Professional Development Short Course On:

Self-Organizing Wireless Networks

Instructor:

Timothy D. Cole

ATI Course Schedule:  http://www.ATIcourses.com/schedule.htm

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INTRODUCTION: Objectives/goals

• The course introduces technologies that spawned mote-sized wireless sensors
  ◆ Sensor modalities stemming from MEMs and/or miniaturization
  ◆ Radio stack (chip) development
  ◆ Distributed processing (middleware) functionality & implementation

• Efforts in self-organizing wireless networks and are discussed including that associated with the DARPA/NEST program:

• Background information that describes ad hoc networking,
  ◆ Mote core designs, mote-based sensor design rules
  ◆ Issues associated with data exfiltration and deployment
  ◆ Provides insights concerning mote-field C² interfaces
  ◆ Data associated with mote arrays resulting from testing
  ◆ Trade-off criteria and evaluation procedures
  ◆ Hands-on experiences and issues that are being worked…
INTRODUCTION: Objectives/goals

- **Course does not:**
  - Teach how to code using C (NesC) nor wield TinyOS, TinydB, Deluge, Serial Forwarder, C2PC…
  - Indicate to layout & design a mote core
  - Demonstrate programming issues due to concurrent real-time programming
    - Hint: get a RTOS! Hint hint: get a debugger
  - Indicate how to specifically setup simulations (TOSSIM)

- **Prerequisites, assume familiarity with:**
  - Computer languages and OS environments
  - Principles behind RF communication theory and implementation
  - Protocol in MAC, routing, and capacity of multi-hop wireless network

- **Good news:**
  - TinyOS = open source, a LOT of help exists online (join TinyOS help)
    - [https://www.millennium.berkeley.edu/mailman/listinfo/tinyos-help](https://www.millennium.berkeley.edu/mailman/listinfo/tinyos-help)
  - Same for TOSSIM, tutorial: [http://www.tinyos.net/tinyos-1.x/doc/tutorial/lesson5.html](http://www.tinyos.net/tinyos-1.x/doc/tutorial/lesson5.html)
  - If C programmer, not too difficult to make transition to NesC
  - TinyOS et al, takes some spin up time, but tutorials abound!
  - Also, Java Virtual Machine (JVM) for motes coming to town
INTRODUCTION: Instructor Background

Timothy D. Cole, wbi@mac.com, 813.468.6233 (813.205.2661)

- **Education**
  - JHU undergraduate (BES/EE) & graduate (MSEE, MS) degrees
  - Univ. of Alabama, physics

- **Work Experience**
  - JHU/APL – SSD (4 years), Space Dept (17 years)
  - Teledyne – BMDSCOM (5 years)
  - Raytheon – MUOS (1.5 y)
  - Northrop Grumman IT (TASC) – National Intel (*last* 4 years)
    - DARPA NEST & EXANT Programs
    - DIA ANDSC/D Program
    - IRaD, Micro-Laser Radar (MLR), Sensor Exfil Relay Integration (SERI), PulseNET™

- **MOTE PROGRAMS:**
  - NEST: 2000-2005 DARPA Embedded Sensor Technology
  - ANSC/D: 2005 DIA Motefield/Sensor Integration and Test
  - MLR/SERI:2006-2007 NGIT IRaD Motefield R&D
## INTRODUCTION: Concepts involved

| 1. **Mote core** (fundamental): *radio-stack*, low-power *microprocessor* systems, power distribution, memory, uC/uP, data acquisition microsystems (ADC). |
| 2. **Programming environment.** Real-time, event-driven, with OTA programming, deluge, distributed processing (middleware) |
| 3. **Low-power.** Mote design, field design, overall architecture regulation & distribution, |
| 4. **Localization.** Autonomous (iterative) solutions, GPS chipset, & interface(s). |
| 5. **Sensor modalities.** Design goals and objectives. descriptions and examples of mote passive and active (e.g., ultra wideband, UWB) sensors |
| 6. **RF propagation.** Multi-path, fading, scattering, attenuation at ground level. RF reliability. |
| 8. **Mote Field Architecture.** Mote field logistics. Mote field initialization. Relay definition and requirements. Backhaul data communications: Cellular, SATCOM, LP-SEIWG-005A. |
| 11. **Situational Awareness.** Situational displays employed. Sensor injection design rules and examples - capabilities and examples, including: C2PC, COT, Falcon View, PULSEnet. |
INTRODUCTION: Mote subsystems

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
INTRODUCTION: Motivation

- Evolution of Computing

  One to Many  
  Billions of Computers

  One to One  
  Millions of Computers

  Many to One  
  Thousands of Computers
INTRODUCTION: Motivation

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

In the ultimate volumes
INTRODUCTION: Motivation

- Ad hoc networking of sensors – power in numbers
  - Ad hoc, meaning what?
  - Smart reconnaissance?
  - Mission types served?

- Concept of using small (<30 in³) micro-sensors (referred to as “motes”) within a wireless ad hoc network
  - Why not use sophisticated sensors? ($/km², agility, SPOF, versatility)
  - Through distributed processing of sensory signals within a networked field, motes can accomplish a myriad of tasks.
  - Mote “fields” can be applied using numerous configurations that allow for novel security and/or military applications.
INTRODUCTION: WSN Overview

A wireless sensor network (WSN) is a wireless network consisting of spatially distributed autonomous devices using sensors to cooperatively monitor physical or environmental conditions (temperature, sound, vibration, pressure, motion, chem) at different locations.

- Originally motivated by military applications, as battlefield surveillance.
- Now used in many civilian application areas.

In addition to one or more sensors, each node in a sensor network is typically equipped with a radio transceiver or other wireless communications device, a small microcontroller, and an energy source, usually a battery.

- The envisaged size of a single sensor node vary from shoebox-sized to devices the size of grain of dust -- functioning 'motes' of genuine microscopic dimensions yet to be created.
- The expected cost of sensor nodes is similarly variable, ranging from hundreds of dollars to a few cents, depending on size of sensor network & complexity required of individual nodes.
- Size and cost constraints on sensor nodes result in corresponding constraints on resources such as energy, memory, computational speed and bandwidth.

A sensor network constitutes a wireless ad hoc network, meaning that it each sensor supports a multi-hop routing algorithm (several nodes may forward data packets to the base station).
INTRODUCTION: WSN Overview

- Unique characteristics of a WSN require:
  * Small-scale sensor nodes
  * Limited power (ample capacity and supply, harvest and/or storage)
  * Harsh environmental conditions
  * Node failures tolerance
  * Ad hoc placement and localization of nodes
  * Dynamic network topology
  * Communication link failures
  * Heterogeneity of nodes
  * Large scale deployment
  * Unattended operation (command, control, data extraction)
  * Integration into an unified system capability
INTRODUCTION: WSN Overview

- Motes (nodes) can be imagined as small computers, extremely basic in terms of their interfaces and their components.
  - Consist of a processing unit with limited computational power and limited memory
  - Sensors (including specific conditioning circuitry)
  - Communication device (usually radio transceivers or alternatively optical), and a power source usually in the form of a battery.
  - Other possible inclusions are energy harvesting modules, secondary ASICs, and possibly secondary communication devices (e.g. RS-232 or USB).

- More field architecture requires
  - Large numbers of motes
  - Adherence to RF-range, network reliability, terrain (topography), and sensor performance
  - Typically, exfiltration occurs via base stations are one or more distinguished components of the WSN with much more computational, energy and communication resources -- gateway between sensor nodes and GIG (end users)
Recent excitement comes from cost per unit and ability to use large numbers of ad hoc nodes to autonomously instrument any objective;

- industrial
- commercial
- environmental
- military
- governmental

These characteristics combine to address a plethora of data AND communication intensive missions via a cost-effective and adaptable approach.
INTRODUCTION: Final final thoughts...
AGENDA

- INTRODUCTION
- BACKGROUND
- MOTE DESIGN
- CASE STUDIES
- DESIGN CONSIDERATIONS
BACKGROUND: Agenda

- Historical/Evolution/Revolution
- Seminal Program (DARPA’s NEST)
- Mote Defined
- Integration with the World
- Subsystem considerations
- Interface considerations
- Overview of Applications
BACKGROUND: The IC Revolution

1st Transistor, 1947

TI REGENCY TR-1, 1955, $450 (today)

Sony TR-610, 1958

1st Integrated Circuit, ~1958

Integrated Circuit, 1963

Today ~$5
## BACKGROUND: Computer Revolution

### Original IBM PC (1981) vs. MICAZ Mote (2005)

<table>
<thead>
<tr>
<th></th>
<th><strong>Original IBM PC (1981)</strong></th>
<th><strong>MICAZ Mote (2005)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Clock Speed</td>
<td>4.77 MHz</td>
<td>4 MHz</td>
</tr>
<tr>
<td>RAM</td>
<td>16-256 KB RAM</td>
<td>128 KB RAM</td>
</tr>
<tr>
<td>Floppies</td>
<td>160 KB Floppies</td>
<td>512 KB Flash</td>
</tr>
<tr>
<td>Cost</td>
<td>~ $6K (today)</td>
<td>~ $35</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>~ 64 W</td>
<td>~14 mW</td>
</tr>
<tr>
<td>Size</td>
<td>25 lb, 19.5 x 5.5 x 16 inch</td>
<td>0.5 oz, 2.25 x 1.25 x 0.25 inch</td>
</tr>
</tbody>
</table>
BACKGROUND:

Wireless (cellular) technology evolves
BACKGROUND:
µP & wireless combine, following Moore’s law

Gordon E. Moore, Intel CEO, 2x transistor count/IC every 2 years

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
BACKGROUND: Wireless Revolution

Small size, low-cost, low-power, ubiquitous!

Investment in infrastructure!
BACKGROUND: The wireless evolution

Size reduction of cellular telephones

- Chicago Trial Unit
- Early AMPS
- Commercial Service Trunk Mountable
- Transportable Terminal
- Portable
- MicroTAC
- MicroTAC Lite
- PCMCi
- Soft Radio

Year:
- 1978
- 1982
- 1986
- 1990
- 1994
- 1998
- 2002
BACKGROUND: Integration with worldwide data communication architectures

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
BACKGROUND: Autonomy + Sensors + RF + worldwide distribution = new missions

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
BACKGROUND: Micro-Electro-Mechanical-Systems (MEMS)

Sensor uses electrochemical and photonic properties to perform bioanalysis
BACKGROUND: Use of small RF-connected nodes to perform complex tasks

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
BACKGROUND: Groundswell of WSN & associated technologies

- **Reasons for wireless networks**
  - Low Power/Small Physical Size
  - Reduced setup costs (no wires needed)
  - Ability to monitor remote test sites
  - Ability to monitor large areas with minimal hardware
  - Capability to monitor data in real time
  - Great versatility (programmable/upgradeable)

- **Combination of emerging technologies into unified system approaches requiring distributed measurement capabilities**
  - Existing backbone data communication systems (e.g., SATCOM, GSM, CDMA, IP)
  - *Borrowed* RF technology off cellular technologies & infrastructures
  - *Borrowed* processing technology off device technologies & infrastructures
  - *Borrowed* embracement of distributed processing (recall The Mersenne prime search formed 1996, -- a new world-record Mersenne prime discovered every year; also SETI@home originated in a conversation w/ David Gedye & Craig Kasnov in 1994. In May 1999, after several months of testing, the project launched. 15 December 2005, turned off server of SETI@home Classic, ending the largest computation in history.)
  - Arrival of low-power, low-cost sensor modalities (e.g., MEMS)
BACKGROUND: Evolution of Technologies used in WSN

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In 2000, DARPA sought novel approaches to the design and implementation of software for networked embedded systems.

- Embedded information processing primary source for superiority in weapon systems.
- Wave of inexpensive MEMS-based sensors and actuators and continued progress in photonics and communication technology accelerated this trend.
- Weapon systems increasingly “information rich,” where embedded monitoring, control & diagnostic functions penetrate deeper with smaller granularity in physical component structures.

Separation of physical and information processing architectures not sustainable.

- Strong mutual interdependence requires fusion at fine levels of granularity, i.e. the distribution of information processing among physical components.
- Coordinated operation of distributed embedded systems makes embedding, distribution, & coordination = fundamental technical challenge for embedded software.
BACKGROUND: DARPA NEST

- **BAA #01-06**
  Networked Embedded Software Technology (NEST)
  CBD Reference
  Networked Embedded Software Technology (NEST)
  SOL BAA 01-06 DUE: 01/05/2001
  POC: DR. JANOS SZTIPANOVITS, DARPA/ITO
  E-Mail: baa01-06@darpa.mil
  FAX: (703) 522-7161

- **What is NEST trying to do?**
  - Develop technology for building dependable, real-time, distributed, embedded applications comprising 100-100,000 simple computing nodes:
    1. Provide **formally verified** algorithms and code for real-time coordination in networked embedded systems
    2. Develop theory and technology for **synthesis methods** that are embeddable in real-time systems.
    3. Develop methods and tools for the automated composition and customization of coordination services with **guaranteed** properties.
BACKGROUND: NEST “Players”

- AFRL
- UCB
- UVA
- OSU
- Vanderbilt
- ...
- Northrop Grumman
- Raytheon
- Crossbow
- ...
- Intel
- MITRE
- Kestrel
- CACI
- ...

❖ Countless “fathers” of SOWN/WSN, motes, etc, countless “Firsts” & “successes”
❖ Insure middleware and/or hardware employed does what it claims!
❖ At Issue:
  ❖ BIG on R&D
  ❖ typical 6.1, 6.2
  ❖ applications flow due to “opportunities”
BACKGROUND: *System-level technology*

NEST assessments --> DARPA ExANT Program

**Simultaneous motes; net & tracking**

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>XSM/XSS Tier2 (OSU+)</td>
</tr>
<tr>
<td>2004</td>
<td>ExSCAL</td>
</tr>
<tr>
<td></td>
<td>VigilNet</td>
</tr>
<tr>
<td></td>
<td>TASC T&amp;I</td>
</tr>
<tr>
<td>2005</td>
<td>ExANT E2E (TASC LSI)</td>
</tr>
<tr>
<td>2006</td>
<td>ANSCD (TASC)</td>
</tr>
</tbody>
</table>

**Important Dates**

- **LineInTheSand** Aug 03
- **CLEAN POINT** Dec 04
- **ANSCD** Sep 05
- **ExA FA1** Mar 06
- **DEMO** Nov 06

Successful Assessments Evolved from Successful R&D Contributions
BACKGROUND: Let’s get technical…
So what constitutes a mote, motefield, and/or a WSN???

What is a mote?

- What are the mote subsystems?
  - How do motes interact?
  - How are mote cores similar?
  - How do mote cores differ?
  - Which sensors?

- How do you design and create mote software (middleware)

- What is the power behind netted sensors (motefield)?

- How do wireless sensor networks connect to the real world? And how do they interface to the existing data communication networks?
  - What are the interfaces?
  - Why pick one exfiltration scheme over another?
  - How do you deploy the field?
  - …
BACKGROUND: What is a mote?

... “MOTE” ...

- “Tiny piece of anything”
- Low-power (RF) transceiver

Microcontroller system
  - Clocks
  - Memory
  - I/O
  - ADC

Operating system
Programming language
Simulation environment
Debugger
BACKGROUND: Concepts involved (Tmote Sky diagram), The Mote Core

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Microcomputer (w/ADC)
BACKGROUND: Concepts involved (Tmote Sky), Mote Core Implementation (note USB)

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
BACKGROUND: Simple Sensor Nodes

Mote ≡ Transducer (sensors) + Motecore (μC, Radio stack, RAM, power/dist)

- Resource-constrained sensing & reporting
- Application-specific (embedded software)
- Data-centric routing; node = independent data collector
- Provide high-resolution information from array of nodes.
- Unattended, self-sufficient power sourced (e.g., batteries)
  - Energy/transmit-bit v. processed instruction energy
  - Operational duration
  - Energy battle: RF Tx v. sensor op v. μP-cycles

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### BACKGROUND: WSN Vendors and Products

#### MOTES/NODES:
- BTnode rev2
- BTnode rev3
- Ember
- eyesIFXv1
- eyesIFXv2.1
- FireFly
- Fleck
- Imote
- Imote2
- Mica
- Mica2
- Mica2Dot
- MicaZ
- Particles
- Rene
- ScatterWeb
- Sensinode
- SHIMMER
- SquidBee
- Sun SPOT
- Telos
- TinyNode 584
- Tmote Mini
- Tmote Sky
- T-Nodes
- WeBee
- WeC
- WiseNet

#### PROCESSORS:
- ARM7
- Atmel AVR
- Intel Xscale
- Intel 8051
- PIC
- TI MSP430

#### RADIO STACKS:
- Chipcon CC1000
- Chipcon CC1020
- Chipcon CC2420
- Xemics XE1205
- 802.15.4 Chipsets and SoC
BACKGROUND: So what would a WSN do for you?

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
BACKGROUND: Differentiation of WSN from other technologies such as RFID

- Small computers with wireless capability
- Alternative to RFID

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BACKGROUND: so why WSN-based sensing vs. “traditional” sensors?
BACKGROUND: Integration of motes (motefield) into the end-user’s path

REQUIRES/DESIRESES

• **Exfiltration path (RELAY function)**
  - mote-based processing minimal
  - field-wide processing
  - extended RF range, at *ground* level

• **Worldwide (GIG) access**

• **Standardized situational awareness display(s) & GUI**
  - C2PC
  - COT
  - FalconView …
  - GoogleEarth (KML)

• **Sensor-web enablement (SWE)**
  - Open Geospatial Consortium (OGC) Standards
  - Northrop Grumman --> PULSENet™
    … MITRE, iGOV, SAIC, Raytheon, Sun Microsystem …

• **Diagnostic testing apparatus (throughout life-cycle)**
BACKGROUND: Local/IP network

**WISENET - SYSTEM BLOCK DIAGRAM**

**CLIENT**
- INTERNET
  - HTTP
  - TCP/IP
  - WEB BROWSER

**SERVER**
- HTTP SERVER
  - WEB PROGRAM
  - SQL DATABASE
  - WISEDB

**SENSOR MOTE NETWORK**
- GATEWAY
- OFFICE #1
- OFFICE #2
- LAB A
- LAB B
- 900 MHz RF COMM
- RS-232 SERIAL

**DATA ANALYSIS SUBSYSTEM**
- DASHED LINES

**DATA ACQUISITION SUBSYSTEM**
- DASHED LINES
BACKGROUND: Basic architecture of motefields (netted sensors)
BACKGROUND: Worldwide integrated motefield

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BACKGROUND: Preview of applications

- Border patrol, linear surveillance, little/no infrastructure
- Container tracking; numerous surveillance areas, multiple situations in close quarters, status tracking
BACKGROUND: Evolving mission and dynamics

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BACKGROUND: What are others doing?

- Health care and emergency response
- Public safety and first responders
- Monitoring critical infrastructure
- Rail industry
- Logistics
- Asset management
- Smart toys

Essentially, cross-industry applications where physical data is necessary or optimizes the application.
BACKGROUND: Status -- Technology Maturity

Five (5) Key Characteristics –

1. Processor – already mature and at production volume
2. Network – already self-configuring and self-healing mesh
3. Power – conservation strategies available and successful
4. Software / Integration – availability of open source and/or offers standards-based
5. Packaging – can be engineered to necessary environmental conditions
BACKGROUND: Next step -- push towards standards

### Previous Approaches
- Non-standards based
- Costly embedded programming
- No base platform services
- Code reusability limited
- Application tied to HW
- Minimum 18mo+ dev cycle

### Emerging Approach
- OGC (Open Geospatial Consortium)
- Standards based
- Java programming
  - Scalable platform services provided
  - Better code reusability
  - Application more independent of HW
  - 1-2 mo dev equiv

--> Which leads to –
- Reduced implementation costs
- Faster time to market
- Scalability thru standards
### OBJECTIVES

- Design, develop, integrate & demonstrate middleware deployed on a mini-sensor network of thousands of sensors capable of:
  - self organizing
  - grouping
  - localizing
  - geo-referencing
  - power managing
  - reprogramming
  - detecting
  - categorizing
  - reporting presence of physical entities

- **Final product**
  - Creation of middleware applications & services library that conform to Common Architecture Framework.
  - Sensor services and applications library with re-use utility as part of a transition strategy.

### GOALS

- Develop technology, using sensing/processing nodes, that address:
  - reliability
  - robustness
  - real-time
  - distributed sensing and processing
  - enable embedded applications
  - scalable
  - Demonstrate technology capabilities for operationally-relevant applications
  - Integrate application outputs with accepted end user dissemination architectures
  - Develop foundation software services for exploitation of large networks based upon wireless sensing/processing nodes.
  - Demonstrate required capabilities in realistic environments for technology transition.

### BACKGROUND: Recap of WSN -- objective/goals
BACKGROUND: Now to implement....

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
BACKGROUND: Rest of the course, break down

- Introduction
- Background
- Motes
- Architecture
- Case Studies
- Design Considerations
  - Localization
  - Power
- Refs

Hardware
Network Mgmt Syst (NMS)
Software (IDE, SDK)
Sensor Modalities
You have enjoyed ATI's preview of

**Self-Organizing Wireless Networks**

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