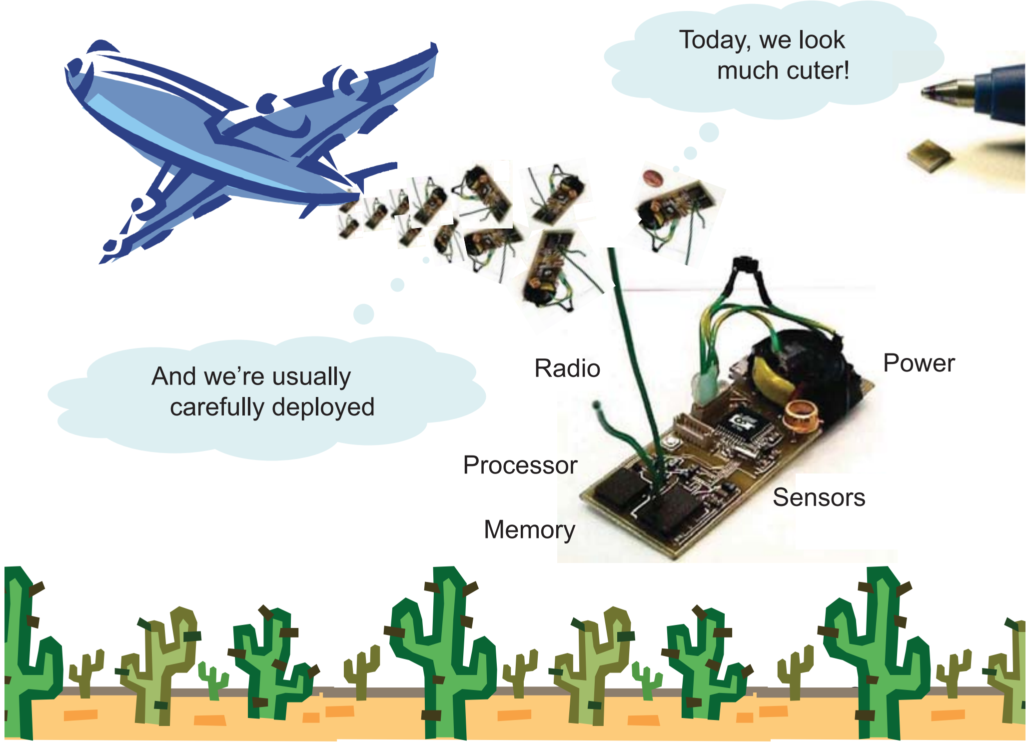
Introduction

Chapter 1

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich



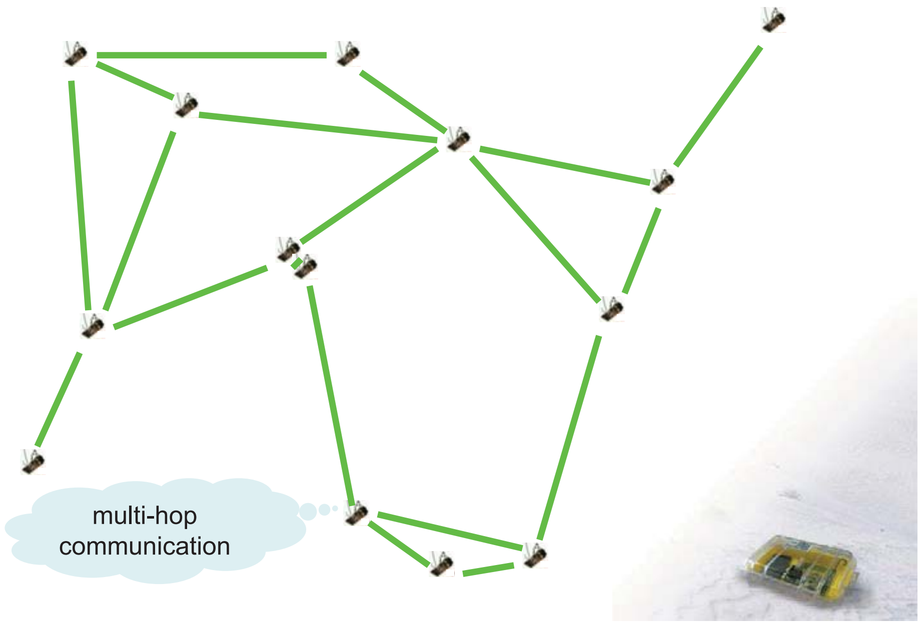
A Typical Sensor Node: TinyNode 584

[Shockfish SA, The Sensor Network Museum]

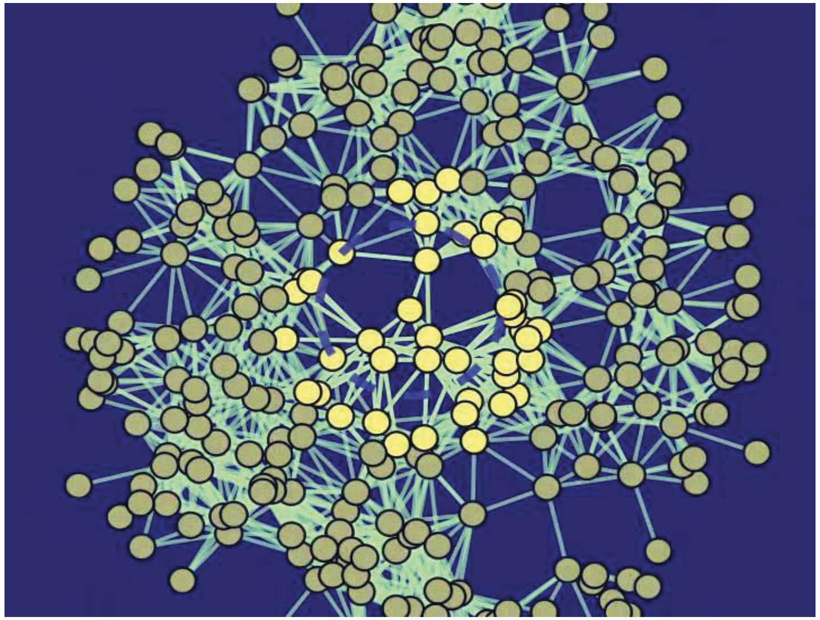
- TI MSP430F1611 microcontroller @ 8 MHz
- 10k SRAM, 48k flash (code), 512k serial storage
- 868 MHz Xemics XE1205 multi channel radio
- Up to 115 kbps data rate, 200m outdoor range

	Current Draw	Power Consumption
uC sleep with timer on	6.5 uA	0.0195 mW
uC active, radio off	2.1 mA	6.3 mW
uC active, radio idle listening	16 mA	48 mW
uC active, radio TX/RX at +12dBm	62 mA	186 mW
Max. Power (uC active, radio TX/RX at +12dBm + flash write)	76.9 mA	230.7mW

After Deployment



Visuals anyone?



Ad Hoc Networks vs. Sensor Networks

Ad Hoc Networks	Sensor Networks
Laptops, PDA's, cars, soldiers	Tiny nodes: 4 MHz, 32 kB, …
All-to-all routing	Broadcast/Echo from/to sink
Often with mobility (MANET's)	Usually no mobility – but link failures
Trust/Security an issue – No central coordinator	One administrative control
Maybe high bandwidth	Long lifetime → Energy

There is no strict separation; more variants such as mesh or sensor/actor networks exist

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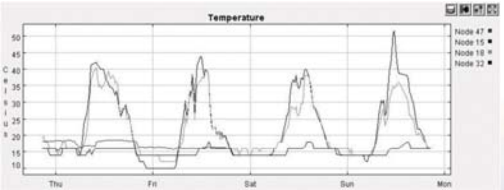
Overview

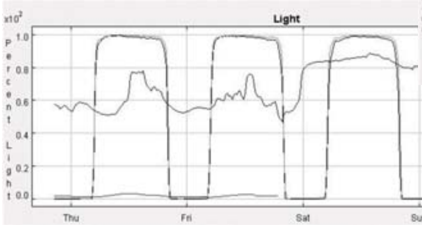
- Introduction
- Application Examples
- Related Areas
- Course Overview
- Literature

- For CS Students: Wireless Communication Basics
- For EE Students: Network Algorithms Overview

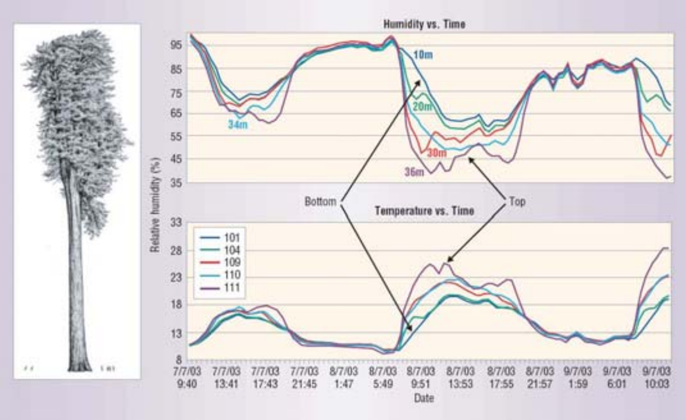
Animal Monitoring (Great Duck Island)

1. Biologists put sensors in underground nests of storm petrel
2. And on 10cm stilts
3. Devices record data about birds
4. Transmit to research station
5. And from there via satellite to lab





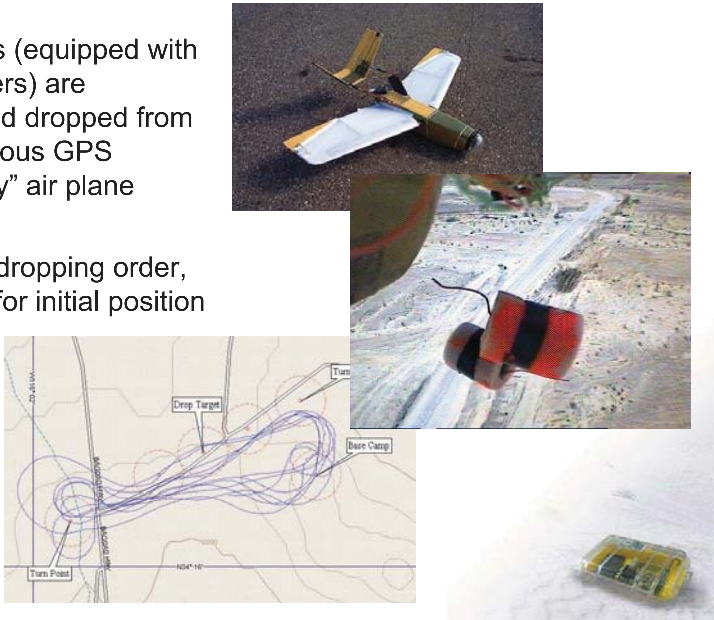
Environmental Monitoring (Redwood Tree)



- Microclimate in a tree
- 10km less cables on a tree; easier to set up
- Sensor Network = The New Microscope?

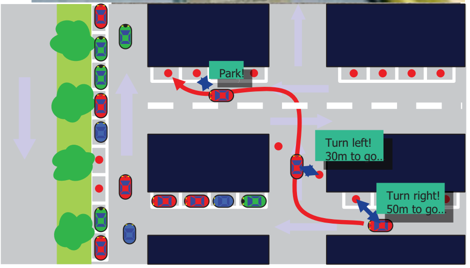
Vehicle Tracking

- Sensor nodes (equipped with magnetometers) are packaged, and dropped from fully autonomous GPS controlled “toy” air plane
- Nodes know dropping order, and use that for initial position guess
- Nodes then track vehicles (trucks mostly)



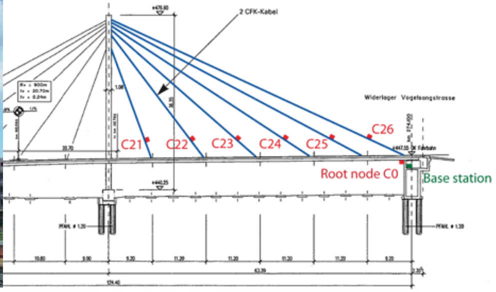
Smart Spaces (Car Parking)

- The good: Guide cars towards empty spots
- The bad: Check which cars do not have any time remaining
- The ugly: Meter running out: take picture and send fine



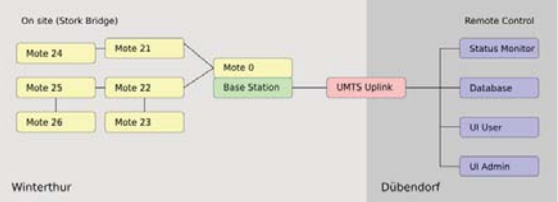
[Matthias Grossglauser, EPFL & Nokia Research]

Structural Health Monitoring (Bridge)



Swiss Made [EMPA]

Detect structural defects, measuring temperature, humidity, vibration, etc.


On site (Stork Bridge)

Mote 24
Mote 21
Mote 25
Mote 22
Mote 26
Mote 23
Mote 0
Base Station
UMTS Uplink

Remote Control

Status Monitor
Database
UI User
UI Admin

Winterthur

Dübendorf

Virtual Fence (CSIRO Australia)

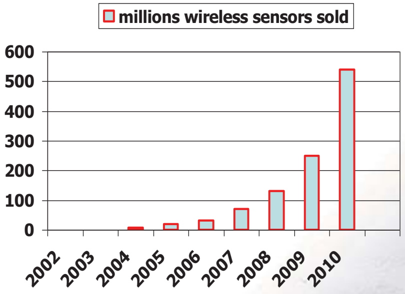
- Download the fence to the cows. Today stay here, tomorrow go somewhere else.
- When a cow strays towards the co-ordinates, software running on the collar triggers a stimulus chosen to scare the cow away, a sound followed by an electric shock; this is the "virtual" fence. The software also "herds" the cows when the position of the virtual fence is moved.
- If you just want to make sure that cows stay together, GPS is not really needed…

Cows learn and need not to be shocked later… Moo!

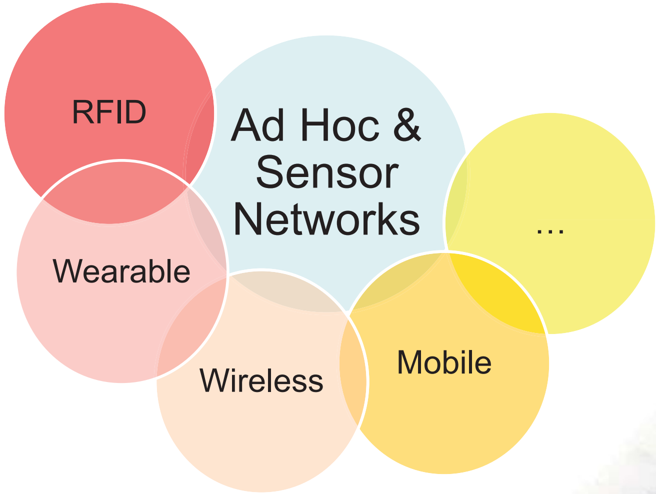
Economic Forecast

[Jean-Pierre Hubaux, EPFL]

- Industrial Monitoring (35% – 45%)
    - Monitor and control production chain
    - Storage management
    - Monitor and control distribution
- Building Monitoring and Control (20 – 30%)
    - Alarms (fire, intrusion etc.)
    - Access control
- Home Automation (15 – 25%)
    - Energy management (light, heating, AC etc.)
    - Remote control of appliances
- Automated Meter Reading (10-20%)
    - Water meter, electricity meter, etc.
- Environmental Monitoring (5%)
    - Agriculture
    - Wildlife monitoring



Related Areas



RFID

Ad Hoc & Sensor Networks

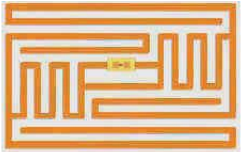
…

Wearable

Wireless

Mobile

RFID Systems



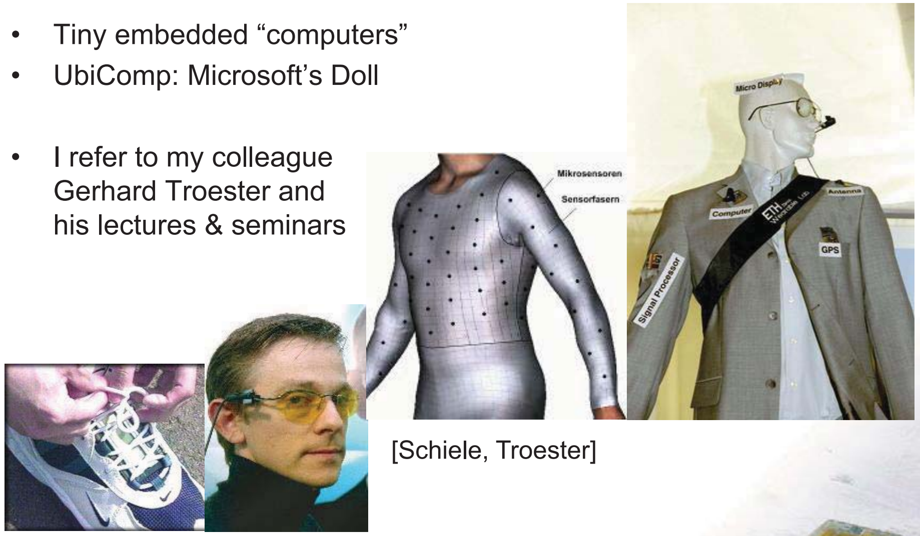
- Fundamental difference between ad hoc/sensor networks and RFID: In RFID there is always the distinction between the passive tags/transponders (tiny/flat), and the reader (bulky/big).
- There is another form of tag, the so-called active tag, which has its own internal power source that is used to power the integrated circuits and to broadcast the signal to the reader. An active tag is similar to a sensor node.

- More types are available, e.g. the semi-passive tag, where the battery is not used for transmission (but only for computing)

Wearable Computing / Ubiquitous Computing

- Tiny embedded “computers”
- UbiComp: Microsoft’s Doll

- I refer to my colleague Gerhard Troester and his lectures & seminars



[Schiele, Troester]

Wireless and/or Mobile

- Aspects of mobility
  - User mobility: users communicate “anytime, anywhere, with anyone” (example: read/write email on web browser)
  - Device portability: devices can be connected anytime, anywhere to the network
- Wireless vs. mobile Examples

Wireless	mobile	Examples
✗	✗	Stationary computer
✗	✓	Notebook in a hotel
✓	✗	Historic buildings; last mile
✓	✓	Personal Digital Assistant (PDA)

- The demand for mobile communication creates the need for integration of wireless networks and existing fixed networks
  - Local area networks: standardization of IEEE 802.11 or HIPERLAN
  - Wide area networks: GSM and ISDN
  - Internet: Mobile IP extension of the Internet protocol IP

Wireless & Mobile Examples

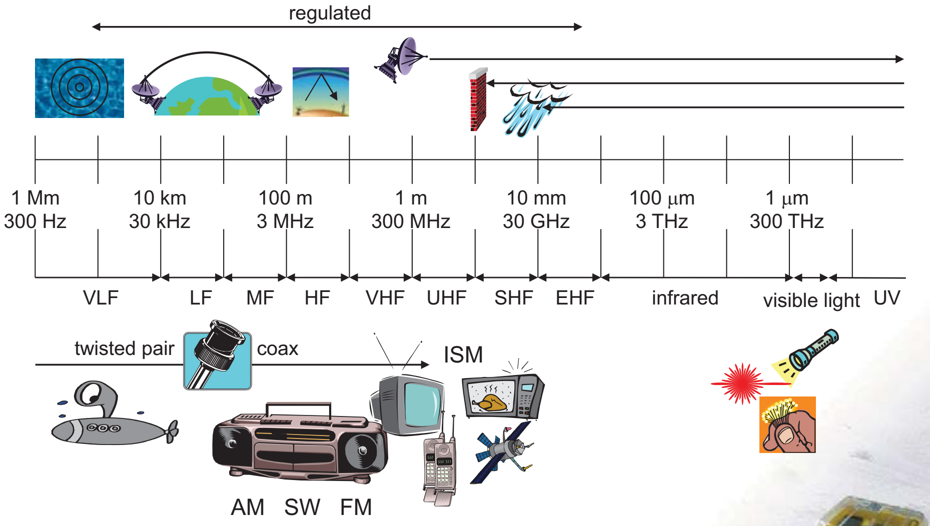
- Up-to-date localized information
  - Map
  - Pull/Push
- Ticketing
- Etc.

[Asus PDA, iPhone, Blackberry, Cybiko]

General Trend: A computer in 10 years?

- Advances in technology
  - More computing power in smaller devices
  - Flat, lightweight displays with low power consumption
  - New user interfaces due to small dimensions
  - More bandwidth (per second? per space?)
  - Multiple wireless techniques
- Technology in the background
  - Device location awareness: computers adapt to their environment
  - User location awareness: computers recognize the location of the user and react appropriately (call forwarding)
- “Computers” evolve
  - Small, cheap, portable, replaceable
  - Integration or disintegration?

Physical Layer: Wireless Frequencies



Frequencies and Regulations

- ITU-R holds auctions for new frequencies, manages frequency bands worldwide (WRC, World Radio Conferences)

	Europe (CEPT/ETSI)	USA (FCC)	Japan
Mobile phones	**NMT** 453-457MHz, 463-467 MHz **GSM** 890-915 MHz, 935-960 MHz, 1710-1785 MHz, 1805-1880 MHz	**AMPS**, **TDMA**, **CDMA** 824-849 MHz, 869-894 MHz **TDMA**, **CDMA**, **GSM** 1850-1910 MHz, 1930-1990 MHz	**PDC** 810-826 MHz, 940-956 MHz, 1429-1465 MHz, 1477-1513 MHz
Cordless telephones	**CT1+** 885-887 MHz, 930-932 MHz **CT2** 864-868 MHz **DECT** 1880-1900 MHz	**PACS** 1850-1910 MHz, 1930-1990 MHz **PACS-UB** 1910-1930 MHz	**PHS** 1895-1918 MHz **JCT** 254-380 MHz
Wireless LANs	**IEEE 802.11** 2400-2483 MHz **HIPERLAN 1** 5176-5270 MHz	**IEEE 802.11** 2400-2483 MHz	**IEEE 802.11** 2471-2497 MHz

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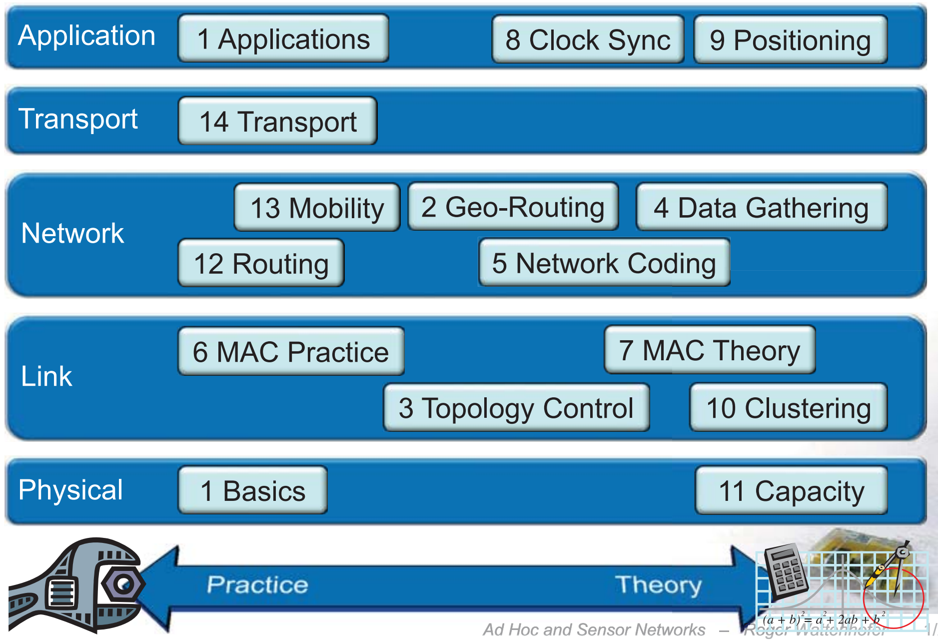
Course Overview



Application: 1 Applications, 8 Clock Sync, 9 Positioning

Transport: 14 Transport

Network: 13 Mobility, 2 Geo-Routing, 4 Data Gathering, 12 Routing, 5 Network Coding

Link: 6 MAC Practice, 7 MAC Theory, 3 Topology Control, 10 Clustering

Physical: 1 Basics, 11 Capacity

Course Overview: Lecture and Exercises

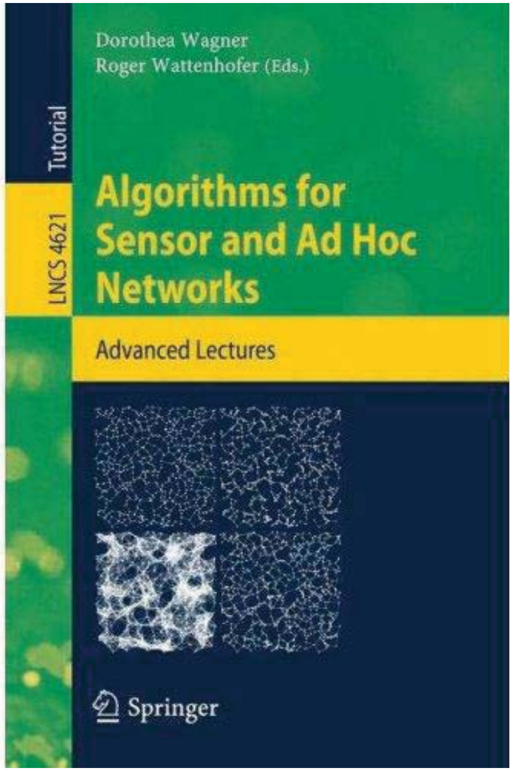
- Maximum possible spectrum of theory and practice
- New area, more open than closed questions
- Each week, exactly one topic (chapter)

- General ideas, concepts, algorithms, impossibility results, etc.
  - Most of these are applicable in other contexts
  - In other words, almost no protocols

- Two types of exercises: theory/paper, practice/lab
- Assistants: Philipp Sommer, Johannes Schneider

- www.disco.ethz.ch → courses

Literature


Dorothea Wagner
Roger Wattenhofer (Eds.)

Tutorial

LNCS 4621

Algorithms for Sensor and Ad Hoc Networks

Advanced Lectures

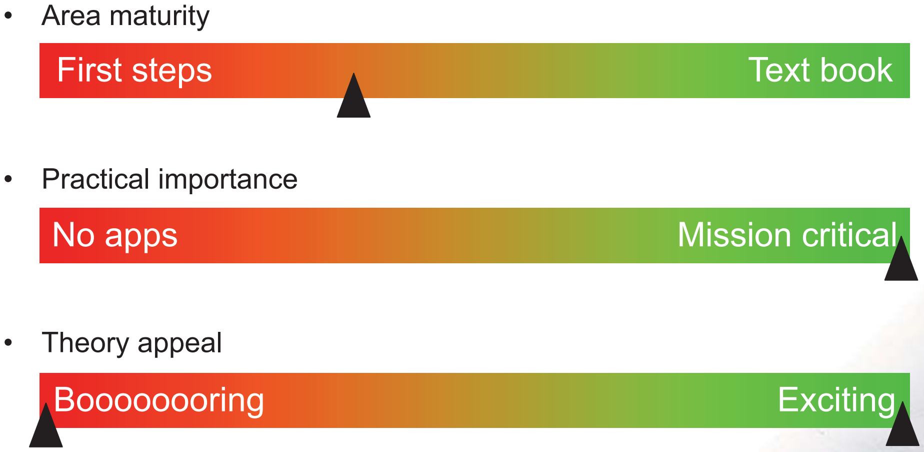
Springer

More Literature

- Bhaskar Krishnamachari – *Networking Wireless Sensors*
- Paolo Santi – *Topology Control in Wireless Ad Hoc and Sensor Networks*
- F. Zhao and L. Guibas – *Wireless Sensor Networks: An Information Processing Approach*
- Ivan Stojmeniovic – *Handbook of Wireless Networks and Mobile Computing*
- C. Siva Murthy and B. S. Manoj – *Ad Hoc Wireless Networks*
- Jochen Schiller – *Mobile Communications*
- Charles E. Perkins – *Ad-hoc Networking*
- Andrew Tanenbaum – *Computer Networks*

- *Plus tons of other books/articles*
- *Papers, papers, papers, …*

Rating (of Applications)


- Area maturity

- Practical importance

- Theory appeal

Open Problem

- Well, the open problem for this chapter is obvious:

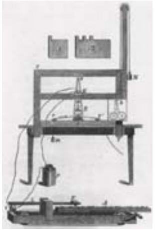
- Find the killer application! Get rich and famous!!

…this lecture is only superficially about ad hoc and sensor networks. In reality it is about new (and hopefully exciting) networking paradigms!

For CS Students: Wireless Communication Basics

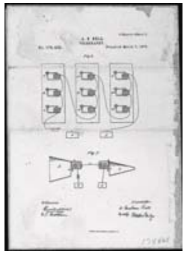
- Brief history of communication
- Frequencies
- Signals
- Antennas
- Signal Propagation
- Modulation

A brief history of communication



- Electric telegraph invented in 1837 by Samuel Morse
- First long distance transmission between Washington, D.C. and Baltimore, Maryland in 1844: «What hath God wrought»

- Invention of the telephone by Alexander Graham Bell in 1875



Going Wireless

- Guglielmo Marconi demonstrates first wireless telegraph in 1896.
- A wireless telegraph service is established between France and England in 1898.
- 1901 first wireless communication accross the atlantic

- First amplitude modulation (AM) radio transmission in 1906
- Edwin Howard Armstrong invents frequency modulation (FM) radio in 1935

- Digital Audio Broadcasting (DAB) since late 90’s

Wireless Telephony

- First experiments with mobile phone systems in 1950s

- Fully automated mobile phone system for vehicles launched in Sweden around 1960

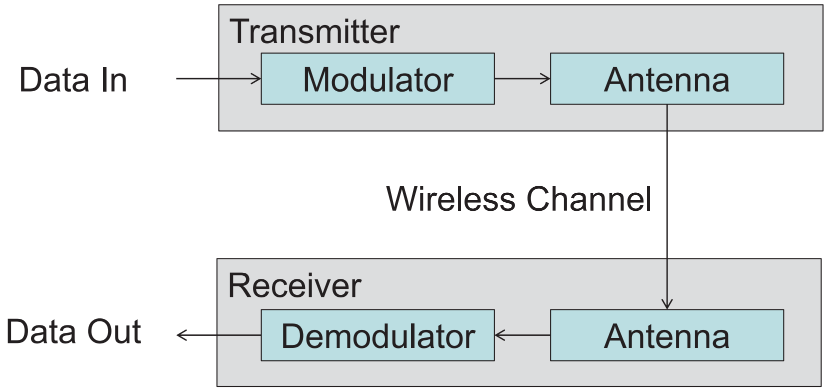
- First generation (1G): cellular networks in Japan (1979)

- Second generation (2G): GSM introduced in 1990s Digital network, SMS, roaming

- Third generation (3G): high-speed data networks (UMTS)

Block Diagram of a Wireless Communication System

- Modulation is required to transfer data over a wireless channel



Data In

Transmitter

Modulator

Antenna

Wireless Channel

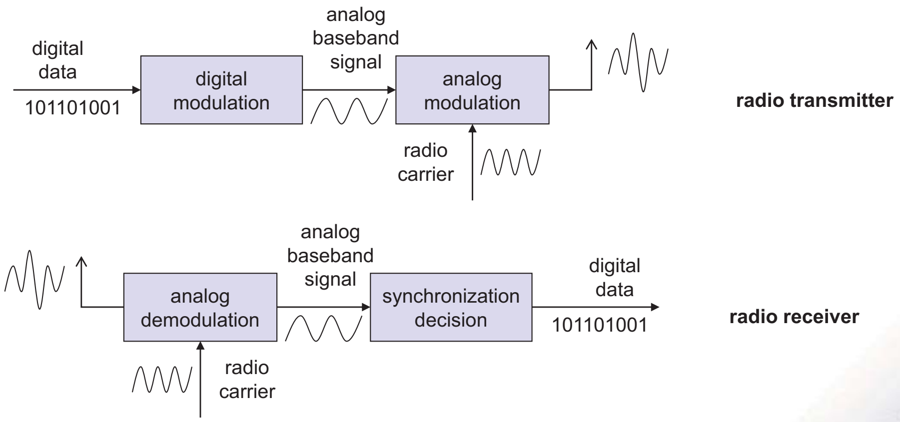
Receiver

Demodulator

Antenna

Data Out

Modulation and demodulation



digital data

101101001

digital modulation

analog baseband signal

analog modulation

radio carrier

radio transmitter

analog demodulation

analog baseband signal

synchronization decision

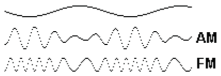
digital data

101101001

radio carrier

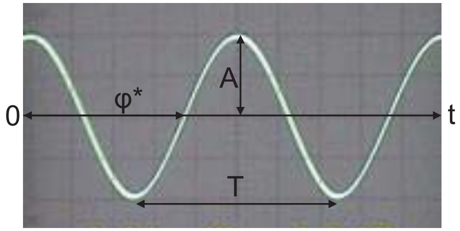
radio receiver

- Modulation in action:



Periodic Signals

- $g(t) = A_t \sin(2\pi\, f_t\, t + \varphi_t)$

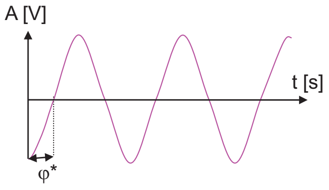


- Amplitude A
- frequency f [Hz = 1/s]
- period T = 1/f
- wavelength λ with $\lambda f = c$ ($c=3\cdot10^8$ m/s)
- phase φ

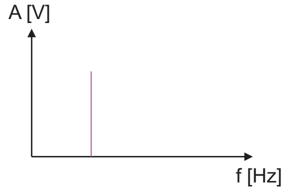
- $\varphi^* = -\varphi T/2\pi$ [+T]

Different representations of signals

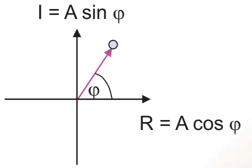
- For many modulation schemes not all parameters matter.



amplitude domain



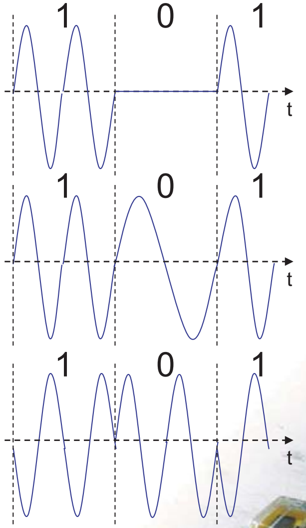
frequency spectrum



phase state diagram

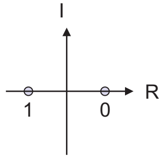
Digital modulation

- 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

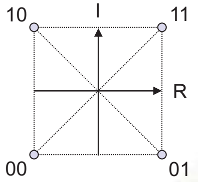


Advanced Phase Shift Keying

- BPSK (Binary Phase Shift Keying):
  - bit value 0: sine wave
  - bit value 1: inverted sine wave
  - Robust, low spectral efficiency
  - Example: satellite systems

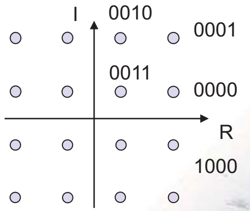


- QPSK (Quadrature Phase Shift Keying):
  - 2 bits coded as one symbol
  - symbol determines shift of sine wave
  - needs less bandwidth compared to BPSK
  - more complex



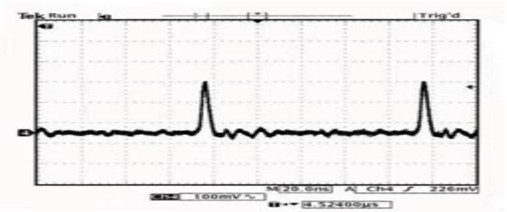
Modulation Combinations

- 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, but different amplitude. 0000 and 1000 have different phase, but same amplitude.
- Used in 9600 bit/s modems



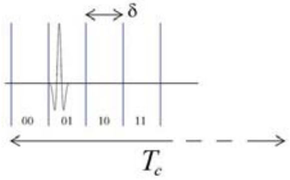
Ultra-Wideband (UWB)

- An example of a new physical paradigm.
- Discard the usual dedicated frequency band paradigm.
- Instead share a large spectrum (about 1-10 GHz).
- Modulation: Often pulse-based systems. Use extremely short duration pulses (sub-nanosecond) instead of continuous waves to transmit information. Depending on application 1M-2G pulses/second

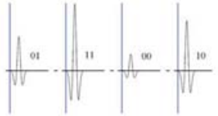


UWB Modulation

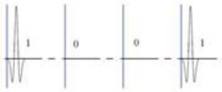
- PPM: Position of pulse



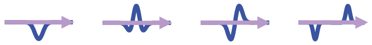
- PAM: Strength of pulse



- OOK: To pulse or not to pulse

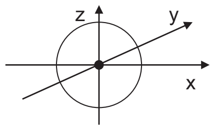


- Or also pulse shape



Antennas: isotropic radiator

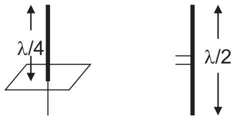
- Radiation and reception of electromagnetic waves, coupling of wires to space for radio transmission
- Isotropic radiator: equal radiation in all three directions
- Only a theoretical reference antenna
- Radiation pattern: measurement of radiation around an antenna
- Sphere: $S = 4\pi r^2$



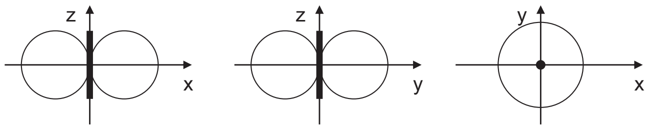
Ideal isotropic radiator

Antennas: simple dipoles

- Real antennas are not isotropic radiators but, e.g., dipoles with lengths λ/2 as Hertzian dipole or λ/4 on car roofs or shape of antenna proportional to wavelength



- Example: Radiation pattern of a simple Hertzian dipole

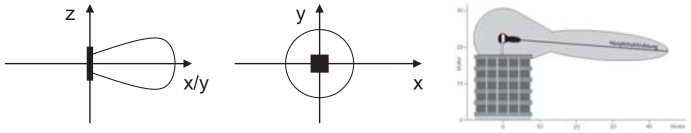


side view (xz-plane) side view (yz-plane) top view (xy-plane)

simple dipole

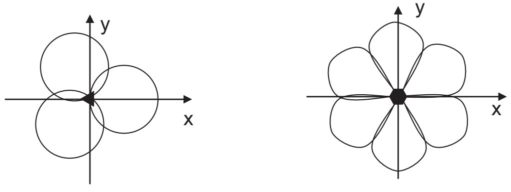
Antennas: directed and sectorized

- Often used for microwave connections or base stations for mobile phones (e.g., radio coverage of a valley)



side (xz)/top (yz) views side view (yz-plane) [Buwal]

directed antenna

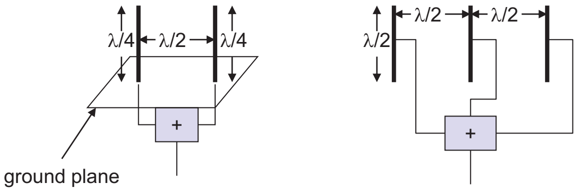


top view, 3 sector top view, 6 sector

sectorized antenna

Antennas: diversity

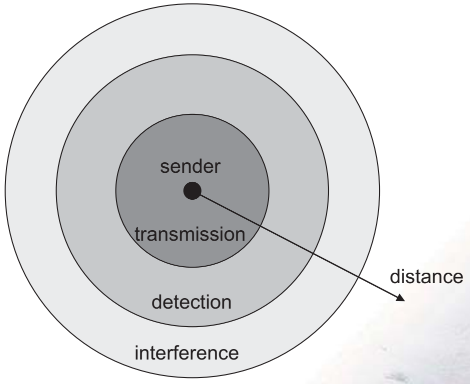
- Grouping of 2 or more antennas
  - multi-element antenna arrays
- Antenna diversity
  - switched diversity, selection diversity
    - receiver chooses antenna with largest output
  - diversity combining
    - combine output power to produce gain
    - cophasing needed to avoid cancellation



- Smart antenna: beam-forming, MIMO, etc.

Signal propagation ranges, a simplified model

- Propagation in free space always like light (straight line)
- 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

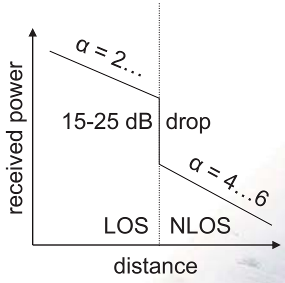


Signal propagation, more accurate models

- Free space propagation $P_r = \dfrac{P_s G_s G_r \lambda^2}{(4\pi)^2 d^2 L}$
- Two-ray ground propagation $P_r = \dfrac{P_s G_s G_r h_s^2 h_r^2}{d^4}$
- P_s, P_r: Power of radio signal of sender resp. receiver
- G_s, G_r: Antenna gain of sender resp. receiver (how bad is antenna)
- d: Distance between sender and receiver
- L: System loss factor
- λ: Wavelength of signal in meters
- h_s, h_r: Antenna height above ground of sender resp. receiver
- Plus, in practice, received power is not constant („fading“)

Attenuation by distance

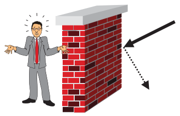
- Attenuation [dB] = 10 $\log_{10}$ (transmitted power / received power)
- Example: factor 2 loss = 10 $\log_{10} 2 \approx 3$ dB
- In theory/vacuum (and for short distances), receiving power is proportional to $1/d^2$, where d is the distance.
- In practice (for long distances), receiving power is proportional to $1/d^\alpha$, $\alpha = 4\ldots6$. We call α the path loss exponent.

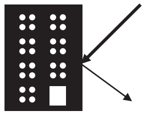


- Example: Short distance, what is the attenuation between 10 and 100 meters distance?
  Factor 100 (=$100^2/10^2$) loss = 20 dB

Attenuation by objects

- Shadowing (3-30 dB):
  - textile (3 dB)
  - concrete walls (13-20 dB)
  - floors (20-30 dB)
- reflection at large obstacles
- scattering at small obstacles
- diffraction at edges
- fading (frequency dependent)


shadowing

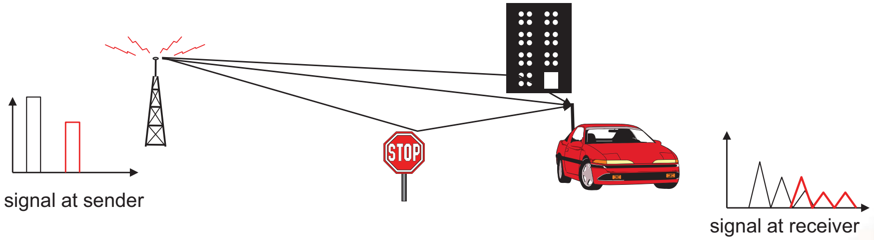

reflection


scattering


diffraction

Multipath propagation

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



- 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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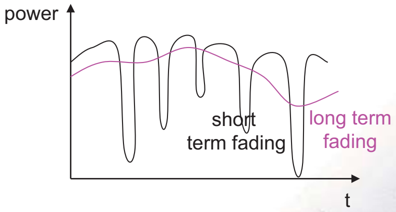
Effects of mobility

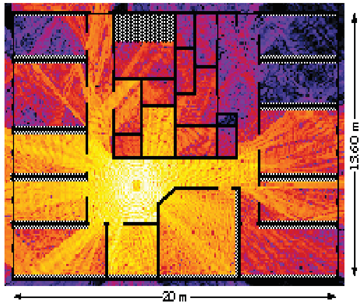
- Channel characteristics change over time and location
  - signal paths change
  - different delay variations of different signal parts
  - different phases of signal parts
- quick changes in power received (short term fading)

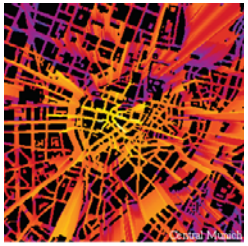
- Additional changes in
  - distance to sender
  - obstacles further away
- slow changes in average power received (long term fading)

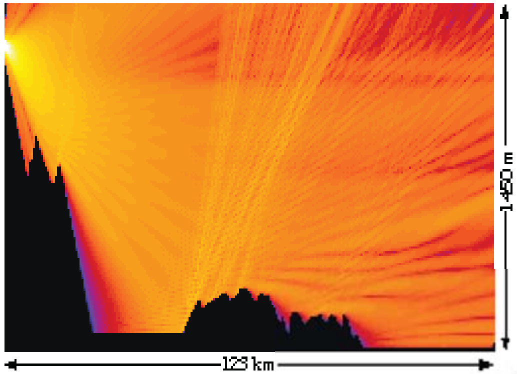


- Doppler shift: Random frequency modulation

Real World Examples





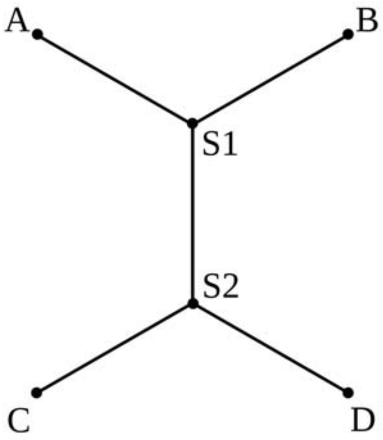


For EE Students: Network Algorithms Basics

- A Motivating Example: Steiner Tree
- Complexity and Hardness
- Approximation Algorithms
- Minimum Spanning Tree

Connect with Minimal Cost

- Given *n* points in the plane, for instance *n*-1 sensors and one sink.
- Can you connect all these points at minimum cost?



- Example: Connect the four nodes *A*, *B*, *C*, *D*, using a wire of minimum cost (minimum total length)
- Optimal Solution: A spanning tree known as Steiner tree, with two additional helper points (Steiner points)
- Jakob Steiner: Swiss mathematician, 1796 – 1863

Steiner Tree Facts

- It is known that Steiner points must have a degree of 3, and that the three edges incident to such a point must form three 120 degree angles.
- It follows that the maximum number of Steiner points that a Steiner tree can have is $n - 2$, where n is the initial number of given points.
- How can we compute the optimal Steiner tree?

Time Complexity

- The time complexity of an algorithm quantifies the amount of time taken by an algorithm to run as a function of the size of the input to the problem, e.g. time = $5n^3 + 17n - 2$.
- Time complexity is commonly computed by simply counting the number of elementary operations (such as additions or multiplications) performed by the algorithm, where an elementary operation takes a one time unit.
- Often multiplicative constants and lower order terms are suppressed, and the answer is given in “big Oh” notation, e.g. $5n^3 + 17n - 2 = O(n^3)$.
- Since an algorithm may take a different amount of time even on inputs of the same size, one commonly focuses on the so-called worst-case time complexity, the maximum amount of time taken on any (including the worst) input of size *n*.

Hardness

- A time complexity which is polynomial in the input is usually considered feasible, e.g. O(n^{1000}) is okay.
- An algorithm becomes problematic if its time complexity is not polynomial anymore, e.g. exponential such as O(1.1^n).
- In this example the first function may look scarier than the second, but for large enough n, the second function is much larger (well, after all it grows exponentially).

- In layman's terms, if a problem is NP-hard, then it is a "difficult" problem. For problems that are NP-hard it is generally believed that there is no polynomial time algorithm which can solve the problem. However, this is just a conjecture. If you can proof it, you get very famous.

- The Steiner tree problem is known to be NP-hard.

What can one do if a problem is hard?

- If you are lazy, you may take it as a excuse to propose a heuristic (an algorithm without quality guarantees).

- Another way to go is to propose so-called fixed parameter algorithms. Some algorithms with exponential running time are still much better than others, e.g. O(1.1^n) is much faster than O(n^n) or O($n!$)

- A very popular alternative is to propose so-called approximation algorithms. These are polynomial-time algorithms which cannot guarantee to find the optimum, but they can guarantee to find a solution which is at most a factor c worse than the (unknown) optimum.

- Is there an approximation algorithm for the Steiner tree problem?

Steiner Tree Approximations?

- What if you connect all the nodes directly to some arbitrarily chosen (root) node?
  - How much worse than the optimum solution will this be?

- Alternatively we might connect the nodes with the minimum cost spanning tree that does not use additional (Steiner) points. Such a spanning tree is known as the Minimum Spanning Tree (MST).
  - How can we compute such an MST?
  - How much worse than the optimum solution will this be?

- Indeed, for the Euclidean Steiner Tree problem there is even a polynomial-time approximation scheme (PTAS). This means that one can approximate the optimal solution up to a factor $1+\varepsilon$, for an arbitrarily small $\varepsilon > 0$. However, the running time will grow as a function of ε.

Minimum Spanning Tree

- There are several simple algorithms that can compute the MST quickly. For instance the following:

- Choose the closest two nodes which are not yet connected (through a path) and connect them, until all nodes are connected by a spanning tree.

- Exercise: Proof that this is optimal.