ECE 194C Sensor Networks and Applications
Course Format
www.ece.ucsb.edu/Faculty/Iltis/ece194c

• Regular lectures, Faculty/Guest Speakers.
• Choose a sensor topic of interest.
  – Think about possible product/markets?
  – Problems of energy, distributed estimation, communications.
• 5-10 page report due at end of course
• ~15 minute ppt. presentation on your ideas and findings.
ECE 194C Sensor Networks

• Applications driven
  – Global environmental monitoring. Temperature, pressure, long-term climactic changes in atmosphere and in oceans. (e.g. ORION project.)
  – Local environmental monitoring. Energy conservation, HVAC control. (Micro-motes, smart dust.)
  – Localization of people, animals, objects. Security, search-and-rescue. (Motes, acoustic arrays.)
  – Structure monitoring. Stresses/loads in buildings, bridges, roads. (ROADNet)

• Key problems
  – Wireless networking and protocols.
  – Energy consumption.
  – Disposal (Motes and batteries in forest problem.)
  – Distributed Estimation
Example of Eco-Sensing – Volcanic Activity


Uses Tmote Sky 802.15.4 sensor nodes.

Freewave radio for long-distance communication (900 Mhz.)

GPS for time synchronization of events.

“Semi-acoustic” seismometers.
Example of Underwater Eco-Sensing

Source: L. Washburn MSI PISCO/SBC-LTER.

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latitude

longitude

-120  -119.8  -119.6  -119.4  -119.2  -119

Stearns Wharf

Pt. Conception

UCSB

Pt. Sal

Thermistor string and ADCP
Thermistor string and S4
Thermistor string only
LTER sites (Therm. string, CTD, ADCP)
Pressure measurements

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Inlet diagram:

- Floatation (100 Lbs.)
- Temperature logger
- Instrumnetation package:
  - Fluorometer
  - Optical Backscatter instrument
  - SBE 37 Sea Cat with pressure sensor
- Temperature logger
- Chain line anchor (100 Lbs.)
- Seafloor
- Sea surface

Source: L. Washburn MSI PISCO/SBC-LTER.
Sensor Retrieval

Pt. Sal
Pt. Conception

USSB

-2 m
10 - 15 m

TEMPERATURE LOGGER
INSTRUMENTATION PACKAGE:
FLUOROMETER
OPTICAL BACKSCATTER INSTRUMENT
SBE 37 SEA CAT with PRESSURE SENSOR
TEMPERATURE LOGGER

ADCP (600 KHz)

SEALOGIC
CHAIN LINE ANCHOR
SEAPLOR (300 Lbs.)
FLOATATION (100 Lbs.)

SEA SURFACE
Wireless Undersea Sensor Network (FRONT)

Source: J.A. Rice  SPAWAR “Seaweb network for FRONT…”, www.benthos.com
FRONT Network

ADCP = Acoustic Doppler Current Profiler

Source: J.A. Rice SPAWAR “Seaweb network for FRONT…”

and http://nopp.uconn/edu/ UCONN FRONT program
Regional Sensor Network – UCSD ROADNet

Source: roadnet.ucsd.edu
Generic Protocol Stack Definition – Wireless Sensors

- **Application Layer**
- **Network Layer**
  (Topology selection, routing.)
- **Medium Access Control (MAC) Layer**
  (802.15.4, Bluetooth, CSMA/CA)
- **Physical Layer (PHY)**
  (802.15.4, FSK/FH)
Physical (PHY) Layer for Sensor Networks

- Options
  - CDMA direct-sequence spread-spectrum (e.g. cdma2000 cellphones)
    - Complex demodulation and equalization, high power consumption.
  - Frequency-hopping/FSK
    - Used in lower-cost sensor networks e.g. Bluetooth.
    - Sensitive to multipath interference.
  - Complementary code keying (CCK) 802.11b.
    - 11 mbps unneeded for most sensor applications, too expensive and power-hungry.
  - Orthogonal frequency-division multiplexing (OFDM).
    - 802.11a/g
    - 54 mbps again not needed in most sensor applications.
    - High power consumption due to FFT/equalization operations for demodulation.
  - 802.15.4 (Zigbee). Based on direct-sequence type waveforms with simple detection.
    - Optimized for sensor networks, supplanting earlier FSK implementations.
    - Up to 250 kbps in the 2.4 GHz band.
Example of Mote Radio

Source:
Chipcon Corp.
www.chipcon.com

Chipcon CC1000
Carrier Freq. 300 MHz – 1 GHz
FSK data rate up to 76 kbps
PLL Detection

www.xbow.com
MICA2
FSK Signaling

\[ s(t) = \begin{cases} 
\cos(2\pi t / T), & t \in [nT, (n+1)T), \ b(n) = 1 \\
\cos(4\pi t / T), & t \in [nT, (n+1)T), \ b(n) = \frac{-1}{2} 
\end{cases} \]
PLL Detection in FSK Sensor Radios

VCO offset frequency is proportional to voltage \( v(t) \).
Voltage \( v(t) \) tracks FSK frequency deviation.

\[
\frac{1}{2\pi} \frac{d\phi_v(t)}{dt} = f_v(t) - f_c = k_v v(t)
\]
802.15.4 PHY Layer – 868-915 MHz
Direct-Sequence Spread-Spectrum

\[ d(n) = \pm 1 \]

20/40 kbps
300/600 k chips/sec
20/40 k bps -- 15 chips/symbol
BPSK/raised cosine pulse shaping

L.O. ~900 MHz
PA

15 chip PN sequence
300/600 kcps
Simplified 802.15.4 PHY Receiver

Zero IF design – conversion directly to baseband but requires complex-valued signal representation.
Medium Access Control

• Options include
  – Time-division multiple access (TDMA)
    • Used in some sensor networks (Bluetooth) – requires central coordination.
  – Code-division multiple access (CDMA)
    • Too expensive for sensors, used in cellphones, military comms.
  – Carrier sense multiple access/collision avoidance (CSMA/CA)
    • Least complex to implement (just use RSSI.) Suffers from low throughput, hidden and exposed terminal problems.
    • Used in Chipcon FSK/FH radios and 802.15.4 (Zigbee)
Basic TDMA

Coordinator – transmits sync. beacon.
(Alternative to beacon – use GPS or atomic clocks in each sensor.)
Bluetooth TDMA/FH

Transmission between Coordinator/Client only

Synchronous mode – 2 slots/client trans.

1600 hops/sec.
710 kbps
79 channels

Frequency

Time
**CSMA/CA (802.11x, 802.15.4)**

Carrier sense multiple access – asynchronous, no central coordination required. Only need RSSI indicator in sensor radio.

DIFS = Distributed Interframe Space, SIFS = Short Interframe Space.

NAV = Network Allocation Vector, CW = Contention Window

Source

Dest

Other

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Data

DIFS

ACK

SIFS

NAV/CW– Defer for random time

Data

DIFS
CSMA Collisions

Source A

Data A

DIFS

DIFS

Source B

Data B

T

Destination C

aT  Propagation Delay

A collides with B
Fundamental CSMA Throughput


\[ S = \frac{Ge^{-aG}}{G(1+2a)+e^{-aG}} \]

Key Problem: Due to propagation delay \( a \), node B may not sense node A’s initiation of transmission – collision.
Simplified Network Layer -- Zigbee


Zigbee network needs at least one “full function device” (Coordinator)

- FFD establishes networks, routing tables, assigns “bindings” to devices (application.)
- Coordinator knows which client owns which sensor.
- 64 bit long addresses or 16 bit short addresses for each device.

![Star Topology Diagram]

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Sensor 1  →  Coordinator  ←  Sensor 2

Client
Star versus Mesh Network -- Zigbee

Star Topology – Similar to Bluetooth. Each client/end device communicates only through the coordinator.

Mesh Network – Clients/end devices can communicate directly with each other. Need routing algorithm and tables.
Zigbee Routing

- Uses AODV/tree/cluster-based routing.

**Summary of AODV (ref. C. E. Perkins, E. Royer 99.)**
  - Ad hoc on-demand distance-vector algorithm
  - Only nodes on an active path maintain routing information (tables).
  - Path Discovery
  - Node transmits Route Request RREQ to neighbors.
  - Neighbor transmits either Route Reply (RREP) if it has a route to the destination, or rebroadcasts RREQ to its own neighbors
  - RREQ packets set up reverse path
  - As RREQ travels back, forward pointers to origin of RREQ are set up.
  - Forward pointers establish forward path to destination.
AODV Routing/Zigbee

GPS-less Positioning

Methods: Signal strength – requires mapping.
Connectivity – high sensor density.
DS-CDMA handshaking using round-trip travel time (RTT)
Radiolocation/Multipath

Transmitter
Sparse Multipath Estimation Problem

Node 1: Multipath Intensity Profile

Node 2: Multipath Intensity Profile

Node 3: Multipath Intensity Profile

Node 4: Multipath Intensity Profile

- **True Channel**
- **True TOA**
- **GSIC/MP Estimated Channel**
- **GSIC/MP Estimated TOA**

[x 0.1 µs.]
Distributed Estimation – Information Graph
Estimation Problem -- Radiolocation

• Round-trip travel time is nonlinear function of x-y position.

\[ z_{ij} = \frac{1}{c} \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} + n_i \]

• Estimation techniques
  – Pseudo-linearization of \( z_{ij} \) followed by linear least-squares
  – Extended Kalman filter
  – Unscented Kalman, particle filters.
DS-CDMA Radiolocation Gives GPS-type Performance

![Graph showing average position estimation error vs. packets for different methods: 1' Round-Robin, 3' 4/8 Optimal, 4' 4/8 Suboptimal, 7' RTT-only Opt., and 8' RTT-only Sub.](image-url)
Localization Using Sensor Networks

Time-of-arrival (line-of-bearing) obtained via beamforming in direction of strongest acoustic signature.

Delay and Sum Beamforming

$$r_1(t)$$  
$$r_2(t)$$  
$$r_3(t)$$

$$\tau_1$$  
$$\tau_2$$  
$$\tau_3$$

Acoustic Wavefront
Delay and Sum Beamforming

Example: Linear sensor array. \( d \) = inter-sensor spacing, \( c \) = speed-of-sound.
Delay and Sum Beamforming (Cont’d)

Delays are functions of angle-of-arrival and sensor index.

\[ g(\theta) = \int_0^T \left\| \sum_{k=1}^{N} r(t - \tau_k(\theta) + \tau_k(\hat{\theta})) \right\|^2 dt \]

\[ g(\theta) = \sum_{n=0}^{N-1} \sum_{k=1}^{N_s-1} R_k(n) e^{i2\pi n \tau_k(\theta)} \]

\[ \hat{\theta} = \arg \max_{\theta} g(\theta) \]

\[ R_k(n) = \sum_{l=0}^{N-1} r_k(m) e^{-i2\pi nm/N} \]

FFT-based beamforming/direction-of-arrival estimation (Wang and Chandrakasan.)
Energy Issues

• Batteries
  – Insufficient lifetime, disposal, effect on environment.

• Solar ("Power of the Sun" Video)
  – What about sensors in buildings, under foliage, caves?
  – Underwater?

• Power scavenging
  – Reasonable for low data rates, 1 bits/sec.
    • Use motion, ambient light, broadcast RF signals?
  – Sources for power scavenging underwater? Currents? Plankton?
Example of Power Scavenging

- Vibration converted to variable capacitance –

Sources of vibration: Microwave oven, windows next to street, “person nervously tapping heel”, CD drive on laptop computer.

Vibration changes capacitance.
Fixed charge, $V$ changes
$V = q/C$

Piezoelectric – vibration directly generates voltage.