Wireless Sensor Networks

A New Paradigm for Ubiquitous Sensing and Information Processing

Distinguished Lecturer Program

IEEE Circuits and Systems Society

Martin Haenggi

Department of Electrical Engineering

University of Notre Dame

Circuits and Systems

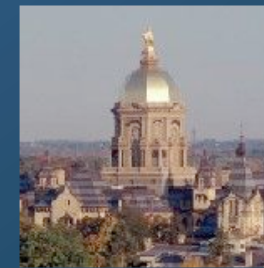
Overview

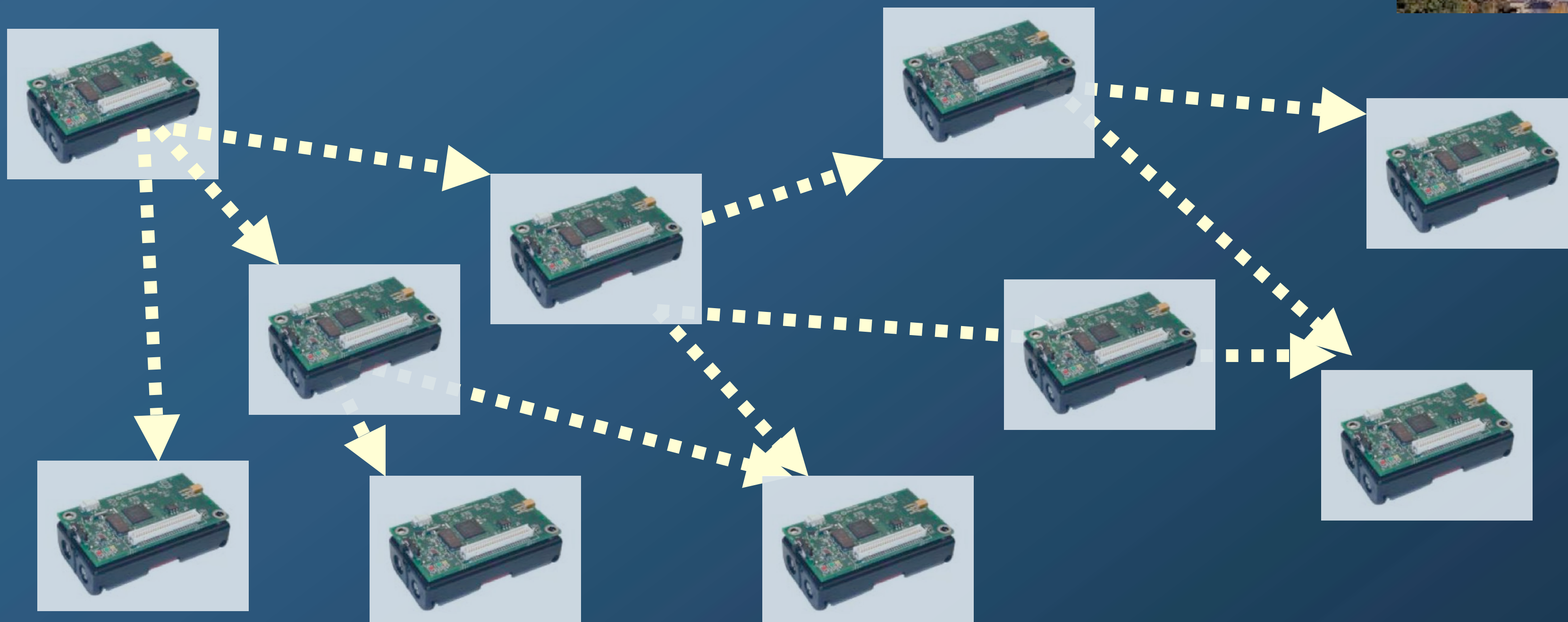
- What are sensor networks?
- Applications
- What makes sensor networks special?
- Hardware overview
- Outlook and concluding remarks

PART 1

What are Wireless Sensor Networks?

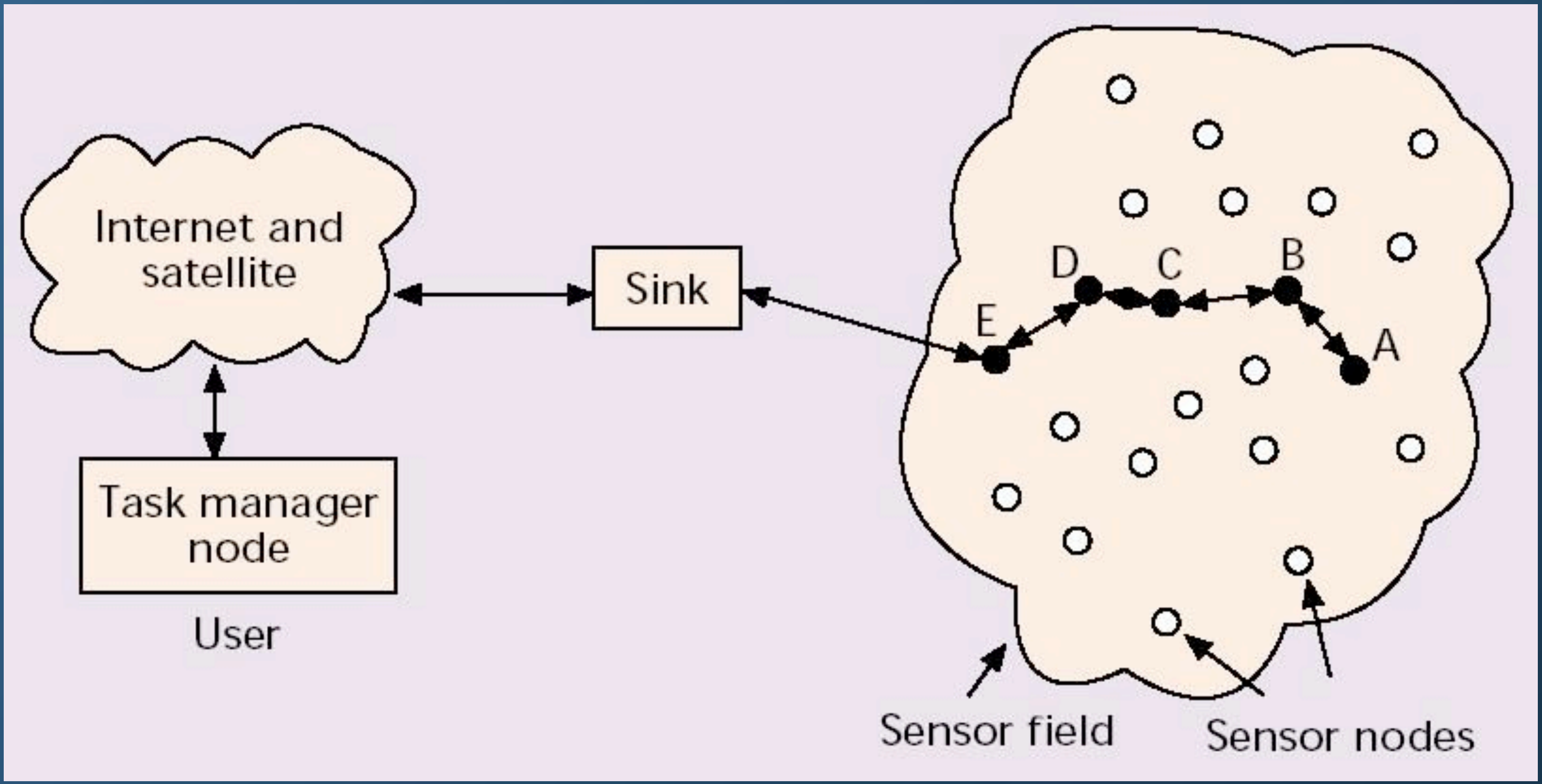
Wireless Sensor Networks





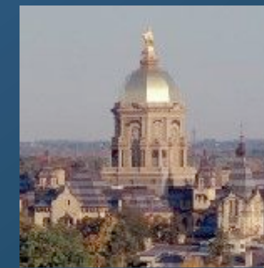
- Self-powered wirelessly-networked sensing devices with built-in processing capabilities
- Data exchange is possible only locally

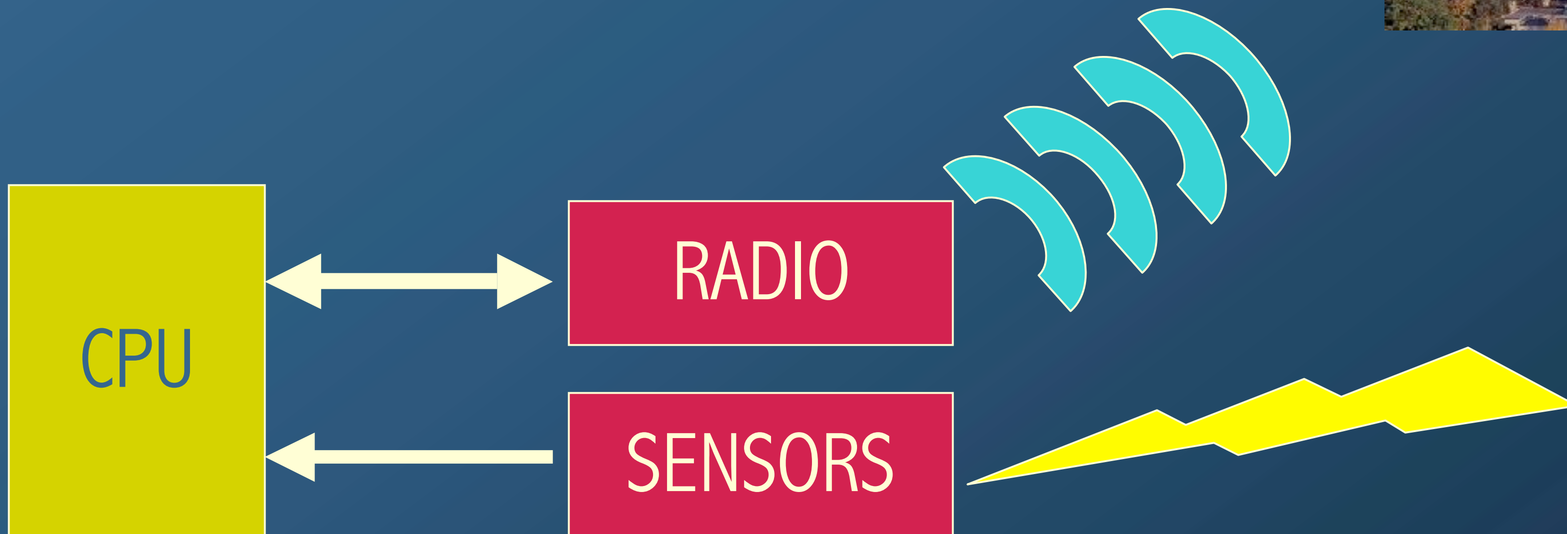
Embedded Sensor Networks



Source: Akyildiz et al., IEEE Comm. Mag., Aug. 2002

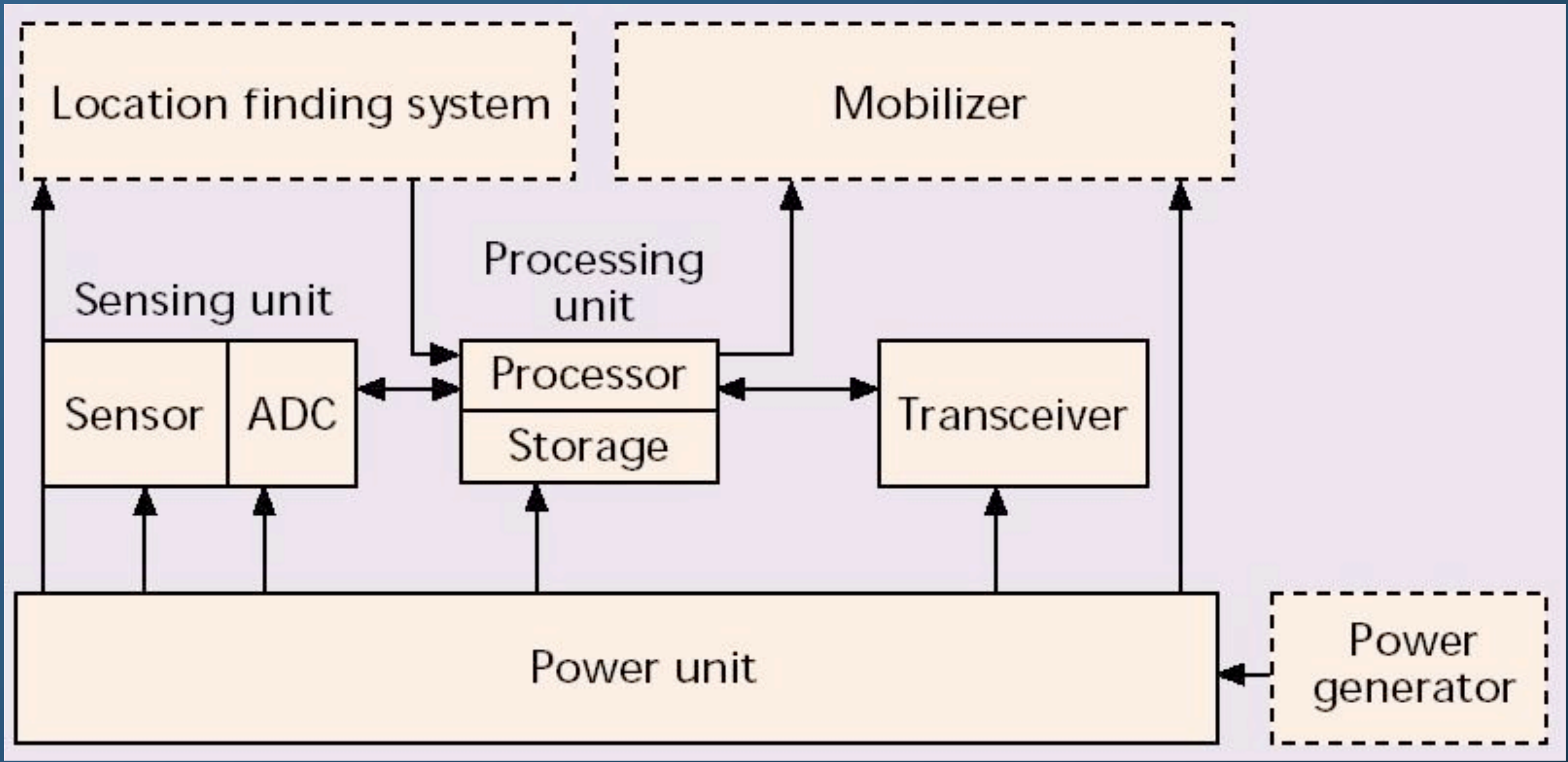
Sensing Nodes





- Physical phenomena are detected/sensed
- Basic processing is performed
- Information is transmitted and (received) wirelessly

Sensor Node Components



Source: Akyildiz et al., IEEE Comm. Mag., Aug. 2002

PART 2

Applications of Wireless Sensor Networks

Application Areas

Countless applications in many different fields, including:

- Environmental monitoring
- Seismic activity detection; planetary exploration
- Industrial monitoring and control
- High-precision agriculture
- Structural health monitoring
- Social studies; healthcare and medical research
- Homeland security and military applications; surveillance, detection of chemical/biological agents
- New areas keep emerging.

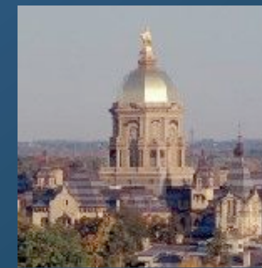
Environmental Monitoring (1)

Great Duck Island

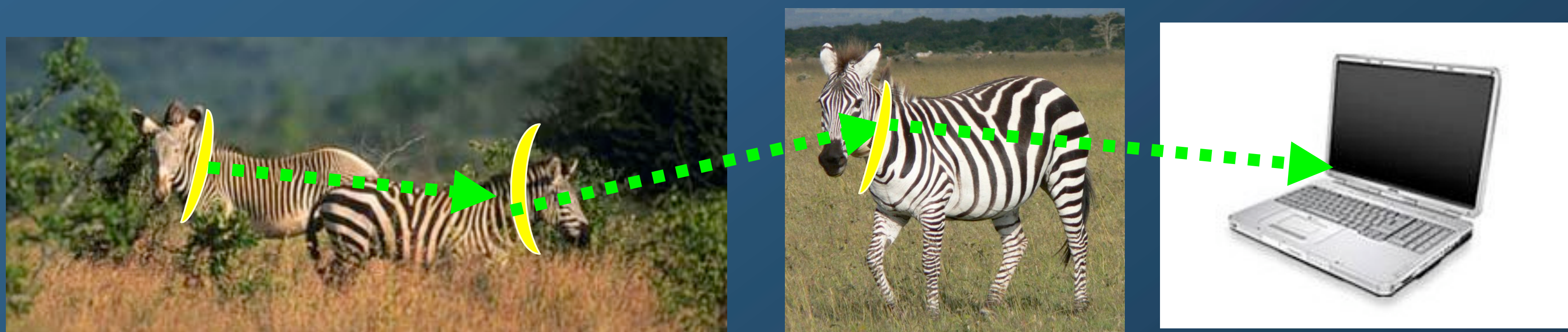
UC Berkeley/College of the Atlantic

- 150 sensing nodes deployed throughout the island relay data temperature, pressure, humidity, …) to a central device.
- Data are made available on the Internet through a satellite link.

Environmental Monitoring (2)



Zebranet: a WSN to study the behavior of zebras

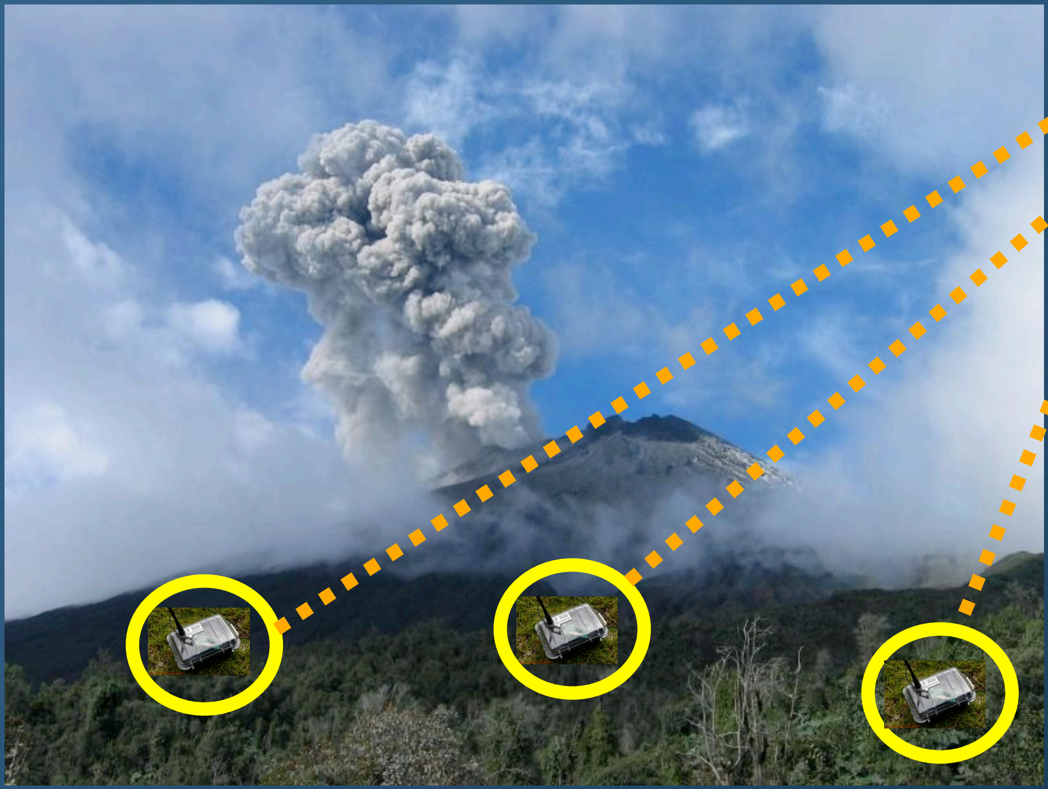


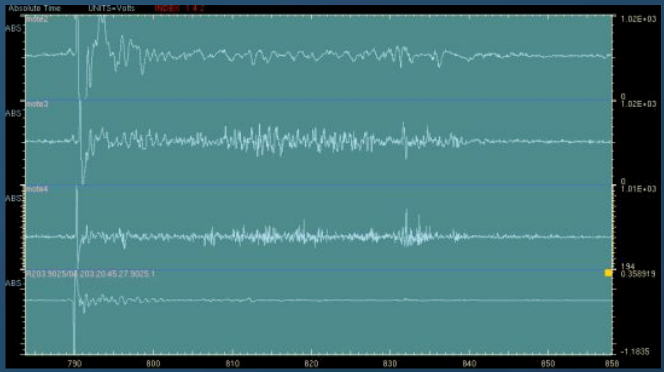
Princeton University

- Special GPS-equipped collars are attached to zebras
- Data exchanged with peer-to-peer info swaps
- Coming across a few zebras gives access to the data

Environmental Monitoring (3)

Volcano Monitoring in Ecuador





Phenomena whose monitoring discourages human presence are best observed with WSNs.

Harvard, Univ. of New Hampshire, Univ. of NC

Agricultural Monitoring

Wireless Vineyard

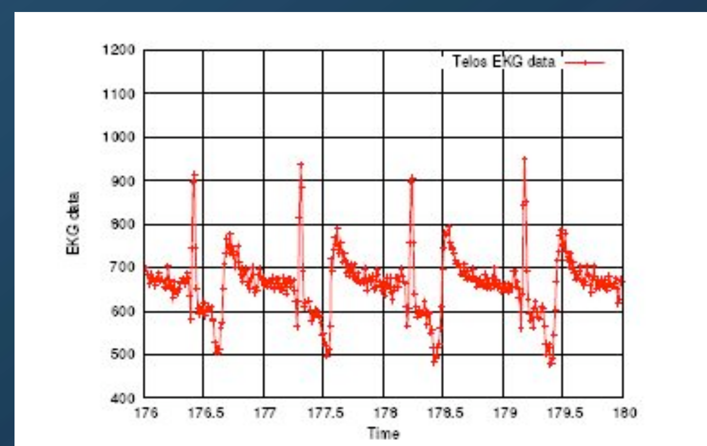
Data are collected and processed to make decisions

For example: Detect parasites to automatically choose the right insecticide

Medical Research

- Vital sign monitoring
- Accident recognition
- Monitoring the elderly

Patient data is acquired with wearable sensing nodes



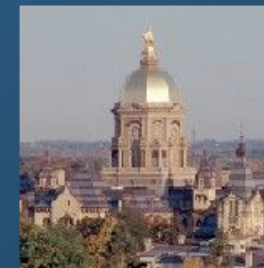
Intel deployed a 130-node network to monitor the activity of residents in an elder care facility.

Smart Buildings

- Wireless sensor and actuator network integrated within a building
- Distributed monitoring and control to improve living conditions and reduce energy consumption

Structural Health Monitoring

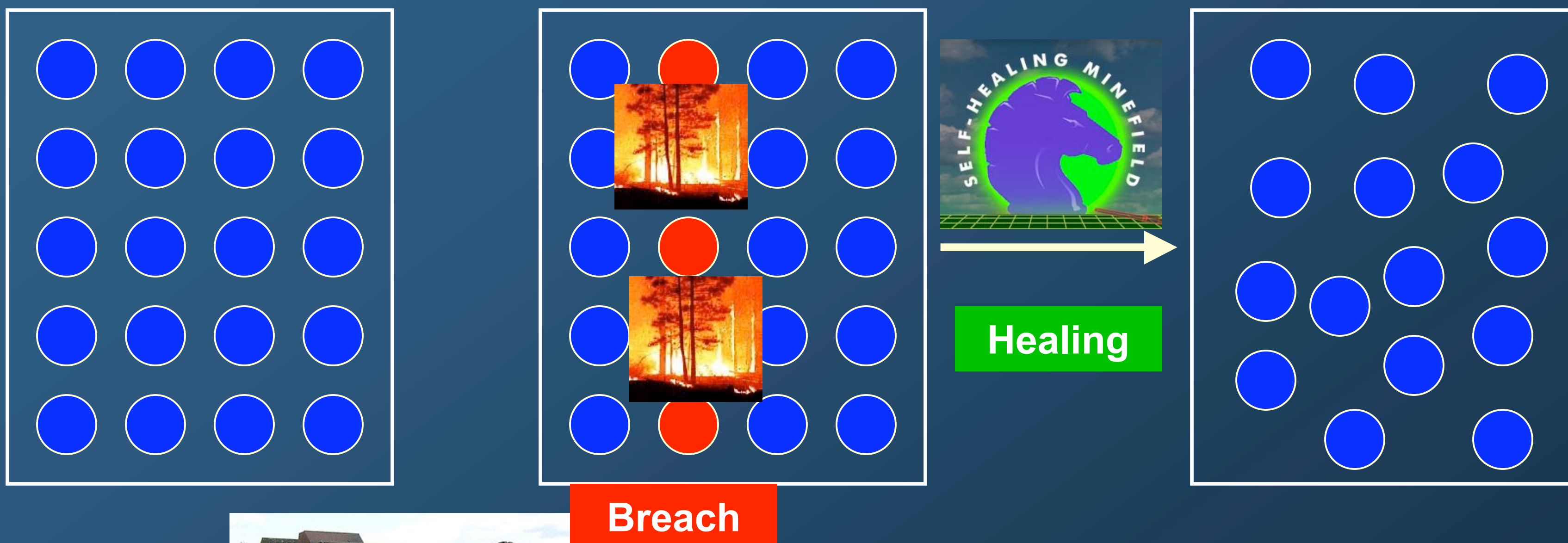
Detect the health status of structures using a network of accelerometers and strain gages



Self-healing Minefields

Networked mines automatically rearrange themselves to ensure optimal coverage

1999-2003, see http://www.darpa.mil/ato/programs/SHM/

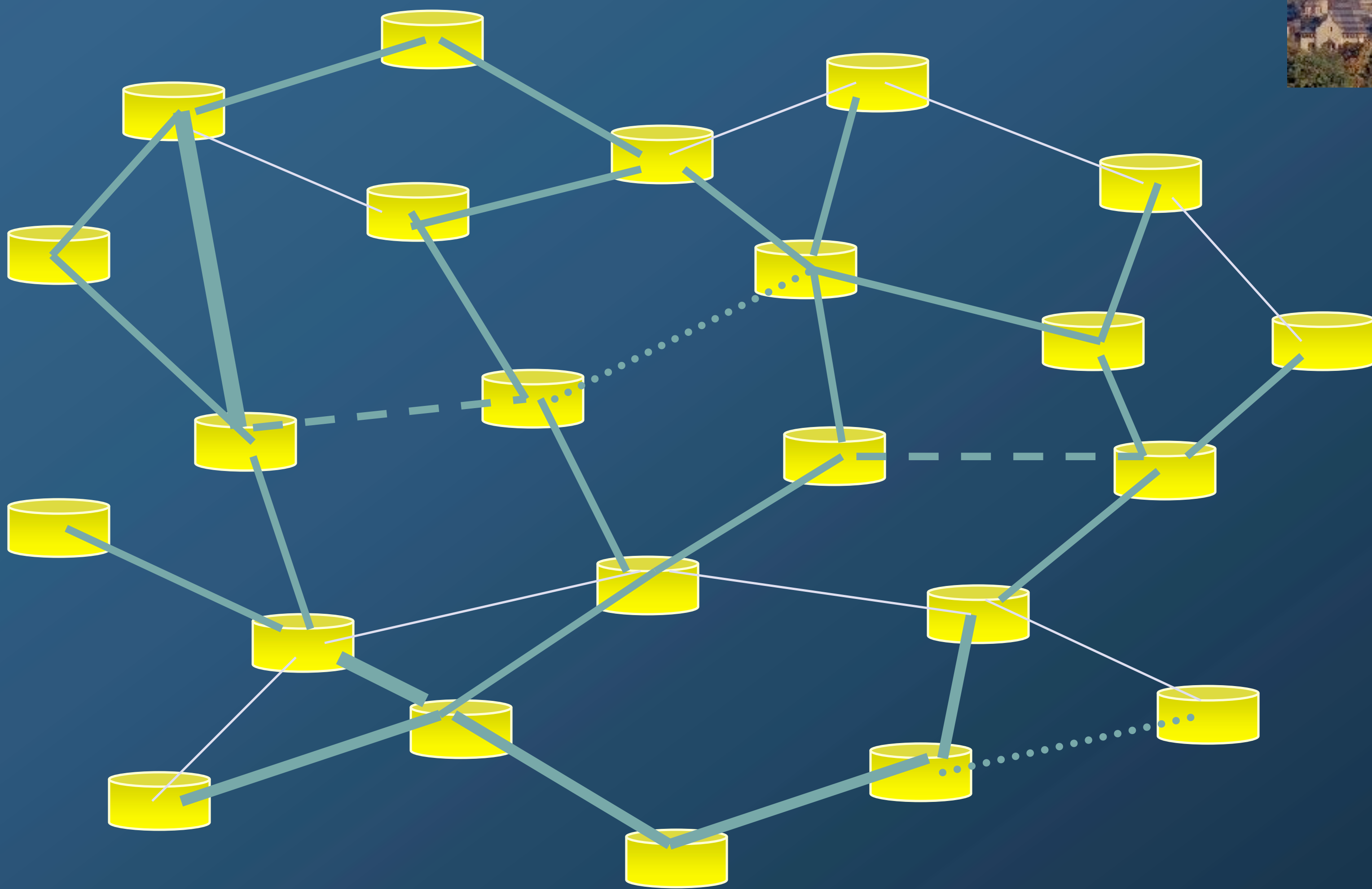


Mines can move up to 10m in 10s (hopping)

PART 3

What makes Wireless Sensor Networks so special?

Ad Hoc Wireless Networks



Ad Hoc Wireless Networks

- Large number of self-organizing static or mobile nodes that are possibly randomly deployed
- Near(est)-neighbor communication
- Wireless connections
  - Links are fragile, possibly asymmetric
  - Connectivity depends on power levels and fading
  - Interference is high for omnidirectional antennas
- Sensor Networks and Sensor-Actuator Networks are a prominent example.

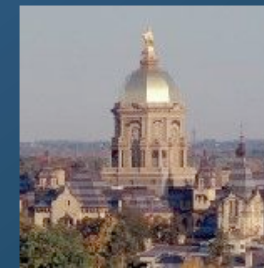
Distinguishing Features

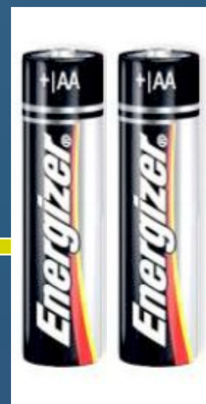
WSNs are ad hoc networks (wireless nodes that self-organize into an infrastructureless network).

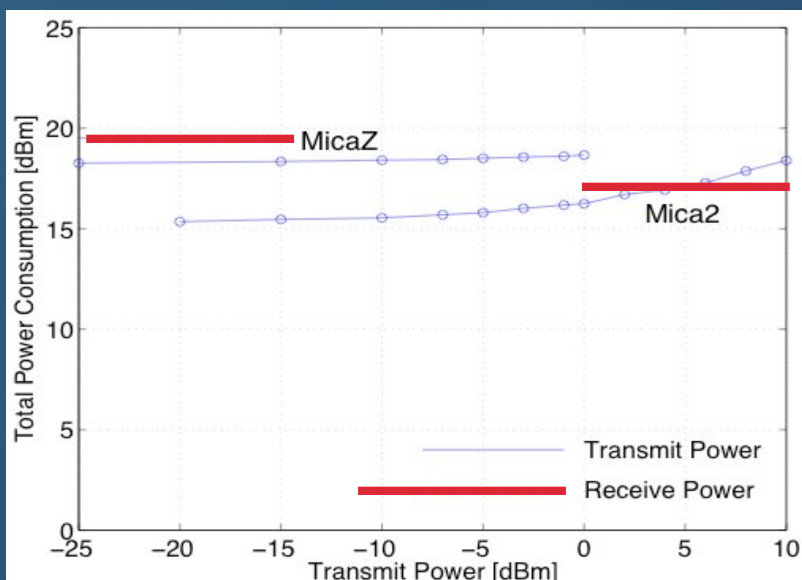
BUT, in contrast to other ad hoc networks:

- Sensing and data processing are essential
- WSNs have many more nodes and are more densely deployed
- Hardware must be cheap; nodes are more prone to failures
- WSNs operate under very strict energy constraints
- WSN nodes are typically static
- The communication scheme is many-to-one (data collected at a base station) rather than peer-to-peer

Lifetime





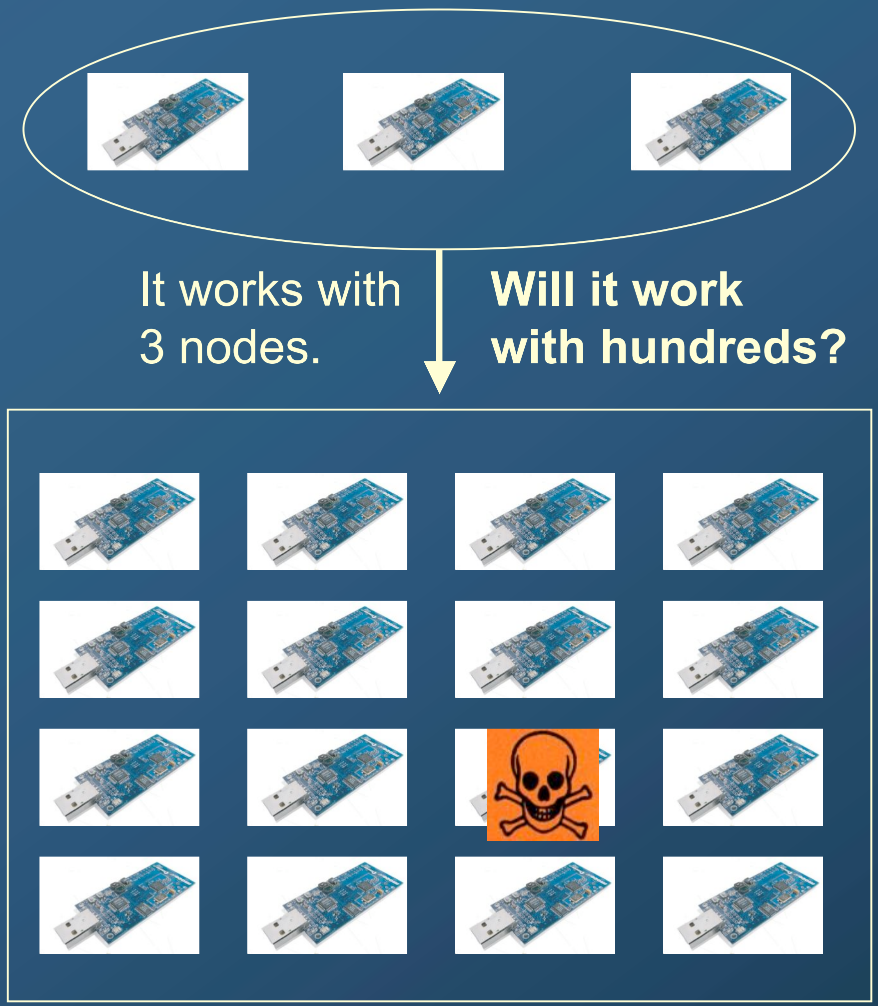


- Nodes are battery-powered
- Nobody is going to change the batteries. So, each operation brings the node closer to death.
  →**Lifetime is crucial!**

To save energy:

- Sleep as much as possible.
- Acquire data only if indispensable.
- Use data fusion and compression.
- Transmit and receive only if necessary. Receiving is just as costly as sending.

Scalability and Reliability

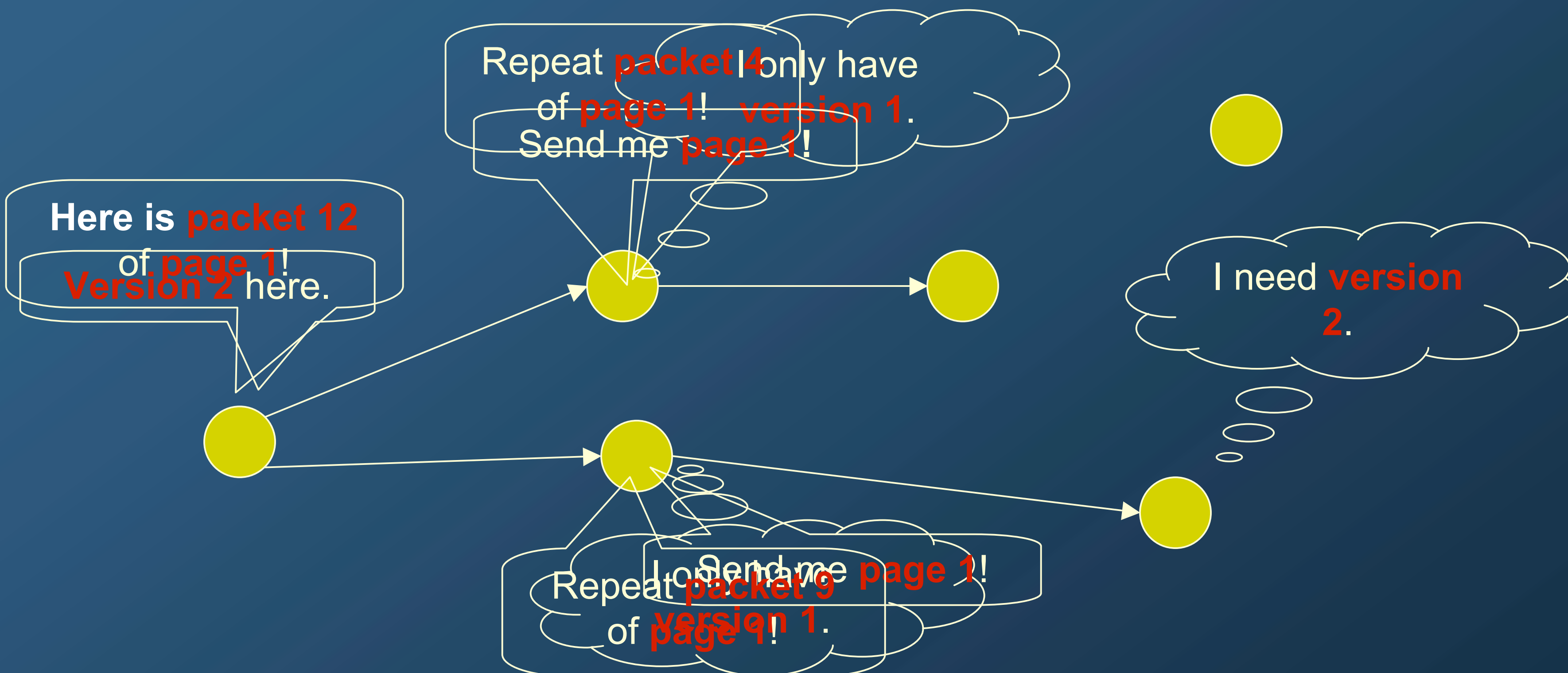


WSNs should

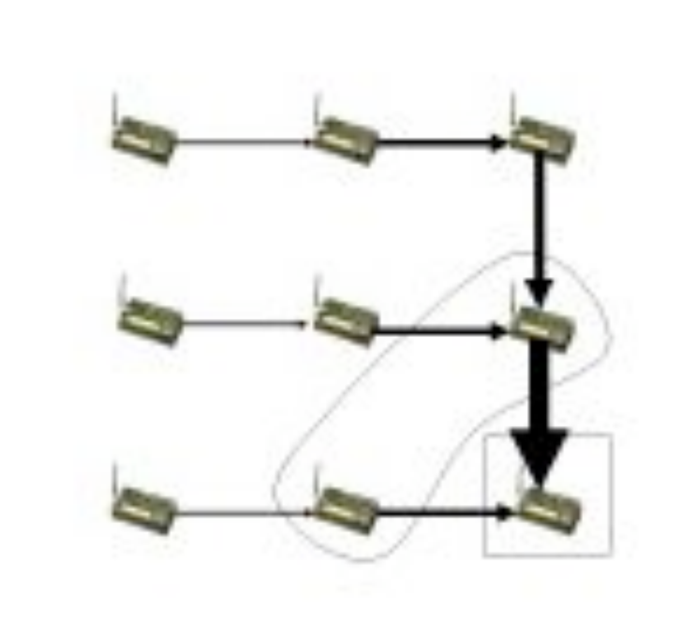
- selfconfigure and **be robust** to topology changes (e.g., death of a node)
- maintain connectivity**:** can the BS reach all nodes?
- ensure coverage**:** are we able to observe all phenomena of interest?

Maintenance

Reprogramming is the only practical kind of maintenance.
It is highly desirable to reprogram wirelessly.



Data Collection



- Centralized data collection puts extra burden on nodes close to the base station. Clever routing can alleviate that problem
- Clustering: data from groups of nodes are fused before being transmitted, so that fewer transmissions are needed

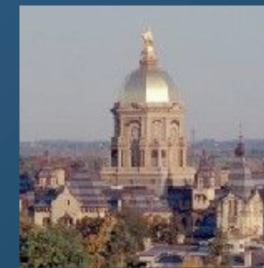
- Often getting measurements from a particular area is more important than getting data from each node
- Security and authenticity should be guaranteed. However, the CPUs on the sensing nodes cannot handle fancy encryption schemes.

Power Supply

- AA batteries power the vast majority of existing platforms. They dominate the node size.
- Alkaline batteries indeed offer a high energy density at a cheap price. The discharge curve is far from flat, though.
- Lithium coin cells are more compact and boast a flat discharge curve.

- Rechargeable batteries: Who is recharging?
- Solar cells are an option for some applications.
- Fuel cells may be an alternative in the future.
- Energy scavenging techniques are a hot research topic (mechanical, thermodynamical, electromagnetic).

Radio



- Commercially-available chips
- Available bands: 433 and 916MHz, 2.4GHz ISM bands
- Typical transmit power: 0dBm. Power control.
- Sensitivity: as low as -110dBm

- Narrowband (FSK) or Spread Spectrum communication. DS-SS (e.g., ZigBee) or FH-SS (e.g., Bluetooth)
- Relatively low rates (<100 kbps) save power.

CPU and Sensors

- Microcontrollers are the primary choice for in-node processing.
- Power consumption is the key metric in MCU selection.
- The MCU should be able to sleep whenever possible, like the radio.
- Memory requirements depend on the application
- ATmega128L and MSP430 are popular choices

- The power efficiency of the sensors is also crucial, as well as their duty cycle.
- MEMS techniques allow miniaturization.

PART 4

Hardware Overview

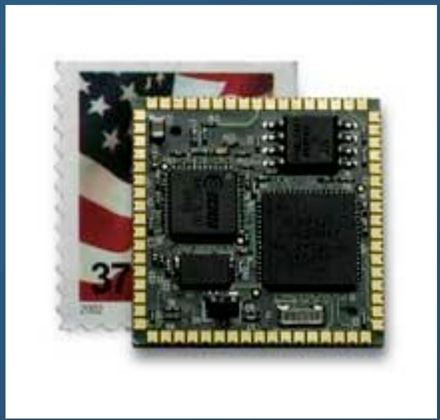
Berkeley Motes

Berkeley
University of California

Mica 2

Mica Z

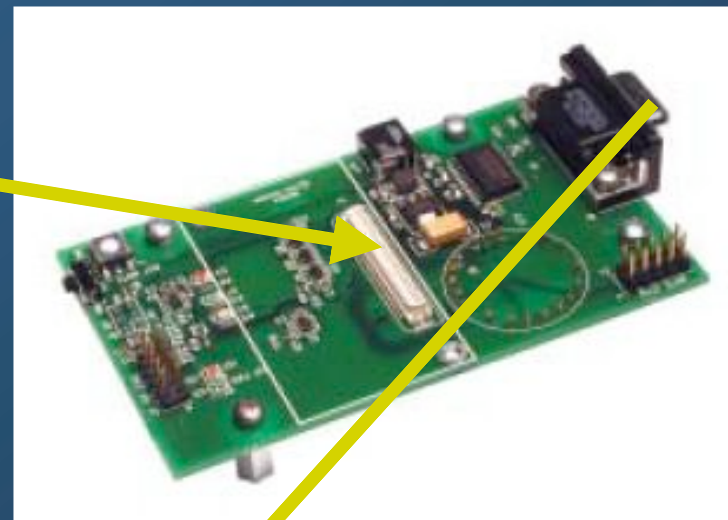
- Used by over 100 research organizations
- Originally designed by UCB, commercialized by Crossbow (www.xbow.com)
- CPU: ATMega128L

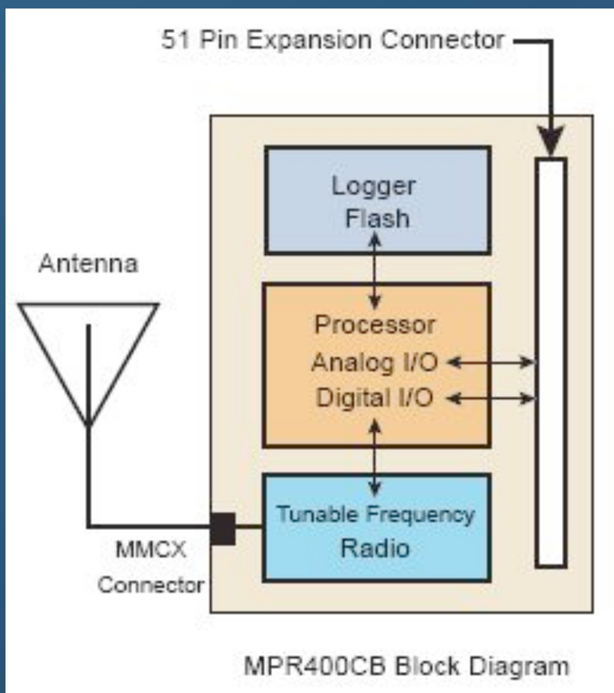


- Radio: 433MHz FSK in Mica2, 2.4GHz DS-SS (ZigBee) in latest generation MicaZ
- Special connector for Crossbow sensor boards
- Alkaline/Lithium batteries
- Special Operating System: TinyOS

MICA 2

Crossbow





A serial gateway bridges the MICA2 mote to a PC

http://www.xbow.com/

MICA Z and SKYMOTE

Crossbow

Mica Z

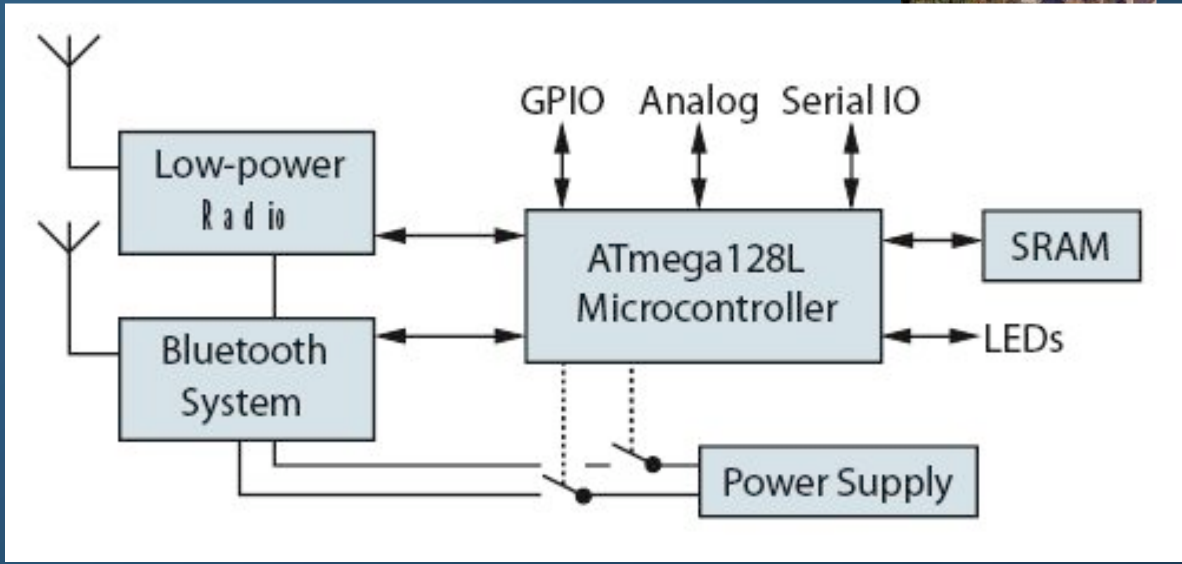
moteiv

SKYMOTE

- Same radio (CC2420, 2.4GHz ZigBee)
- Different MCU: Atmel for MICA Z, TI MSP for Skymote
- SKYMOTE is commercialized by MOTEiv (3 UCB graduates)
- The initial version was based on a study done at UCB. Crossbow started selling it, too, as the design belonged to UCB.

BT Node

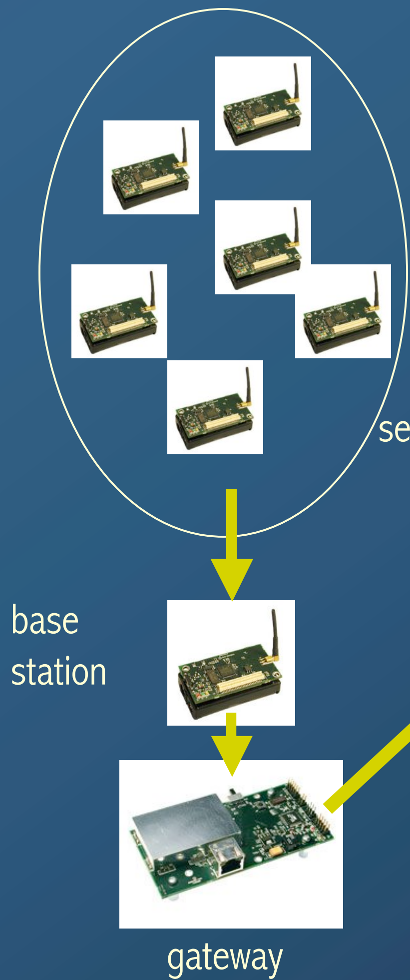
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

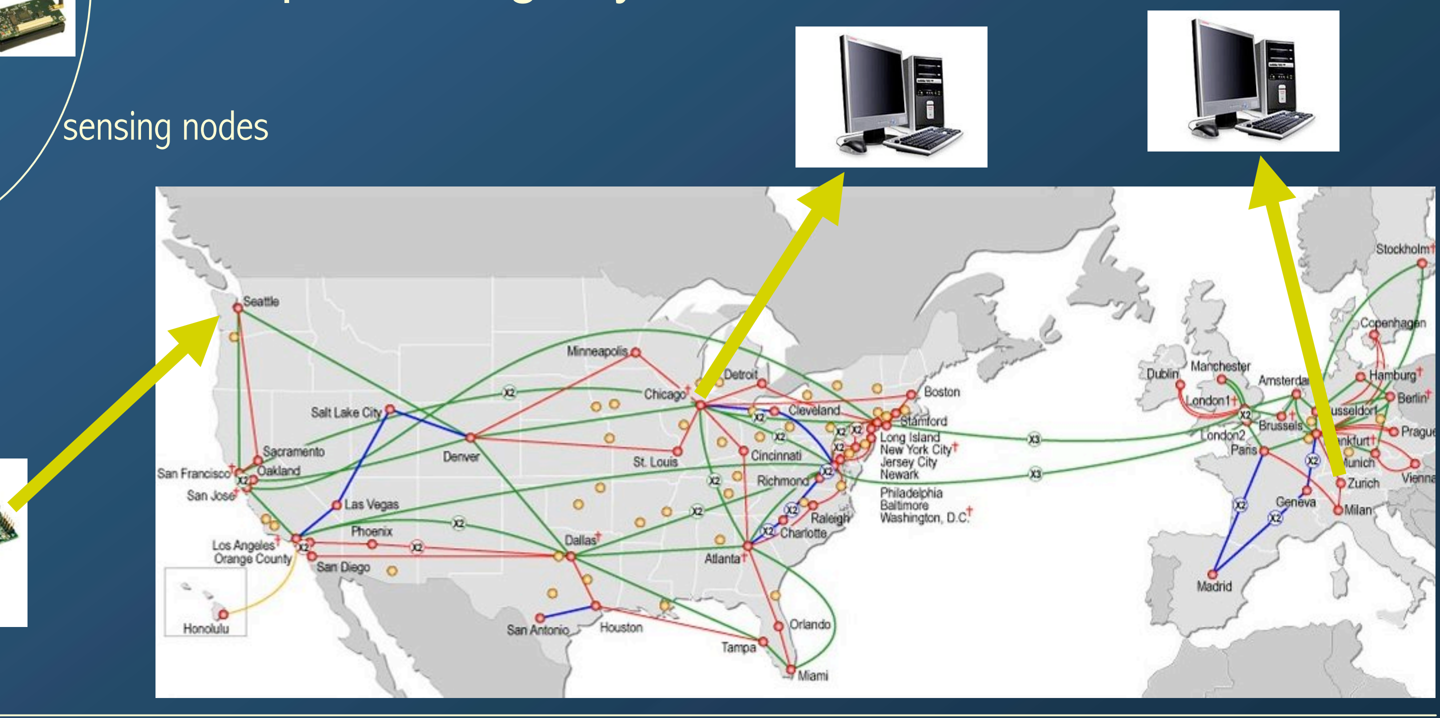


- Similar to Berkeley motes, but features Bluetooth compatibility
- Bluetooth: protocol for short-distance wireless communication
- Can be interfaced with other classes of Bluetooth devices.

Base Stations and Gateways

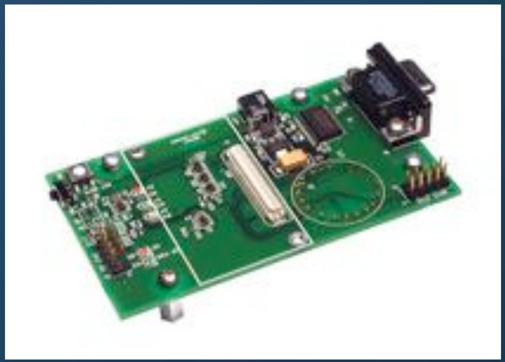
- A gateway bridges a sensor network with another network, such as the Internet.
- We can gather data on rainfall in Seattle and do the processing anywhere.





Gateways

Ethernet Gateway: bridges a sensor network of Berkeley motes to the Internet



Serial Gateway: bridges a sensor network to a single PC

Stargate: bridges a sensor network of Berkeley motes to an 802.11 network

Crossbow

Sensors

Available sensors for the Berkeley mote:

- Photo-detector
- Temperature sensor
- 2D accelerometer
- Microphone (Acoustic threshold detector)
- Buzzer
- Magnetometer

PART 5

Outlook and Conclusions

Key Issues

- Energy consumption; network lifetime
- Robustness; reliability through redundancy
- Self-organization; evolvability through autonomous reconfiguration
- Scalability
- Verifiability
- Modeling and simulation
- Synchronization and localization
- Wireless (RF, optical) issues

Wireless Issues

- Multihop routing
- Fading channel
- Channel access
- Power control
- Connectivity
- Quality of service (QoS)
- Security (trust)
- Modeling

Networked Embedded Systems

- "Thousands of tiny sensors and actuators embedded in our physical world-inside our clothing, buildings and ecosystems-collecting data, and most importantly, acting on it on our behalf."
- "IT will eventually become an invisible component of almost everything in everyone's surroundings."
- "Networked Systems of Embedded Computers," US National Academy of Sciences Project, 2001. "Embedded, Everywhere."
- "Pervasive Computing: Strongly emerging trend towards numerous casually accessible, often invisible computing devices, frequently mobile or embedded in the environment connected to an increasingly ubiquitous infrastructure composed of a wired core and wireless edges."

NASA on Future Warfare

Summary - Major Influences of IT/Bio/Nano Upon Future Warfare

- Ubiquitous miniaturized/networked multi physics,hyperspectral sensors
- Robotics/Automatics "in the large"
- Long range precision strike/targeting
- Info/net Warfare
- Mini/micro/nano Sats, Cruise, UAV's
- Binary Bio Weaponry
- Miniature/ubiquitous "smart mines"

From a presentation by Dennis M. Bushnell, Chief Scientist at the NASA Langley Research Center, July 2001, about warfare in 2025.

NASA Sensor Swarms

Some Sensor "Swarms"

- SMART DUST
  - Cubic mm or less
  - Combined sensors, comms and power supply
  - Floats in air currents
- NANOTAGS
  - Placed on everything/everywhere
  - Identification and Status Info
- Co-opted INSECTS

Mobile Sensor-Actuator Networks…

… are large networks of integrated wireless sensors and actuators.

Pervasive micro-sensing and –actuation will revolutionize the way we monitor, understand, and manipulate complex physical systems.

This offers enormous opportunities for almost every scientific discipline.

Smart Dust Vision

In 2010, MEMS sensors will be everywhere and sensing virtually everything. Scavenging power from sunlight, vibration, thermal gradients, and background RF, sensor motes will be immortal, completely self-contained, single-chip computers with sensing, communication, and power supply built in. Entirely solid state, with natural decay process, they may well survive the human race.

Quote from Kris Pister, UC Berkeley, Smart Dust PI.

In 2010, the "nano age" has barely begun.

I would like to acknowledge:

- My graduate student Daniele Puccinelli's help with this presentation
- The DARPA/IXO "Networked Embedded Software Technology" Program
- The support of the National Science Foundation through grants ECS03-29766 and CAREER CNS 04-47869.
- The IEEE CAS society for sponsoring the Distinguished Lecturer Program
- The efforts of the local organizers

Source Materials

D. Puccinelli and M. Haenggi
WSN: Applications & Challenges of Ubiquitous Sensing
IEEE CAS Magazine, Sep. 2005

I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci
A survey on sensor networks
IEEE Communications Magazine, Aug. 2002

C.Y. Chong and S.P. Kumar
Sensor networks: Evolution, opportunities, and challenges
IEEE Proceedings, Aug. 2003