Wireless Embedded Systems and Networking

Foundations of IP-based Ubiquitous Sensor Networks

Next-Tier of the Internet - IP-based Wireless Sensor Networks

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Lecture Outline

- Introductions
- Ubiquitous Networks => Integration Real World Information
- Overview of Wireless Sensor Networks
  - Technology Enablers
  - Application Opportunities
  - Systems Challenge
- Overview of the week's course
- Discussion

Introductions

- Instructor: Dr. David E. Culler
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  - http://www.eecs.berkeley.edu/~jaein
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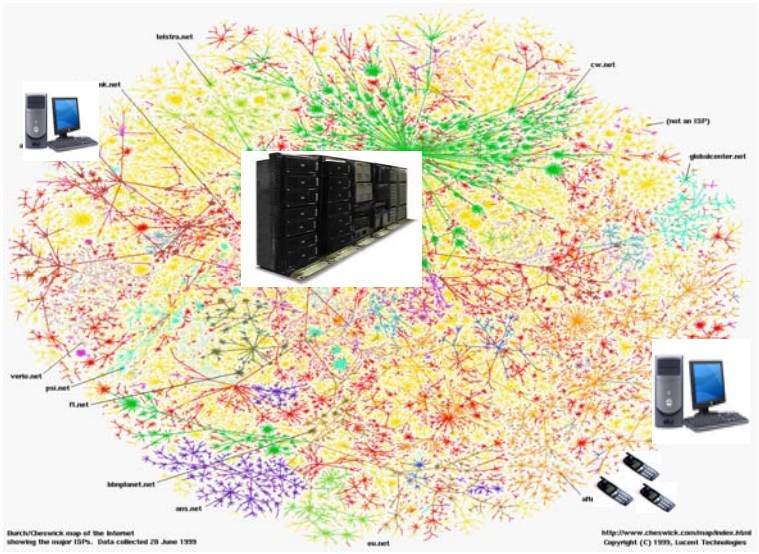
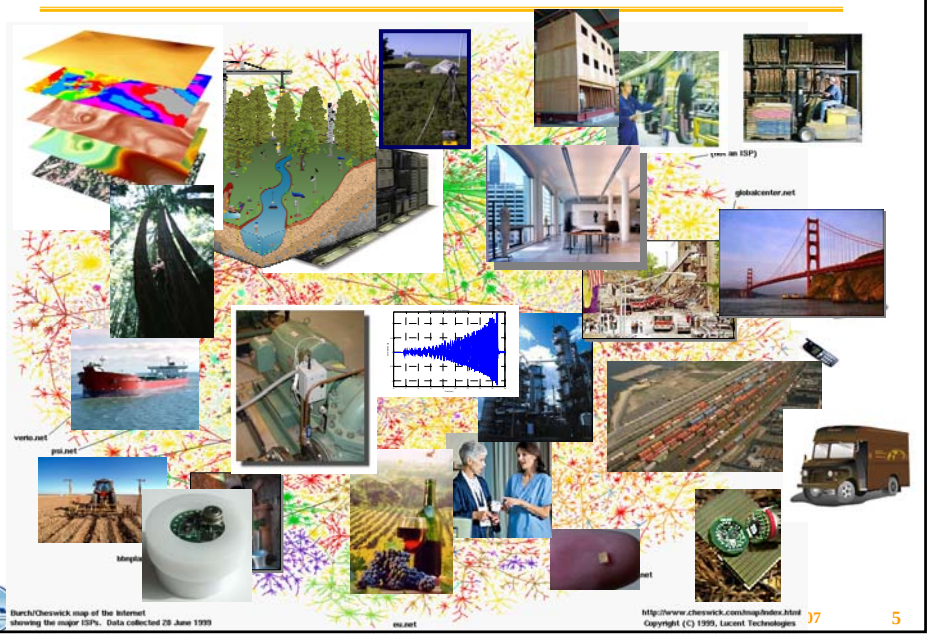
- Class Members …

The Internet today



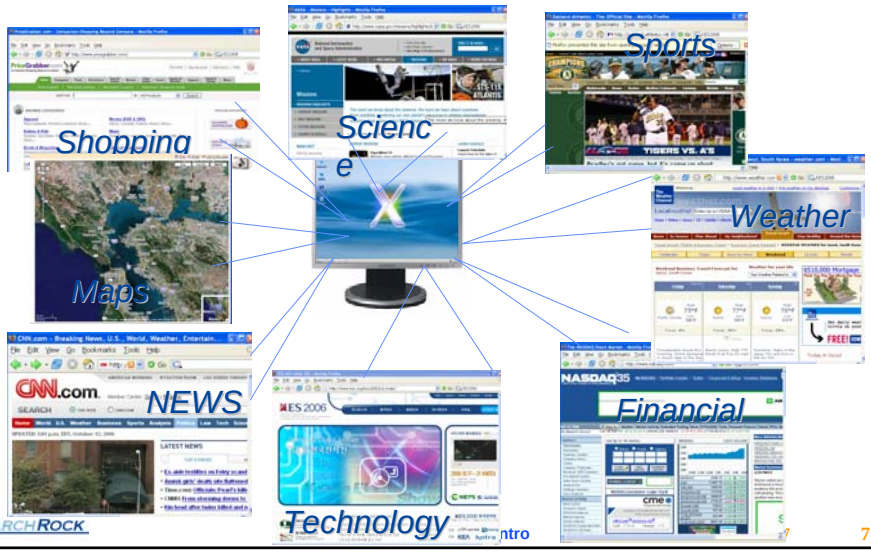
The Real Internet ahead



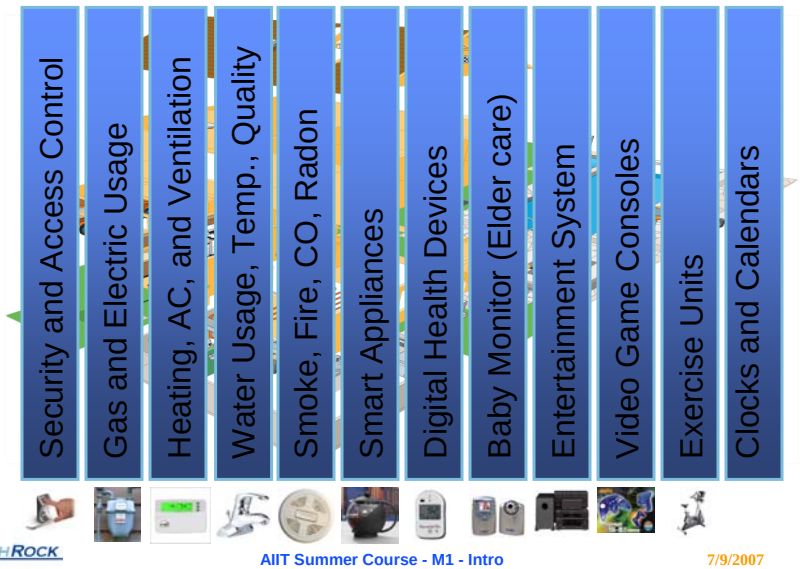
Why "Real" Information is so Important?

The Web Today

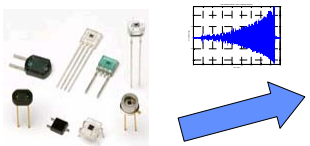
Integrates the World's *Human Generated* Information



Most Real World Information goes "down the drain"



Physical Information Streams



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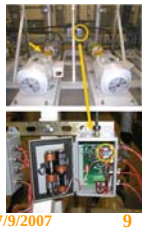
- **Sensors are everywhere**
  - **But the data is mostly dropped on the floor**
- **Physical => Digital => *Information***
- **Each sensor becomes a** network citizen

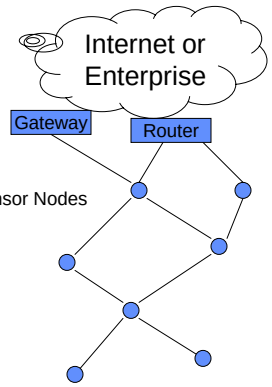


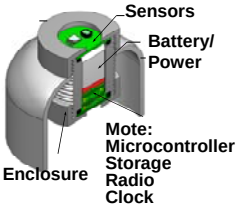
Wireless Sensor Network

- **Network of tiny footprint computers**
- **Optimized for long life on low power**
- **Equipped to sense physical data**
- **Networked using low-power radio**

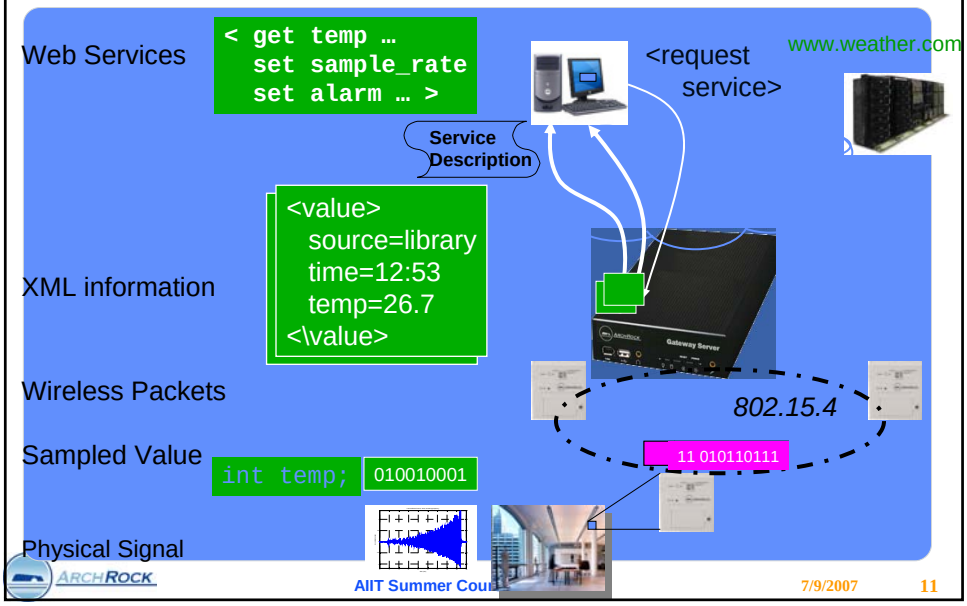
- **Function:**
  - **Sense any measurable parameter**
    - » **Light, motion, chemicals, proximity, biometrics**
  - **Form network and communicate**
    - » **Automatic meshing and routing over the air**
  - **Apply user-defined business logic**
    - » **Sampling, summarizing, reporting events**

- **Form:**
  - **Mote (Processor, Radio, Storage) + Sensors**
  - **Embedded Operating System and Networking**
  - **Router & Gateways towards Enterprise IT systems**



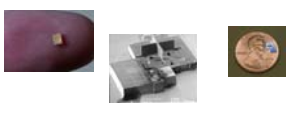


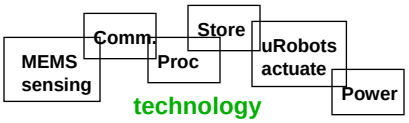
Our goal: Ubiquitous Real Internet



Technology Push / Application Pull

Monitoring & Managing Spaces and Things

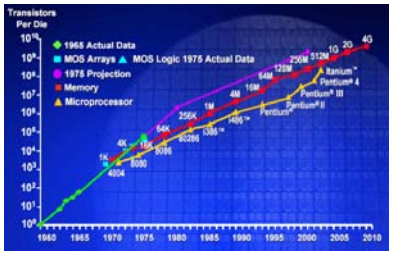




Miniature, low-power connections to the physical world

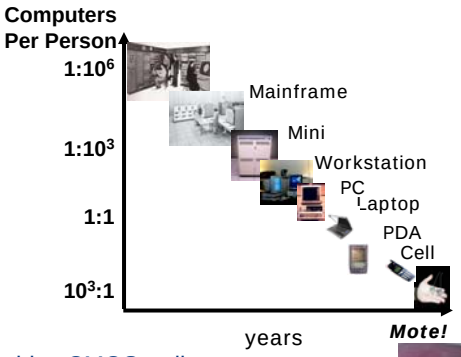
Broad Technology Trends

Moore's Law: # transistors on cost-effective chip doubles every 18 months



Today: 1 million transistors per $

Bell's Law: a new computer class emerges every 10 years



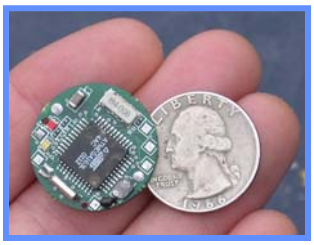
Same fabrication technology provides CMOS radios for communication and micro-sensors

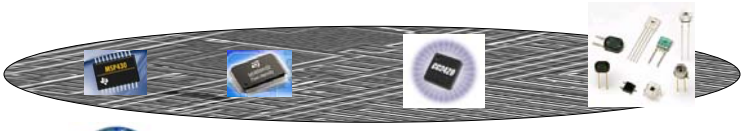
Enabling Technology

Microcontroller | Flash Storage | Radio Communication | Sensors

IEEE 802.15.4

Enabling Technology





The New Power Point

- **Microcontrollers:**
  - 1-10 mW active, 1 uW passive => 10-100 uW average
- **Micro-sensors (MEMS, Materials, Circuits)**
  - acceleration, vibration, gyroscope, tilt, magnetic, heat, motion, pressure, temp, light, moisture, humidity, barometric
  - chemical (CO, CO2, radon), biological, microradar, ...
  - actuators too (mirrors, motors, smart surfaces, micro-robots)
- **Micro-Radios**
  - CMOS, short range (10 m), low bit-rate (200 kbps), 10 mW
- **Micro-Power**
  - Batteries: 1,000 mW*s/mm^3, fuel cells
  - solar (10 mW/cm^2, 0.1 mW indoors), vibration (~uW/gm), flow
- **1 cm^3 battery => 1 year at 1 msgs/sec**

Technology Push / Application Pull

Monitoring & Managing Spaces and Things

applications

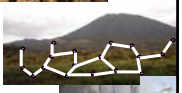
MEMS sensing
Comm.
Proc
Store
uRobots actuate
Power

technology

Miniature, low-power connections to the physical world

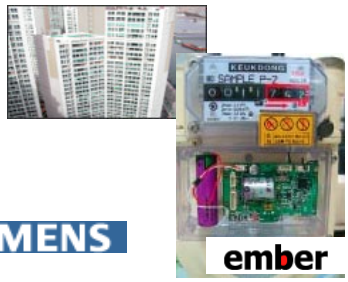
WSN Applications

- Monitoring Spaces
  - **Env. Monitoring, Conservation biology, ...**
  - **Precision agriculture,**
  - **built environment comfort & efficiency ...**
  - **alarms, security, surveillance, EPA, OSHA, treaty verification ...**
- Monitoring Things
  - **automated meter reading**
  - **condition-based maintenance**
  - **disaster management**
  - **Civil infrastructure**
- Interactions of Space and Things
  - **manufacturing, asset tracking, fleet & franchise**
  - **context aware computing, non-verbal communication**
  - **Assistance - home/elder care**
- Action and control
  - **Optimizing processes**
  - **Automation**



Early Industrial Examples

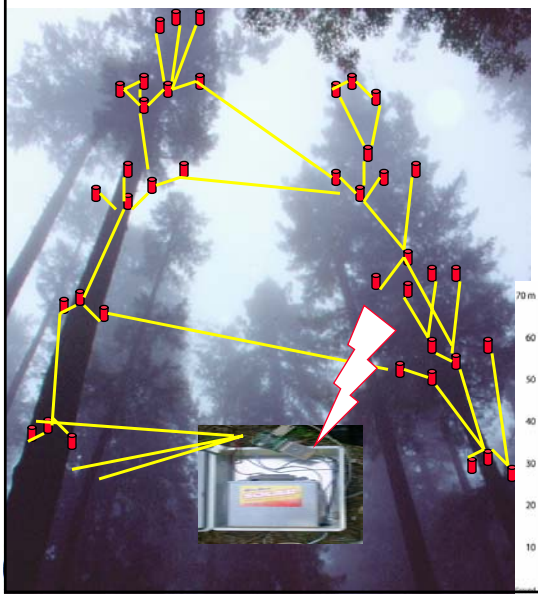
Temperature and Energy Monitoring



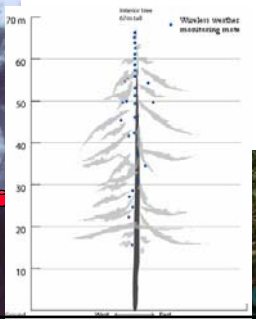
SIEMENS

AMI – NURI Telecom & SK Telecom :

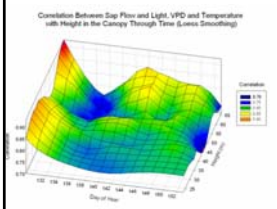
Example: A Month in the Life of a Redwood Tree

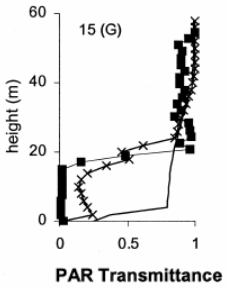


- Time: *1 month*
- Period: *5 minutes*
- Height: *15m to 70m*
- Angle: *west side*
- Radius: *10-100cm*
- Count: *33 nodes/tree*
  - *155 sensors*
- Spacing: *~2m*

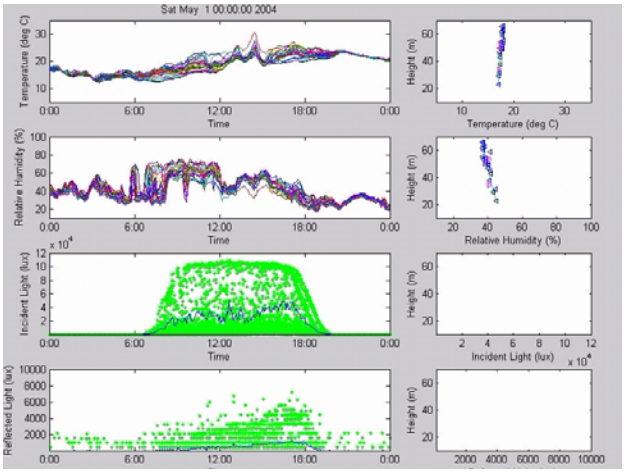


The Result: Spatial Gradients over time





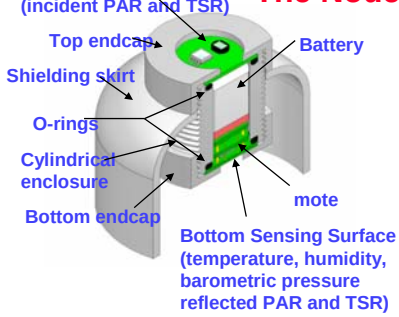
(Mariscal et al. 2004)



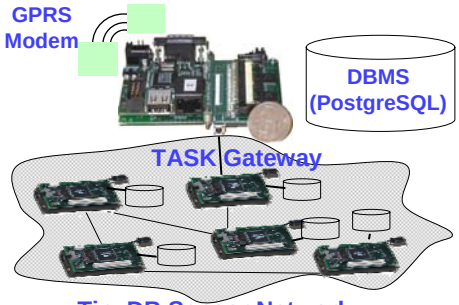
Macroscope in the Redwoods, Tolle et all, ACM SENSYS 2005

The Complete Solution

The Node



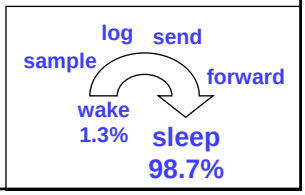
The Infrastructure



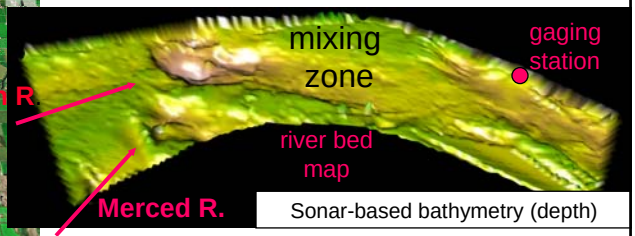
The Program

```
SELECT
result_time, epoch, nodeid,
parent, voltage, depth,
humidity, humid_temp,
hamatop, hamabot
FROM sensors
SAMPLE PERIOD 5 min
```

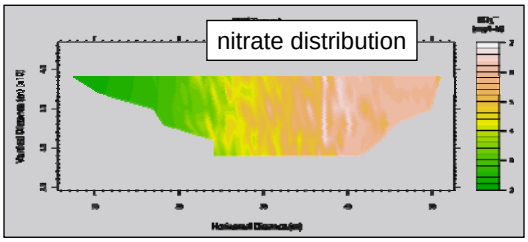
The Behavior



NIMS RD Merced and San Joaquin River Confluence (Harmon, Kaiser, et al)



Sonar-based bathymetry (depth)



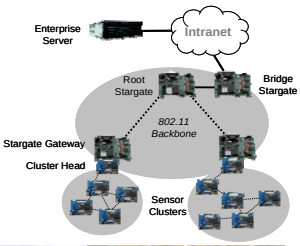
Environmental Monitoring Characteristics

- Large number of nodes spread over physical space of interest
- Low sample rate (of multiple sensor modes)
  - Further reduced by node signal processing and compression
- Reliable dissemination of configuration, command, or query
- Low-rate scalar data collection
  - Many options for reliability, Predictable reporting delays
- Low duty cycle for long lifetime

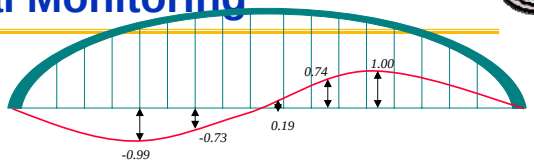
- Energy availability is application specific
- Extension to event detection and triggering demands more responsive protocols
- Extension to control requires predictable outward routing

Intel Fab & BP Machine Monitoring

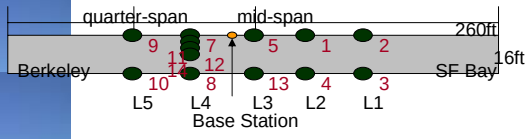
- **Goal: Pre-empt equipment failures through non-destructive analysis**
- **Media Gap: Majority of data is collected by hand**
  - **Thousands of sense points**
- **Intel Fab and an Oil Tanker engine room**
- **Wireless vibration data collection**
  - **High-speed sampling, reliable bulk transfer**
  - **Sensor-to-Analysis App flow**
  - **Overcome interference**
  - **Support disconnected operation**
- **Loch Rannoch Network**
  - **150 accelerometers**
  - **26 motes**
  - **4 stargates**
  - **1 PC**
- **Efficient installation and management**
  - **36hr install period on tanker**
  - **No crew intervention**

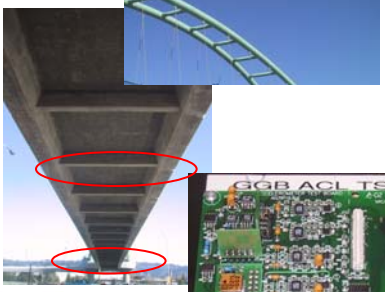


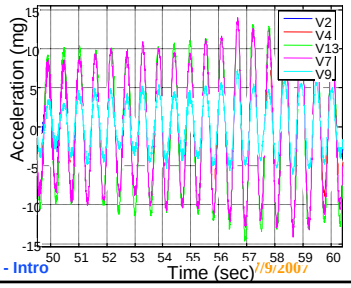
GGB Structural Monitoring



Frequency: 1.41 Hz
Damping Ratio: 2%





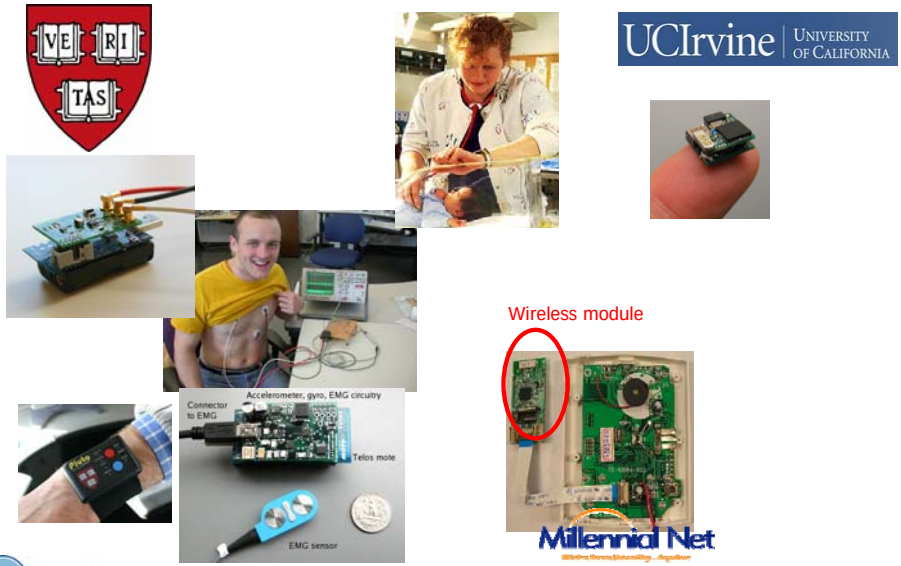


Machine Monitoring Characteristics

- Nodes clustered on specific equipment
- High sample rate (over short bursts)
  - Substantial local signal processing
- Control and management is like Env. Monitoring
- Data collection in single-point streams
  - Reliable end-to-end transport
- Shallow networks in practice

- **Well understood**
  - **but not yet well supported**
- Energy availability is site specific
- Natural extensions for local access (inspector)
- Structural monitoring is much harder than CBM
  - Time coordinated samples, cross-node data analysis
- Environmental factors critical to sensing accuracy

Medical Monitoring



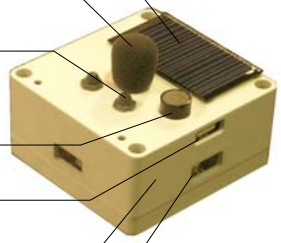
Large-Scale Security and Tracking

- **557 nodes over several km**
- **Self-powered, self-maintaining**
- **2 person-day deployment**
- **OTA programming and management infrastructure**

Solar Cell

Microphone

User / Reset



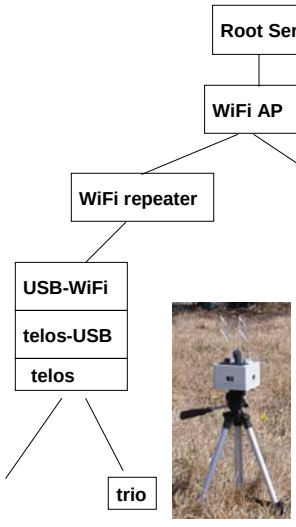
Buzzer

USB Port

Magnetometer

Passive IR x4

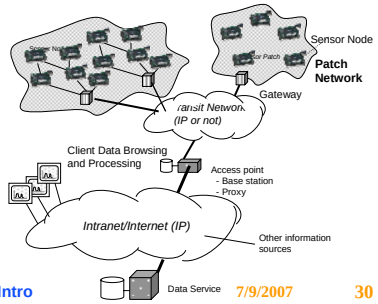
Example Tiers



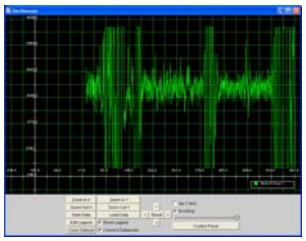
802.15.4 – 802.11 gateway

UCB Trio node

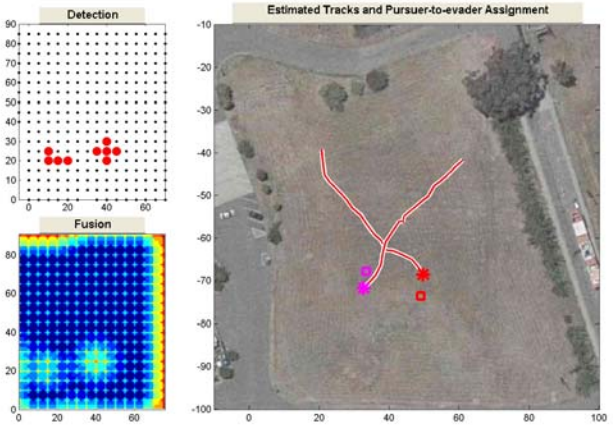
557 node DARPA NEST Aug 05



Sensing => Understanding

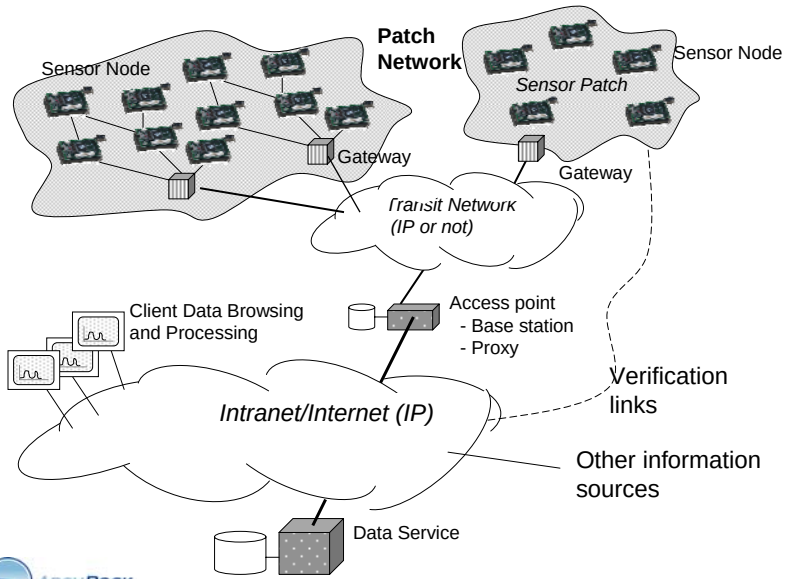


Wireless PIR readings



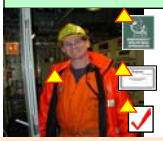
Plus UAV exfiltration, distributed tracking

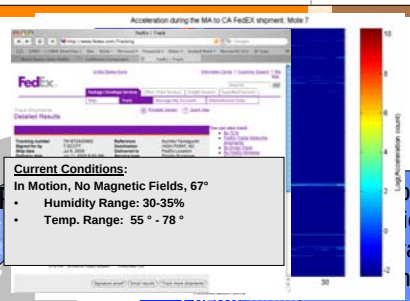
Canonical SensorNet Network Architecture



Proximity, Tracking, Compliance

Safety:
Chemical-to-chemical safety alerts
Human-to-chemical safety alerts





…pping QoS:
…ion threshold
…ature/humidity
…reshold

environmental

Home: Lighting

"The information about the package is as valuable as the delivery of the package itself."

-Fred Smith
CEO, FedEx

Interaction Monitoring Characteristics

- **Many different forms of monitoring**
  - **Untagged vs tagged items**
- **Mobility is central**
  - **Mobile nodes moving through stationary networks**
  - **Networks moving through networks**
  - **Proximity detection and action**
- **Wide range of communication patterns**
  - **Mobile-mobile routing**
- **Adaptive protocols**
- **Sophisticated routing**
- **Reliability through custody transfer**
- **Deep interactions with IT infrastructure**

Example: Petroleum Industry

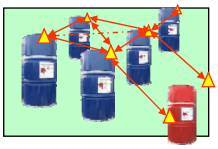
Condition-based Maintenance



Pipelines

integrity
security

Safety


workers

storage

process

Tracking

tank
cars

construction
assets

"This technology will transform everything we touch, not just in business but in our personal lives as well."
--P.P. Darukhanavala, CTO, British Petroleum

ARCHROCK

Characteristics of Sensor Nets?

- ***Not Universal pt-pt file transfer and keystrokes between hosts!***
- **Aggregate communication**
  - **dissemination, data collection, aggregation**
- **Resource constraints**
  - **Limited bandwidth, limited storage, limited energy**
- **In-network processing and storage**
  - **Really**
- **Intermittent connectivity**
  - **Low-power operation, out of range, obstructions**
- **Communicate with data or logical services, not just devices**
  - **Datacentric**
- **Mobility**
  - **Devices moving, tags, networks moving through networks**

Core challenges

- Long-lived, unattended, reliable operation
  - Power
    - » Wireless often means self-powered
      - Batteries
      - Ambient sources (light, current, vibration, heat, …)
  - Limited Memory
  - Self-organization and Management
  - Error, fault, noise mitigation
- Ease of broad application development
  - New forms of information
  - Integration into enterprise processes and actions
  - Extracting value from vast, novel sources of information

A Systems Challenge

Monitoring & Managing Spaces and Things

applications

data mgmt

service

network

system

architecture

Comm.

Store

MEMS sensing

Proc

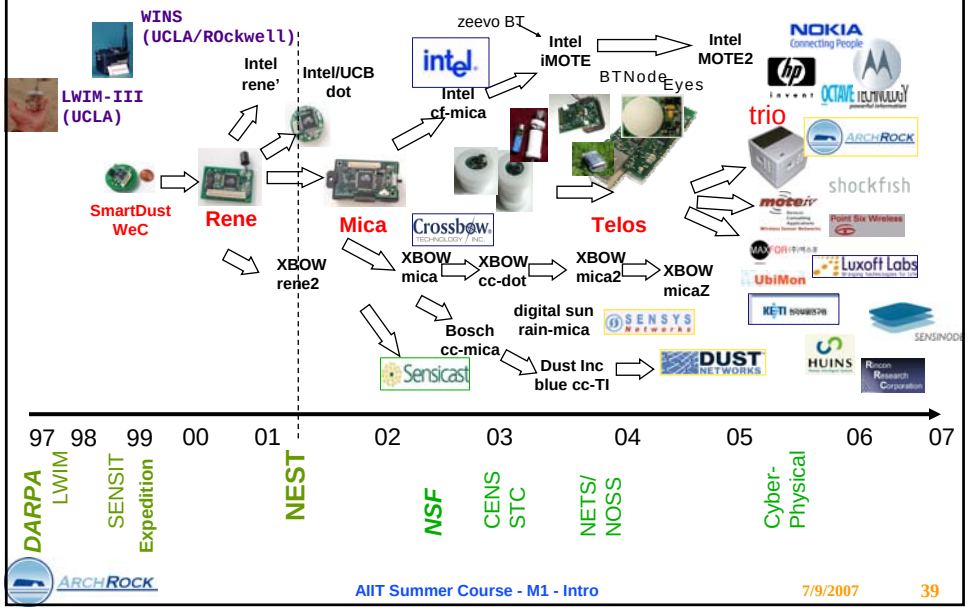
uRobots actuate

Power

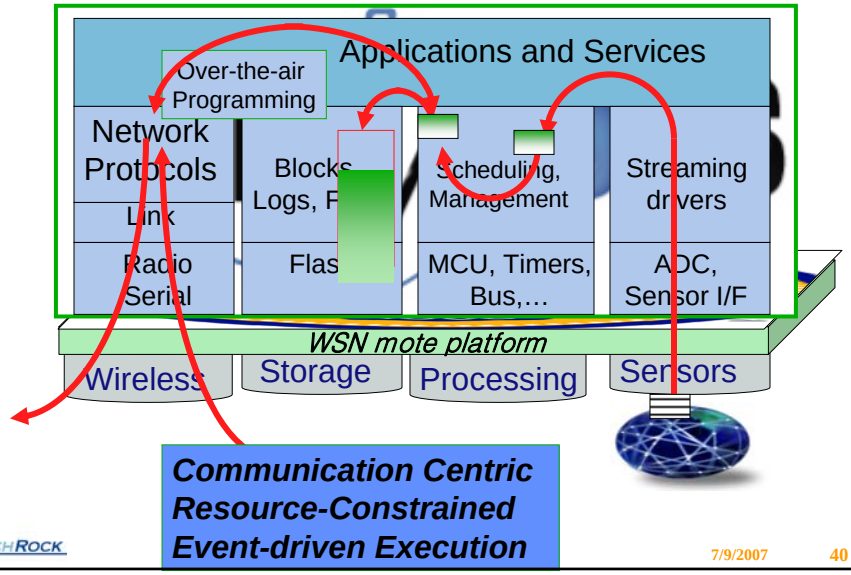
technology

Miniature, low-power connections to the physical world

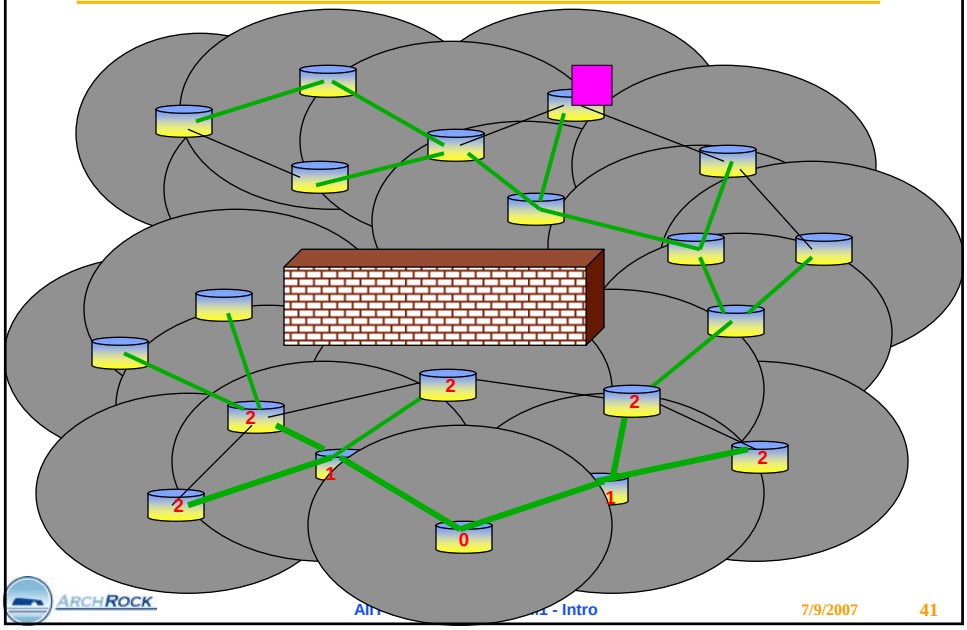
Mote Architecture Evolution



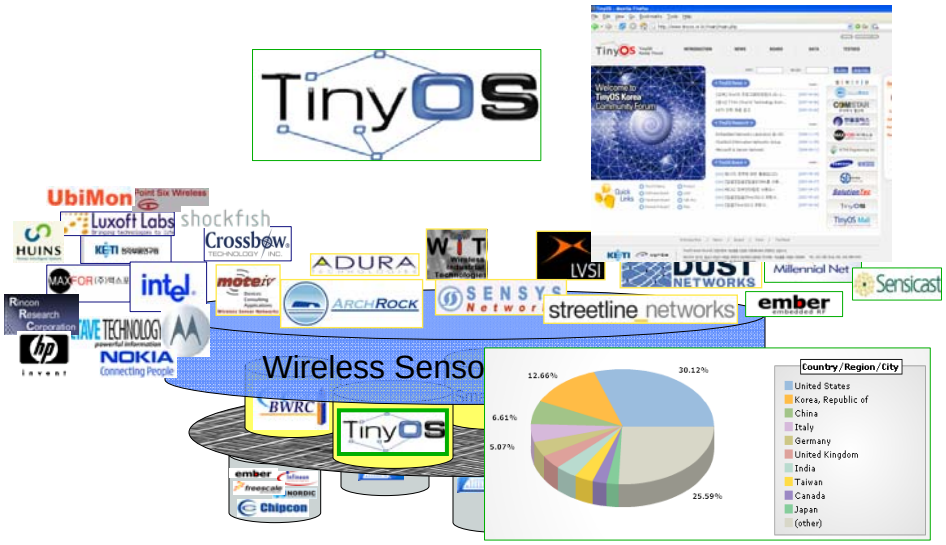
Operating Systems and Networking



Self-Organized Mesh Routing



A worldwide community



Plan for the Course

Technical Depth and Detail →

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

Perspective on the Labs

- **Traditional TinyOS "bootcamp"**
  - Start with raw hardware, learn installation tools, learn lowest level system concepts, follow series of lessons from blinking the LED, on up.
  - If lucky have very basic "hello' app at the end
- **This week's State-of-the Art approach**
  - Begin with complete sensor network solution – rich application, built on web services, over embedded IP, robust, low-power, responsive mesh networking.
  - Deploy and test custom application, and work our way down
  - Web services – full programmatic access from the infrastructure
  - IP network layer
  - Embedded programming on a powerful, communication-centric kernel
  - Experience with the open-source tools and code base.

Technology That We'll Use

- **Broad Open-Source Resources**
  - www.tinyos.net, http://sourceforge.net/projects/tinyos/
    - » TinyOS 2.0, NesC
  - Sourceforge, Cygwin, Redhat, FSF, GCC, PHP., Java, …
- **Key Commercial Offerings**
  - Mote Hardware
    - » Arch Rock, KETI, Crossbow, Moteiv, Maxfor, …
  - IP / Web Service Based Wireless Sensor Network Solution
    - » Arch Rock Primer Pack / IP
  - Widely available Wintel / Linux systems, networking & Prog.

Questions