Wireless Embedded Systems and Networking

Foundations of IP-based Ubiquitous Sensor Networks

Advanced Institute of Information Technology
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Goals

The goal of this course is to introduce faculty who are teaching embedded or wireless sensor networking to the foundations of the field and the practical application of the technology. The course will focus on modern, well-developed systems and networking software for integrating ubiquitous instrumentation of the physical world with leading-edge IT capabilities. It will focus on the use of open standards at several levels, including the TinyOS 2.0 embedded operating system, IEEE 802.15.4 radio, 6LoWPAN, Internet Protocols, and Web Services. Lectures will cover the theoretical foundations, key findings, and state-of-the-art in the primary elements of these embedded, distributed systems. Laboratory sessions will provide in-depth hands-on experience in the application of core concepts using the Arch Rock's IPv6 wireless sensor network application and development environment based on TinyOS 2.0.

Prerequisites

Professionals with basic knowledge of networking and operating systems, with C programming highly recommended and familiarity with some Web development tools encouraged.

Readings

Original research papers and on-line text books, including Programming TinyOS, Phil Levis, will complement lecture materials.

Course Outline

The course consists of three lecture sessions and a lab session on each day according to the schedule shown below. All students will be provided with a copy of lecture notes, readings, and lab materials.

Course at a glance

	Monday	Tuesday	Wednesday	Thursday	Friday
Topic 1	Next-Tier of the Internet - IP-based Wireless Sensor Networks (WSN) [ppt]	TinyOS 2.0 and Application Services	Self-Organized Multihop Routing	Timers and System Resources	Micro-Power Systems
Topic 2	WSN Technology and Hardware Architectures [ppt]	Robust Embedded Networking [ppt]	Low-Power Wireless Communication	Time-Synchronization and Embedded Distributed Systems	Security and Reliability
Topic 3	Operating Systems for Communication-Centric Devies TinyOS-based IP-WSNs [ppt]	Embedded Web Services and Industrial Standards [ppt]	6LoWPAN and IP Concepts [ppt]	In-networking Processing and Sensor Data Analysis	Future Developments
Lab	Experience with IP-based Wireless Sensor Networks [lab1.1] [lab1.2]	Making USNs ubiquitous - build WSN applications as Web Services [lab2.1] [lab2.2] [lab2.3]	Using IP and 6LoWPAN Networking [lab3.1]	TinyOS 2.0 based embedded Applications	Deep Embedded Systems Development or Self-Directed

Biography of the Lecturer

David Culler is a Professor of Computer Science at the University of California, Berkeley and CTO of Arch Rock Corporation. Professor Culler received his B.A. from U.C. Berkeley in 1980, and M.S. and Ph.D. from MIT in 1985 and 1989. He has been on the faculty at Berkeley since 1989, where he holds the Howard Friesen Chair. He is a member of the National Academy of Engineering, an ACM Fellow, an IEEE Fellow and was selected in Scientific American's 'Top 50 Researchers' and in Technology Review's '10 Technologies that Will Change the World'. He received the NSF Presidential Young Investigators award in 1990 and the NSF Presidential Faculty Fellowship in 1992. He was the Principal Investigator of the DARPA Network Embedded Systems Technology project that created the open platform for wireless sensor networks based on TinyOS, and was the founding Director of Intel Research, Berkeley. He has done seminal work on networks of small, embedded wireless devices, planetary-scale internet services, parallel computer architecture, parallel programming languages, and high performance communication, and including TinyOS, PlanetLab, Networks of Workstations (NOW), and Active Messages. He has served on Technical Advisory Boards for several companies, including Inktomi, ExpertCity (now CITRIX on-line), and DoCoMo USA. He co-authored the leading textbook on Parallel Computer Architecture and over 150 research publications. He serves on numerous program committees, editorial boards, and government panels.

Monday 6/9/2007

- Topic 1: Next-Tier of the Internet - IP-based Wireless Sensor Networks (WSN)
  - Brief history and overview of wireless sensor networks. Technology Trends. Application classes. Systems gap. Introduce mote, tinyos, mesh routing, low-power operation, architecture of typical deployment.
  - Critical issues and factors: memory contraints, power, uncertainty, and loss.
  - Ubiqutous sensor networks => IP and Web services
  - Relationship to Home automation, Industrial Instrumentation, Web Integration
  - Overview of the course.
  - *Suggested Readings:*
    - Overview of Sensor Networks, Culler, Estrin, Srivastafa, IEEE Computer Special Issue Aug. 2004..
    - Wireless Integrated Network Sensors, Pottie and Kaiser, CACM, May 2000
  - *Useful Resources:*
    - www.tinyos.net - Open source hardware, software, tutorials, examples, tools, community
    - www.tinyosmall.co.kr
    - Several recent books have been published.
      - Krishnamachari, “Networking Wireless Sensors” provides a well-organized synopsis of many of the research papers.
      - Karl & Willig, “Protocols and Architectures for Wireless Sensor Networks” provides a somewhat more in-depth treatment, but with less of the algorithmic analysis
      - Haenselmann, “Sensor Networks” available free online
      - Pottie & Kaiser, “Principles of Embedded Networked System Design” brings some excellent information theory perspective, but is primarily focused on WINS
      - Zhao & Guibas, “Wireless Sensor Networks”.

        - Callaway, “Wireless Sensor Networks” - has some useful coverage of industry developments. Essentially a reprint of his PhD thesis.

- Topic 2: WSN Technology and Hardware Architectures
    - Mote architecture, Mote geneology
    - Microcontrollers, Radios, Flash., IEEE 802.15.4
    - Power subsystem., Mechanical design issues.
    - Motes in the market.
    - *Suggested Readings:*
        - ***System Architecture Directions for Networked Sensors,* J. Hill, R. Szewcyk, A. Woo, D. Culler, S. Hollar, K. Pister, ASPLOS 2000.** 93-104 **(pdf)**
        - ***Mica: A Wireless Platform for Deeply Embedded Networks***, Jason Hill and David Culler, IEEE Micro., vol 22(6), Nov/Dec 2002, pp 12-24 (pdf).
        - **Telos: Enabling Ultra-Low Power Wireless Research**, Joseph Polastre, Robert Szewczyk, David Culler *The Fourth International Conference on Information Processing in Sensor Networks: Special track on Platform Tools and Design Methods for Network Embedded Sensors* IPSN 2005: 364-369, *April 25-27, 2005*
    - *Useful Resources:*
        - ***Trio: enabling sustainable and scalable outdoor wireless sensor network deployments***.Prabal Dutta, Jonathan Hui, Jaein Jeong, Sukun Kim, Cory Sharp, Jay Taneja, Gilman Tolle, Kamin Whitehouse, David E. Culler: IPSN 2006: 407-415. (pdf)
        - Arch Rock Primer Pack / IP
        - btnode
        - CSIRO fleck
        - Crossbow motes
        - kmote
        - Maxfor (Korea)
        - Moteiv Tmote Sky
        - Sensinode

- Topic 3: Operating Systems for Communication-Centric Devices - TinyOS-based IP-WSNs
    - TinyOS concepts and Design Issues
    - TinyOS 2.0
    - Execution model, Concurrency and Storage
    - Composition in Systems, Architectural Layers and Modularity
    - Network stacks
    - IP and Embedded Services
    - *Suggested Readings:*
        - TinyOS: Operating System Design for Wireless Sensor Networks, David Culler, Sensors, May 2006

    - [TinyOS: An Operating System for Sensor Networks](), Philip Levis, Sam Madden, David Gay, Joseph Polastre, Robert Szewczyk, Kamin Whitehouse, Alec Woo, David Gay, Jason Hill, Matt Welsh, Eric Brewer, and David Culler, *Ambient Intelligence.* W. Weber, J. Rabaey, and E. Aarts (Eds.), Springer-Verlag, 2005
    - **[Flexible Hardware Abstraction for Wireless Sensor Networks]()**, Vlado Handziski, Joseph Polastre, Jan-Hinrich Hauer, Cory Sharp, Adam Wolisz, David Culler,*In Proceedings of the Second European Workshop on Wireless Sensor Networks (EWSN '05), January 31-February 2, 2005..*
  - Resources:
    - http://www.tinyos.net/tinyos-2.x/doc/
    - [TinyOS Programming](), Phil Levis

- Lab part 1: [First Table-top IP/WSN]()
  - Form six groups of five people each. Each group will have a dedicated wireless sensor network with a gateway server and a collection of Arch Rock Primer Pack nodes and kmotes.
  - Build a table top network. Open a browser and connect to the group server. Using the deployment page, pick a name for the deployment and select a 802.15.4 channel. Select a security passphrase. Place the server on the map. Program the bridge node. Remove the bridge node. Program each of the motes. Replace the bridge node. On the nodes page, discover the nodes. Register all the nodes. Place each node on the map. Ping each node and see it flash the blue LED. Push ident and see it flash on the screen. Identify which node is which by EUID64. See that they have a short address, an IPv6 address, and an IPv4 address.
  - Do some table top sensing: Using the sensor and actuators page. Enable all internal sensors. Set the sample rate to 2 secs. Go to the sensor data page. Set the refresh. Cover nodes. Blow on them. Put them in warm places.
  - Click on the name of a node and open up the node web page view. See the graphs of the data over time.
  - Pick a node. Set thresholds. Adjust the sample rate. Configure it to send email on alarm.
  - Adjust the heartbeat to 30 secs. Turn off a node. See it go red. Try to ping it. Look at the data.
  - Get is EUID and use the REST URL to retreive various data on demand.
  - Notice that we are running the network about 100x what it would normally be. How fast a change is missed?
  - Quick little sheet to fill out for this portion.
- Lab part 2: [Build a self-organized mesh over a physical extent.]()
  - Discuss as a group where to place your nodes in the lab and in its vicinity. Identify interesting places to sense. In addition to the environmental sensors, you can imagine adding open/close sensors, tilt, or other inputs. Draw a rough sketch of the floorplan of the space that you will cover and indicate where you will place the nodes. Use all but one of

the nodes, so we one set aside for later. Discuss what you will be able to observe through the sensors. Discuss what you think the wireless connectivity will be among the nodes. Discuss how you think information will get routed to the server.
    - Upload your sketch, either by scanning it in or by rendering it in powerpoint or your favorite drawing program to create a jpeg.
    - Select nodes to place at the intended spots in your lab space. For each one, name it in your network. Place it at the point of interest. Place its representative at the corresponding point on your map. Continue to use an accelerated rate. Maybe 5 s is enough.
    - Observe whether all the nodes are part of the mesh. Are any missing?
    - Study the connectivity by going to the connectivity page. Study the map view. What is routing through which. Go to the list view. See the RSSI and link quality.
    - Run a site survey from each of the nodes.
    - Discuss how the connectivity compares to your expectations.
    - Discuss how the mesh routing to the server compares to your expectations.
    - Network too sparse => add a node to fill it in.
    - Network too shallow => extend with a node farther out.
    - Use the reliability page. Reset the reliability statistics. Let it go for a bit.
    - Move nodes around, move them on the map. See how the connectivity remains.
    - Try to obstruct it and see how the routing changes.
    - Go to the energy page and see the duty cycle. Adjust the sample rate to something more typical, more typical, say 300s.
- Lab wrap up.
    - Place nodes where they can run over night. Verify that the network is robust. Turn on data warehouse. Reset stats. Let them run till tomorrow.

Tuesday 6/10/2007

- Topic 1 - TinyOS 2.0 and Application Services
    - Tasks, Components, Commands and Events
    - Interfaces, Provides and Uses
    - Component: Modules and Configuration
    - Split-Phase Operation
    - Parameterized Interfaces
    - Generic Modules
    - Generic Configurations
    - HPL / HAL / HIL
    - Application Services
    - *Suggested Readings:*
        - **Flexible Hardware Abstraction for Wireless Sensor Networks**, Vlado Handziski, Joseph Polastre, Jan-Hinrich Hauer, Cory Sharp,

Adam Wolisz, David Culler, *In Proceedings of the Second European Workshop on Wireless Sensor Networks (EWSN '05), January 31-February 2, 2005.*

- **The Emergence of Networking Abstractions and Techniques in TinyOS**
  Philip Levis, Sam Madden, David Gay, Joseph Polastre, Robert Szewczyk, Alec Woo, Eric Brewer, and David Culler, First Symposium on Network Systems Design and Implementation, NSDI 2004: 1-14, Mar. 2004

- Additional Resources:
  - http://www.tinyos.net/tinyos-2.x/doc/
  - TinyOS Programming, Phil Levis
  - http://www.tinyos.net/tinyos-2.x/doc/html/tutorial/

- Topic 2 - Robust Embedded Networking - "Achieving a Good Hop"
  - Topology Discovery, Topology Management, Route formation, and Forwarding
  - Communication patterns: dissemination, collection, neighborhood, point-to-point
  - Charateristics of a Link
  - Signal, Noise, Range, RSSI, Link estimation, Sensitivity, Tranmission power
  - Modulation, coding
  - Forms of Divsersity: retranmission, receiver diversity, path diversity
  - Media Access Control, Contention, CCA
  - Clustering and its limitations
  - Readings:
    - ***Taming the Challenges of Reliable Multihop Routing in Sensor Networks***, Alec Woo and David Culler, ACM SenSys Nov. 2003. [pdf]
    - Marco Zuniga, Bhaskar Krishnamachari, "Analyzing the Transitional Region in Low Power Wireless Links", IEEE SECON 2004. [pdf]
    - **Understanding the causes of packet delivery success and failure in dense wireless sensor networks,** Kannan Srinivasan, Prabal Dutta, Arsalan Tavakoli, and Philip Levis [pdf]
  - Useful resources
    - TI CC2420 Product description - http://focus.ti.com/lit/ds/symlink/cc2420.pdf
    - Radio Channel Quality in Industrustrial Wireless Environments, Dan Sexton, et. al SICON'05 [pdf]
    - Ni, S.Y., Tseng, Y.C., Chen, Y.S., Sheu, J.P.: *The broadcast storm problem in a mobile ad hoc network*. In: Proceedings of the Fifth Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom'99). (1999) 152--162.

- Topic 3 - Embedded Web Services and Industrial Standards
  - HTML, XML, WSDL
  - Communication, Object & Data Representation, Application Profiles

- HART, BACNet, LONworks, CIP, Zigbee, IEEE 1451, ODSL
- REST, SOAP
- Suggested readings:
  - Embedded Web Services: Making Sense out of Diverse Sensors, David Culler and Gilman Tolle, Sensors, May 2007. [draft pdf]
  - Web Services - Program Integration across Application and Organization boundaries
  - Kamin Whitehouse, Gilman Tolle, Jay Taneja, Cory Sharp, Sukun Kim, Jaein Jeong, Jonathan Hui, Prabal Dutta, David E. Culler: ***Marionette: using RPC for interactive development and debugging of wireless embedded networks.*** IPSN 2006: 416-423 [pdf]
- additional resources::
  - TinyDB - http://telegraph.cs.berkeley.edu/tinydb/
  - http://www.ibm.com/developerworks/library/w-ovr/
  - http://www.hartcomm2.org/hart_protocol/protocol/hart_data.html
  - http://www.hartcomm.org/hart_protocol/applications/white_papers /compnet.html
  - http://www.bacnet.org/Tutorial/
  - Common Industrial Protocol - http://www.odva.org/default.aspx?tabid=205

- Lab Part 1 - add your own sensors.
  - Study the resistance of the mag reed sensor open and closed. Discuss pull up, expected voltage and current.
  - Connect to expansion port.
  - Configure the switch port. Name the states.
  - Discuss interupt versus sampling.
  - Set the alarms. (Can this go anywhere?)
  - Study the resistance of the RTD in ice water versus room temperature versus tea.
  - Discuss voltage divider, reference voltage. Mapping readings to engineering units.
  - Attach RTD to ADC port.
  - Configure ADC port, resistor, reference.
  - Conduct same measurements, Compare results to expectations.
  - Pull data into excel and do the conversions.
  - Having some fun utilizing multiple sensor modes.
- Lab Part 2 - Custom IP/USN application via web services
  - walk through PHP web services tutorial
  - compare REST and SOAP.
  - Get to sensor service
  - Do the conversion to physical units.
  - Maybe extend with some calibration.
- Lab Part 3 - Custom analysis of the networking
  - Go through how to pull mgmt data out and how to perform survey

- Put the nodes on a circle and draw the connectivity on the chords.
- Maybe do some tracking the tree over time.
- Database access.
- Correlation between environmental conditions and network changes.

Wednesday 6/11/2007

- Topic 1 - Self-Organized Multihop Routing
  - Route-free communication
  - Dissemination, Flooding, Trickle.
  - Tree-reversal and associated issues
    - assymetry, filtering, storage, cachning
  - Comparison with established routing protocols
    - Distance-vector vs link state, RIP, OSPF, OLSR, MANET, ...

  - Suggested reading:
    - ***Taming the Challenges of Reliable Multihop Routing in Sensor Networks***, Alec Woo and David Culler, ACM SenSys Nov. 2003. [pdf]
    - P. Levis, N. Patel, D. Culler, and S. Shenker. Trickle: A Self-Regulating Algorithm for Code Propagation and Maintenance in Wireless Sensor Networks. In First Symposium on Network Systems Design and Implementation (NSDI), Mar. 2004.
    - **The Dynamic Behavior of a Data Dissemination Protocol for Network Programming at Scale**
      Jonathan W. Hui and David Culler. *The 2nd ACM Conference on Embedded Networked Sensor Systems (SenSys'04)*, November 3-5, 2004.
  - Additional Resources:
    - Krishnamachari, “Networking Wireless Sensors”, Chapter 8.
    - Ni, S.Y., Tseng, Y.C., Chen, Y.S., Sheu, J.P.: *The broadcast storm problem in a mobile ad hoc network*. In: Proceedings of the Fifth Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom'99). (1999) 152--162
    - Deepak Ganesan, Bhaskar Krishnamachari, Alec Woo, David Culler, Deborah Estrin and Stephen Wicker, **Complex Behavior at Scale: An Experimental Study of Low-Power Wireless Sensor Networks** , *UCLA Computer Science Technical Report UCLA/CSD-TR 02-0013.* (An older version of the report can be found **here** .)
    - W. Heinzelman, J. Kulik, and H. Balakrishnan, **``Adaptive Protocols for Information Dissemination in Wireless Sensor Networks,''** *Proc. 5th ACM/IEEE Mobicom Conference (MobiCom '99)*, Seattle, WA, August, 1999.

- Topic 2 - Achieving Low-Power Wireless Communication
    - Where the energy goes
    - The Idle listening problem
    - Scheduling vs. sampling
    - Low Power Listening and its Extensions
    - TDMA, FPS, TSMP
    - Classic debates
    - MAC vs Media Management
    - Suggested Reading
        - Versatile Low Power Media Access for Wireless Sensor Networks, Joe Polastre and David Culler, *The Second ACM Conference on Embedded Networked Sensor Systems*, SenSys 2004: 95-107, *Nov. 2004*. [pdf]
        - Technical Overview of the Time Synchronized Mesh Protocol (TSMP) http://www.dustnetworks.com/docs/TSMP_Whitepaper.pdf [pdf]
    - Additional ressources
        - V. Bharghavan and A. Demers and S. Shenker and L. Zhang, "MACAW: Media Access Protocol for Wireless LANs", Proceedings of the ACM SIGCOMM Conference, 1994. http://citeseer.nj.nec.com/bharghavan94macaw.html
        - **An Energy-Efficient MAC Protocol for Wireless Sensor Networks** Wei Ye, John Heidemann and Deborah Estrin In Proceedings of the 21st International Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2002), New York, NY, USA, June, 2002. (Phil Levis)
        - Alec Woo and David E. Culler,***A transmission control scheme for media access in sensor networks***, The seventh annual international conference on Mobile computing and networking 2001 July 16 - 21, 2001, Rome Italy. Pages 221-235

- Topic 3 - 6LoWPAN and IP Concepts
    - IP over 802.15.4
    - Trade-offs, issues, and advantages
    - Cross-layer header compression
    - Stacked Header Concept
    - Layering
    - Analysis and Comparisons
    - v4 vs v6
    - Relationship to other IETF activities
    - Suggested Reading
        - Secure, low-power, IP-based connectivity with IEEE 802.15.4 wireless networks, David Culler, Industrial Embedded Systems, May 2007
    - Additional Resources:
        - Transmission of IPv6 Packets over IEEE 802.15.4 Networks

    - Kannan Srinivasan, Prabal Dutta, Arsalan Tavakoli, and Philip Levis
      "Some Implications of Low-Power Wireless to IP Routing." In *Proceedings of the Fifth Workshop on Hot Topics in Networks (HotNets V)*, 2006. [ppt]

- Lab 3 Part 1 - IP-based WSN
    - Connection between WSN and LAN is a LoWPAN router, not a server or gateway
    - Understanding IP. Get client IP address and IPv6 address. Subnets, prefix, interface identifier. Ping LAN clients and router LAN interface. Ping6.
    - Set up route for LoWPAN subnet via LoWPAN router (route, netsh)
    - Ping. Router LoWPAN interface. Ping/Ping6 LoWPAN nodes. Ping/Ping6 multihop nodes.
    - ICMP, TCP, UDP ports and services
    - nc / telnet to standard ports - UDP/7 echo, TCP/7 echo, TCP/11 systat, TCP/15 netstat
    - nc / telnet to WSN ports - TCP/30 raw sensor reading, UDP/10 LED server
    - command line application specific processing using standard tools - stream readings to a file, etc.
    - Java/PHP/C client side programming. Addresses, ports, transport, buffers.
    - Well-known multicast address (All-nodes link local, all-nodes site-local)
    - Wireshark to watch traffic on the network.
    - Time permitting start on Embedded Programming

Thursday 6/12/2007

- Topic 1 - Deep Dive into System Resources and TinyOS 2.0 implementation
    - Tour of the subsystems: Timers, ADC, Busses (UART, I2C, SPI, OneWire), Arbiters, Radios, Flash
    - System service Abstractions
    - TEPs
    - Illustration of design trade-offs
    - Suggested Readings
        - http://www.tinyos.net/tinyos-2.x/doc/html/overview.html
    - Additional Resources
        - http://www.tinyos.net/tinyos-2.x/doc/

- Topic 2 - Time-Synchronization and Embedded Distributed Systems
    - Time-stamp exchange protocol
    - Sources of error
    - NTP - defensive distributed system design
    - Impact of the broadcast medium
    - System opportunities: post-arbitration timestamping
    - FTSP and its contemporaries

- Suggested Readings
  - Mills, D.L. Internet time synchronization: the Network Time Protocol. *IEEE Trans. Communications COM-39, 10* (October 1991), 1482-1493. PostScript | PDF
  - Maroti M., Kusy B., Simon G., Ledeczi A.: The Flooding Time Synchronization Protocol, SenSys 04, Baltimore, November 2004
- Additional Resources
  - *Timing-sync Protocol for Sensor Networks*, Saurabh Ganeriwal, Ram Kumar, and Mani B. Srivastava (UCLA), Sensys 2003, (http://www.ee.ucla.edu/~ram/webpage_files/TimeSync.pdf)
  - Fine-Grained Network Time Synchronization using Reference Broadcasts (also available as PDF) Jeremy Elson, Lewis Girod and Deborah Estrin. In Proceedings of the Fifth Symposium on Operating Systems Design and Implementation (OSDI 2002), Boston, MA. December 2002. (http://lecs.cs.ucla.edu/Publications/papers/broadcast-osdi.pdf)

- Topic 3 - In-networking Processing and Sensor Data Analysis
  - Signals perspective on physical phenomena
  - Climate example
  - Structural vibration example
  - CENS
  - Readings: TBD

- Lab 4 - TinyOS Programming on an Embedded Network Kernel
  -

Interfaces	TinyOS Concept	TEP	Start	Produce	tools / configs
LED, Notify	module, configuration, command, event		Push	Toggle	make, deluge
sprintf	network debugging				
Timer	generics, virtualized services		Blink	Count	max timers
Read	sensing, split-phase, parameterized		single	dual	peripherals
Task	post, task		raw	smooth	max task
send UDP, ipv6	buffer, memory		counts	readings	
receive UDP	dispatch		echo	rate control	ports

UDP linklocal bcast	peer-to-peer			remote LED	
Local Time			flash	ring	
options	cmds, timesych, route, reliability, DTN				

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Friday 6/13/2007

- Topic 1 - Energy, Power, and Sustainable Operation
  - Storage devices: batteries, caps, supercaps, fuel cells
  - Energy sources: solar, vibration, electricity
  - Systems solutions
  - Suggested Readings
    - Prabal Dutta, David E. Culler: ***System software techniques for low-power operation in wireless sensor networks.*** ICCAD 2005: 925-932.

- Topic 2 - Security and Reliability
  - Shared key and public key encryption on embedded devices
  - AES128 and 802.15.4
  - Research results and open problems
  - Suggested Readings
    - Security Considerations for IEEE 802.15.4 Networks, Naveen Sastry and David Wagner. ACM WiSe 2004, October 1, 2004. [pdf]
  - Additional Resources
    - TinySec: A Link Layer Security Architecture for Wireless Sensor Networks, Chris Karlof, Naveen Sastry, and David Wagner. ACM SenSys 2004, November 3-5, 2004. [pdf]
    - Sizzle: A Standards-based end-to-end Security Architecture for the Embedded Internet, *Pervasive and Mobile Computing Journal* (special issue on selected papers from PerCom 2005), Vol 1, Issue 4, Dec 2005, pp. 425-445.
    - A. Perrig, J. Stankovic, and D. Wagner, Security in Wireless Sensor Networks, CACM, Vol. 47, No. 6, June 2004.
    - SPINS: Security Protocols for Sensor Networks, A. Perrig, R. Szewczyk, V. Wen, D. Culler, and J.D. Tygar, Mobile Computing and Networking, Rome, Italy, 2001

- Topic 3 - Future Developments
    - deeply integrated devices
    - mobility
    - classification, search, ...
    - Open Discussion

- Lab 5
    - Completion of Embedded Programming, Team Extensions