Wireless Sensor Networks

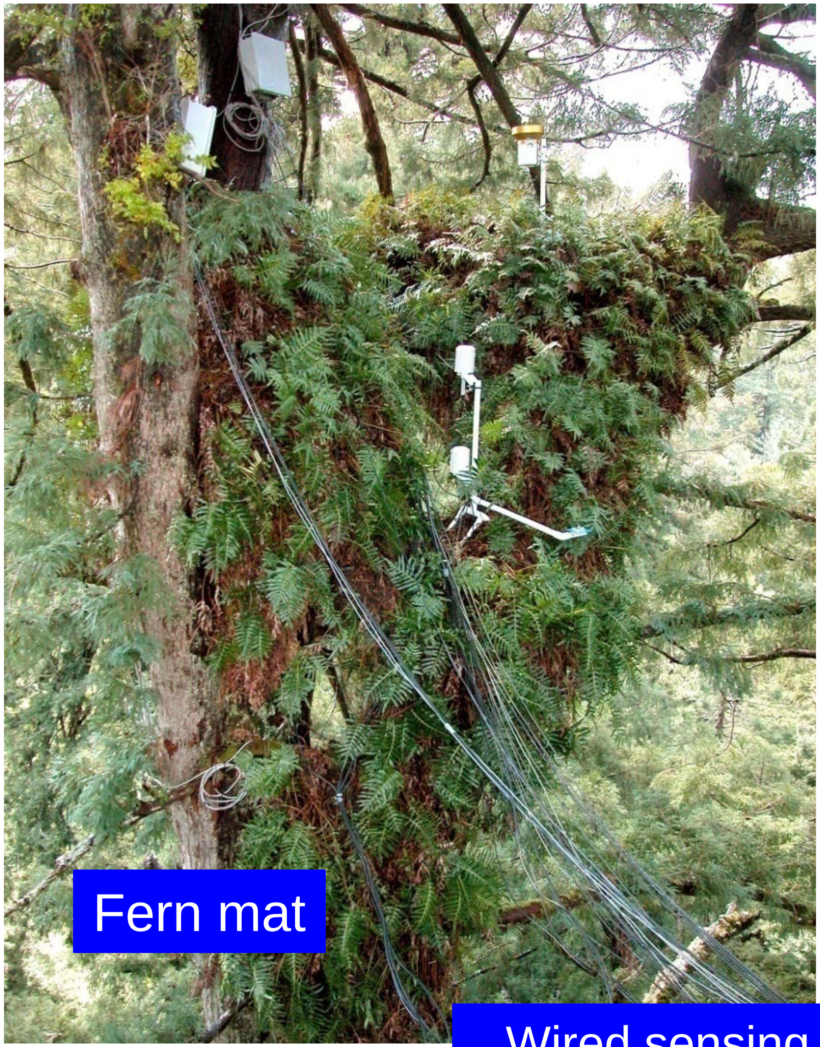
Understanding Complex-Engineered Systems By Example

muse

Outline

CA Coastal Redwoods

CA Coastal Redwoods



Fern mat

Wired sensing infrastructure requires over 1 km of cable per tree

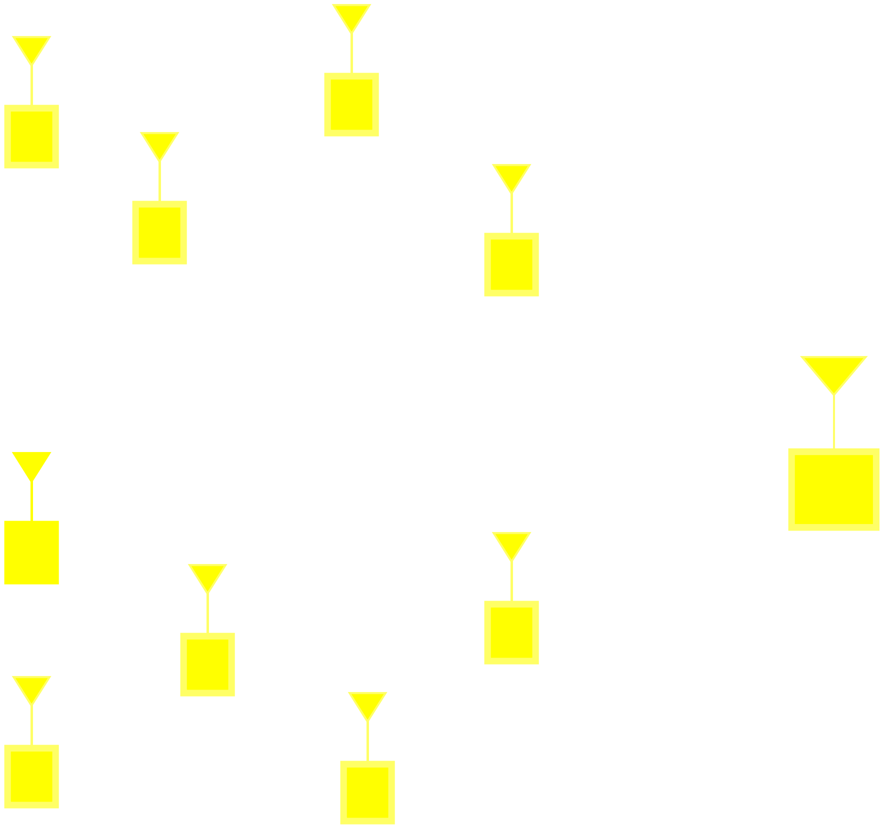
Wireless Ad Hoc Networking of Physically-Embedded Sensors

Dense, minimally-invasive array of sensors to monitor microclimate variables such as temperature and light. Standalone or wired sensor arrays are invasive and difficult to deploy and operate.

<u>Opportunity:</u> Wireless networking of the sensors

- dramatically improve coverage and spatial density, and ultimately, our understanding of environments and ecosystems...
- …while greatly reducing the total monitoring cost

WiSARDNET Concept



In situ monitoring of the environment: Why?

Key ecological questions:

In situ monitoring of the environment: Why?

Key ecological questions:

1. Biodiversity
2. Effects of global climate change
3. Invasive species
4. Infectious diseases
5. Effects of human land and water use

In situ monitoring of the environment: Why?

Key ecological questions:

1. Biodiversity
2. Effects of global climate change
3. Invasive species
4. Infectious diseases
5. Effects of human land and water use

Need ability to construct predictive ecological models across scales of space and time

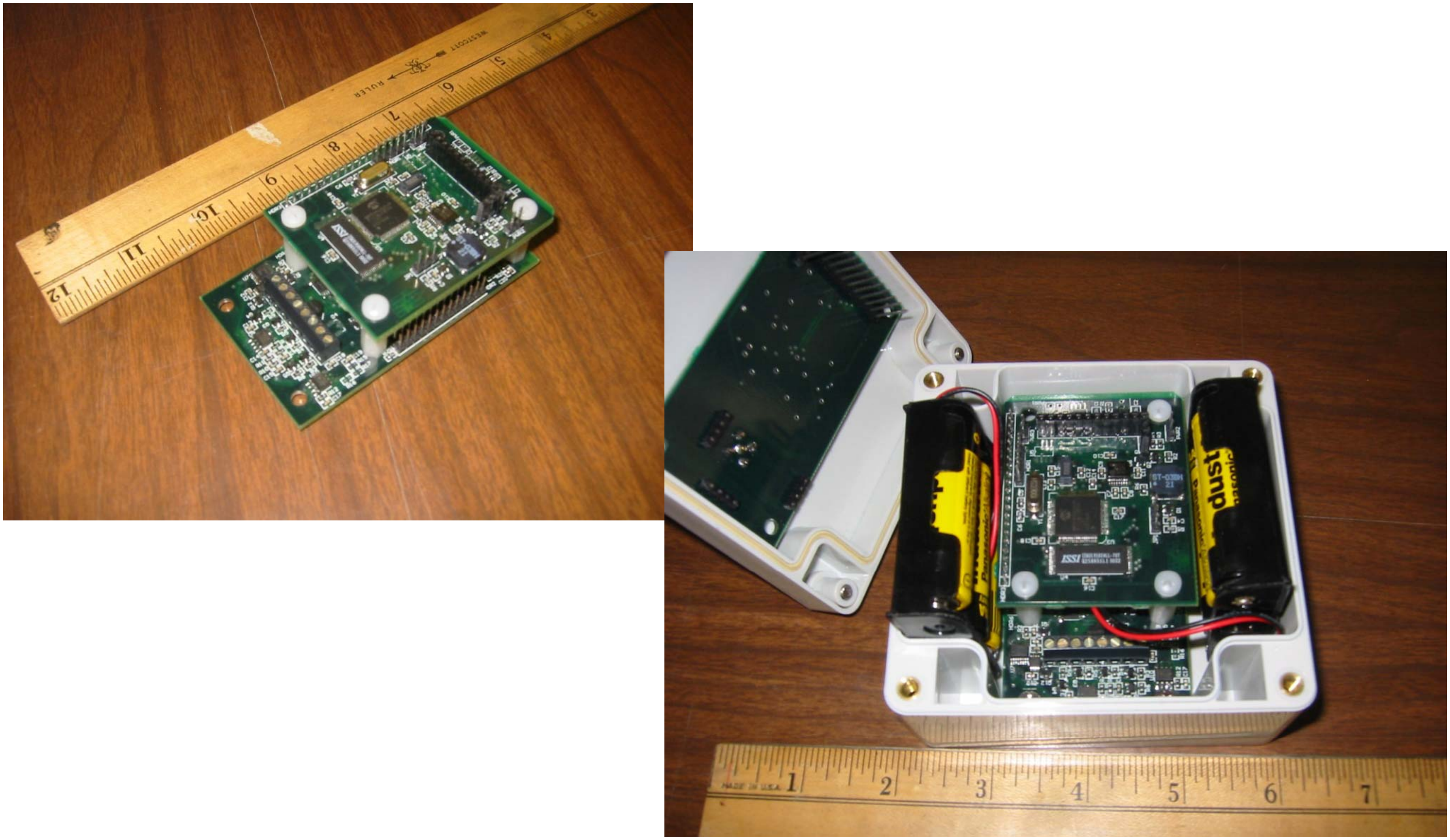
Requirements – Environmental Sensing

- Long battery life
- Minimal invasiveness
- Scientific accuracy
- Support of a broad spectrum of probes
- Support incremental deployment
- Scalable in network size and density
- Ease of installation and maintenance
- Support of internet connectivity
- Rugged, weatherproof packaging
- Low life cycle cost

2nd Generation WiSARD

Modular hardware design

- Dual-processor architecture
- Three-board stack



WiSARDNet Design

Communication and Networking

- 902 – 928 MHz ISM band
- Non-Coherent Binary FSK (NC-BFSK) modulation
- Slow time/frequency hopping spread spectrum via pseudo-random number generator
- CRMA radio channel sharing algorithm
  - Distributed control
  - Local information
  - Scalable

Self Organization

- Forms minimum power-cost tree from gateway node
- Periodic search for new nodes
- Can add, move, or delete nodes

Power Management

- Monitor power status
- Report battery voltage
- Adaptive radio transmit power (under development)

Scheduler

- Time-triggered s/w architecture
- Dynamic scheduling of communication

Dynamic Reporting

- Report on significant change only

User Interface

- Command line from PC
- User selection of ID, sample rates
- Rich on-line diagnostics

G2 WiSARD H/W Capabilities

Built-in probe interfaces

- 12-bit A/D conversion
- 4 temperature channels
  - thermocouple
- 4 light (PAR) channels
  - photodiode
- 2 general purpose probe channels, two power outputs and two CCP modules (Capture/Compare/PWM)
  - Soil moisture
    - Decagon Ech2oprobe
  - Serial communication with intelligent probes
  - Sap flux (Granier method)

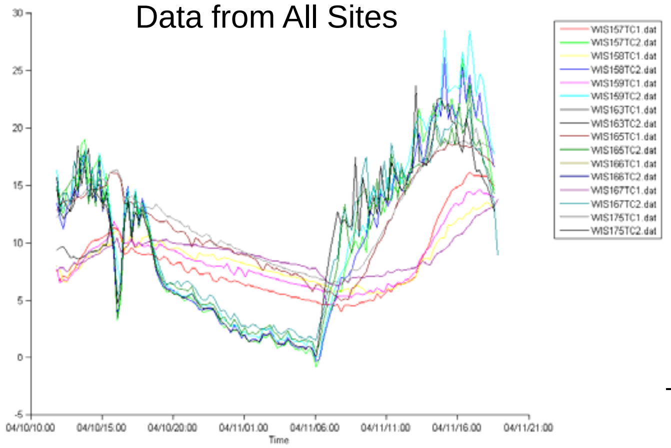
Interface for multiple additional intelligent probes

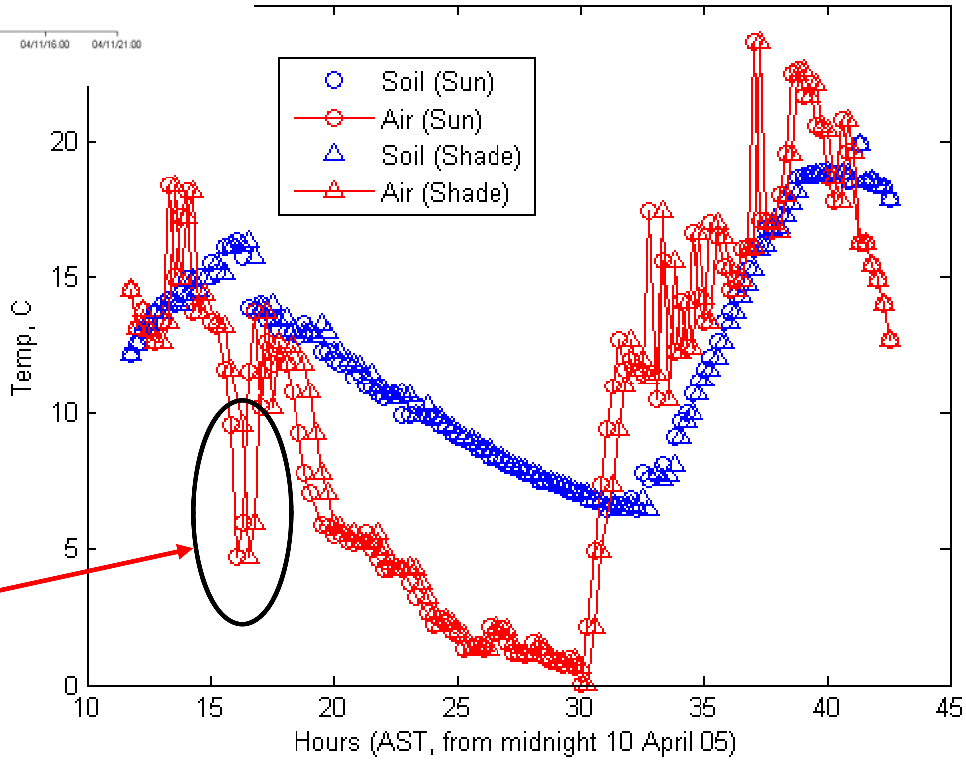
- One-wire bus

Provision for external energy supplies

- Supports autonomous switching between internal and external energy sources
- Battery-backed solar

Trial Deployment, April 2005: Grasslands site, C. Hart Merriam Elevational Gradient


Data from All Sites



Microburst and brief cloud cover

Example Wireless Sensor Node Technologies: Research

Self-healing mesh WSN technologies-

- BTnodes (ETH Zurich)
  - 915 MHz + Bluetooth
  - BTnut executive (thread support)
  - Can be purchased: raw board – 165 Euros
- Motes (UC Berkeley) MicaZ, T-Mote Sky, Telos, many more
  - 2.4 GHz
  - Event-driven TinyOS (events, tasks, FIFO scheduler)
- WiSARDNet (NAU)
  - 915 MHz
  - Time-triggered executive with synchronized wake-up
  - Interfaces for Type-T thermocouples, quantum PAR, Echoprobe SM, Vaisala WXT-510
- Many more…

Example Wireless Sensor Node Technologies: Commercial

- Microstrain V-Link
  - Single-hop (star)
  - 2.4 GHz
  - $500 per node
  - Needs enclosure
- Crossbow eKo
  - Mesh
  - 2.4 GHz
  - $570 per node
- National Instruments
  - CompactRIO – LabView
  - 802.11g (2.4 GHz)
  - Needs enclosure
  - ~$3,000 per node
  - See www.sensorkit.net (UCLA CENS)

Economics of WSNs for Environmental Monitoring

How much does a sensor net cost?

Per Sensor Node		**Total**
Node	$70 (incl. packaging)	$70
Light	2 x ($50 - $300)	$300
Temperature (thermocouple)	2 x $15	$30
Soil moisture	$80	$80
Cost per node		**$480**
One Station per Site		
RH (VPD), rain, wind speed/velocity + solar pwr	$3000	$3000

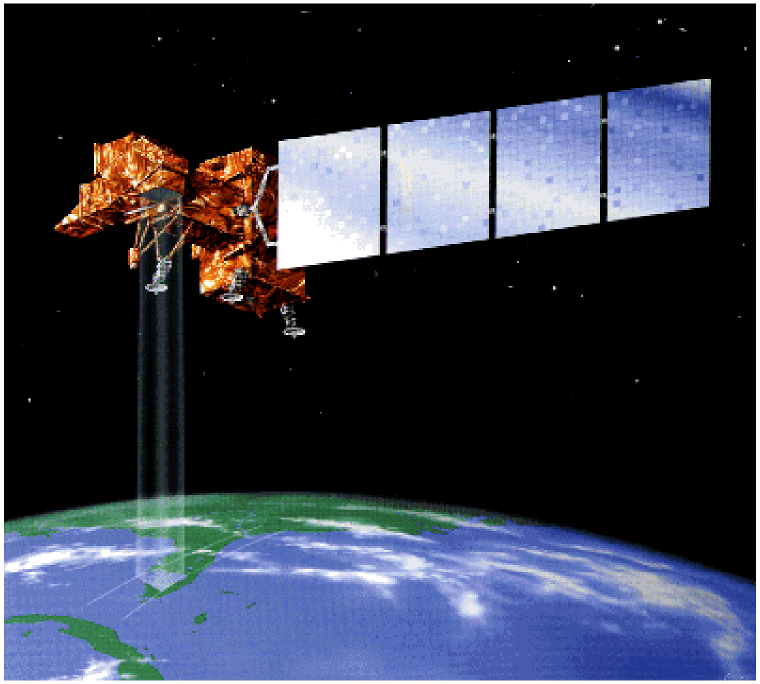
How much does a sensor net cost?

Per Sensor Node		**Total**
Node	$70 (incl. packaging)	$70
Light	2 x ($50 - $300)	$300
Temperature (thermocouple)	2 x $15	$30
Soil moisture	$80	$80
Cost per node		**$480**
One Station per Site		
RH (VPD), rain, wind speed/velocity + solar pwr	$3000	$3000

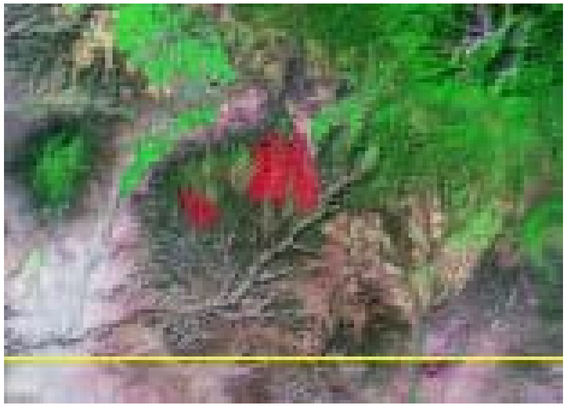
Sap flux, Trunk growth, Leaf respiration, Eddy Covariance, Seed baskets, Tree ID/location, Surveys, Deployment…

Monitoring the planet…

- Suppose we have $100M (OCO ~ $300M)
- Assume sensors cost $100 including installation
- Assume have average of ~ 2 per hectare… (Current deployments have ~ 9 sensors/hectare)



Why not just use satellites?



- Need ground truth data
- Undercanopy measurements
- Biotic responses
- Resolution: individual organism
  - Sap flux
  - Leaf-based measurements

We Need WSNs

- But the technology needs to be dramatically improved
- Are there other application domains?

Can we generalize from the environmental monitoring app?

Applications

<u>The Challenge</u>

Environmental sensor networks in 30 seconds

SENSING

- Lots of dataloggers scattered in the environment
- They require energy
- Their measurements are error-prone

NETWORKING

- Transmitting the measurements to where they can be used
  - takes a lot more energy/batteries (than just taking a sample)
  - is very error-prone

Energy is #1

Sensors $s$ample, $c$ommunicate, and $h$ibernate

Typically

$$i_S = 500\ i_H$$

$$i_C = 1000\ i_H = 2.5\ i_S$$

How can we improve energy efficiency?
1. Embedded Systems

1. **Goal: ensure that every electronic component uses the minimum amount of energy to do its job**
    - Optimize process technologies
        - Digital, analog, RF
    - Improve power regulation and management

2. **Goal: no electronic component uses energy unless it is doing something useful**
    - Clock domains (and gating)
    - Power domains (and gating)
    - Dynamic voltage scaling

How can we improve energy efficiency?

2. Communication and Networking

1. Minimize useless radio operation
   - transmitting when there is no relevant node to receive
   - listening when no relevant node is transmitting

2. Transmit only what is necessary to solve the problem of model/data inference
   - exploit spatio-temporal redundancy of the data
   - use coding to protect data

WSN Engineering

Course: Motivation

Today's curricula have failed to cultivate the concept of *systems thinking*

Undergraduate electrical engineering curricula are

Yet real engineered systems are

Course Objectives

- Develop in-depth technical understanding of the multiple subdisciplines required for the design of WSNs.
- Promote understanding of *systems thinking*---the ability to integrate knowledge from the subdisciplines in the engineering of WSNs.
  - Focus onWSN applications to environmental monitoring
  - Describe how WSN's have very different properties and design challenges from those of infrastructured wireless networks.
  - Review a broad range of technical issues, ranging from basic research questions to state-of-the-art designs

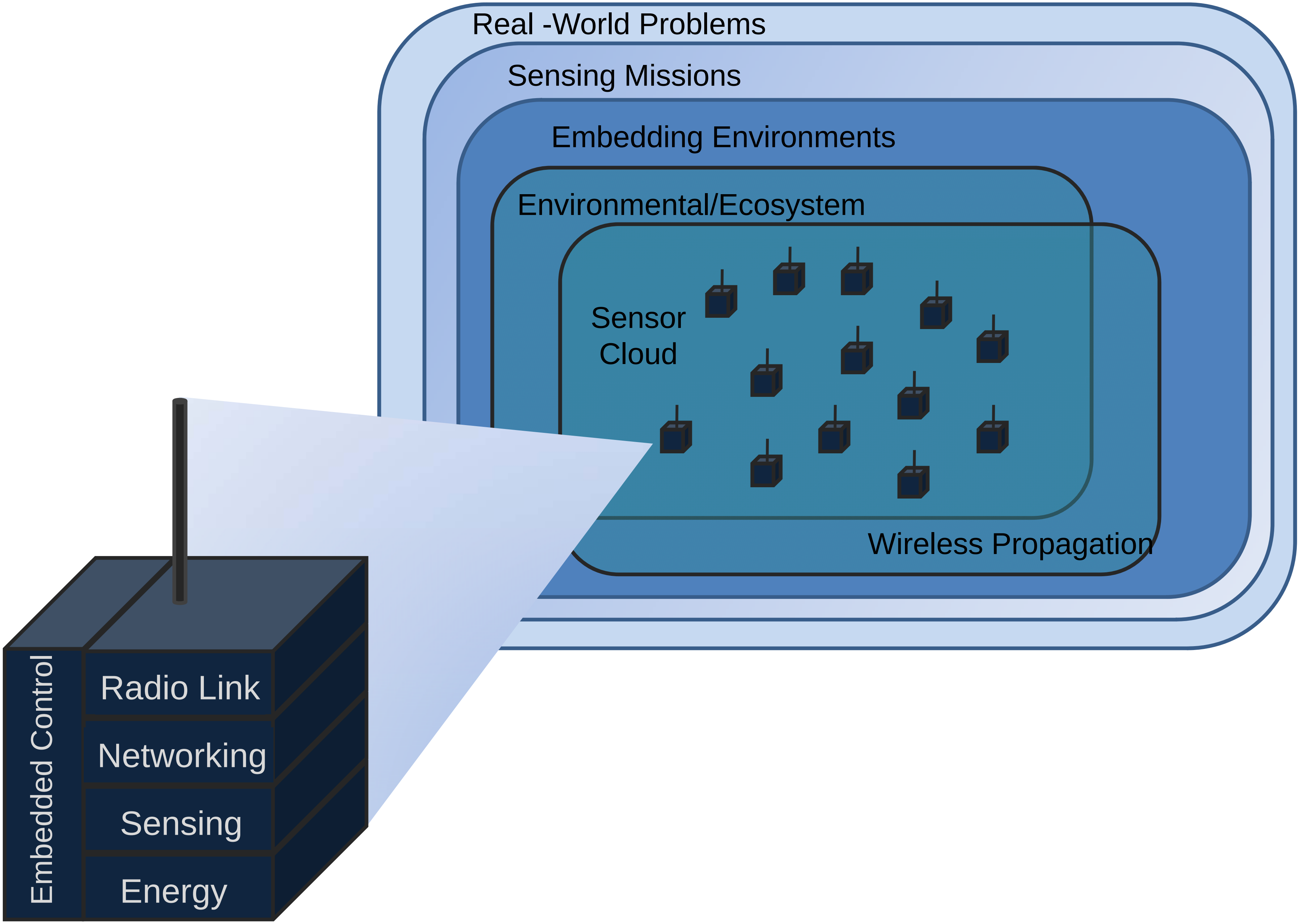
What this course is about

1. **Helping you understand behavioral models of a complex engineered system at different layers**

2. **Thinking about models of interaction between layers that determine performance according to a variety of interdependent measures, such as fidelity, delay, and energy efficiency.**

- In contrast to traditional, subdiscipline-specific courses, the course will emphasize the modeling, analysis, and simulation of complex engineered systems.

- See beyond the parts lists and toolsets of specific disciplines to the overall structure of the design.


Real -World Problems
Sensing Missions
Embedding Environments
Environmental/Ecosystem
Sensor Cloud
Wireless Propagation
Embedded Control
Radio Link
Networking
Sensing
Energy

Take Home Messages

Hardware Technology Prospects: Today and Tomorrow

- Node hardware costs can be made small
  - Leverage volume-manufactured chips
- Transducers remain expensive
- Embedded in inhospitable 3D space

Possible to have redundancy in nodes, but not transducers

- Installation/maintenance costs dominate
  - Battery replenishment

Future

- Node hardware costs can vanish
- Energy supply (provision and replenishment) and harvesting difficult (but there is hope)
- Transducer costs will depend on technology and size of market
- Installation/maintenance costs fixed (?)

WSN engineering invokes cross-layer design challenges!

- PHY and MAC
- Routing and Application (self-organization)
- MAC and Embedded Software (co-design)
- Embedded Software and ULP MCU’s
- Source and Channel Coding

References

Book

H. Karl and A. Willig. *Protocols and Architectures for Wireless Sensor Networks*. Wiley, 2007. ISBN 978-0-470-51923-3.

Overview paper

H. Karl and A. Willig. A short survey of wireless sensor networks. TKN Technical Report TKN-03-018. Berlin, October 2003.