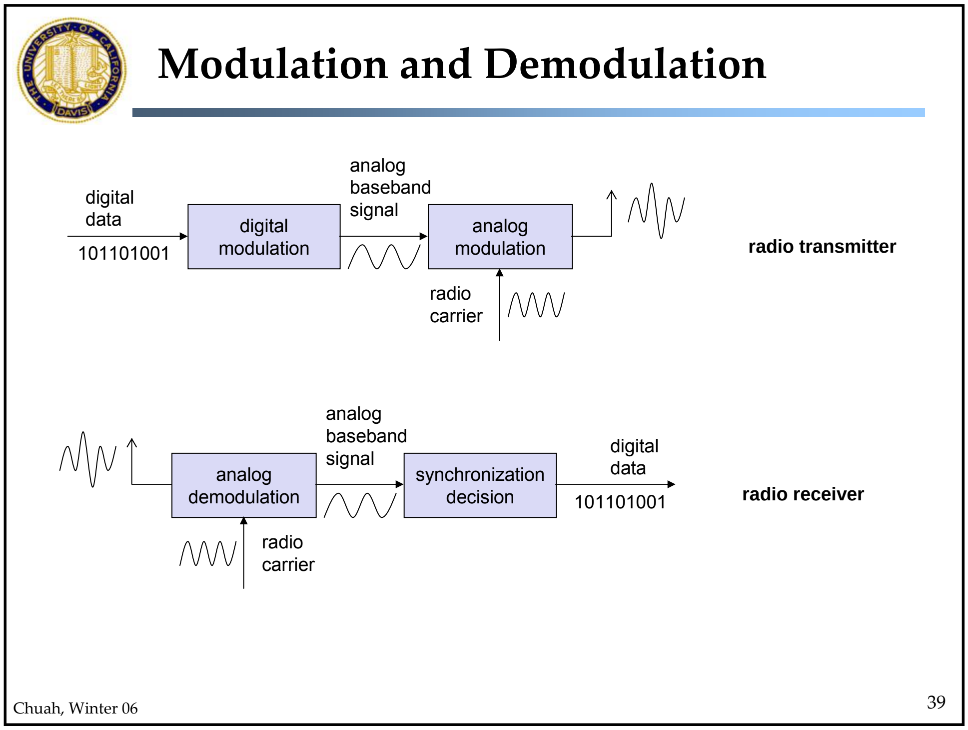
  What will be the maximum distance?

Link Performance Measure (2): Efficiency

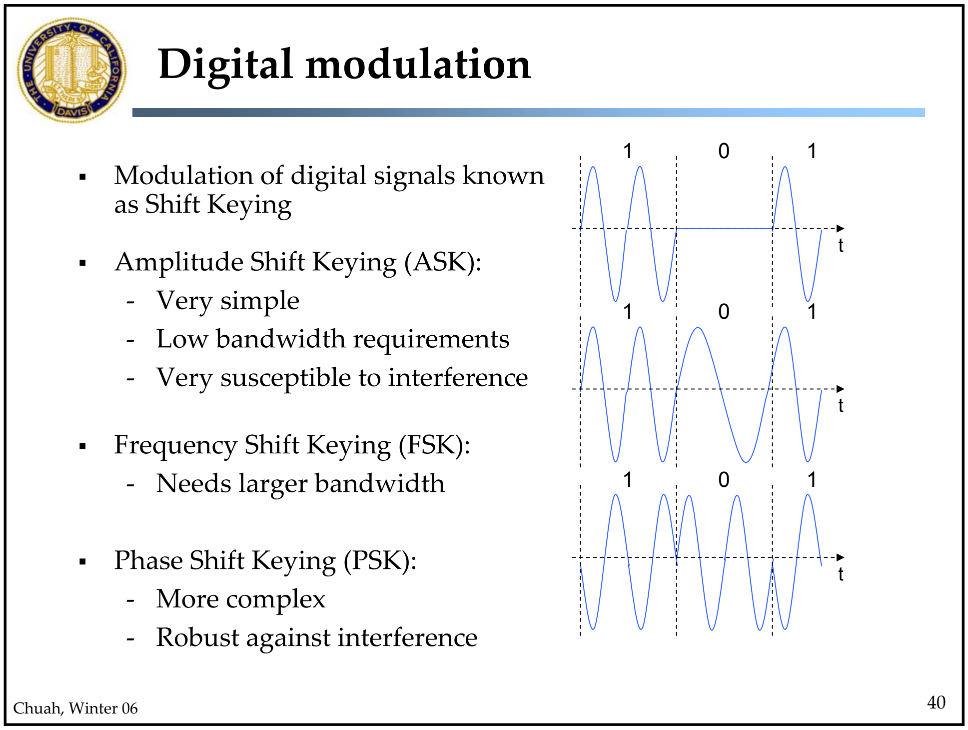
- **Spectral Efficiency:** a measure of the data rate per unit bandwidth for a given bit error probability and transmitted power
- **Power Efficiency:** a measure of the required received power to achieve a given data rate for a given bit error probability and bandwidth
- **Throughput/Delay**

Modulation - 1

- Digital modulation
  - Digital data is translated into an analog signal (baseband)
- Analog modulation
  - Shifts center frequency of baseband signal up to the radio carrier
- Basic schemes
  - Amplitude Modulation (AM)
  - Frequency Modulation (FM)
  - Phase Modulation (PM)



Modulation and Demodulation



Digital modulation

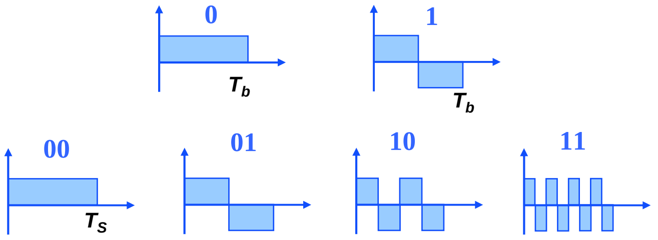
- Modulation of digital signals known as Shift Keying
- Amplitude Shift Keying (ASK):
  - Very simple
  - Low bandwidth requirements
  - Very susceptible to interference
- Frequency Shift Keying (FSK):
  - Needs larger bandwidth
- Phase Shift Keying (PSK):
  - More complex
  - Robust against interference

Grouping the Information Bits into Symbols

b bits/symbol = M possible waveforms

1 bit/symbol

2 bits/symbol

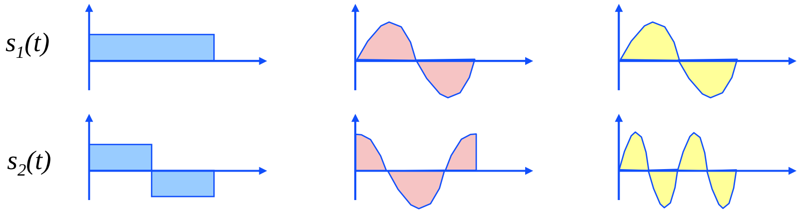


- If $M \rightarrow \propto$ the 'performance' goes up, but at a cost of complexity (Shannon limit)

Signal Space Representation

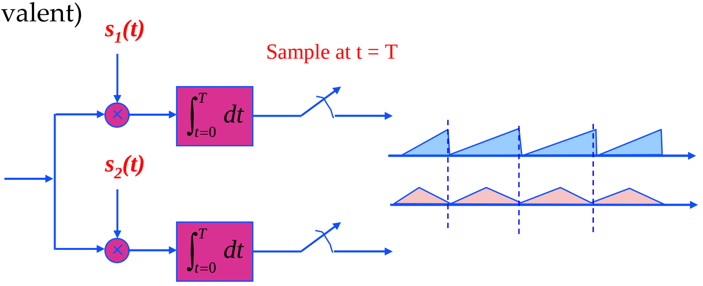
- The basic idea is that we can transmit information in parallel over a set of orthogonal waveforms with respect to the symbol interval **T**. The inverse of this interval is called the symbol rate: **Rs = 1/T**.

$$\int_{t=0}^{T} s_1(t) \cdot s_2(t)\ dt = \delta_{ij}$$



Detection of the Symbols

- Correlation or matched filter detector (basically equivalent)



$$\int_{t=0}^{T} s_1(t) \cdot s_2(t)\ dt = \delta_{ij}$$

=> Look at example waveform in HW 1

Digital Modulation

- Any modulated signal can be represented as

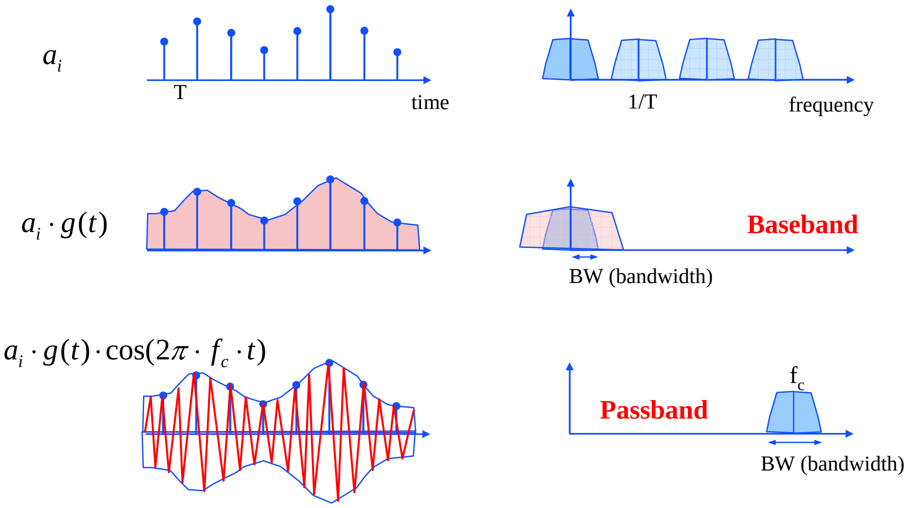
$$s(t) = \underset{\text{amplitude}}{A(t)} \cos [\omega_c t + \underset{\text{phase or frequency}}{\phi(t)}]$$

$$= \underbrace{A(t) \cos \phi(t) \cos \omega_c t}_{\text{in-phase}} - \underbrace{A(t) \sin \phi(t) \sin \omega_c t}_{\text{quadrature}}$$

- Linear versus nonlinear modulation
  ⇒ Impact on spectral efficiency

- Constant envelope versus non-constant envelope
  ⇒ hardware implications with impact on power efficiency

Frequency Domain



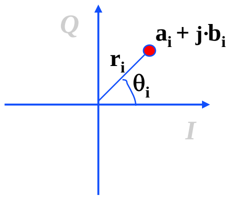
Alternative Interpretation

$$s_i(t) = a_i \cdot g(t) \cdot \cos(2\pi \cdot f_c \cdot t) - b_i \cdot g(t).\sin(2\pi \cdot f_c \cdot t)$$

$$s_i(t) = \mathrm{Re}\left[g(t) \cdot (a_i + j \cdot b_i) \cdot e^{j \cdot 2\pi \cdot f_c \cdot t}\right]$$

$$s_i(t) = \mathrm{Re}\left[g(t) \cdot \left(r_i \cdot e^{j\theta_i}\right) \cdot e^{j \cdot 2\pi \cdot f_c \cdot t}\right]$$

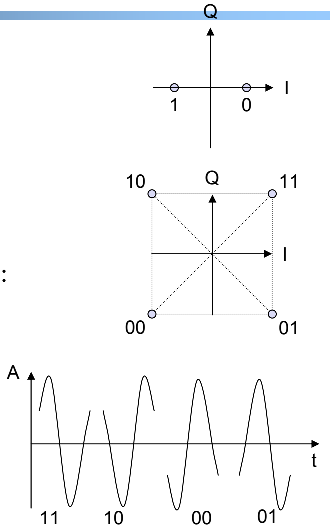
$$s_i(t) = \mathrm{Re}\left[g(t) \cdot r_i \cdot e^{j \cdot (2\pi \cdot f_c \cdot t + \theta_i)}\right]$$



$$s_i(t) = g(t) \cdot r_i \cdot \cos\left(2\pi \cdot f_c \cdot t + \theta_i\right)$$

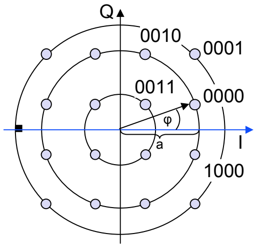
Advanced Phase Shift Keying

- BPSK (Binary Phase Shift Keying):
  - Bit value 0: sine wave
  - Bit value 1: inverted sine wave
  - Very simple PSK
  - Low spectral efficiency
  - Robust, used e.g. in satellite systems
- QPSK (Quadrature Phase Shift Keying):
  - 2 bits coded as one symbol
  - Symbol determines shift of sine wave
  - Needs less bandwidth compared to BPSK
  - More complex



Quadrature Amplitude Modulation

- Quadrature Amplitude Modulation (QAM): combines amplitude and phase modulation
- It is possible to code n bits using one symbol
- 2^n discrete levels, n=2 identical to QPSK
- bit error rate increases with n, but less errors compared to comparable PSK schemes



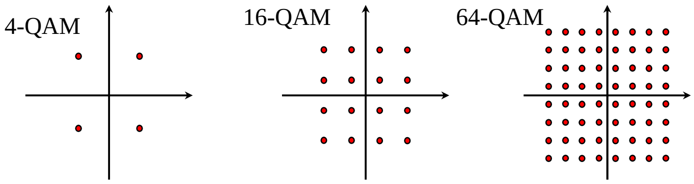
Example: 16-QAM (4 bits = 1 symbol)

Symbols 0011 and 0001 have the same phase φ, but different amplitude a. 0000 and 1000 have different phase, but same amplitude.

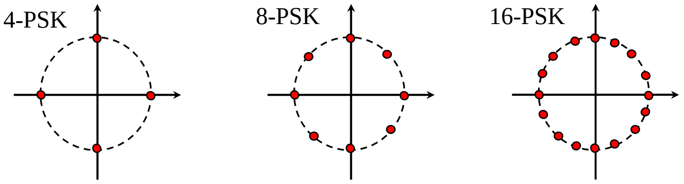
➔ used in standard 9600 bit/s modems

QAM and PSK

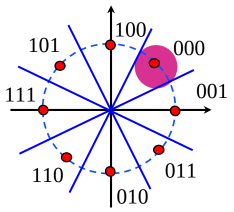
QAM (Quadrature Amplitude Modulation)

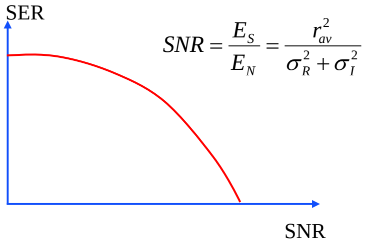


PSK (Phase Shift Keying)



Symbol Error





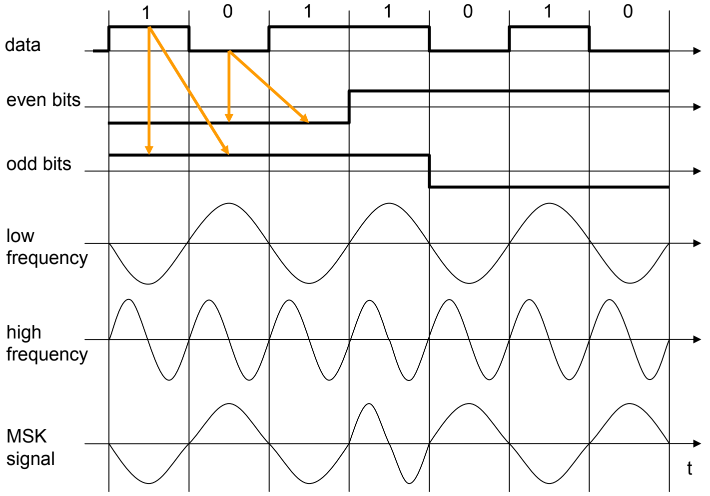
$$SNR = \frac{E_S}{E_N} = \frac{r_{av}^2}{\sigma_R^2 + \sigma_I^2} = \frac{r_{av}^2}{2 \cdot \sigma^2}$$

- The demodulator chooses the symbol that is closest to the received one (maximum likelihood decoding)
- If the noise (and distortions) is such that we are closer to another symbol than the correct one, a symbol error occurs.
- Each symbol error results in a number of bit errors. By carefully choosing the mapping from bits to symbols (Gray encoding), one symbol error typically results in just one bit error.

Advanced Frequency Shift Keying

- Bandwidth needed for FSK depends on the distance between the carrier frequencies
- Special pre-computation avoids sudden phase shifts
  ➔ MSK (Minimum Shift Keying)
  - Bit separated into even and odd bits, the duration of each bit is doubled
  - Depending on the bit values (even, odd) the higher or lower frequency, original or inverted is chosen
  - The frequency of one carrier is twice the frequency of the other
- Equivalent to offset QPSK
- Even higher bandwidth efficiency using a Gaussian low-pass filter
  ➔ GMSK (Gaussian MSK), used in GSM

Example of MSK



bit	
even	0 1 0 1
odd	0 0 1 1
signal value	h n n h - - + +

h: high frequency
n: low frequency
+: original signal
-: inverted signal

No phase shifts!

Selecting a Modulation Scheme (1)

- High Bit Rate
- Robustness to Impairments
  - Provides low bit error rates (BER) at low signal-to-noise ratios (SNR)
  - Performs well in multipath fading
  - Performs well in time varying channels (symbol timing jitter)
- High Spectral Efficiency: occupies minimal bandwidth
- High Power Efficiency
- Low cost and easy to implement
- Low carrier-to-cochannel interference ratio
- Low out of band radiation
- Constant or near-constant “envelope”
  - constant: only phase is modulated
    - may use efficient non-linear amplifiers
  - non-constant: phase and amplitude modulated
    - may need inefficient linear amplifiers

Selecting a Modulation Scheme (2)

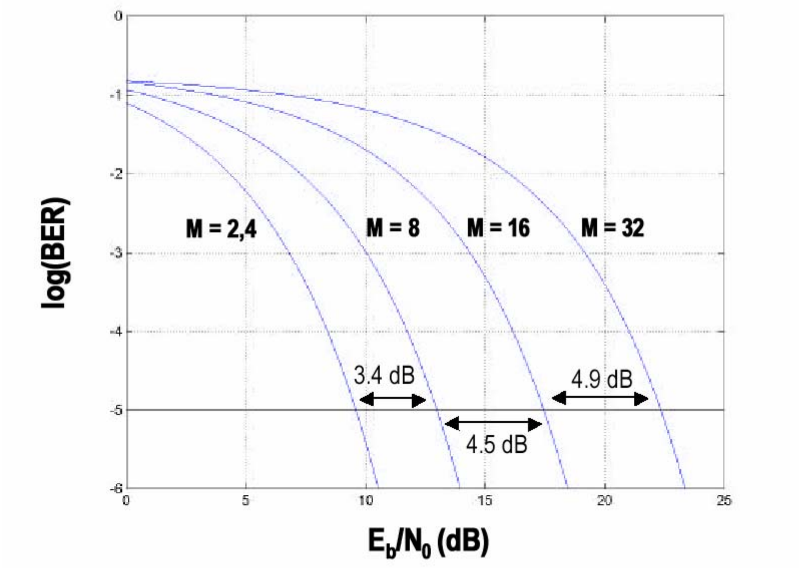
- Other design rationale
  - Smaller antennas (e.g., $\lambda/4$)
  - Frequency Division Multiplexing
  - Medium characteristics

No perfect modulation scheme - a matter of trade-offs!

Two metrics:

- Energy efficiency E_b/N_0 for a certain BER and
- Bandwidth efficiency R/B

Receiver Performance



Energy-Bandwidth Trade-off

	E_b/N_0	BW Eff.
BPSK	9.09	1
QPSK	9.09	2
8-PSK	19.82	3
16-PSK	55.41	4
32-PSK	171.20	5
8-QAM	13.93	3
16-QAM	22.05	4
32-QAM	34.67	5
BFSK	17.78	1
4-FSK	9.77	1
8-FSK	7.08	0.75
16-FSK	5.62	0.5
32-FSK	4.52	0.3125
GMSK	10	1.35

[redacted]