Today’s lecture

- Course overview
- Introduction to WSNs
- Network optimization
Today’s learning outcome

- What are the components of a WSN?
- What are typical applications of a WSN?
- What is a networking protocol?
- How to design applications and protocols?
- What is the role of network optimization?
Office: Osqudas väg 10, floor 6.

Office Times: By appointment.

Work load: 2h per lecture + research work.

Prerequisites: Familiarity with linear algebra and analysis.

Meeting times: Tuesdays, 13.15-15.00.

Exceptions: Friday October 14, 13.15-15:00,
            Friday November 11, 10:00-11:00.
# Classrooms

<table>
<thead>
<tr>
<th>Tid</th>
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<tr>
<td>Tuesday, 2011-09-13, 13:00 - 15:00</td>
<td>Teknikringen 33 2tr (H1)</td>
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Course content

- Lec 1: Introduction
- Lec 2: WSN Programming, invited lecture, Olaf Landsiedel
- Lec 3: Iterative methods for parallel computation
- Lec 4: Consensus algorithms
- Lec 5: Fast-Lipschitz optimization
- Lec 6: Network optimization: max flow and min cut
- Lec 7: Guest lecture
- Lec 8: Medium access control and IEEE 802.15.4
- Lect 9: Routing and ZigBee, WirelessHART, ROLL
- Lect 10: Conclusion and presentation of the research projects
Course goal

After finishing the course, the attendant will

- Know the essential theoretical tools to cope with WSNs.
- Know the fundamentals of parallel computation and network optimization.
- Know how to design WSNs.
- Develop a research project.
- Develop presentation skills.
Evaluation

- **Ph.d. version:**
  - The course is worth 5 credits plus 2.5 optional credits based on an original research project (highly recommended).
  - Grades (pass/fail) will be based on attendance (50%) and exercises plus presentations (50%).

- **Master students version:**
  - The course is worth 7.5 credits.
  - Grades (pass/fail) will be based on attendance, exercises, presentation (5 credits) and a research project (2.5 credit).
  - Less/different exercises than the Ph.D. version.

- **Exercises**
  - Contain theoretical as well as practical parts (mainly through simulations).
  - Have to be delivered before the next lecture following the assignment.
Student presentations

- Each student has to present a paper/book chapter during the course.
  - See the list on the course website after Sept. 16

- Choose papers/book chapter from the list.
  - E-mail me with the preferred papers by Sept. 19
  - You can propose to present a paper that is not in the list, but I reserve to check if it is relevant to the course.
  - I will then assign the papers to the presenters by Sept 22.
You can propose your own project, or ask to have a project:

- Distributed estimation over networks
- Estimation over smart grids
- Handover optimization in Intelligent Transportation Systems
- Distributed optimization
- Distributed localization
- Cognitive radio protocols
- Network coding
- ...
Research projects

- Project title: e-mail by September 30, 2011.

- A project can be developed in collaboration with max 2 students.

- Presentation: November 15, 2011.

- Project report: max 5 pages, IEEE conference format paper.
  - Best project report award!

Text books

  http://dspace.mit.edu/handle/1721.1/3719

- D. P. Bertsekas, Network Optimization: Continuous and Discrete Models
  http://www.athenasc.com/netbook.html

  http://www.cs.uni-aderborn.de/index.php?id=1119&L=1
Useful links

WSNs Standard

http://www.hartcomm.org/
http://www.ieee802.org/15/pul/TG4.html
http://www.ietf.org/dyn/wg/charter/roll-charter.html
http://www.ipso-alliance.org/Pages/Front.php
http://www.isa.org/
http://www.tinyos.net/
http://www.sics.se/contiki/
http://www.zigbee.org/

http://www.wsnblog.com/
http://www.wsn-security.info/index.htm

Blogs

http://www.dustnetworks.com/
http://www.sensinode.com/
http://www.sentilla.com/

Industries

http://www.ee.kth.se/~mikaelj/wns_course.shtml
http://www.cs.berkeley.edu/~culler/eecs194/
http://bwrc.eecs.berkeley.edu/Research/energy_efficient_systems.htm
http://wsnl.stanford.edu/
http://courses.csail.mit.edu/6.885/spring06/readings.html
http://www.eecs.harvard.edu/~mdw/course/cs263/fa04/
http://www.cs.sunysb.edu/~jgao/CSE595-spring09/

University courses
Today's lecture

- Course Overview
- Introduction to WSNs
- Network Optimization
Wireless Sensor Networks

Computer Networking  Wireless Communications

Systems and Control

Wireless Sensor Networks
Wireless sensor networks (WSNs) make Internet of Things possible

Computing, transmitting and receiving nodes, wirelessly networked together for communication, control, sensing and actuation purposes

Characteristics of WSNs
- Battery-operated nodes
- Limited wireless communication
- Mobility of nodes
- No/limited central manager

Typical power consumption of a node
History of WSNs

DARPA DSN node, 1960

Mica2 mote, 2002

Tmote-sky mote, 2003

Smart Dust, 200?
Application of WSNs

Industrial control

Environmental monitoring

Transportation

Marine monitoring

Health care

Fall 2011

Principles of Wireless Sensor Networks

Carlo Fischione
Applications: Building Monitoring

- Sensors used to measure response to traffic, tidal and seismic activity
- Deployed on Golden Gate Bridge
  - http://www.cs.berkeley.edu/~binetude/ggb/
Habitat Monitoring

- Non-intrusive monitoring of animal habitat.
- Example: Nesting of Leach’s Storm Petrels

Storm petrel chick

Sensor node
Smart Buildings

WSNs to Control of temperature, light intensity, air and humidity.

Source: Ed Arens

www.instablogsimages.com
Smart grids

source: http://deviceace.com/

- Smart grids: “Smart Grids: It’s All About Wireless Sensor Networks” (http://stanford.wellsphere.com)
**Added flexibility**
- Sensor and actuator nodes can be placed more appropriately
- Less restrictive maneuvers and control actions
- More powerful control through distributed computations

**Reduced installation and maintenance costs**
- Less cabling
- More efficient monitoring and diagnosis
Distributed Camera Calibration

- WSN allows one to perform distributed camera calibration
- Application: massive graphic effects in film production
Old Market Forecasts for WSNs

WSNs population forecast 2010

1+ Trillion

500 Billion

2 Billion

1 Billion Info Devices:
Mobile Phones
PDA’s
Web Tablets etc.

Smart Devices:
Appliances
Machinery
Vehicles
Bldg. Eqpt.
etc.

Microprocessors:
4-64+ bits CPU’s etc.

RFID/Sensors:
Location
Humidity
Temperature
Vibration
Liquid
Weight etc.

300 Million PC’s:

Forecast of installed base, 2010
The FocalPoint Group, LLC 2003
http://www.thefpgroup.com

Fall 2011
Principles of Wireless Sensor Networks
Carlo Fischione
New Market Forecasts for WSNs

  - industrial applications of WSN: 4.6 Billion $ by 2011
  - smart building applications of WSN: 2.5 Billion $ by 2011.

- IDTechEx:
  - WSNs and active RFID of about 4B$ by 2012.

- WSNs R&D investments: from 522 Million $ in 2007 to 1.3 Billion $ in 2012.

- 30 millions WirelessHART wireless sensors installed so far worldwide.
Let’s see the components of the network
Participants in a WSN

- **Sources** of data: Measure data, report them “somewhere”
  - Typically equip with different kinds of actual sensors

- **Sinks** of data: Interested in receiving data from WSN
  - May be part of the WSN or external entity, PDA, gateway, ...

- **Actuators**: Control some device based on data, usually also a sink
WSN: Multiple sinks, multiple sources
Deployment options for WSN

- How are sensor nodes deployed in their environment?
  - Dropped from aircraft! **Random deployment**
    - Usually uniform random distribution for nodes over finite area is assumed
  - Well planned, fixed! **Regular deployment**
    - E.g., in preventive maintenance or similar
    - Not necessarily geometric structure, but that is often a convenient assumption
  - **Mobile** sensor nodes
    - Can move to compensate for deployment shortcomings
    - Can be passively moved around by some external force (wind, water)
    - Can actively seek out “interesting” areas
Gateway concepts for WSN?

- Gateways are necessary to the Internet for remote access to/from the WSN
  - Same is true for ad hoc networks; additional complications due to mobility (change route to the gateway; use different gateways)
  - WSN: Additionally bridge the gap between different interaction semantics (data vs. address-centric networking) in the gateway
- Gateway needs support for different radios/protocols, ...

![Diagram of wireless sensor network with gateway nodes and Internet connection](image-url)
WSN to Internet communication

- Example: Deliver an alarm message to an Internet host
- Issues
  - Need to find a gateway (integrates routing & service discovery)
  - Choose “best” gateway if several are available
  - How to find Alice or Alice’s IP?
WSN node components

1. **Controller**
2. **Communication device(s)**
3. **Sensors/actuators**
4. **Memory**
5. **Power supply**
Transceiver states

- Transceivers can be put into different operational states, typically:
  - Transmit
  - Receive
  - **Idle** - ready to receive, but not doing so
    - Some functions in hardware can be switched off, reducing energy consumption a little
  - **Sleep** - significant parts of the transceiver are switched off
    - Not able to immediately receive something
    - **Recovery time** and **startup energy** to leave sleep state can be significant

- Research issue: Wakeup receivers - can be woken via radio when in sleep state (seeming contradiction!)
Switching between modes

- Simplest idea: *Greedily switch to lower mode whenever possible*
- Problem: Time and power consumption required to reach higher modes not negligible
  - Introduces overhead
  - *Switching only pays off if* $E_{\text{saved}} > E_{\text{overhead}}$
- Example:
  - Event-triggered wake up from sleep mode
- Scheduling problem with uncertainty

For a diagram, see the upper right part of the slide.
Let’s now focus on the protocols followed at the communication device and the controller.
The behavior of a node is specified by a set of protocols, or set of rules with which the node operate.

Optimization and Parallel and Distributed Computation Theories are the essential mathematical tools to design WSNs.
The role of optimization

- Energy per correctly received bit
  - Counting all the overheads, in intermediate nodes, etc.
- Energy per reported (unique) event
  - After all, information is important, not payload bits!
  - Typical for WSN
- Delay/Reliability/energy tradeoffs
- Network lifetime
  - Time to first node failure
  - Network half-life (how long until 50% of the nodes died?)
  - Time to partition
  - Time to loss of coverage

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The radio power control problem

- Let \( p = (p_1, p_2, \ldots, p_n) \in \mathbb{R}^n \), \( p \geq 0 \), be a vector of radio powers.
  - Each element of the vector is the radio power used for transmission by a node.
- Let \( I_j(p) : \mathbb{R}^n \rightarrow \mathbb{R} \) be the interference that the radio power has to overcome so that the receiver can receive successfully the transmitted information.
- \( I(p) = (I_1(p), I_2(p), \ldots, I_n(p)) \)  
  
Interference Function

- The radio powers of every sensor must be minimized subject to quality of communication constraints:

\[
\begin{align*}
\min_p & \quad p \\
\text{s.t.} & \quad p \geq I(p)
\end{align*}
\]
**Medium Access Control (MAC)**

- **MAC**: mechanism for controlling when to send a packet and when to listen for a packet
  - MAC is one of the major component for energy expenditure.
  - Especially, idly waiting to receive packets wastes huge amounts of energy

- **MAC is influenced by the transmit radio power**

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Routing: how to choose paths

- Maximum total available battery capacity
  - Path metric: Sum of battery levels
  - Example: A-C-F-H
- Minimum battery cost routing
  - Path metric: Sum of reciprocal battery levels
  - Example: A-D-H
- Conditional max-min battery capacity routing
  - Only take battery level into account when below a given level
- Minimum total transmission power

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The state of a process is sensed by wireless nodes.
State information reaches the controller via multi-hop routing.

How the protocols and the controller interact?
How the protocols and the controller interact?
A Feedback Control Loop over a Network

![Diagram of a feedback control loop over a network involving a process, a wireless sensor network, and a controller, with control decision $u(kh)$, state of the process $x(kh)$, output of the process $y(kh)$, delay, and packet losses.]

- $u(kh)$ control decision
- $x(kh)$ state of the process
- $y(kh)$ output of the process
- $h$ sampling interval
- $k$ discrete time
The state of a control system can be mathematically described by the solution to a differential equation.

**Example:** linear system

\[
x(kh + h) = \Phi x(kh) + \Gamma u(kh)
\]

\[
y(kh) = C x(kh) + D u(kh)
\]

**Solution**

\[
x(k) = \Phi^k x(0) + \sum_{j=0}^{k-1} \Phi^{k-j-1} \Gamma u(j)
\]

**Goal of the controller:** make the state \( x(k) \) “close” to a desired one \( x^*(k) \).
Description in the Z Domain

\[ U(z) \rightarrow \text{Process} \rightarrow Y(z) \rightarrow \text{Wireless sensor network} \rightarrow U(z) \rightarrow \text{Controller} \rightarrow H(z) \rightarrow \]

\[ Y(z) = P(z)U(z) \quad \text{Z transform of the output signal} \]
\[ U(z) = f(H(z)Y(z)) \quad \text{Z transform of the input signal} \]

\[ P(z) \text{ Process pulse transfer function, given.} \]
\[ H(z) \text{ Controller pulse transfer function, to design.} \]
Stability with Random Jitter

Theorem: Consider linear feedback system with $\Delta$ representing a delay $0 \leq \tau(t) \leq \tau_{\text{max}}$. Closed-loop system stable if

$$\left| \frac{P(i\omega)H(i\omega)}{1 + P(i\omega)H(i\omega)} \right| < \frac{1}{\tau_{\text{max}}\omega}$$
State Feedback Stability with Packet Losses


**Theorem:** Suppose that the closed-loop system in the figure above without packet losses is stable. Let $r$ be the successful packet reception probability. Then

- if the open-loop system is marginally stable, then the system is stable for all $0 < r \leq 1$.
- if the open-loop system is unstable, then the system is stable for all

$$\frac{1}{1 - \gamma_1/\gamma_2} < r \leq 1,$$

where $\gamma_1 = \log[\lambda_{\text{max}}^2(\Phi - \Gamma K)]$, $\gamma_2 = \log[\lambda_{\text{max}}^2(\Phi)]$, where $\lambda_{\text{max}}$ is the maximum eigenvalue.

\[ u(kh) = -Kx(kh) \]
\[ \Phi = \begin{bmatrix} 1.3499 & 0.3045 \\ 0 & 0.7408 \end{bmatrix} \quad \Gamma K = \begin{bmatrix} 0.0907 & 0.0408 \\ 0.5184 & 0.2333 \end{bmatrix} \]

- The open loop system is not stable (\( \Phi \) has the maximum eigenvalue larger than 1).
- The closed loop system is stable (the matrix \( \Phi - \Gamma K \) is stable).
- The second statement of the Theorem applies: \( \gamma_1 = -0.1011 \), and \( \gamma_2 = 0.6001 \).

\[ r \geq 0.85 \]

namely that the system can tolerate a packet loss of up about 15%.
Key Questions for WSNs for Control

1. Delay accepted by the controller to get packets?
2. Probability of successful packet transmission tolerated by the controller?
3. Energy consumption?

- A holistic or system-level approach to the joint design of controllers and WSNs is needed

Energy, bounded delay and packet transmission requirements must be ensured by the WSNs:

- Control applications require a packet delivery within some deadline and with a guaranteed packet reception probability.

\[
\begin{align*}
\min_x & \quad E(x) \\
\text{s.t.} & \quad P_i(x) \geq \Omega_i, \quad i = 1, \ldots, n, \\
& \quad \Pr[D_i(x) \leq \tau_i] \geq \Delta_i \quad i = 1, \ldots, n
\end{align*}
\]

- Protocol parameters (MAC, Routing)

- \( n \) clusters of sensors give \( n \) parallel and coupled optimization problems to solve without central coordination
  - How to do by nodes of reduced computational capability?

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**WSNs MAC and Routing for Control**

- Energy Consumption
- Reliability
- Delay
## No WSN Protocol for Control

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- Evaluated but not controlled
- Control and evaluated
- Control and experimentally evaluated

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Protocol Design of WSNs

1. Model mathematically the protocol behaviour
2. Select the metrics (energy, delay, reliability)
3. Optimize (statically or on-line) the protocol parameters

A highly efficient protocol

Protocol parameters: radio powers, MAC retransmissions, routing path...
Network optimization

- The minimum cost flow problem
  - Shortest path
  - Max-flow problem

- Network flow problems with convex cost

- Routing in data networks

- See the black board...
Summary

- We have seen the key aspects of WSNs
  - Applications
  - Difference from other networks
  - Nodes, protocols, and network architecture
  - Network optimization

- Next Lecture: Olaf Landsiedel, “Introduction to WSN Programming”.
Homework

- Mandatory reading:
  - Chapter 1 and 2, P. Levis and D. Gay, TinyOS Programming, Cambridge, 2009: 
    http://dspace.mit.edu/handle/1721.1/3719