Sensor Networks

José Costa

Software for Embedded Systems

Departamento de Engenharia Informática (DEI)
Instituto Superior Técnico

2015-11-16

Outline

- Overview of Sensor Networks
- Sensor Network Applications
- Embedded Network Technology
- Systems Challenge
- Self-Organized Networks
- Conserving Power and Bandwidth
- WSN Tools

Motivation

- Computing capacity becomes exponentially smaller and cheaper with each passing year
- This allows building of radios and exceptionally small mechanical structures that sense fields and forces in the physical world
- These inexpensive, low-power communication devices can be deployed throughout a physical space, providing:
  - dense sensing close to physical phenomena
  - processing and communicating this information
  - coordinating actions with other nodes

Challenges

- Information technology must address a new collection of challenges
- The individual devices in a wireless sensor network (WSN) are inherently resource constrained:
  - limited processing speed
  - limited storage capacity
  - limited communication bandwidth

These devices have substantial processing capability in the aggregate, but not individually, so we must combine their many vantage points on the physical phenomena within the network itself.

Available Energy Resources

- Network must operate for long periods of time

- Limits on available energy resources:
  - batteries
  - energy harvesting

Wireless Nodes Brings Several Complications

- Most of the device's components, including the radio, will likely be turned off most of the time
- The nodes forming the network will experience wide variations in connectivity and will be subject to potentially harsh environmental conditions
- Dense deployment generally means that there will be a high degree of interaction between nodes

Node Deployment

- Deploying and maintaining the nodes must remain inexpensive
- Manually configuring large networks of small devices is impractical
- The nodes must organize themselves
- The nodes must provide a means of programming and managing the network as an ensemble

Applications

Density of instrumentation and the use of pervasive networking technology gives WSNs a new kind of scope that can be applied to a wide range of uses:

- Monitoring space
- Monitoring things
- Monitoring the interactions of both

Monitoring Space

- Environmental and habitat monitoring
- Precision agriculture
- Indoor climate control
- Surveillance
- Treaty verification
- Intelligent alarms
- ...

Monitoring Things

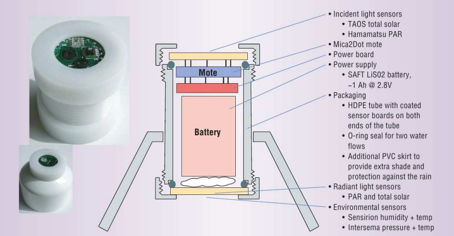
- Structural monitoring
- Ecophysiology
- Condition-based equipment maintenance
- Medical diagnostics
- Urban terrain mapping
- ...

Monitoring Complex Interations

- Wildlife habitats
- Disaster management
- Emergency response
- Ubiquitous computing environments
- Asset tracking
- Healthcare
- Manufacturing process flow
- ...

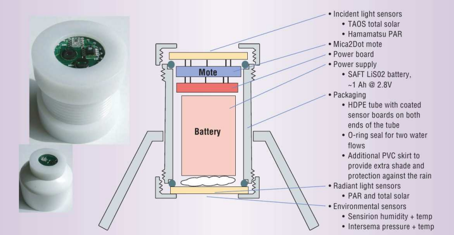
- Ecosystem measurements included several instruments weighting 15Kg
- Must be deployed up a tree
- Serial cables then hang down to the forest floor, where a data logger collects measurements
- Measurements were made at various elevations at distinct points in time over relatively short intervals

With Modern Sensors (1/2)



- An entire wireless weather station fits in a tube about the size of a film canister
- On top, two incident-light sensors measure total solar radiation
- An identical pair of sensors on the bottom, underneath a shade, measure radiant light
- On the bottom there are environmental sensors to monitor relative humidity, barometric pressure, and temperature

With Modern Sensors (2/2)



The weather-protected center of the tube contains:

- a small computer,
- data storage
- battery
- low-power radio

Motion Monitoring Before Modern Sensors

- A modern semiconductor fabrication plant can have several thousand vibration sensors attached to various pieces of routine machinery
- A team of electricians tours the plant with a computing device that attaches to a sensor and logs a sample for a short period
- The team then carries these logs back to a central computer, which analyzes them for signs of wear
- Months elapse between visits to a particular machine
- This scenario applies to a wide range of manufacturing and power generation plants

With Modern Sensors

- Performs local processing at each device
- Transports the data continuously to operations staff
- Sensor nodes can perform signal analysis, communicating only the modes of vibration or detected anomalies.

Reducing the cost of obtaining and processing data reduces costs overall

Wide Range of Information Technology

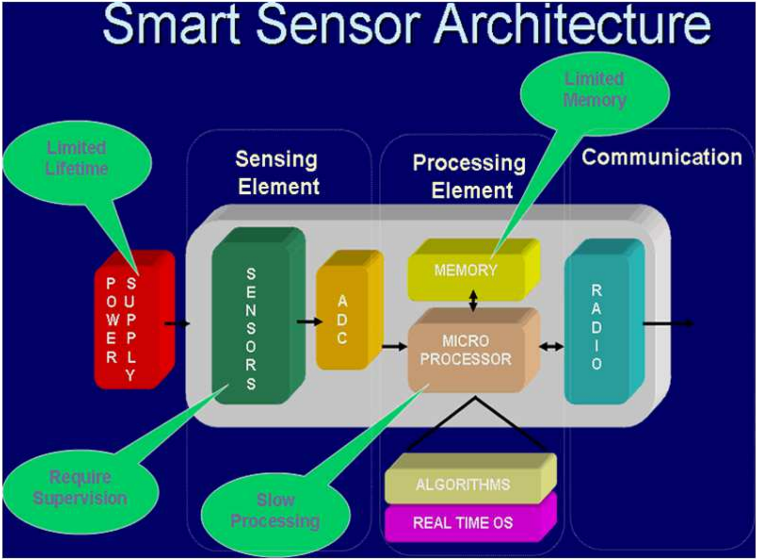
WSNs merge a wide range of information technology that spans:

- Hardware
- Systems software
- Networking
- Programming methodologies

Hardware

- Microprocessor
- Data storage
- Sensors
- Analog-to-digital converters (ADCs)
- Data transceiver
- Controllers that tie the pieces together
- An energy source

Node Architecture



Power

- Solar cells
  - 10 milliwatts per square centimeter outdoors and 10 to 100 microwatts per square centimeter indoors
- Mechanical sources of energy
  - vibration of windows and air conditioning ducts can generate about 100 microwatts.
- Batteries
  - a cubic-centimeter battery stores about 1,000 milliamp-hours
  - can run almost indefinitely in many environments

Storage

- Low-power microprocessors have typically limited storage
  - less than 10 Kbytes of RAM for data
  - less than 100 Kbytes of ROM for program storage
  - or about 10,000 times less storage capacity than a PC has
- This limited amount of memory consumes most of the chip area and much of the power budget
- Designers typically incorporate larger amounts of flash storage, perhaps a megabyte, on a separate chip

Microsensors

- Sensors give these nodes their eyes and ears
- Many materials change their electrical characteristics when subjected to varying environmental conditions
- Microelectromechanical systems (MEMS) can sense a wide variety of physical phenomena cheaply and efficiently
  - various forces
  - chemical concentrations
  - environment factors

Microradios (1/3)

- Manufacturers have always added sensors to many appliances, vehicles, and gadgets
- The breakthrough comes from communicating sensor readings to other devices

Microradios (2/3)

- Radio components can now be manufactured using conventional CMOS technology
- However, the amount of energy required to communicate wirelessly increases rapidly with distance
- Obstructions and interference further attenuate the signal
- Wireless LANs and cell phones consume hundreds of milliwatts and rely on a powerful infrastructure
- WSN radios consume about 20 milliwatts, and their range typically is measured in tens of meters

Microradios (3/3)

- For small devices to cover long distances, the network must route the information hop by hop through nodes
  - much as routers move information across the Internet

- Even so, communication remains one of the most energy-consuming operations
  - each bit costing as much energy as about 1,000 instructions

Systems Challenge

- The network must allocate limited hardware to multiple concurrent activities
  - such as sampling sensors, processing, and streaming data
- The potential interconnections between devices must be discovered and information routed effectively from where it is produced to where it is used
- There must also be a means of programming the ensemble

Operating Systems (1/2)

Conventional operating systems such as Unix run well on:

- A 32-bit microprocessor
- At 50 to 100 MHz
- Several megabytes of RAM
- A gigabyte or more of secondary storage

This can be achieved in a handheld device that runs for several hours on a single charge.

Operating Systems (2/2)

Typical operating point for WSNs is:

- One year
- On a pair of AA batteries
- With a small fraction of the handheld resources

This application focuses on structured interaction with the physical world, rather than on complex human interactivity.

The developers of the open source TinyOS tailored it for this application

TinyOS (1/2)

- TinyOS provides a framework for assembling application-specific systems that can handle:
  - substantial concurrency
  - limited physical resources
- The software components and the underlying operating system support specific event driven functionality

TinyOS (2/2)

- The lowest-level components abstract the physical hardware and deliver physical interrupts as sanitized, asynchronous events
- Each component handles certain events and signals actions in other components, but they never consume processor cycles while waiting for future events
- Each application includes only the components it requires
- The network involves a more complex stack in which:
  - lower levels deal with acquiring the radio channel, framing data streams into packets that receiving nodes can recognize
  - higher levels deal with buffer management, authentication, and multiplexing the network across application components

Network sensor platforms

- Berkeley motes
- Intel iMote
- 32-bit processor-based
- ...

Berkeley Motes

- Berkeley motes and TinyOS are widely used for exploring systems issues and deploying pilot applications
- The microcontroller provides a modest amount of RAM and program storage and contains an internal ADC
- A simple frequency-agile radio with roughly the bandwidth of a modem provides the connectivity that developers can use to construct a network
- Off-chip flash memory provides storage to hold both the program and the data buffering
- Several sensor boards have been designed for this platform

Intel iMote

- Intel iMote is a recent integrated design
- Uses a commercial chip with a powerful ARM microprocessor, storage, and radio integrated into a single package
- TinyOS runs directly on the ARM processor
- The entire design occupies only 5 square millimeters
- It is estimated that at 1 percent active, the chip could run a hundred years on the energy stored in a pair of AA batteries

32-bit processor-based

- 32-bit processor-based devices such as Stargate
- Run traditional operating systems such as Linux
- Are equipped with longer-range radios such as IEEE 802.11 or with cell phone modems
- These nodes operate along with a large battery and some form of recharge such as a solar panel
- Alternatively, when wall outlets are available, the nodes can draw power from them

Self-Organized Networks

- In a wired network, each router connects to a specific set of other routers
- In WSNs, each node has a radio that provides a set of communication links to nearby nodes
- By exchanging information, nodes can:
  - discover their neighbors
  - perform a distributed algorithm to determine how to route data
- Determining connectivity depends on:
  - physical placement (main factor)
  - obstructions, interference, environmental factors, antenna orientation, mobility
- The network discovers and adapts to whatever connectivity is present

Connectivity

Networking capability of WSNs is built up in layers

- The lowest layer controls the physical radio device.
  - it transmits a structured series of bits that form a packet encoded in the radio signal
  - when not transmitting, nodes sample the channel and scan for a special symbol at the start of a packet
- The packet layer:
  - manages buffers
  - schedules packets onto the radio
  - detects or even corrects errors
  - handles packet losses
  - dispatches packets to system or application components

Dissemination and Data Collection (1/2)

- Disseminating information is a basic capability in such networks
- Can be achieved by a flooding protocol in which a root node broadcasts a packet with some identifying information
- Receiving nodes retransmit the packet so that more distant nodes can receive it
- However, a node can receive different versions of the same message from several neighboring nodes, so the network uses the identifying information to detect and suppress duplicates
- Flooding protocols use various techniques to avoid contention and minimize redundant transmissions
- Increasingly, sensor networks deploy disruption tolerant networking approaches

Dissemination and Data Collection (2/2)

- The network uses dissemination to issue commands, convey alarms, and configure the network
- Also uses dissemination to establish routes
- Each packet identifies the transmitter and its distance from the root
- To form a distributed tree, nodes record the identity of a node closer to the root.
- The network can use this reverse communication tree for data collection by routing data back to the root or for data aggregation by processing data at each level of the tree

Conserving Power and Bandwidth (1/2)

- Communication is usually the most energy intensive operation a node performs
- Energy usage minimization is attempted by eliminating communication or by turning off the radio when no communication needs to occur
- Nodes could process data locally and only communicate when they detect an interesting event
- Performing aggregation within the network can reduce communication

Conserving Power and Bandwidth (2/2)

- Compression and scheduling can also conserve energy
- The network can assign specific responsibilities to certain nodes, such as retransmission or aggregation
- The network can also reject uninteresting packets by turning off the radio after receiving only a portion
- Rich and growing body of literature

WSN Control Tools (1/2)

- Octopus Dashboard
  - open-source java-based dashboard developed at University College Dublin
  - visualises and controls a wireless sensor network in the TinyOS 2.x environment.
  - graphical user interface for viewing the live sensor network topology
  - controls the behavior of sensor nodes, such as the energy consumption, the sampling period, the radio duty cycle and formulating application queries to the nodes.
  - includes also multi-platform support and software-based energy estimation

WSN Control Tools (2/2)

- MViz
  - routes sensor values to the collection roots
  - roots send the packets to the serial port
  - MViz java application visualizes packets
- Surge
  - java program for displaying multihop routing topology in sensor networks
  - visual demonstration of the network topology
  - display routes in TinyOS 2.x

WSN Simulators (1/3)

- Ns2
  - C++ discrete event simulator targeted at networking research
  - support for simulation of TCP, routing, and multicast protocols over wired and wireless (local and satellite) networks
- OmNet++
  - C++ open-source, component-based, modular and open-architecture simulation environment
  - strong GUI support and an embeddable simulation kernel
  - targets mainly communication networks
    - also been used in simulation of IT systems, queueing networks, hardware architectures and business processes.

WSN Simulators (2/3)

- Tossim
  - TinyOS-based simulator for wireless sensor networks
  - comes with standard installation of the operating system
  - uses the nesC language that is a dialect of C used for the motes.
  - simulates the TinyOS network stack at the bit level, allowing experimentation with low-level protocols and top-level application systems.
  - supports network of hundreds or thousands of motes
  - same code that is written for Tossim can be directly implemented onto the motes
- J-SIM
  - component-based, compositional simulation environment. It has been built upon the notion of the autonomous component-programming model
  - dual-language simulation environment
    - classes are written in Java (for ns-2, in C++) and "glued" together using Tcl/Java.

WSN Simulators (3/3)

- Qualnet
  - C/C++ network simulator
  - performs accurate and simultaneous emulation of network devices, transmitters, antennas, terrestrial characteristics, and human interactions.
  - version 4.5 supports also sensor networks
  - good models, easy to code, scalable
  - not open source
- Avrora
  - research project of the UCLA Compilers Group
  - set of simulation and analysis tools for programs written for the AVR microcontroller produced by Atmel and the Mica2 sensor nodes
  - contains a framework for simulating and analyzing assembly programs, providing a clean Java API and infrastructure for experimentation, profiling, and analysis

Outline

- Overview of Sensor Networks
- Sensor Network Applications
- Embedded Network Technology
- Systems Challenge
- Self-Organized Networks
- Conserving Power and Bandwidth
- WSN Tools

References

- D. Culler, D. Estrin and M. Srivastava, "Overview of sensor networks", in Computer, IEEE Computer Society, 2004.

Next Class

- Seminar presentations