Wireless Sensor Networks
1. Basics

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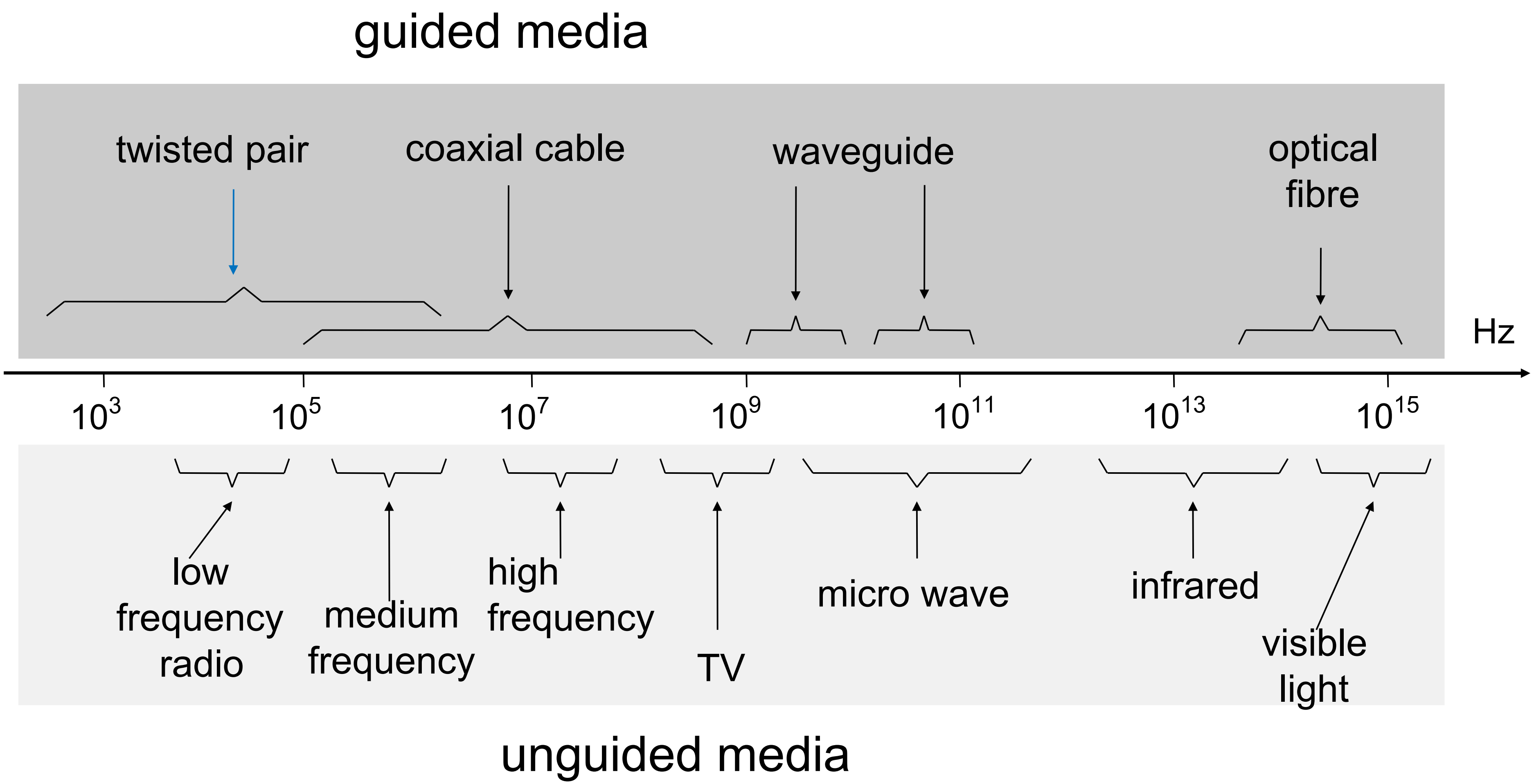
Physics – Background

- Moving particles with electric charge cause electromagnetic waves
  - frequency f : number of oscillations per second
    - unit: Hertz
  - wavelength λ: distance (in meters) between two wave maxima
  - antennas can create and receive electromagnetic waves
  - the transmission speed of electromagnetic waves in vacuum is constant
  - speed of light $c \approx 3 \cdot 108$ m/s
- Relation between wavelength, frequency and speed of light:

$$\lambda \cdot f = c$$

Electromagnetic Spectrum



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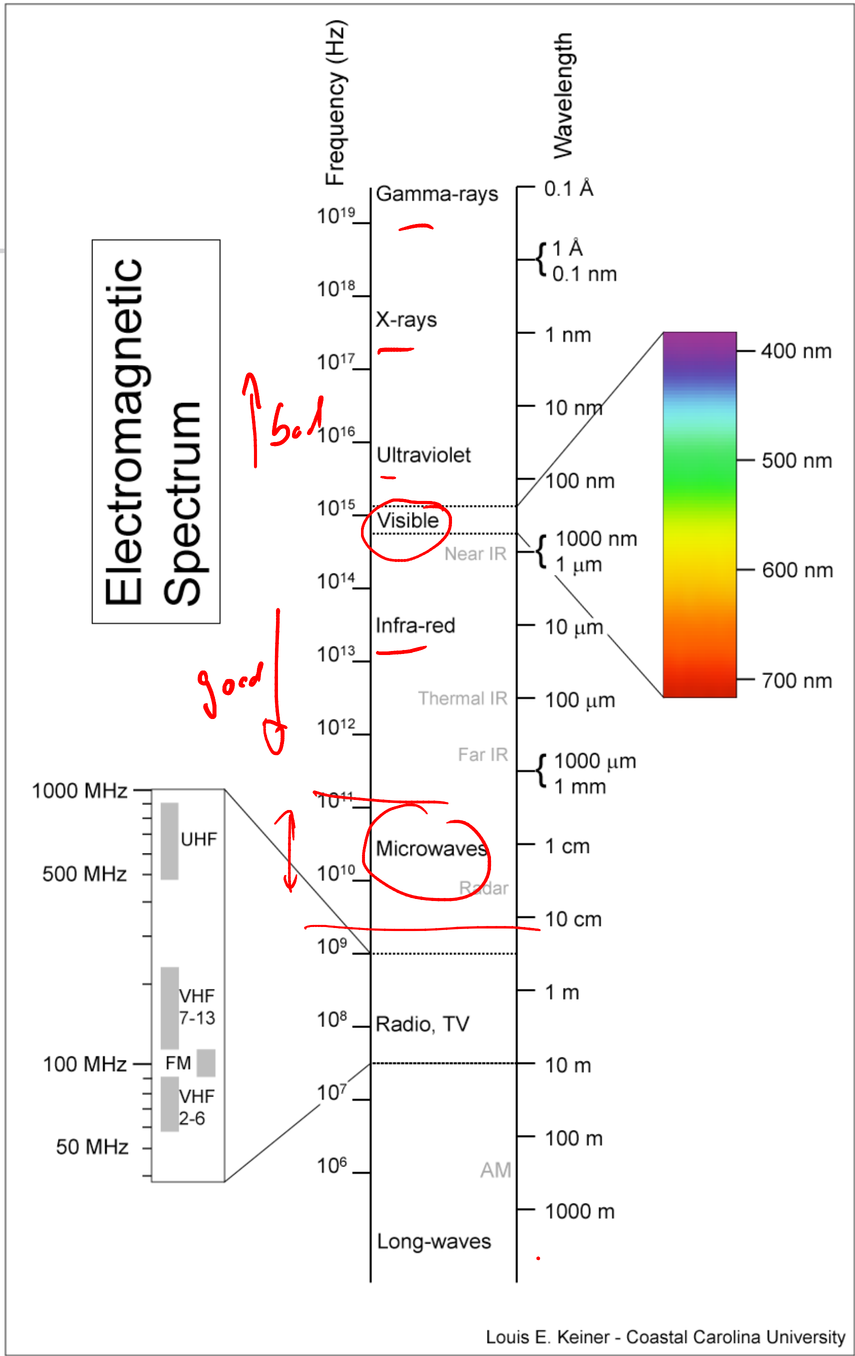
Bands

- LF Low Frequency
- MF Medium Frequency
- HF High Frequency
- VHF Very High Frequency
- UHF Ultra High Frequency
- UV Ultra Violet light



$\lambda \cdot f = c$

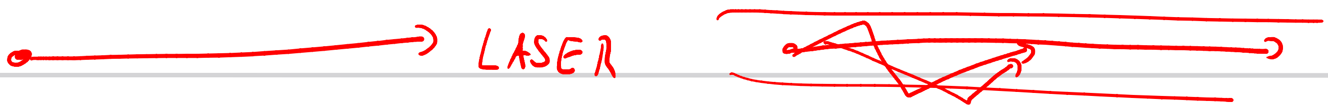
$c = \frac{\lambda}{t}$

$f = \frac{1}{t}$

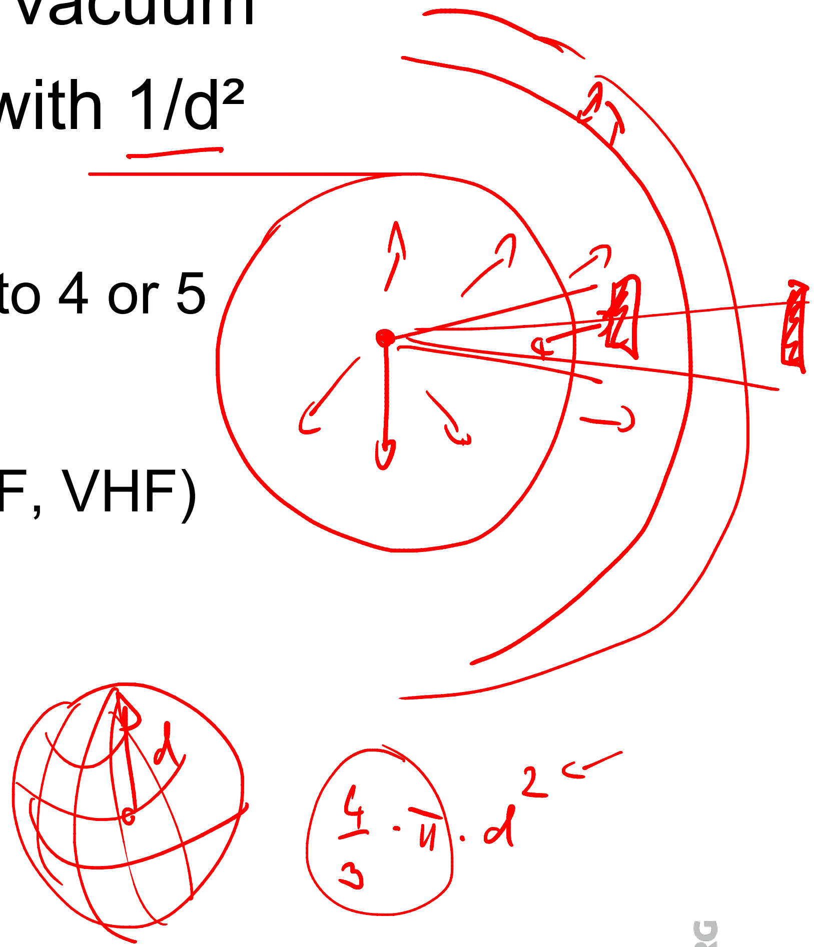
Bands for Wireless Networks

- VHF/UHF for mobile radio
  - antenna length
- SHF for point-to-point radio systems, satellite communication
- Wireless LAN: UHF to SHF
  - planned EHF
- Visible light
  - communication by laser
- Infrared
  - remote controls
  - LAN in closed rooms

Propagation Performance

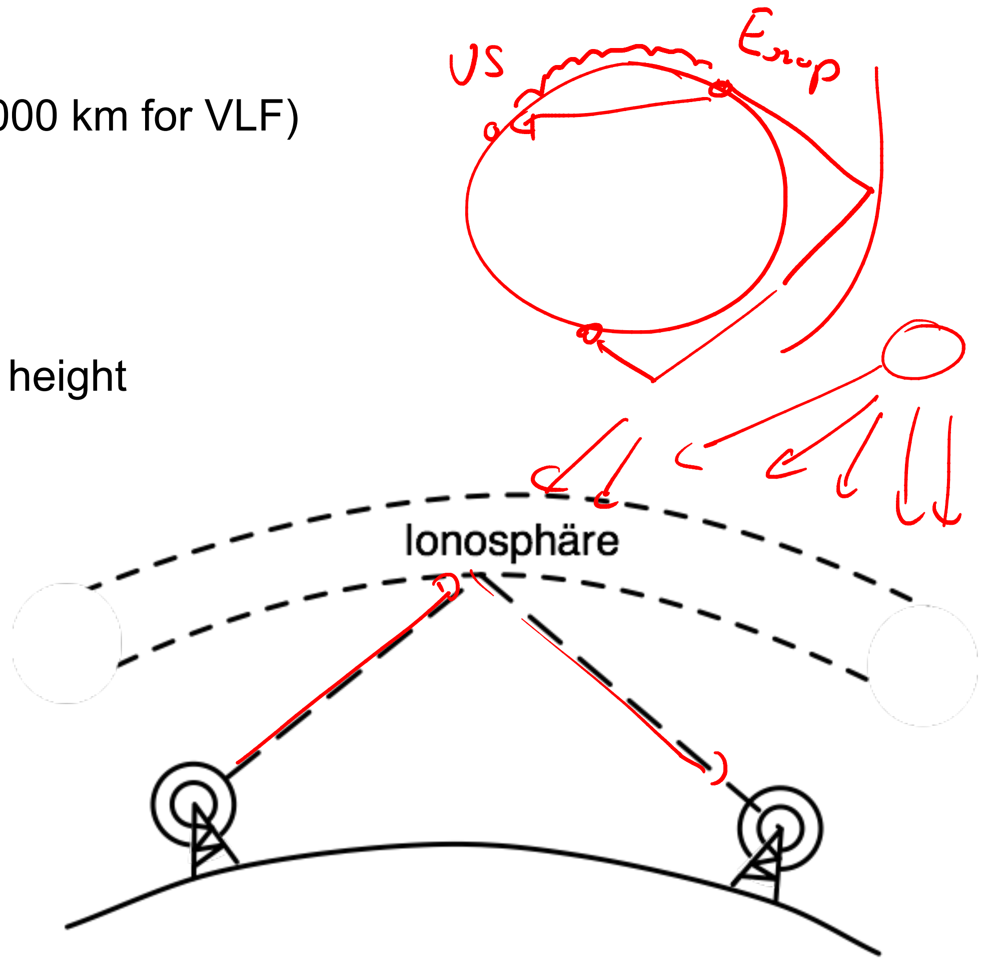


- Straight-lined propagation in vacuum
- Received power decreases with $1/d^2$
  - in theory
  - in practice higher exponents up to 4 or 5
- Reduction because of
  - attenuation in air (in particular HF, VHF)
  - shadowing and mountain effect
  - reflection
  - diffusion at small obstacles
  - diffraction



Frequency Dependent Behavior

- VLF, LF, MF
  - follow the curvature of the earth (up to 1000 km for VLF)
  - permeate buildings
- HF, VHF
  - absorbed by the ground
  - reflected by the ionosphere 100-500 km height
- Over 100 MHz
  - straight-line propagation
  - marginal penetration of buildings
  - good focus
- Over 8 GHz absorption by rainfall



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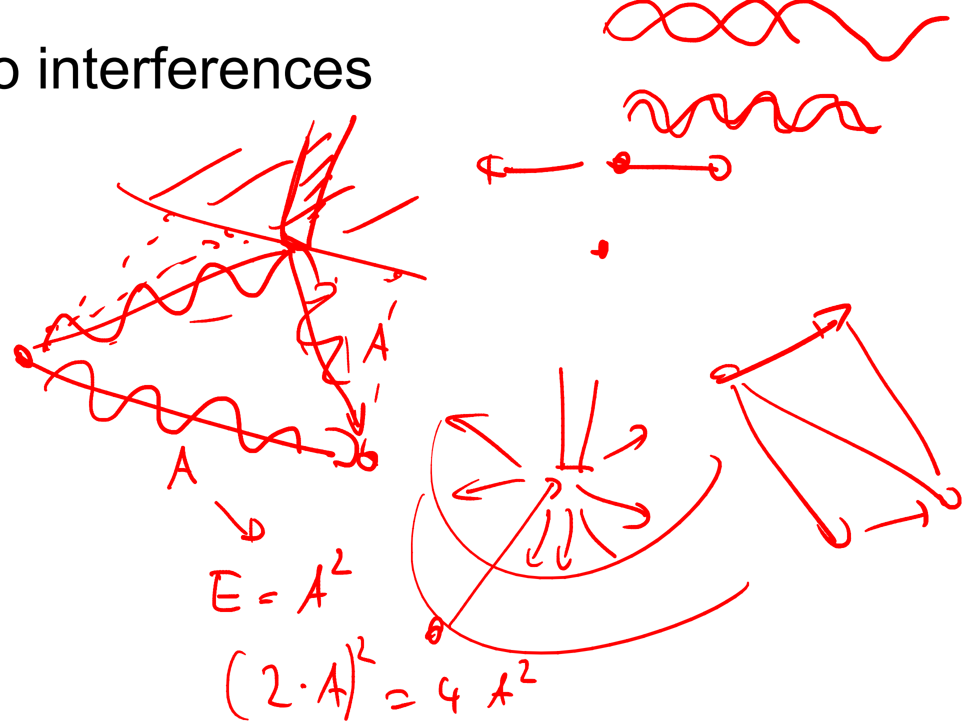
Problems

- Multiple Path Fading
  - Signal arrives at receiver on multiple paths because of reflection, diffusion, and diffraction
  - Signal time variation leads to interferences
    - decoding faults
    - attenuation
- Mobility problems
  - Fast fading
    - different transmission paths
    - different phasing
  - Slow fading
    - increase of distance between sender and receiver



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Noise and Interference

- Noise
  - inaccuracies and heat development in electrical components
  - modeled by normal distribution
- Interference from other transmitters
  - in the same spectrum
  - or in neighbored spectrum
    - e.g. because of bad filters
- Effect
  - Signal is disrupted

Signal Interference Noise Ratio

- reception energy = transmission energy / path loss
  - path loss ~ $1/d^{\gamma}$ α
  - α $\gamma \in [2,5]$
- Signal to Interference and Noise Ratio = SINR
  - S = (desired) Signal energy
  - I = energy of Interfering signals
  - N = Noise

SNR

- Necessary condition for reception

$$\text{SINR} = \frac{S}{I+N} \geq \mathit{Threshold}$$

Path Loss

- Attenuatation
  - Received signal power depends on the distance d between sender and receiver
- Friis transmission equation
  - distance: R
  - wavelength: λ
  - P_r: energy at receiver antenna
  - P_t: energy at sender antenna
  - G_t: sender antenna gain
  - G_r: receiver antenna gain

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2$$

$$P_r(d) = P_r(d_0) \cdot \left(\frac{d_0}{d} \right)^2$$

Path Loss Exponent

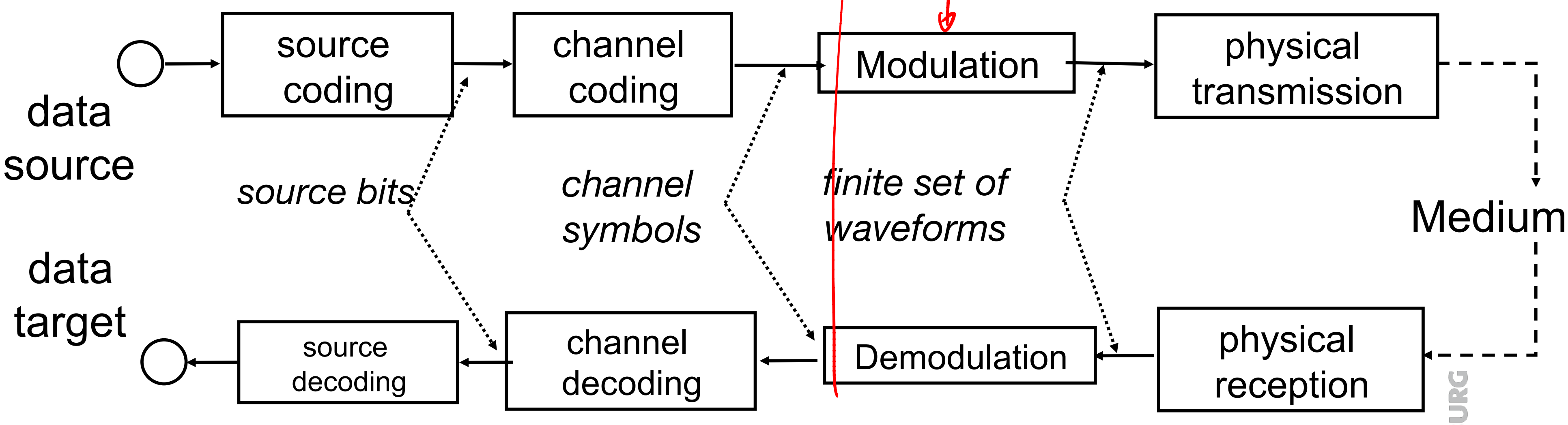
- Measurements
  - path loss exponent
  - shadowing variance σ^2
  - reference path loss at 1m distance

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]

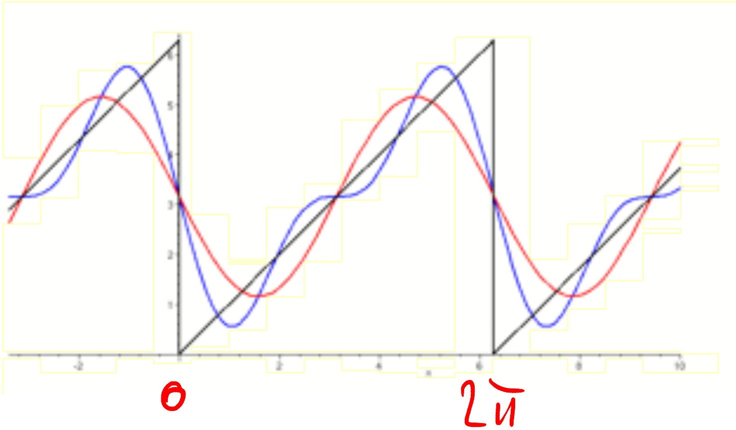
Karl, Willig, Protocols and Architectures for Wireless Sensor Networks, Wiley, 2005

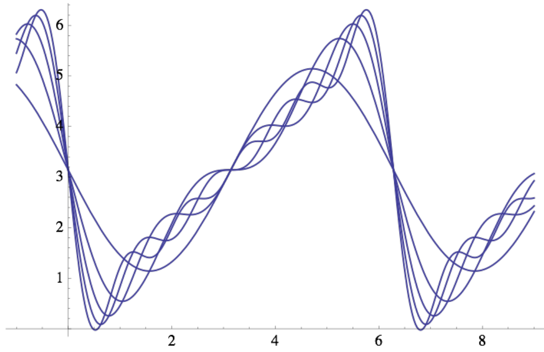
Structure of a *Broadband* Digital transmission

- MOdulation/DEModulation
  - Translation of the channel symbols by
    - amplitude modulation
    - phase modulation
    - frequency modulation
    - or a combination thereof



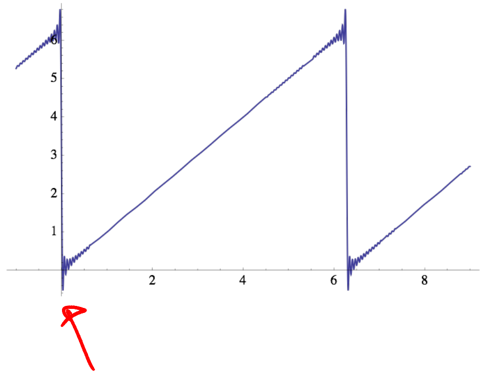
Computation of Fourier Coefficients

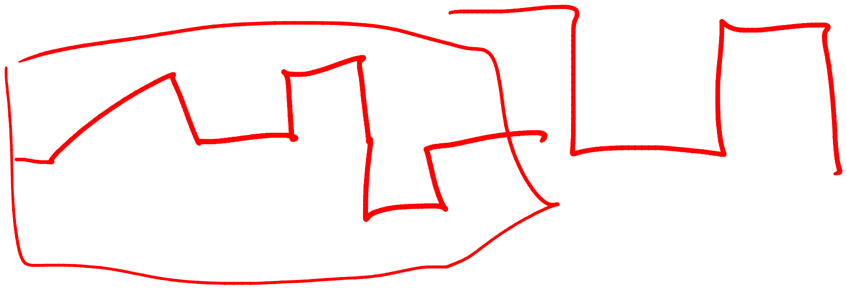




$$f(x) = x \text{ , für } 0 < x < 2\pi$$

$$f(x) = \pi - 2\left(\frac{\sin x}{1} + \frac{\sin 2x}{2} + \frac{\sin 3x}{3} + \ldots\right)$$





Fourier Analysis for General Period

- Theorem of Fourier for period T=1/f:
  - The coefficients c, a_n, b_n are then obtained as follows

$$g(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} a_k \cos(2\pi k f t) + b_k \sin(2\pi k f t)$$

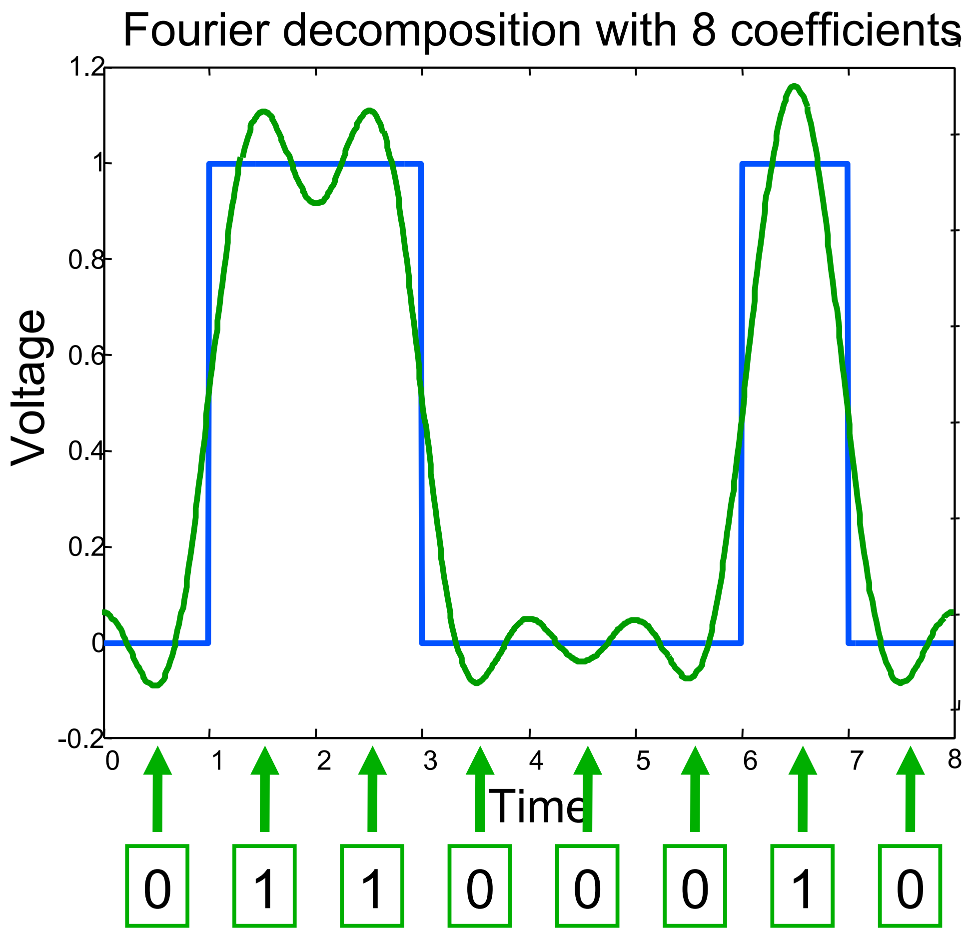
$$a_k = \frac{2}{T}\int_0^T g(t)\cos(2\pi n f t)dt$$

$$b_k = \frac{2}{T}\int_0^T g(t)\sin(2\pi n f t)dt$$

- The sum of squares of the k-th terms is proportional to the energy consumed in this frequency: $(a_k)^2 + (b_k)^2$

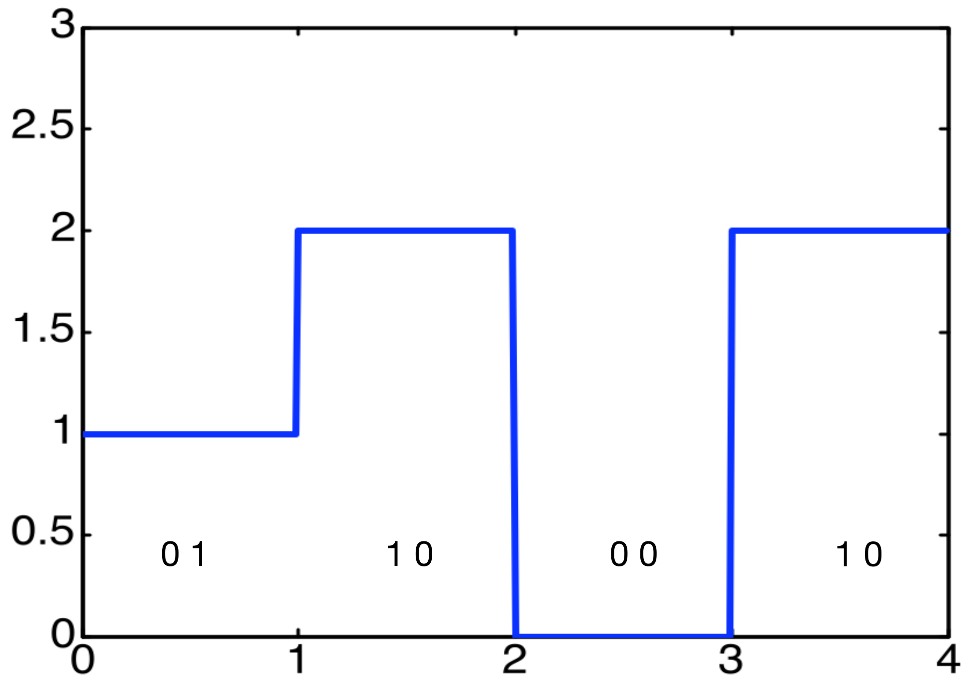
How often do you measure?

- How many measurements are necessary
  - to determine a Fourier transform to the k-th component, exactly?
- Nyquist-Shannon sampling theorem
  - To reconstruct a continuous band-limited signal with a maximum frequency f_{max} you need at least a sampling frequency of 2 f_{max}.



Symbols and Bits

- For data transmission instead of bits can also be used symbols
  - E.g. 4 Symbols: A, B, C, D
    - A = 00, B = 01, C = 10, D =
- Symbols
  - Measured in baud
  - Number of symbols per se
- Data rate
  - Measured in bits per secor
  - Number of bits per second
- Example
  - 2400 bit/s modem is 600 baud (uses 16 symbols)



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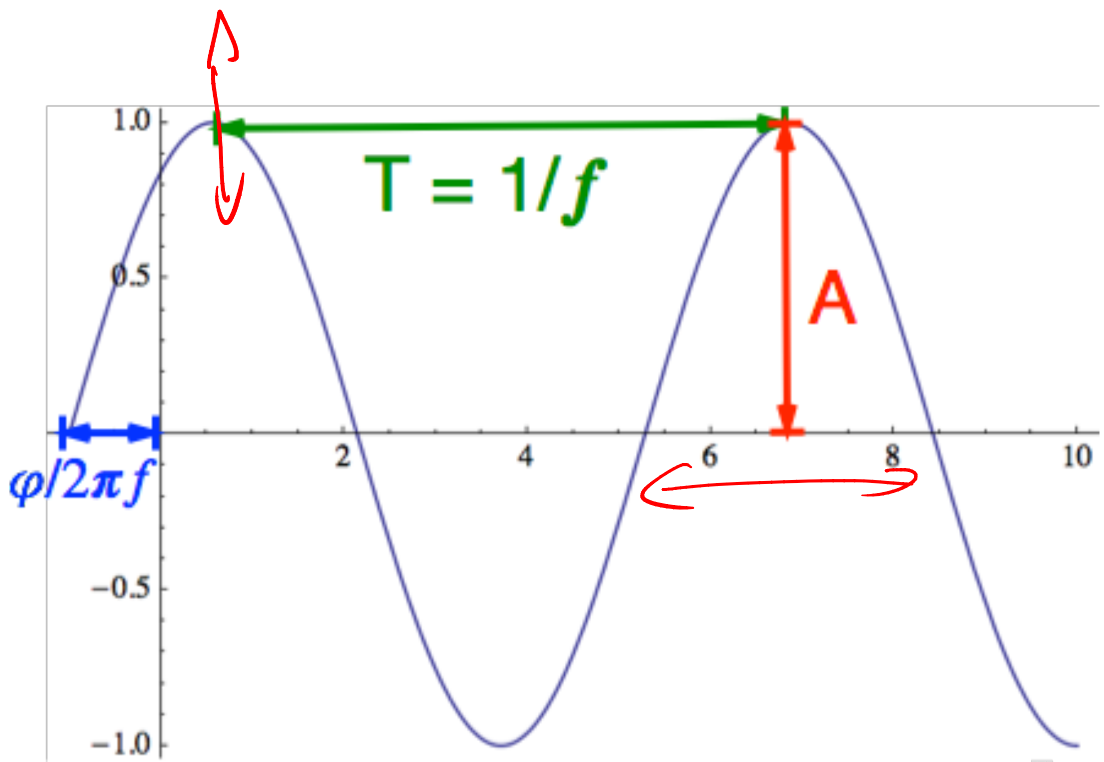
Broadband

- Idea
  - Focusing on the ideal frequency of the medium
  - Using a sine wave as the carrier wave signals
- A sine wave has no information
  - the sine curve continuously (modulated) changes for data transmission,
  - implies spectral widening (more frequencies in the Fourier analysis)
- The following parameters can be changed:
  - Amplitude A
  - Frequency f=1/T
  - Phase φ

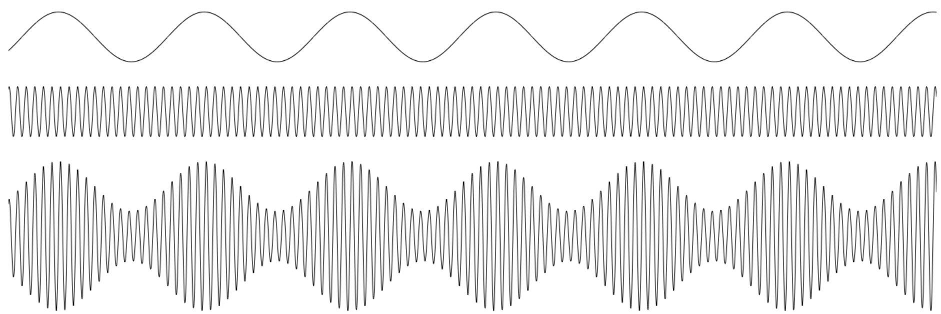
$$s(t) = A\sin(2\pi f t + \phi)$$



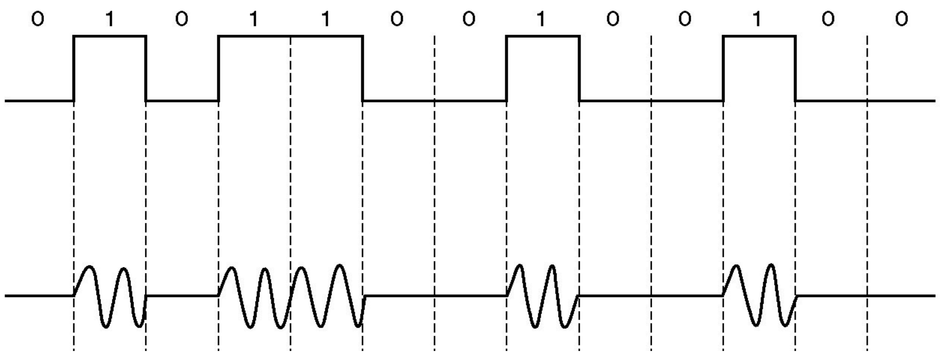
Amplitude Modulation

- The time-varying signal s (t) is encoded as the amplitude of a sine curve:

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

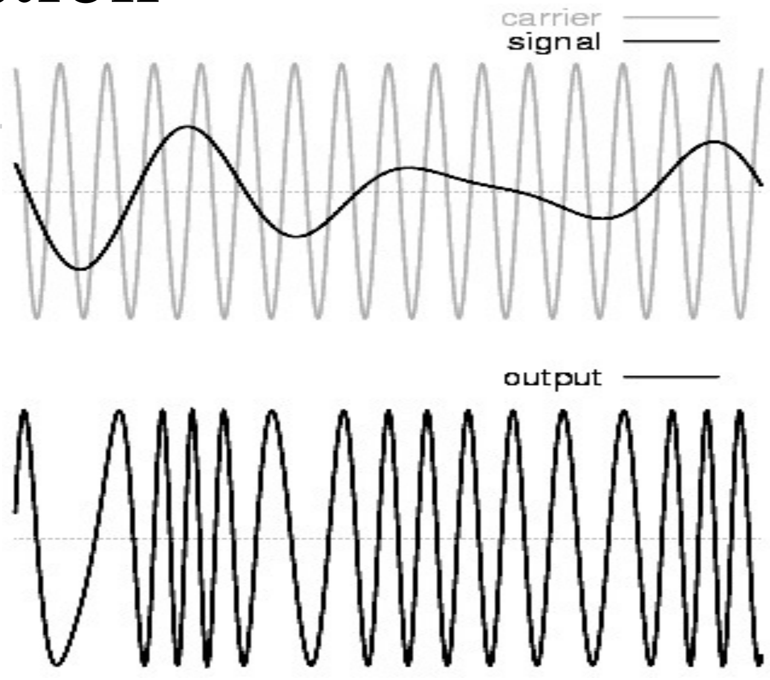


- Analog Signal
- Digital signal
  - amplitude keying
  - special case: symbols 0 or 1
    - on / off keying



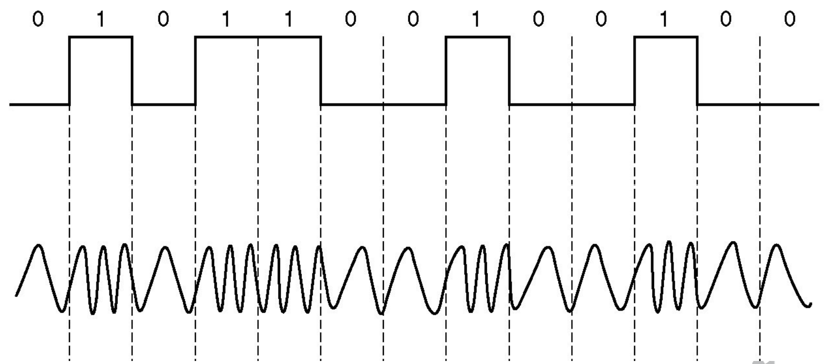
Frequency Modulation

- The time-varying signal s (t) is encoded in the frequency of the sine curve:



$$f_F(t) = a \sin(2\pi s(t) t + \phi)$$

- Analog signal
  - Frequency modulation (FM)
  - Continuous function in time
- Digital signal
  - Frequency Shift Keying (FSK)
  - E.g. frequencies as given by symbols

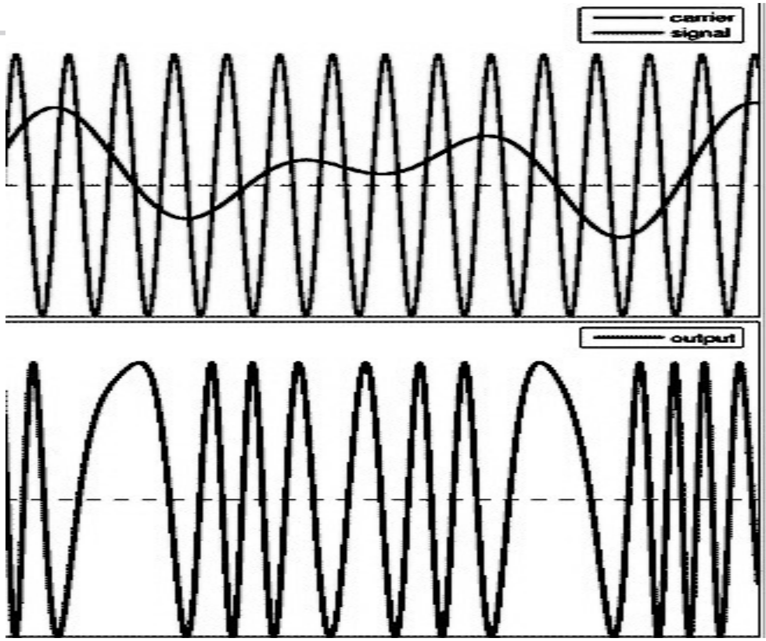


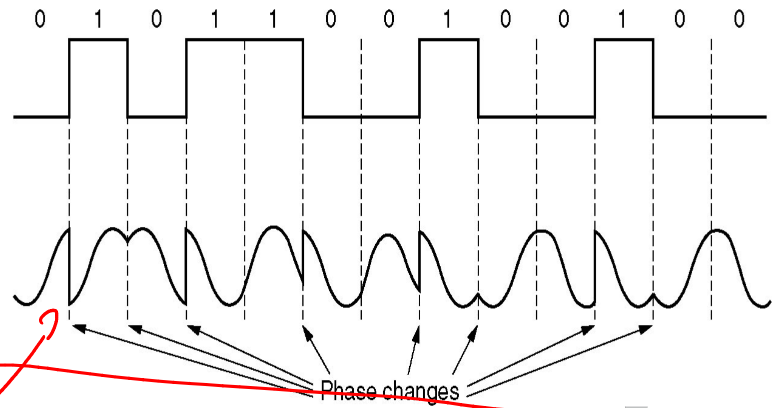
Phase Modulation

- The time-varying signal s (t) is encoded in the phase of the sine curve:

$$f_P(t) = a \sin(2\pi f t + s(t))$$

- Analog signal
  - phase modulation (PM)
  - very unfavorable properties
  - es not used
- Digital signal
  - phase-shift keying (PSK)
  - e.g. given by symbols as phases





Digital and Analog signals in Comparison

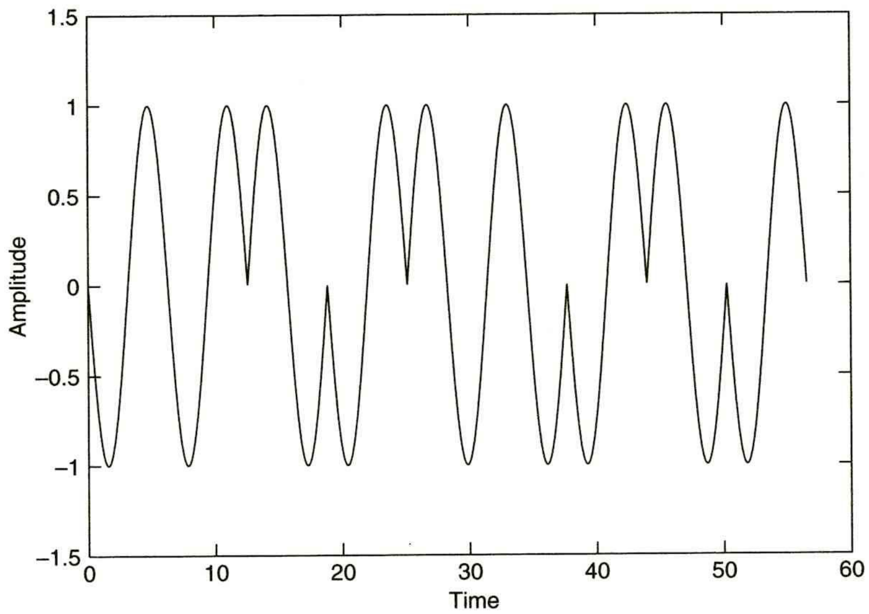
- For a station there are two options
  - digital transmission
    - finite set of discrete signals
    - e.g. finite amount of voltage sizes / voltages
  - analog transmission
    - Infinite (continuous) set of signals
    - E.g. Current or voltage signal corresponding to the wire
- Advantage of digital signals:
  - There is the possibility of receiving inaccuracies to repair and reconstruct the original signal
  - Any errors that occur in the analog transmission may increase further

Phase Shift Keying (PSK)

- For phase signals $\phi_i(t)$

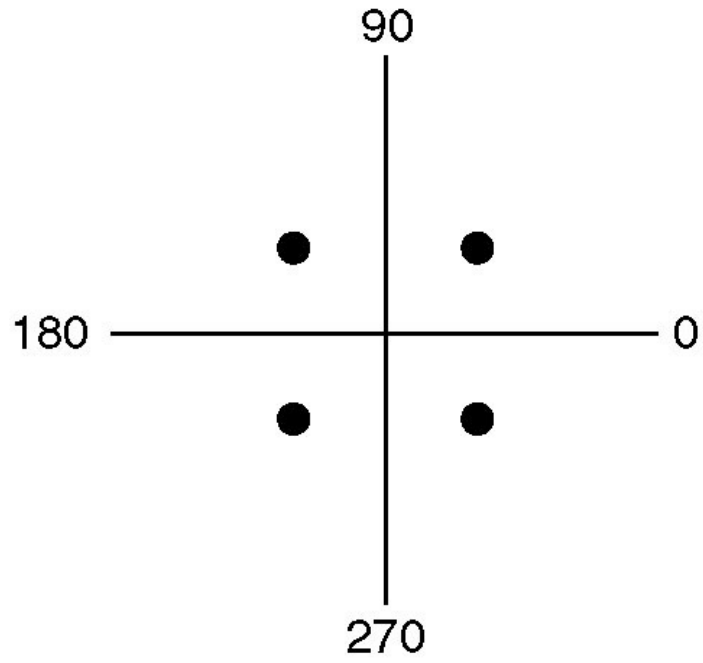
$$s_i(t) = \sqrt{\frac{2E}{T}} \cdot \sin(\omega_0 t + \phi_i(t))$$

- Example:



PSK with Different Symbols

- Phase shifts can be detected by the receiver very well
- Encoding various Symoble very simple
  - Using phase shift e.g. π / 4, 3/4π, 5/4π, 7/4π
    - rarely: phase shift 0 (because of synchronization)
  - For four symbols, the data rate is twice as large as the symbol rate
- This method is called Quadrature Phase Shift Keying (QPSK)



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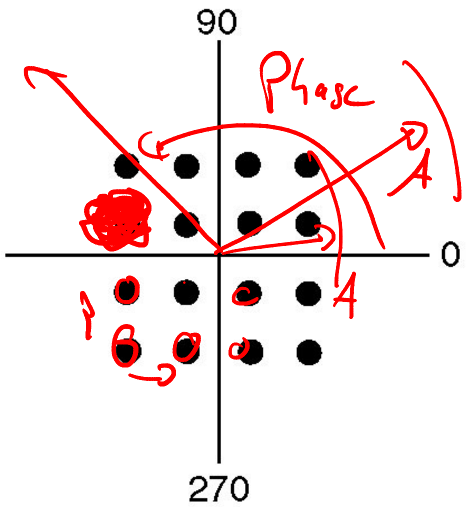
Amplitude and Phase Modulation

- Amplitude and phase modulation can be successfully combined
  - Example: 16-QAM (Quadrature Amplitude Modulation)
    - uses 16 different combinations of phases and amplitudes for each symbol
    - Each symbol encodes four bits ($2^4 = 16$)
  - The data rate is four times as large as the symbol rate



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