Wireless Sensor Networks

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Agenda for today

- Wireless Sensor Networks (WSN)
  - What? Why? and How?
- WSN Deployment
  - Localization
- WSN Networking
  - Routing protocols
  - MAC protocols
- WSN Platforms
  - Hardware and software components
- WSN Design methods
- Summary and Future of WSN

Towards Ambient Intelligence [Weiser]

- Wireless **network** delivers infotainment, communication, navigation, ... anyplace, anytime, for every citizen ...
- **Hidden, pervasive computing**. IT to background, **people in the foreground**, improves quality of life in non-invasive way ...
- Things see, listen, feel, becomes **sensitive and adaptive to people** ...

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What is a sensor network?

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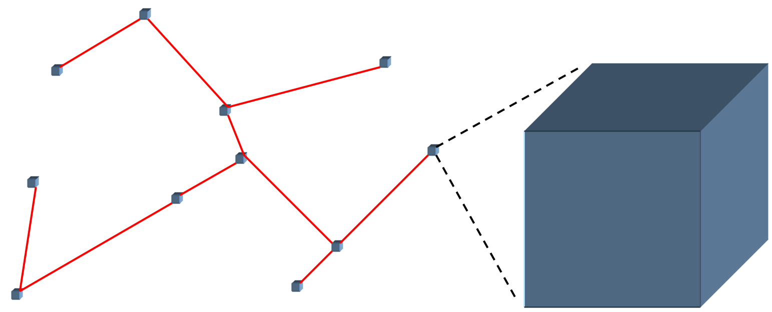
Sensor Network?



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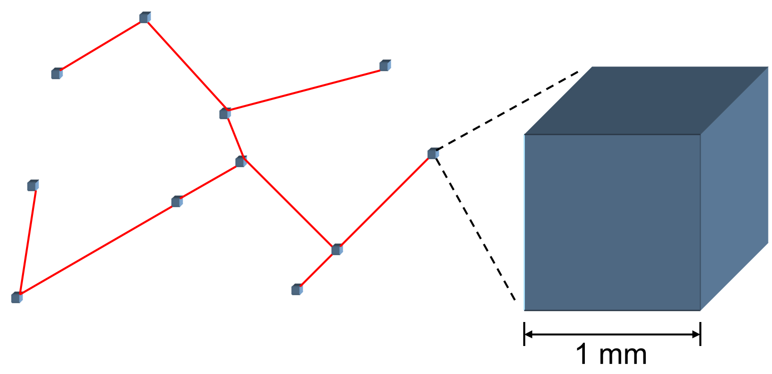
intelligent dust?



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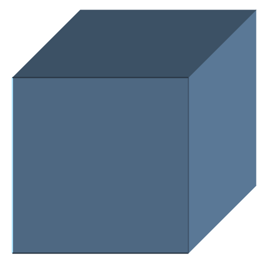
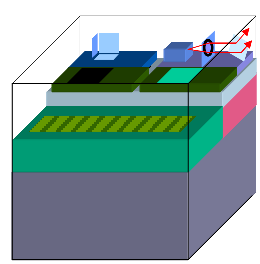
1 mm^3 computer!



1 mm^3 computer!

Thickfilm battery
Solarcell
Power capacitor
Analog I/O, DSP, Control
Sensors
Passive optical transmitter
Active optical transmitter
Optical receiver
RF radio



1 mm^3 computer!

Thick-film battery	1 J/mm^3	
Solar cell	1 J/day/mm^2	1-10 mJ/day/mm^2
Power capacitor	10 mJ/mm^3	
Analog I/O, DSP, Control	1 nJ/sample	1 pJ/inst
Sensors	0.1 nJ/bit	
Passive optical transmitter		
Active optical transmitter	1 nJ/bit	
Optical receiver		

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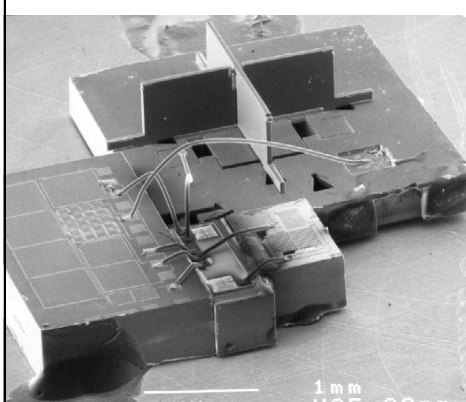
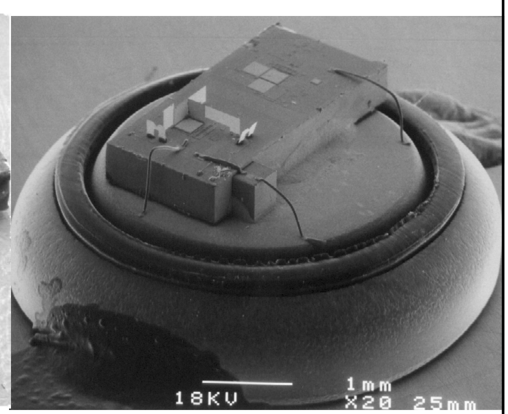
1 mm^3 computer

still science fiction – but …





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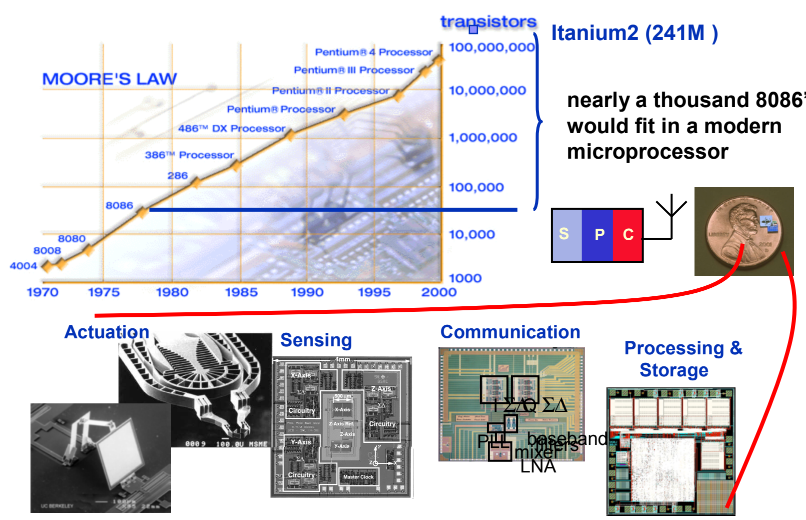
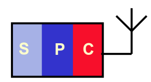
The technology behind sensor networks

CMOS Trends: miniaturization



New Technology SweetSpot (uW – mW)

- **CMOS miniaturization**
  - 1 M trans/$ => tiny (~mm^2), inexpensive processing and storage
  - 1-10 mW active, 1 µW passive (at 1% use 100 µW ave)
- **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)



- **Communication**
  - short range, low bit-rate, CMOS radios (1-10 mW)
- **Power**
  - batteries remain primary storage (1,000 mW*s/mm^3), fuel cells 10x
  - solar (10 mW/cm^2, 0.1 mW indoors), vibration (~uW/gm), flow
  - 1 cm^3 battery => 1 year at 1 msgs/sec

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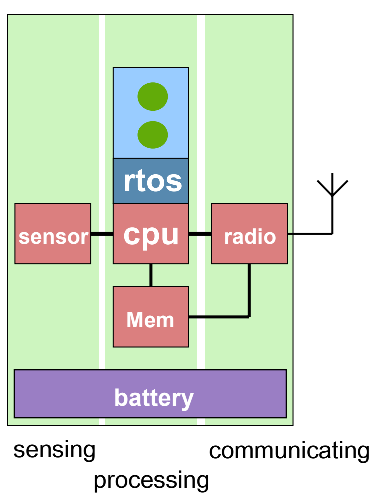
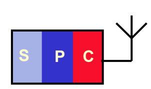
Sensor Node Architecture





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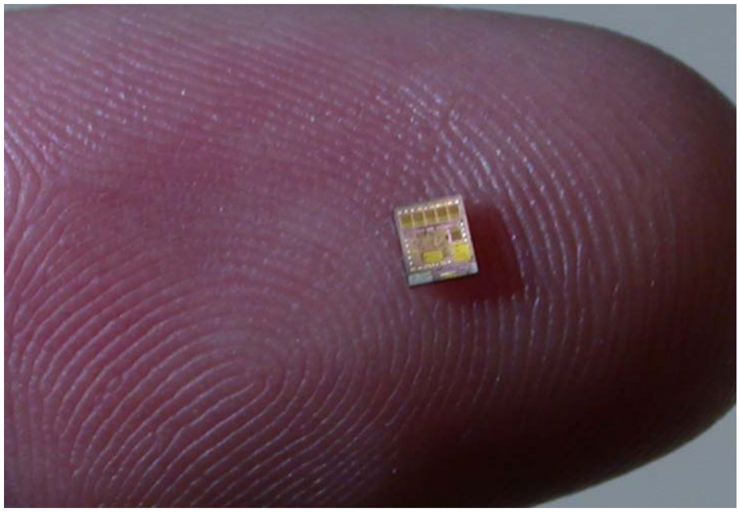
CMOS trend: miniaturisering



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How can we use sensor networks?

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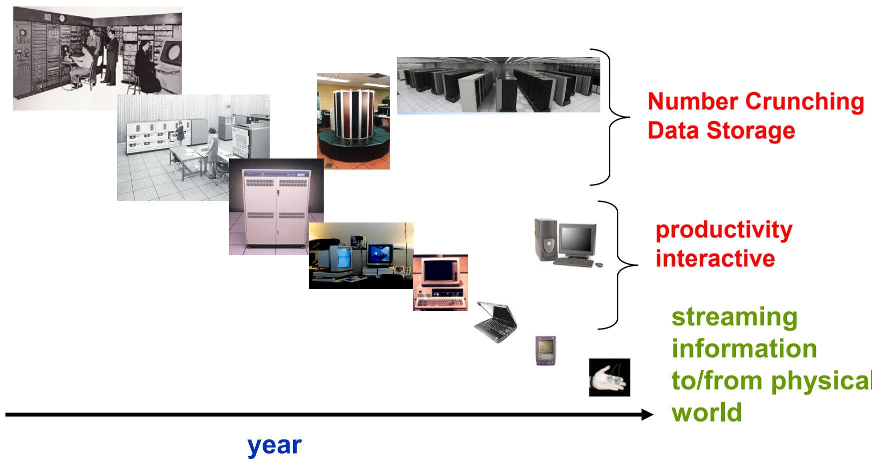
Where Computing is Done



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Health monitoring

courtisy Rudy Lauwereins (MPSOC02)

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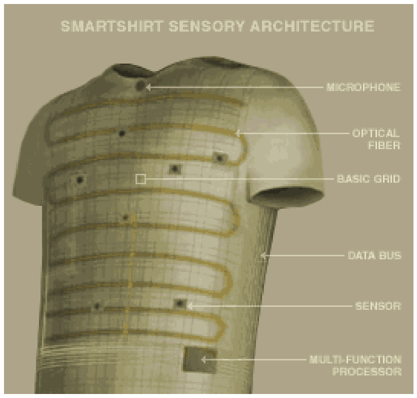
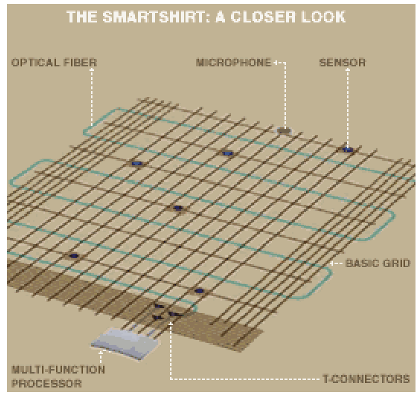
Smartshirt - wearable computing





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... or implants

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Electronic devices for diagnostics

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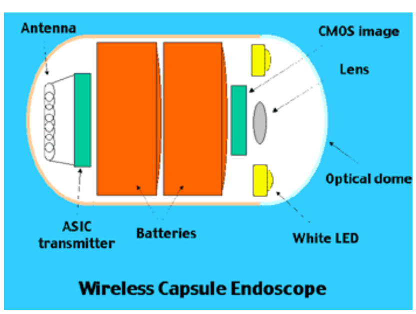
Smart pills – 1st generation



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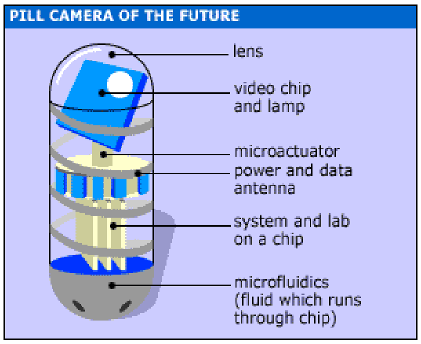
Smart pills – 2nd generation



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Examples of sensor networks

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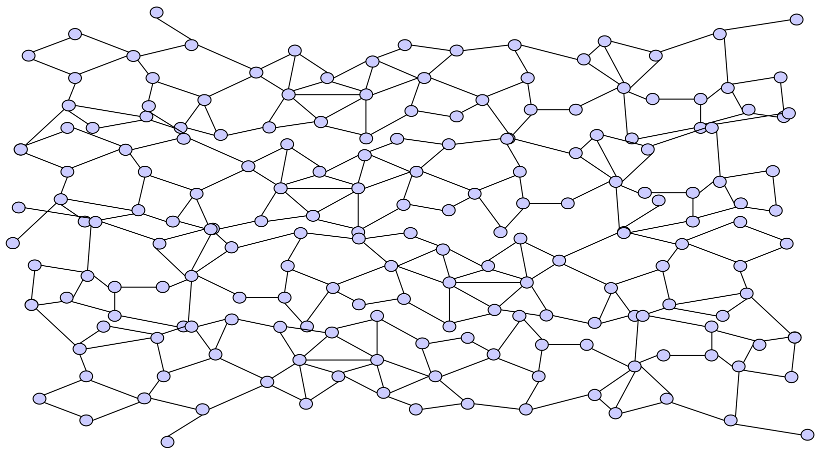
Sensor Network



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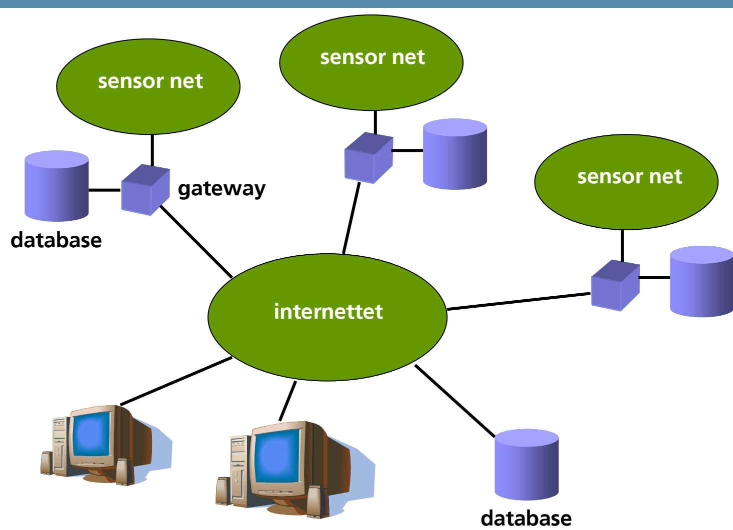
Sensor network



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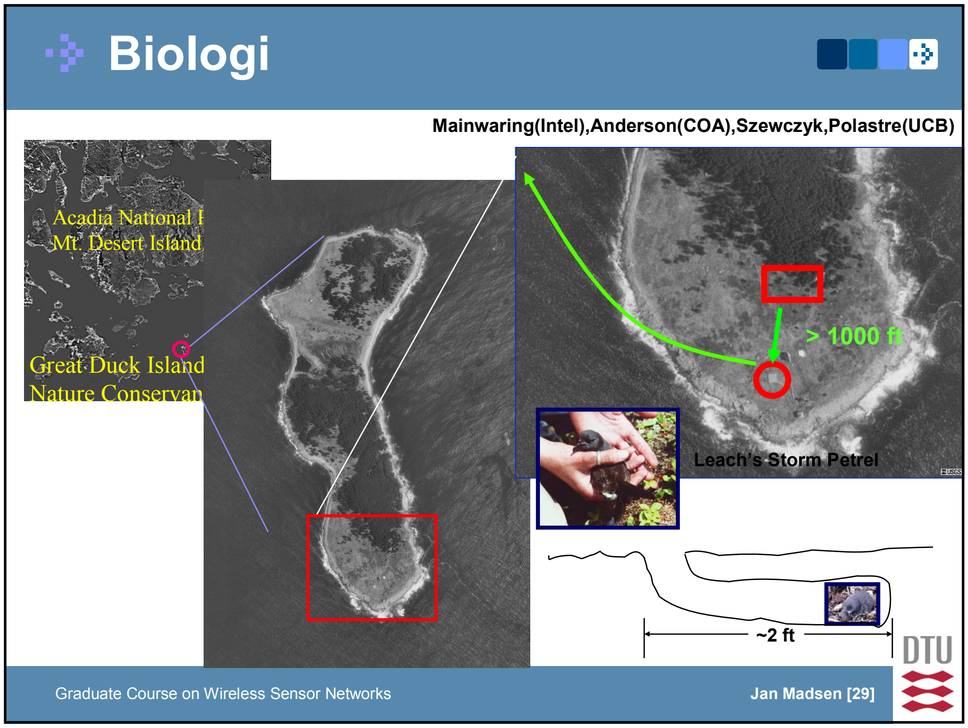
Biologi
Mainwaring(Intel),Anderson(COA),Szewczyk,Polastre(UCB)
Acadia National I
Mt. Desert Island
Great Duck Island
Nature Conservan
> 1000 ft
Leach's Storm Petrel
~2 ft
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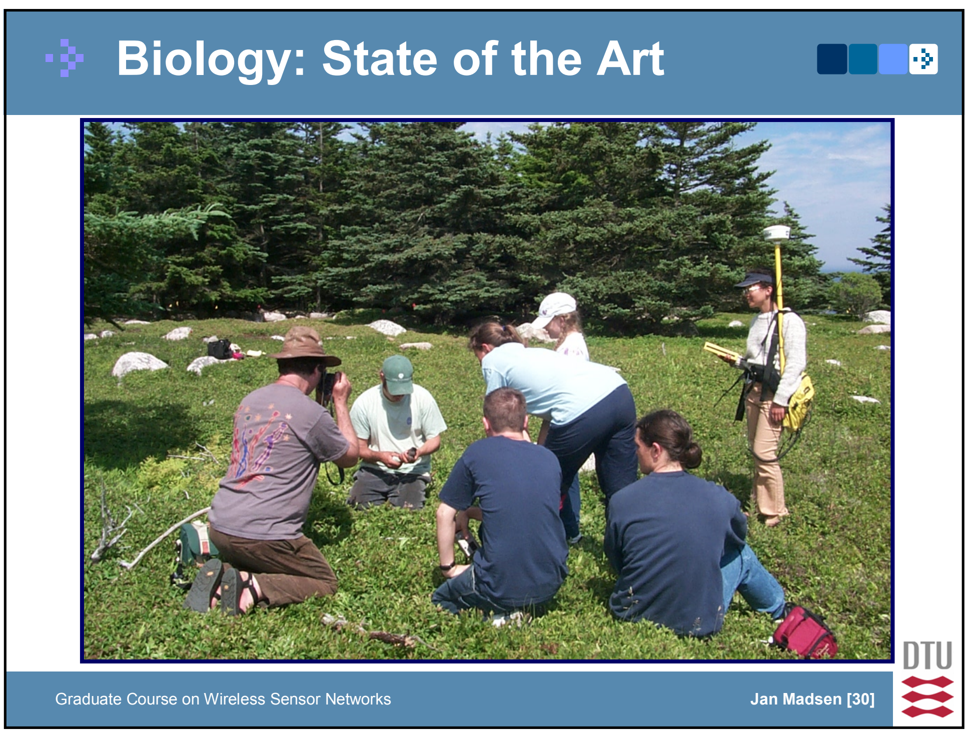
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Solution using sensor networks

http://www.greatduckisland.net

Processing, Storage

Wireless network

Light, Temp, Humidity, Barometer, Passive IR (occupancy)

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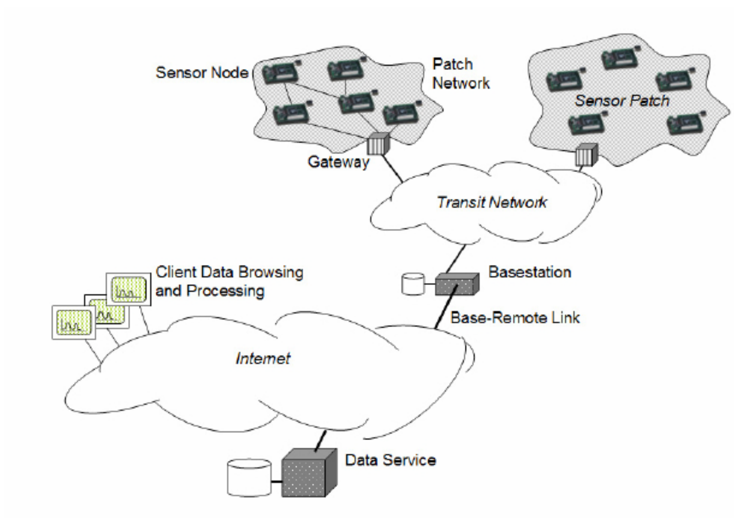
Hierarchical deployment



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Sensors

- Mica platform
  – Atmel AVR w/ 512kB Flash
  – 916MHz 40kbps RFM Radio
    - Range: max 100 ft
    - Affected by obstacles, RF propogation
  – 2 AA Batteries, boost converter
- Mica weather board – “one size fits all”
  – Digital Sensor Interface to Mica
    - Onboard ADC sampling analog photo, humidity and passive IR sensors
    - Digital temperature and pressure sensors
  – Designed for Low Power Operation
    - Individual digital switch for each sensor
  – Designed to Coexist with Other Sensor Boards
    - Hardware “enable” protocol to obtain exclusive access to connector resources
- Packaging
  – Conformal sealant + acrylic tube

– Placement
  – Place above ground and in burrows (propagation?)

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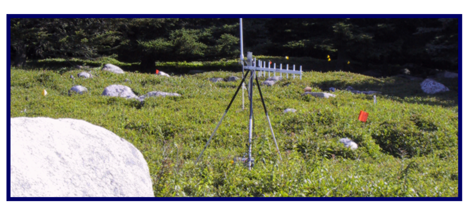
Gateway

- Communicate with sensor and base station.
- Solar powered (sensors are just battery powered).
- Directional antenna pointed toward base station.



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Base station

- Laptops
- In lighthouse keepers house.
- Log all data and transmit via satellite to D.C. and then on to the Internet.

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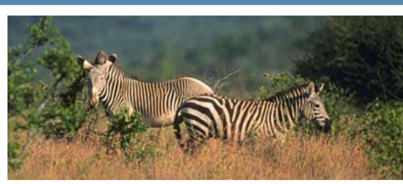
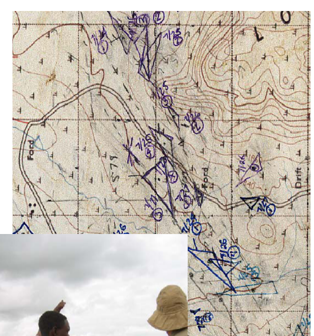
ZebraNet



- Goal: Biologists want to track animals long-term, over longdistances
  - Interactions within a species?
  - Interactions between species?
  - Impact of human development?



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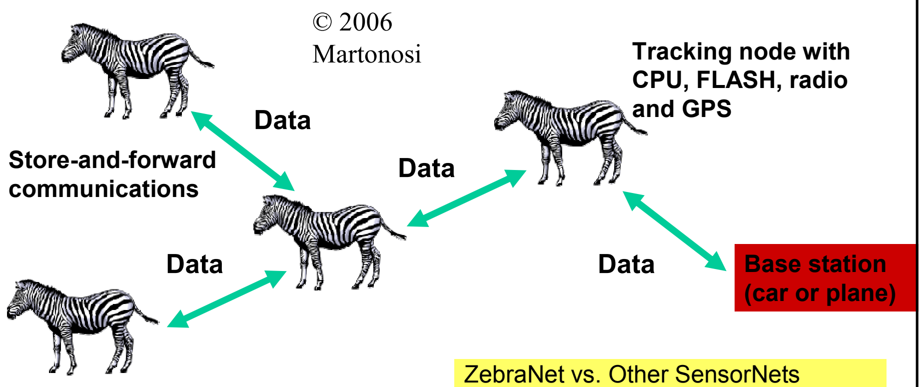
ZebraNet as Computing Research



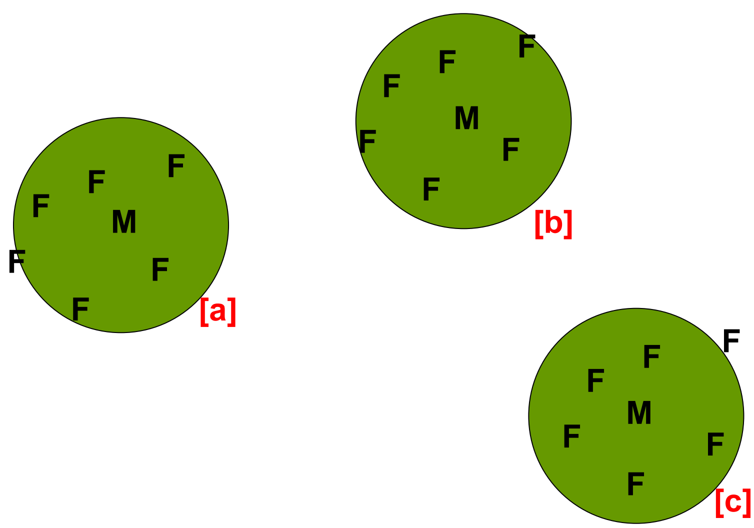
ZebraNet vs. Other SensorNets

- All sensing nodes are mobile
- Large area: 100's-1000s sq. kilometers
- "Coarse-Grained" nodes
- GPS on-board
- Long-running and autonomous

Research Questions

- Protocols and mobility?
- Energy-efficiency?
- Software layering design?

ZebraNet basics



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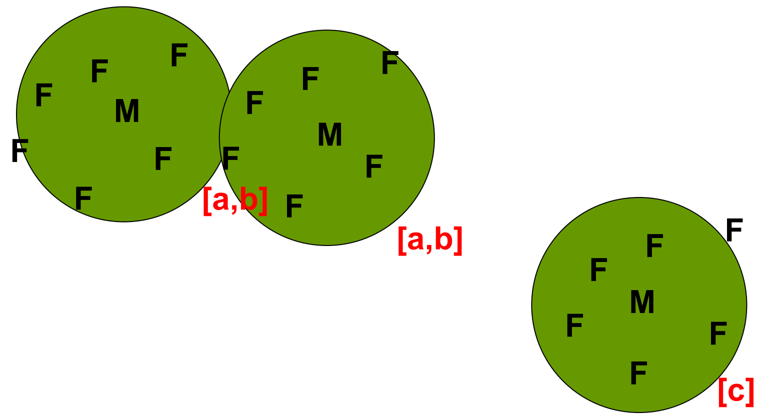
ZebraNet basics



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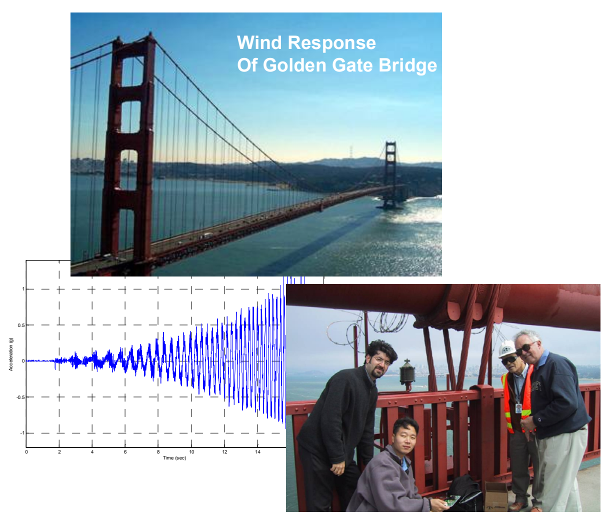
Construction monitoring



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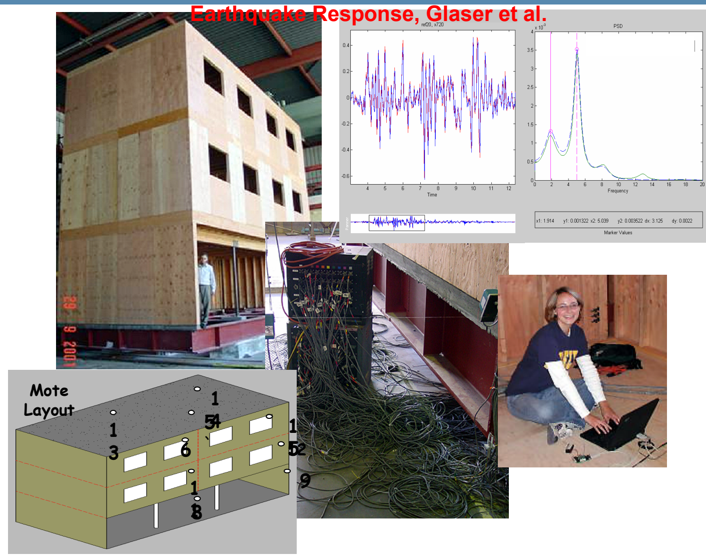
Construction monitoring



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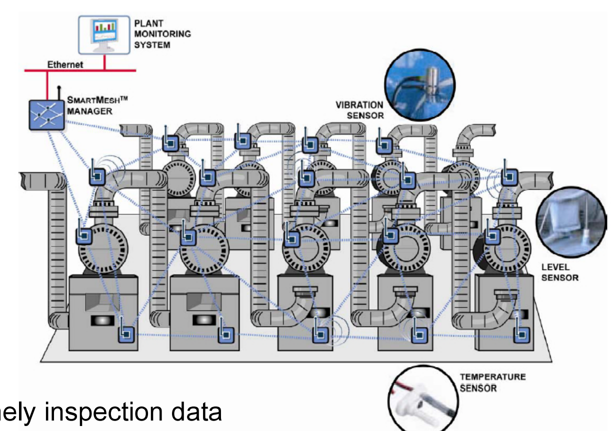
Industrial Automation: Predictive Maintenance



- Frequent and timely inspection data
- Reduced need for human inspection
- Improved quality of diagnostic measurements
- Reduced network installation costs

Dust Networks

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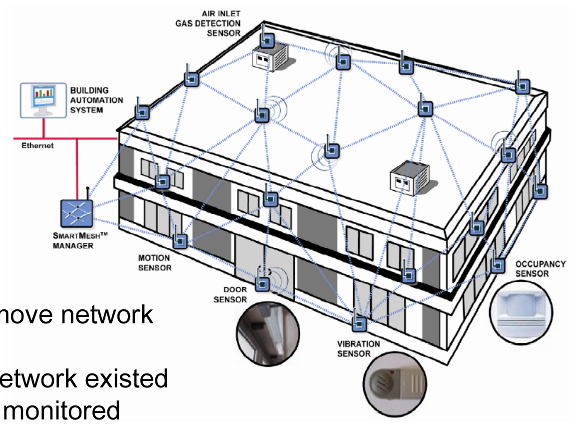
Security: Small to Medium Commercial Property



- Low-cost, low-impact
- Portable . Tenant can move network with the Company
- Deployable where no network existed
- Outlying assets can be monitored

Dust Networks

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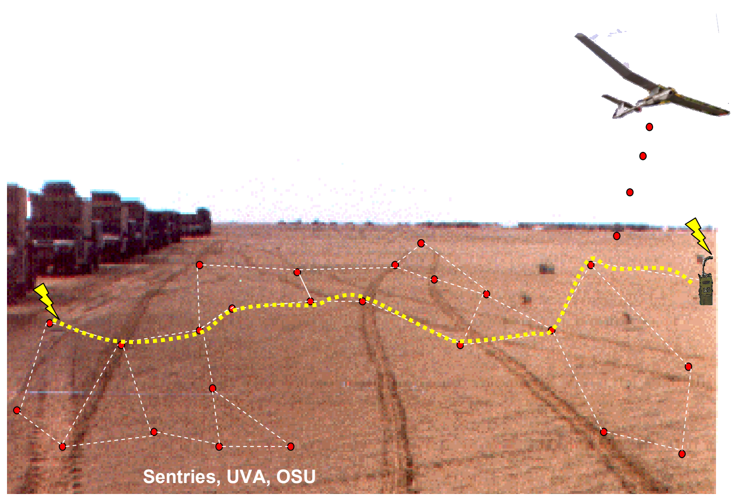
Military applications!



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Shooter localization

Red circle:
→Shooter position

Red line:
→ Shot direction

Large green circle:
→Sensor node (good measurement)

Small green dot:
→Sensor Node (no or unused measurement)

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Precision Agriculture

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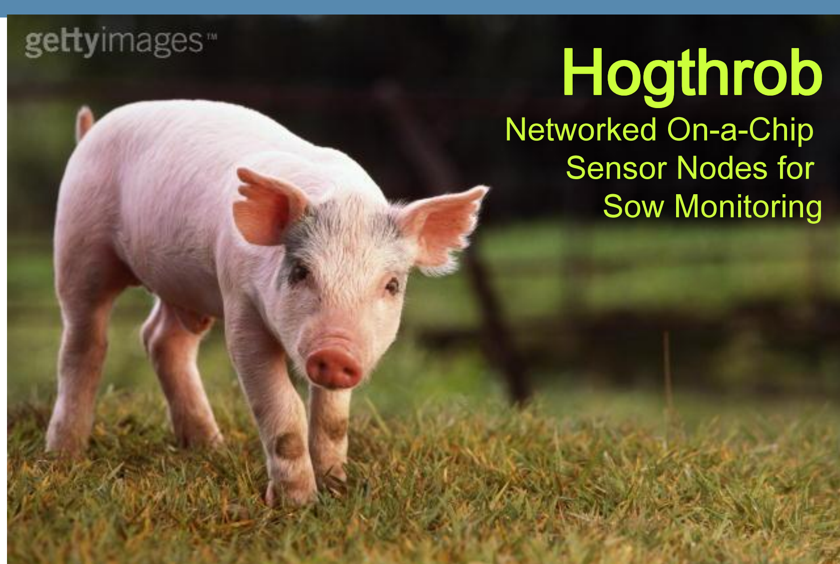
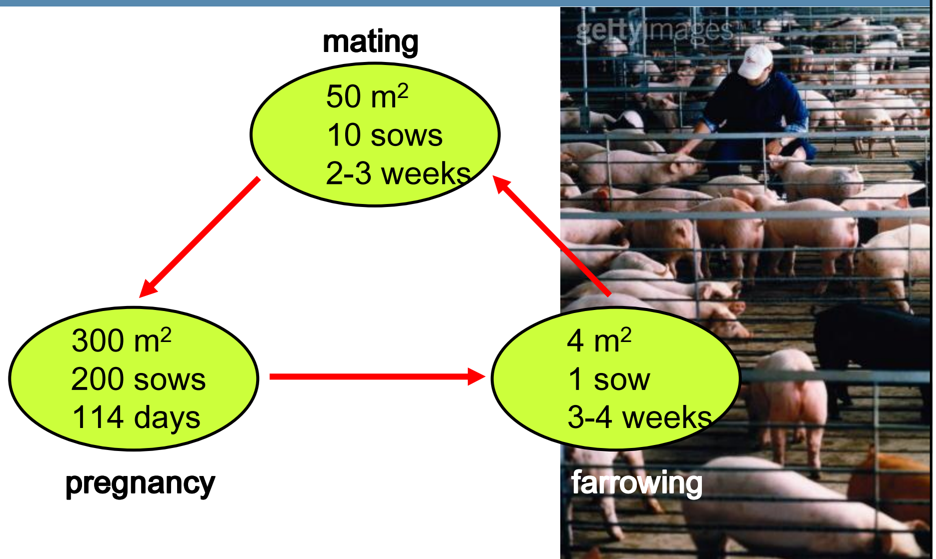
sensor network research at IMM/DTU

Wireless Sensor Networks



Motivation



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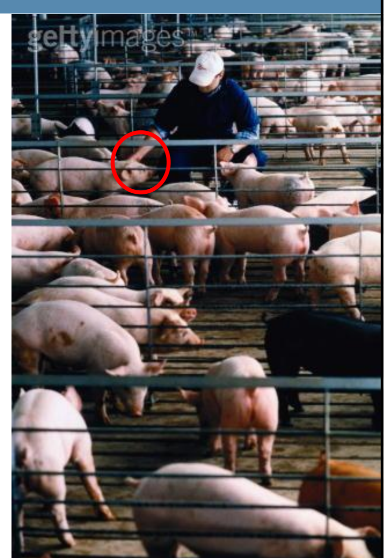
Motivation

Current status for the farmer

- Farmer reads information about sows through RFID ear-tags
- Has to be within 10 cm from the tag
- Important to move sows between pens at the right point in time
- ***Is there a better way?***



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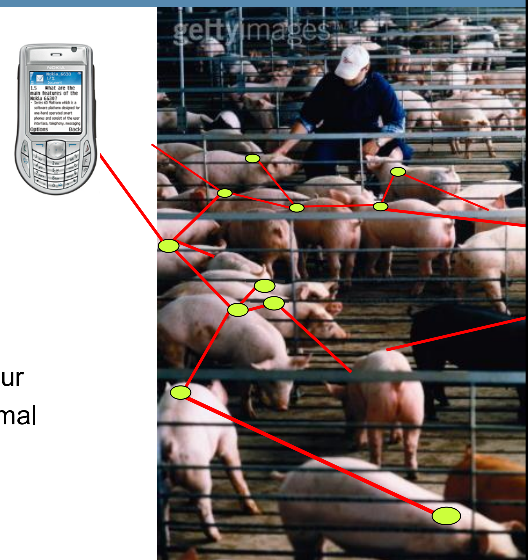
Motivation

- Let the sow phone the farmer when:
  - It needs to be moved
  - Has to give birth
  - Is ill
  - ...
- Sensor network
  - Sensor nodes
  - Ad-hoc network infrastructur
  - Detection of abnormal animal behavior
- ***The Hogthrob project***



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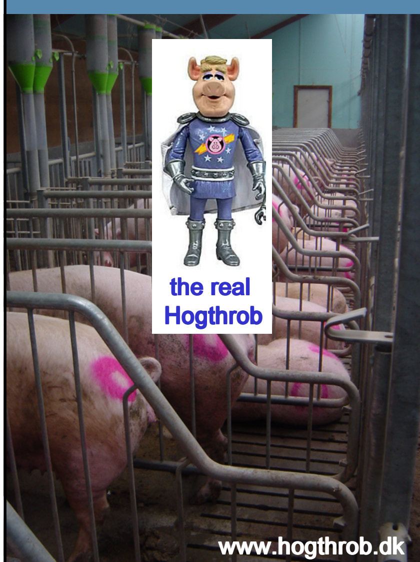
The *Hogthrob* project



- Developing a sensor network infrastructure for sow monitoring
  - Sensor nodes on a chip
  - Sensor network model
  - Monitoring application
- Functionalities
  - Tracking
  - Detecting *heat* period
  - …
- Low cost (~1 €)
- Low energy (2 years lifetime)
- Consortium:
  - DTU
  - DIKU
  - KVL
  - National Committee for Pig Production
  - IO Technologies

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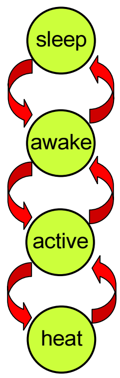
Sow monitoring

Initial application model



Some issues:

- State transitions managed by timer + sensing
  - Different duty cycles (processing / sending)
  - Refined model based on observations of pig behavior
- Trade-offs:
  - Sleeping vs. Sensing and Networking
  - In-channel wakeup vs. Additional, low power radio
  - Embedded detection model vs. Feed to a server-based detection model

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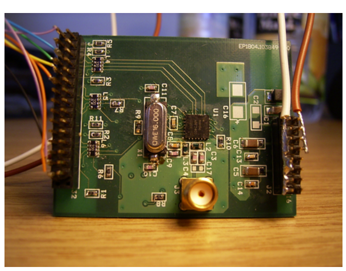
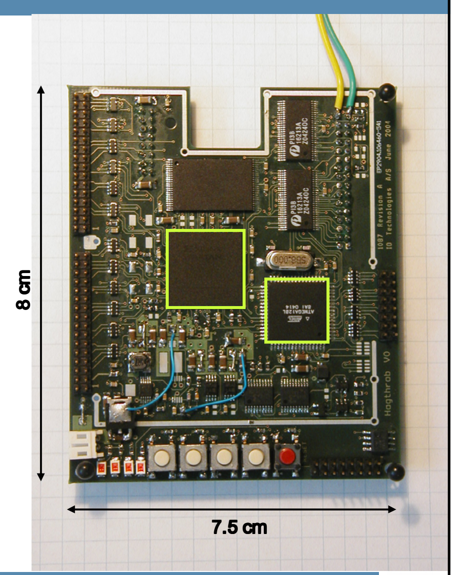
Sensor nodes (V0)





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First field experiments

- Sensor board with 2D and 3D accelerometer
- Tracking motions correlated with video

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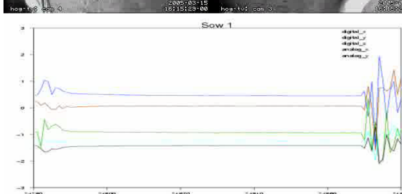
Results from first field experiments



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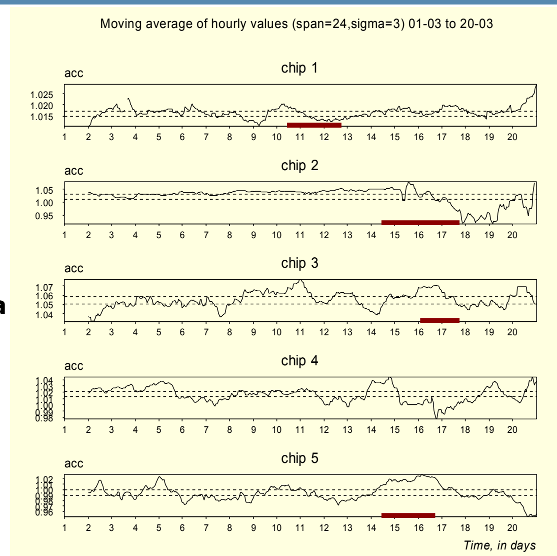
Results from first field experiments

Averages

- **Moving average and Control Chart**
- **EWMA to develop**

Example

- **24 H Moving Average**
- **Control Limit: 3 sigma**
- **under CL**
- **above CL**
- **Need more information**



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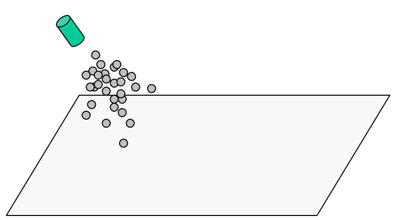
Deployment

- Stochastic modelling
- Random graphs



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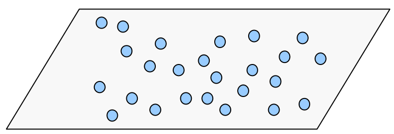
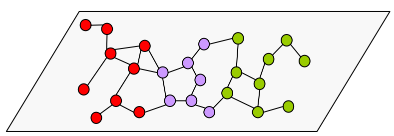
Localization



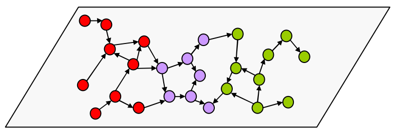
- What to localize?
- When to localize?
- How well to localize?
- How to localize?

Networking



- Graphs
- Protocols
  - Peer to peer
  - broadcast
- Routing

Wireless communication



- Bandwidth and latency
- Collisions and how to avoid them
- MAC

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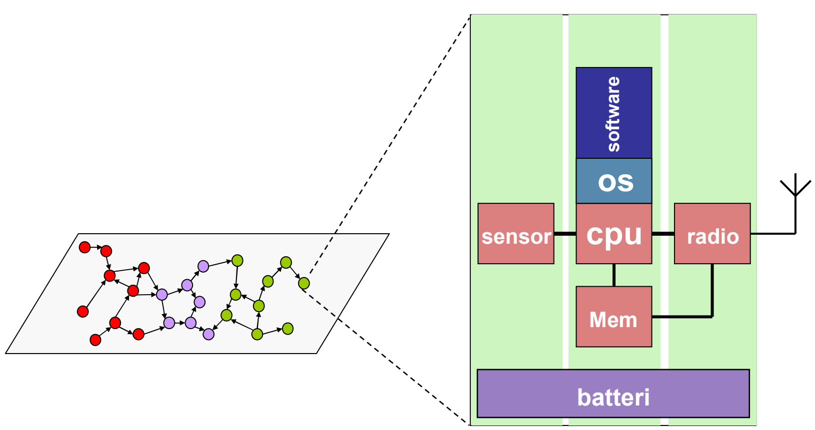
WSN Platform



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Agenda for today

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  - What? Why? and How?
- **WSN Deployment**
  - **Localization**
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  - MAC protocols
- WSN Platforms
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- WSN Design methods
- Summary and Future of WSN

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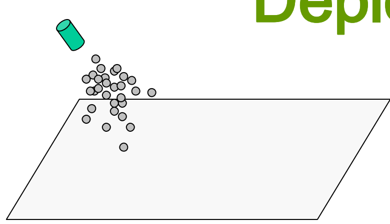
Deployment



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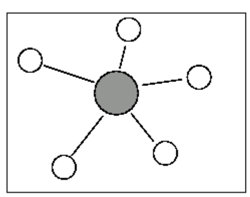
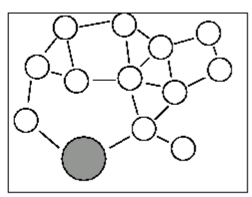
Deployment Issues

- Structured versus Randomized Deployment
- Overdeployed versus Incremental Deployment
- Connectivity and Coverage Metrics of Interest

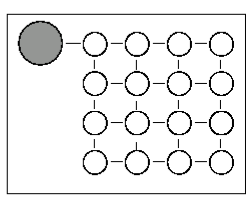
Network Topologies



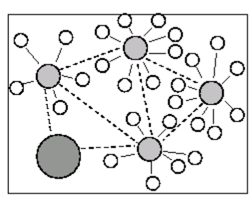
Single-hop star toplogy



Multi-hop mesh toplogy



Structured grid toplogy



Hierarchical cluster toplogy

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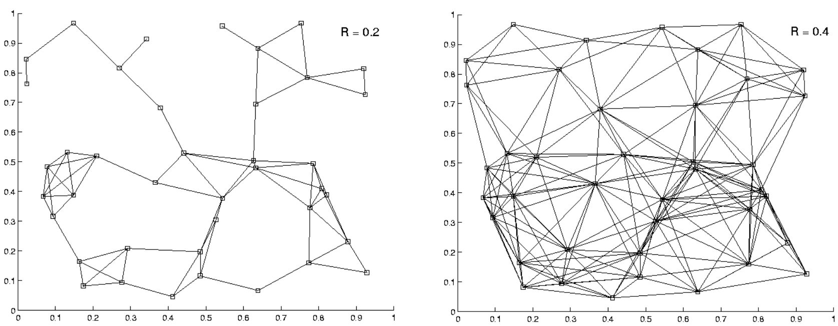
Random Graph Models

- For some applications, WSN nodes could be scattered randomly (e.g. from an airplane)
- Random Graph Theory is useful in analyzing such deployments
- The most common random graph model is
  - G(n,R): deploy n nodes randomly with a uniform distribution in a unit area, placing an edge between any two that are within Euclidean range R.

Geometric Random Graph G(n,R)



sparse dense

Courtesy of Bhaskar Krishnamachari, UCS

Some Key Results

- All monotone graph properties have an asymptotic critical range R beyond which they are guaranteed with high probability *(*Goel, Rai, and Krishnamachari *'04)*
- The critical range for connectivity is $O(\sqrt{(\frac{\log n}{n})})$ (Penrose '97, Gupta and Kumar '98)
- The critical range to ensure that all nodes have at least k neighbors also ensures k-connectivity w.h.p. (Penrose '99)

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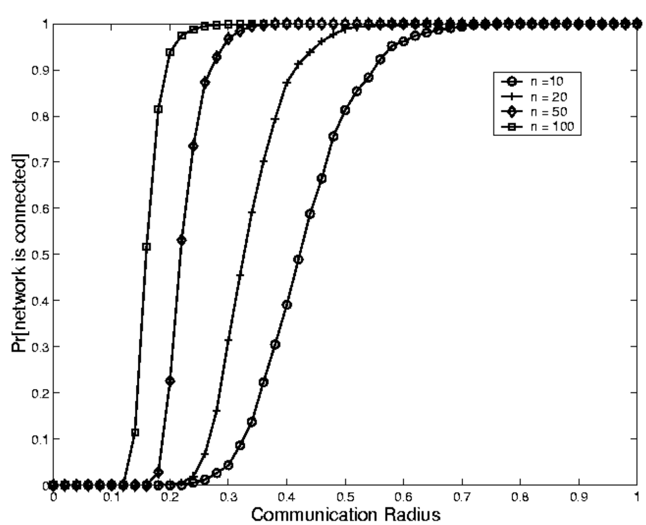
Connectivity in G(n,R)



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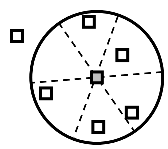
Transmit-Power Control

- Provides a degree of flexibility in configuring the network connectivity after deployment.
- Must carefully balance several factors, including connectivity, energy usage, and interference.



- The Cone-Based Topology Control (Li *et al.* ‘01) provides a distributed rule for global connectivity:
  - *increase power until there is a neighbor within range in every sector of angle $\alpha \leq 5\pi/6$*

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Coverage Metrics

- Much more application specific than connectivity.
- Some that have been studied in particular detail are:
  - Path observation metrics: An example of this is the maximal breach distance, defined as the closest any evasive target must get to a sensor in the field (Meguerdichian *et al.* ‘99)
  - K-Coverage: ensure that all parts of the field are within sensing range of K sensors (e.g. Wang *et al.* ‘03)

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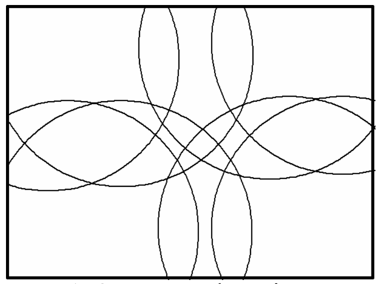
Key Results on K-Coverage

- A field is K-covered if and only if all intersection points between sensing circles are at or inside the boundary of K+1 sensing circles. (Wang *et al. '03*)



A 2-covered region

- If a region is K-covered by n sensors, they also form a K-connected graph if their communication range is at least twice the sensing range. (Wang *et al. '03*)

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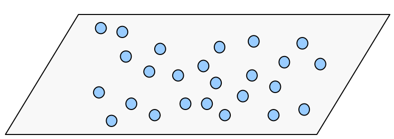
Localization



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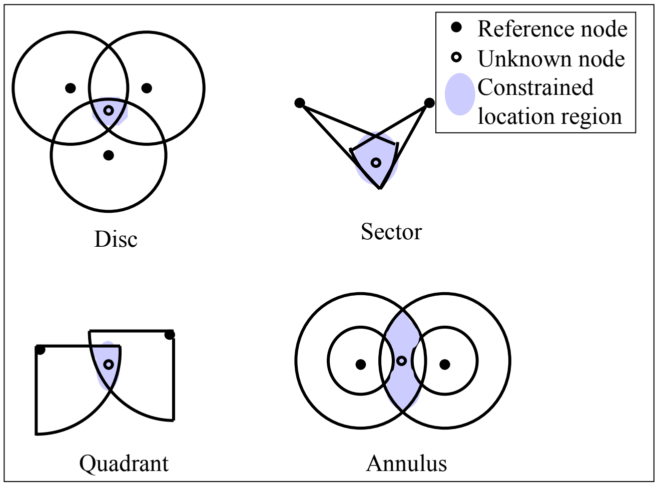
Localization Issues

- Location information necessary/useful for many functions
  - measurement stamps
  - coherent signal processing
  - cluster formation
  - efficient querying
  - routing
- Key Questions:
  - What to localize?
  - When to localize?
  - How well to localize?
  - How to localize?

Coarse Grained Node Localization

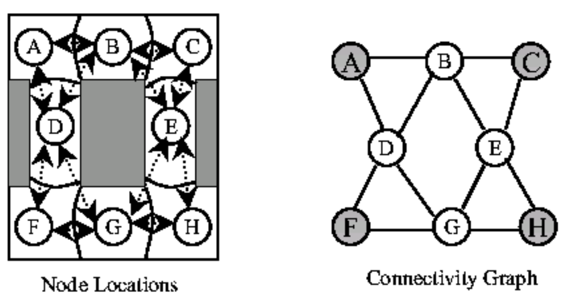
- Several techniques provide approximate solutions for node localization based on the use of *minimal* information:
  - Proximity
  - Centroids
  - Geometric Constraints
  - Approximation Point in Triangle
  - Identifying Codes

Geometric Constraints



(Doherty, Pister and Ghaoui '01)

ID-Codes



Transmitters A, F, C, H provide unique IDs for all node locations

V:	A	B	C	D	E	F	G	H
ID:	A	A,C	C	A,F	C,H	F	F,H	H

(Ray *et al.* '03)

Fine-Grained Node Localization

- Basic Approach: Ranging
  - ranging using radio signal strengths (m-level accuracy)
  - ranging using time difference of arrival (cm-level accuracy over short distances)
- Position estimation is then an MMSE problem:

  $E_j = R_{i,j} - \sqrt{((x_i-x_j)^2+(y_i-y_j)^2)}$

  Find (x_i,y_i) to minimize $\Sigma (E_j)^2$
- Angle of arrival techniques are particularly useful in conjunction with ranging

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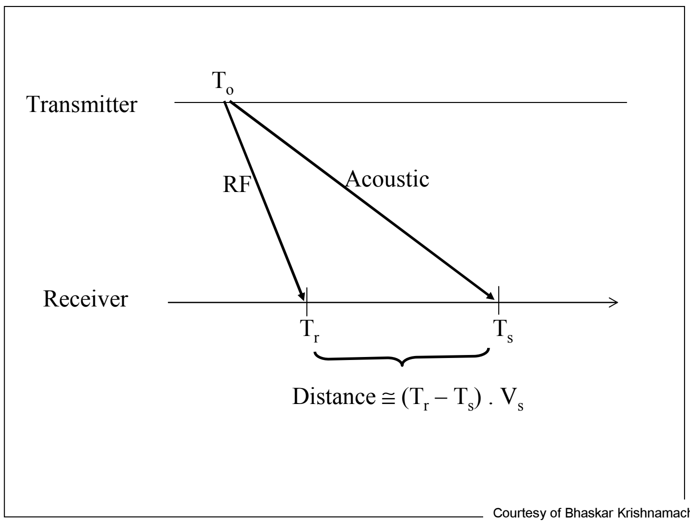
Time Difference of Arrival



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Fine-Grained Node Localization

- Pattern matching techniques such as RADAR (Bahl and Padmanabhan, '00) require pre-training of signal strengths at different locations in the environment.
- Ecolocation (Yedavalli *et al.* '04) is based on sequence decoding.
  - Record the received signal strengths at different reference nodes from a given unknown node, and order these into a sequence
  - Return as the unknown node's location the location that "best matches" the measured sequence

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Network Localization

- Different from node localization. Few reference nodes and several networked unknown nodes.
- Several approaches:
  - Constraint satisfaction/optimization (centralized)
  - Joint estimation using ranging estimates (centralized)
  - Multi-hop distance estimation (distributed)
  - Iterative localization (distributed)
  - Potential fields (distributed)

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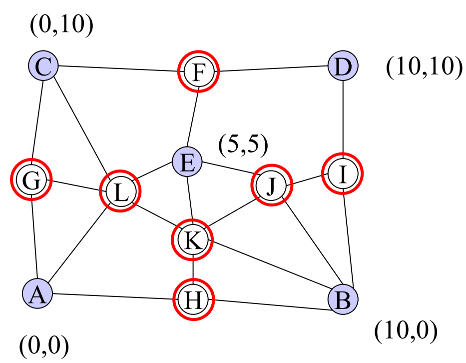
Iterative Localization



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Localization protocol

- Idea:
  - Wait for position/distance from 3 different neighbours
  - Calculate own position
  - Tell all neighbours about position
- Assume
  - Sensors have unique identifier (number)
  - Sensors are fixed, i.e. not mobile
  - All sensors are deployed at start
  - All sensors are working and have unlimited power supply

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Exercise

- Device a protocol for localization of all nodes in a network
- Use the following
- Messages:
  - `HELLO()` sender wants to know position of neighbours
  - `HI(pos)` senders position
- Node data:
  - `Neighbours` tabel of neighbours
    - `(no, pos,distance)` for each neighbour
  - `MyPos` own position (`?` If unknown)

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Solution

```
send HELLO() to all
repeat
  receive b from nb with distance d
    if b=HELLO()
      send HI(MyPos) to nb
    if b=HI(pos)
      add (nb, pos, d) to Neighbours
      if MyPos=? And MyPos can be calculated
                 from Neighbours
        MyPos = position(Neighbours)
        send HI(MyPos) to all
```

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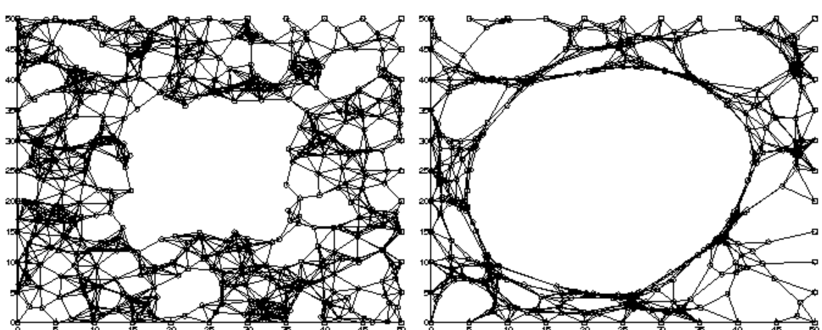
Reference-less Localization

- What if there are no reference nodes with known locations?
- Three-step solution (Rao '03):
  - 1. If all boundary nodes have known locations, use iterative centroid calculations
  - 2. If boundary nodes do not have known locations, use pairwise hop-counts to get approximate locations and apply step 1.
  - 3. If nodes are not aware of boundary, use a flood to identify boundary nodes and apply step 2.
- The solution provides only a relative map, useful for geographic routing

Illustration of Reference-less Localization



Correct locations

Localization assuming only known boundary nodes

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Agenda for today

- Wireless Sensor Networks (WSN)
  - What? Why? and How?
- WSN Deployment
  - Localization
- **WSN Networking**
  - **Routing protocols**
  - MAC protocols
- WSN Platforms
  - Hardware and software components
- WSN Design methods
- Summary and Future of WSN

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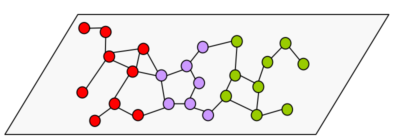
Network routing



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Routing Considerations in Sensor Networks

- Traditional TCP/IP routing not attractive for sensor networks
  - Too much overhead and large routing tables
- Sensor networks are more ad-hoc
  - Each node acts as a router
  - Still different than ad-hoc networks
    - Proactive routing is too expensive
    - Some possibility for reactive routing such as
      - Fish-eye routing, AODV, DSR

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Routing Goal

- Focus on localized state-less routing
  - Consider only local neighborhood
- Classical separation of address and content does not hold
  - Care about reaching the nodes rather than a particular address – what can be sensed by a node can most probably be sensed by neighboring nodes
  - Interested in routing by attributes – ***data centric***
    - Node's location
    - Node's type of sensors
    - Range of values in the sensed data
- Notion of optimality can vary
  - QoS routing – latency is important => shortest path
  - Energy aware routing – longer paths are ok => avoid nodes with less energy

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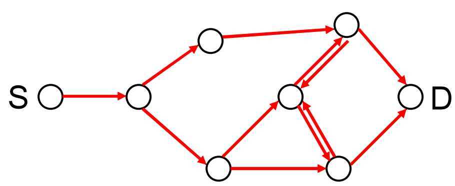
Flooding

- Simple routing protocol
- Assumes connection to neighbors known
- Packets are launched from sender through the whole network
- A node will not send the same message twice



- Very robust
  - but not very efficient in terms of cost

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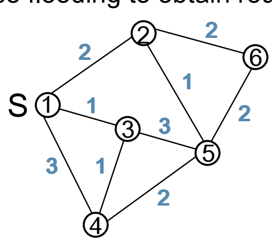
Adaptive routing

- Table based
  - Keep a table of possible paths (e.g. shortes)
  - Multiple paths in order to increase robustness
- Link-state protocols
  - Use flooding to obtain routes



step	N	D(2)	D(3)	D(4)	D(5)	D(6)
0	1	2	1	3	∞	∞
1	1,3	2	[1]	2	4	∞
2	1,2,3	[2]	1	2	3	4
3	1,2,3, 4	2	1	[2]	3	4
4	1,2,3, 4,5	2	1	2	[3]	4
5	1,2,3, 4,5,6	2	1	2	3	[4]

$D(v) = min[D(v), D(w)+c(w,v)]$

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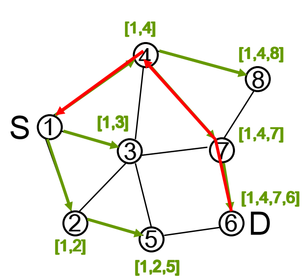
When is the path computed?

- Static
- or Demand Driven
  - Destination sends reply to each query it receives
  - Source selects one of more return paths
- Approaches
  - Dynamic Source Routing (DSR)
  - Ad-hoc On-Demand Vector routing (AODV)

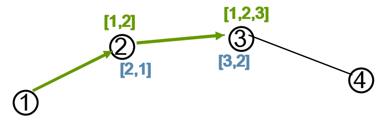
Dynamic Source Routing (DSR)



- RREQ: Route Request
- RREP: Route Reply
- Problem: header may be large!
- Possible optimizations:
  - A node may know about a route
  - If 4 knows about the route to 6, it may immediately tell 1 when receiving RREQ.

Ad-hoc On-Demand Vector routing (AODV)

- Aim:
  - Eliminate routing header
  - Done by requiring nodes to maintain routing tables
- Has to be update if nodes change!



Geographic Routing

- Aims to route based on very limited state information
- Geographic routing protocols assume
  - All nodes know their geographic location
  - Each node knows its 1-hop neighbors
  - Destination is a node with a given location
  - Each packet can hold a limited amount of information as to where it has been in the network
- Any issues with this?
  - Needs to maintain information between node IDs and node location (referred to as location service)

Geographic Forwarding Approaches

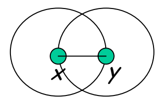
- Greedy distance routing: select the neighbor geographically closest to the destination and forward the data to that neighbor
- Compass routing: pick the next node as the one that minimizes the angle to destination
- What are the problems with the basic approaches
  - Greedy distance routing – may get stuck in local minima
  - Compass routing – may go in loops

Planarization of Routing Graph

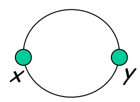
- To get protocols that guarantee data delivery, make graph *planar*
- Remove some edges from your network graph G
  - Aim: Keep the same connectivity but make the graph planar
    - no two edges in G should intersect each other
  - In the planar subdivision of G each node is assumed to know the circular order of its neighbors
  - Convex perimeter routing and other face routing protocols use this property

Common Planarization Methods

- Relative Neighborhood Graph (RNG)
  - The edge xy is introduced if the intersection of circles centered at x and y with radius the distance d(x,y) is free of other nodes



- Gabriel Graph
  - The edge xy is introduced if the diameter xy is free of other nodes



- Both graphs RNG and Gabriel graphs can be found with distributed construction

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Greedy Perimeter Stateless Routing(GPSR)

- Geographic protocol based on the offline construction of planar graphs
  - RDG, Gabriel
  - Has 2 main phases *forwarding* and *recovery*
- *Forwarding* is greedy
- *Recovery* – uses a right-hand rule to recover from holes. It stops as soon as a node closer to the destination is found

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Directed diffusion

Network Communication

- Flooding
  - Redundant data transmission
- Multi-hop routing
  - Large routing tables
  - Frequent updates
  - Complexity

Directed diffusion concepts

- Application-aware communication primitives
  - expressed in terms of named data *(not in terms of the nodes generating or requesting data)*
- Consumer of data initiates interest in data with certain attributes

```
Interest                          Reply

type = four-legged animal         type = four-legged animal
interval = 20 ms                  instance = [125, 220]
duration = 10 sec                 intensity = 0.6
rect = [-100, 100, 200, 400]      confidence = 0.85
                                  timestamp = 01:20:40
```

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Directed diffusion concepts

- Nodes diffuse the interest towards producers via a sequence of local interactions thereby setting up gradients.
- Reinforcement and negative reinforcement used to converge to efficient distribution
- Intermediate nodes opportunistically fuse interests, aggregate, correlate or cache data.
- Dirrected Diffusion illustration

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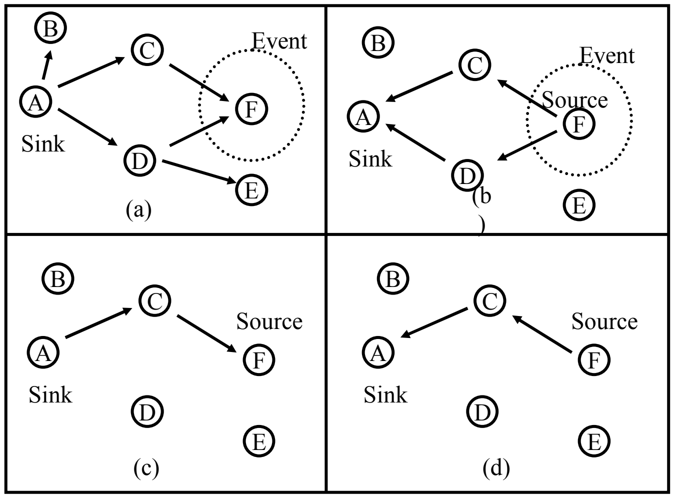
Directed Diffusion illustration



(Intanagonwiwat, Govindan, Estrin '00)

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Local Behavior Choices

1. For propagating interests
   - Flooding
   - More sophisticated behaviors possible: e.g. based on cached information, GPS
2. For setting up gradients
   - Highest gradient towards neighbor from whom we first heard interest
   - Others possible: towards neighbor with highest energy

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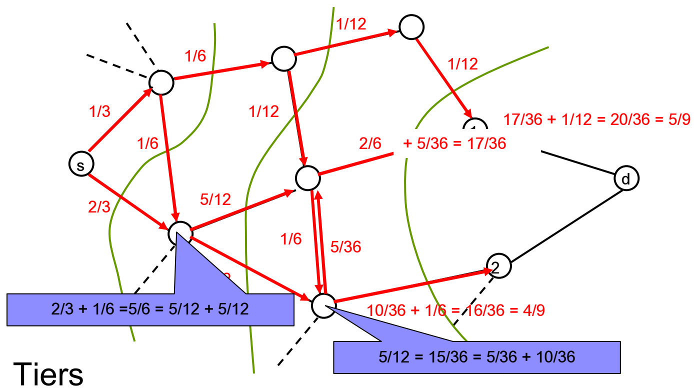
Local Behavior Choices

3. For data transmission
   - Different local rules can result in single path delivery, striped multi-path delivery, single source to multiple sinks and so on.
4. For reinforcement
   - reinforce one path, or part thereof, based on observed losses, delay variances etc.
   - other variants: inhibit certain paths because resource levels are low

Directed Diffusion

- Paths formed probabilistically using a combination of activation and inhibition signals
- Inspired by ants (swarm intelligence)
- Ex. Minimizing energy over the path:
  - Activation: desire to send the message, for which a certain amount of energy is allotted
  - Inhibition: energy cost of traversing the remaining set of links to the destination

Directed Diffusion example



- Tiers
  - Probability to move inside tire is 50% of probability to move between tiers
  - Never move backwards

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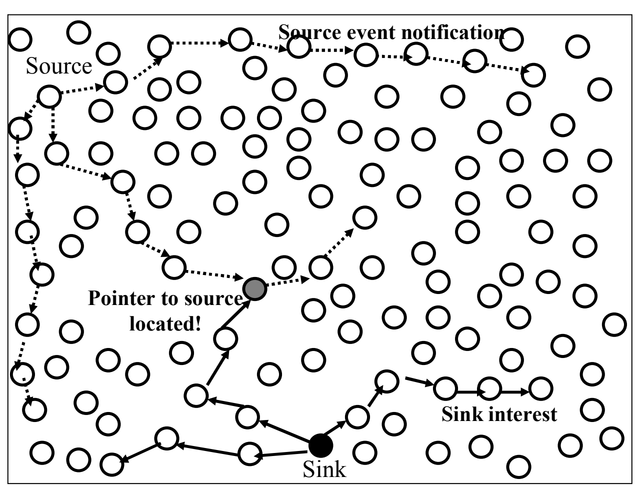
Rumor Routing



(Braginsky and Estrin '02)

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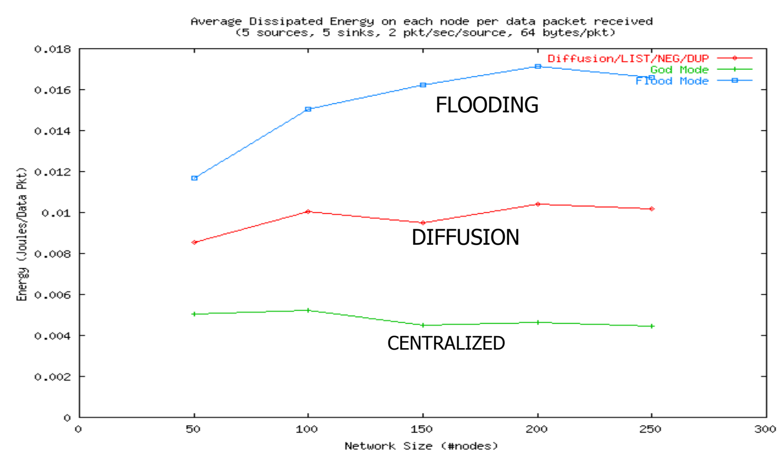
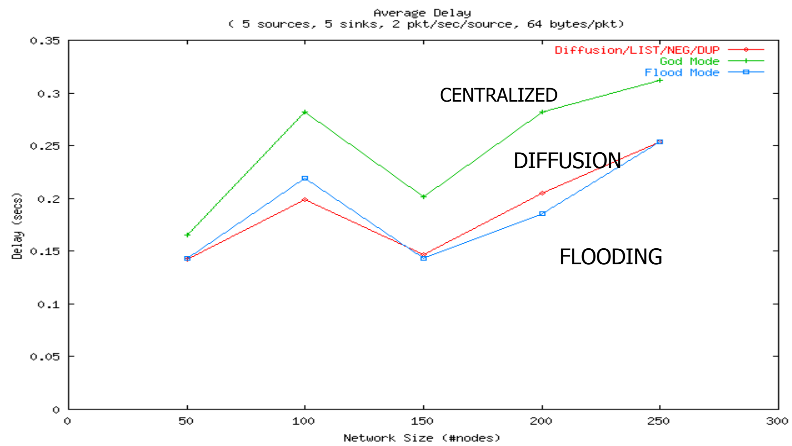
Initial simulation studies
(Intanago, Estrin, Govindan)

- Compare diffusion to
  - a) flooding,
  - b) centrally computed tree (“ideal”)
- Key metrics:
  - total energy consumed per packet delivered (indication of network life time)
  - average packet delay

Simulation results



Simulation results



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Directed diffusion

- Description of networking paradigm
  - Interests, gradients, reinforcement
  - Benefits of in-network processing
  - Aggregation and nested-queries
- Efficient and stable
  - Handles dynamic network well
  - Not substantially more dissipation than static
- Disadvantages
  - Design doesn’t deal with congestion or loss

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Agenda for today

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  - **MAC protocols**
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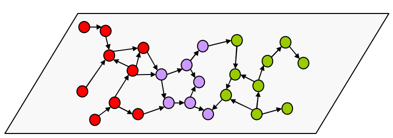
MAC protocols



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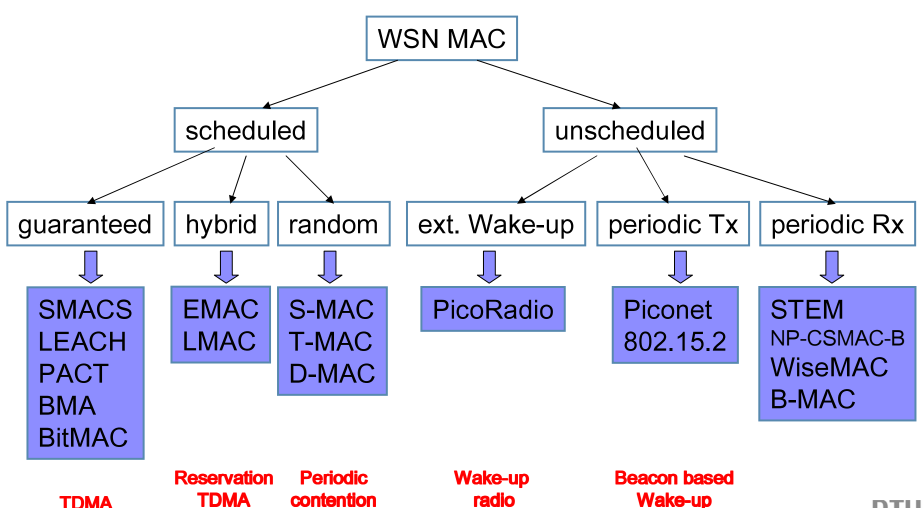
Medium Access Control

- A MAC protocol decides when competing nodes may access the shared channel
- Tries to ensure interference-free transmission
- Two main classes of protocols:
  - Contention-based
  - Schedule-based

MAC protocol classification



Contention-Based Medium Access

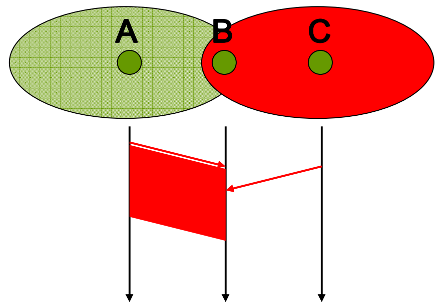
- ALOHA protocol
  - Transmit package as soon as it is generated
  - If no other node is sending
    - Data transmission succeeds
    - Receiver responds with an acknowledgement
  - If collision
    - Then no acknowledgement is received
    - Sender retries after random period
  - Very simple protocol
  - Basic version: Max. channel utilization 18%!
  - Slotted version can reach 35%

Carrier Sense Multiple Access

- CSMA
  - Before transmitting a package
  - Sender listens to the channel for a short period of time
  - If no traffic is sensed
    - Then channel is clear
    - Start transmitting package
  - Problem?
    - Mode switching latency (receive mode to transmit mode)
    - i.e. collisions can occure
  - Max. channel utilization: 50 – 80%

Carrier Sense Multiple Access

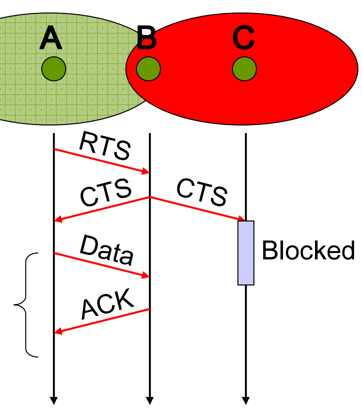
- CSMA
  - Sequence diagram



The hidden terminal problem

Carrier Sense Multiple Access

- CSMA/CA



Carrier Sense Multiple Access

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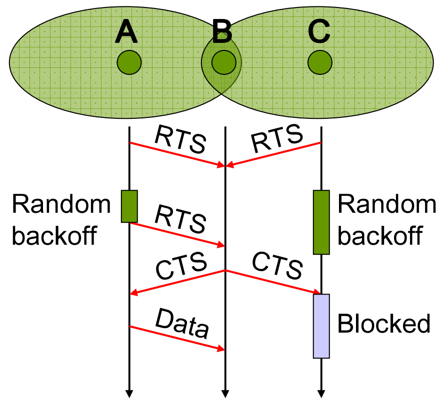

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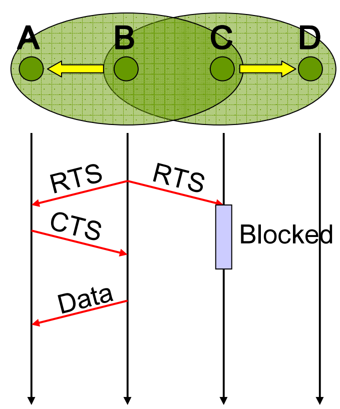
Carrier Sense Multiple Access

- CSMA



The exposed terminal

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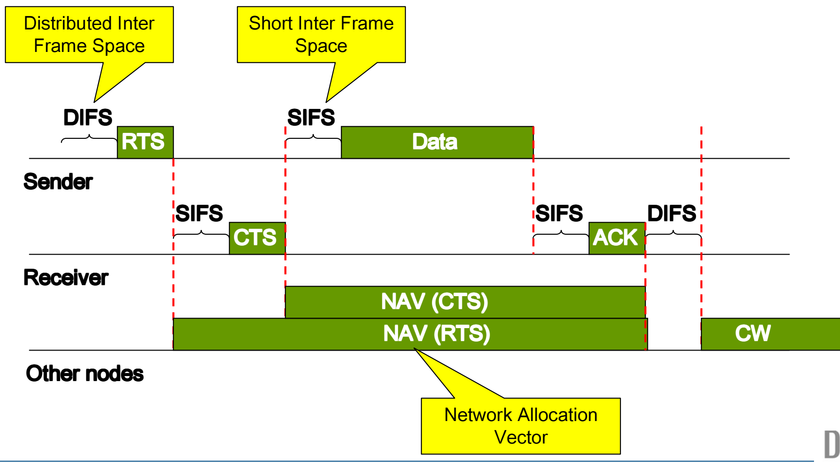
IEEE 802.11 (WLAN)

- CSMA/CA and ACK



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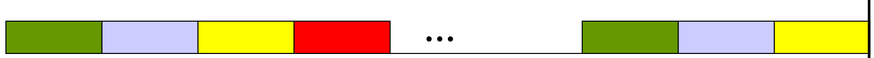
Schedule-Based Meduim Access

- TDMA
  - Collision free
  - No idle listening



- Challenge
  - To adapt TDMA to operate efficiently in ad hoc sensor networks

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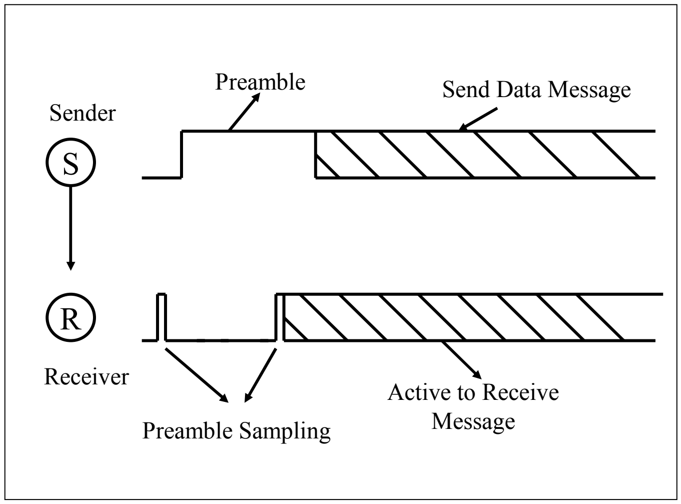
Energy efficiency

- Ad-hoc network with little traffic
- Energy wasted due to:
  - Idle listening
  - Collisions
  - Overhearing
  - Protocol overhead
  - Traffic fluctuations

Energy-Efficient Contention-based MAC

- Low Power Listening / Preamble Sampling: wake up the radio only when needed to transmit, and periodically to check for preamble from transmitter. No synchronization necessary.
- S-MAC/D-MAC: periodic sleep-wake duty cycle, adapted for higher traffic, adjusted to minimize delay.
- Asynchronous: use a periodic schedule but not synchronized across nodes. Useful for highly dynamic scenarios.

Preamble Sampling



(El Hoiydi '02; Hill and Culler '02)

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S-MAC Objectives

- Main objectives
  - Reducing energy consumption
- Main sources of energy waste
  - Collision
  - Overhearing
  - Control packet overheard
  - Idle listening
- S-Mac should also provide good scalability and collision avoidance

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S-MAC Design – Periodic Sleep Cycle

- Nodes' radios are turned down during sleep periods
  - Duty cycle reduced
  - Neighbouring nodes are synchronized together

On	Off	On	Off	…….
On	Off	On	Off	…….
On	Off	On	Off	…….

(Ye, Heidemann and Estrin '02)

- Each node has its own schedule table
- Synchronization is maintained by use of SYNC packets

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S-MAC Design – Collision and Overhearing

- Collision avoidance based on 802.11 technique
  - Physical and virtual carrier sense
  - Exchange of RTS/CTS messages
- Overhearing avoidance
  - Nodes listen to ACK packet
  - Interfering nodes are put in sleep mode

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S-MAC Design – Message passing

- High cost transmission errors in a long message
  - Message re-transmitted if only a few bits corrupted
- S-MAC approach:
  - Message fragmented into small parts
  - Fragments transmitted in a burst
  - Uses CTS /RTS only once for whole message
  - ACK packets are transmitted after each fragments
    - Nodes that wake up in a middle of a transmission can return to sleep mode
    - Fragments lost can be retransmitted

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Agenda for today

- Wireless Sensor Networks (WSN)
  - What? Why? and How?
- WSN Deployment
  - Localization
- WSN Networking
  - Routing protocols
  - MAC protocols
- **WSN Platforms**
  - **Hardware and software components**
- WSN Design methods
- Summary and Future of WSN

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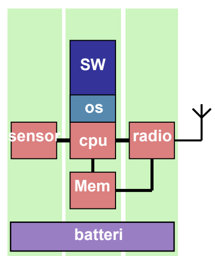
Platform

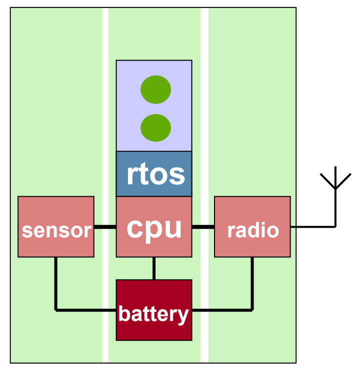


Wide Spectrum of Devices

- Sensors with inplantable RFIDs
- Smart-dust size nodes
  - Typically they act as data-collectors or “trip-wires”
  - Cannot afford to have massive processing and communication
- Mote-size devices
- More powerful gateway nodes etc
- For some applications, form factor is also dictated by the size of individual sensors
- Many designs out there, each design has its own philisophy

Sensor node

- Ultra low energy
- Low flexibility
- Ultra low cost (1$)
- Small size (1..10 Mtr)
- Low clock frequency
- DSP and RF dominated
- Limited memory
- Hardware/software codesign



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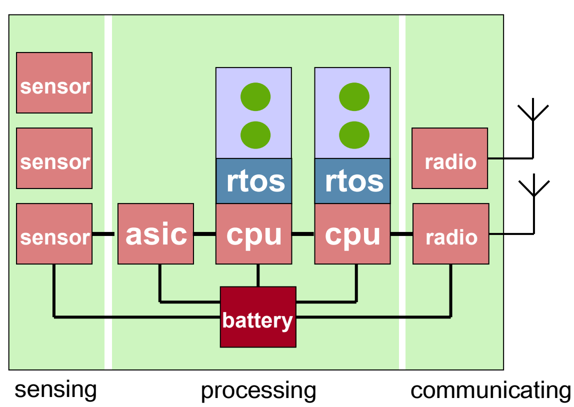
Sensor node design



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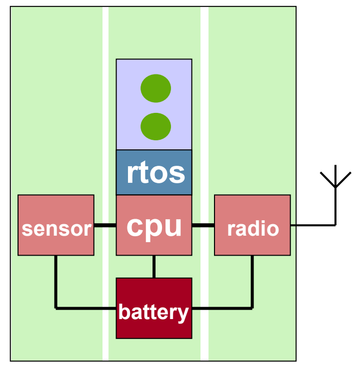
Challenges

- Energy Efficiency
- Responsiveness
- Robustness
- Self-Configuration and Adaptation
- Scalability
- Heterogeneity
- Systematic Design
- Privacy and Security

Components of a WSN platform

Sensor node

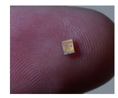


Requirements

- Cost
- Lifetime (when almost always on, when almost always off)
- Performance:
  - Speed (in ops/sec, in ops/joule)
  - Comms range (in m, in joules/bit/m)
  - Memory (size, latency)
- Capable of concurrent operation
- Flexibility (?)
- Reliability, security, size, packaging

Sensor-actuator hardware platforms

1. RFID equipped sensors
2. Smart-dust tags
   - typically act as data-collectors or "trip-wires"
   - limited processing and communications
3. Mote/Stargate-scale nodes
   - more flexible processing and communications
4. More powerful gateway nodes, potentially using wall power



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A closer look

Node Type	Sample "Name" and Size	Typical Application Sensors	Radio Bandwidth (Kbps)	MIPS Flash RAM	Typical Active Energy (mW)	Typical Sleep Energy (uW)	Typical Duty Cycle (%)
Specialized sensing platform	Spec mm^3	Specialized low-bandwidth sensor or advanced RF tag	<50Kbps	<5 <0.1Mb <4Kb	1.8V*10–15mA	1.8V *1uA	0.1–0.5%
Generic sensing platform	Mote 1-10cm^3	General-purpose sensing and communications relay	<100Kbps	<10 <0.5Mb <10Kb	3V*10–15mA	3V *10uA	1–2%
High-bandwidth sensing	Imote 1-10cm^3	High-bandwidth sensing (video, acoustic, and vibration)	~500Kbps	<50 <10Mb <128Kb	3V*60mA	3V *100uA	5–10%
Gateway	Stargate >10cm^3	High-bandwidth sensing and communications aggregation Gateway node	>500Kbs–10 Mbps	<100 <32Mb <512Kb	3V*200mA	3V *10mA	>50%

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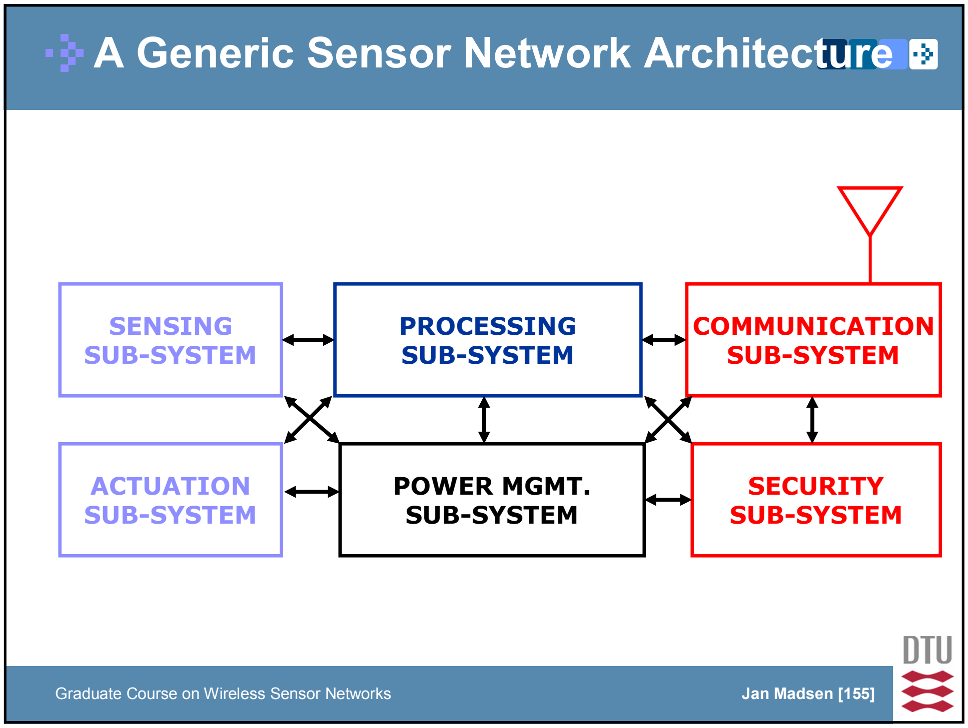
A Generic Sensor Network Architecture
SENSING SUB-SYSTEM
PROCESSING SUB-SYSTEM
COMMUNICATION SUB-SYSTEM
ACTUATION SUB-SYSTEM
POWER MGMT. SUB-SYSTEM
SECURITY SUB-SYSTEM
DTU
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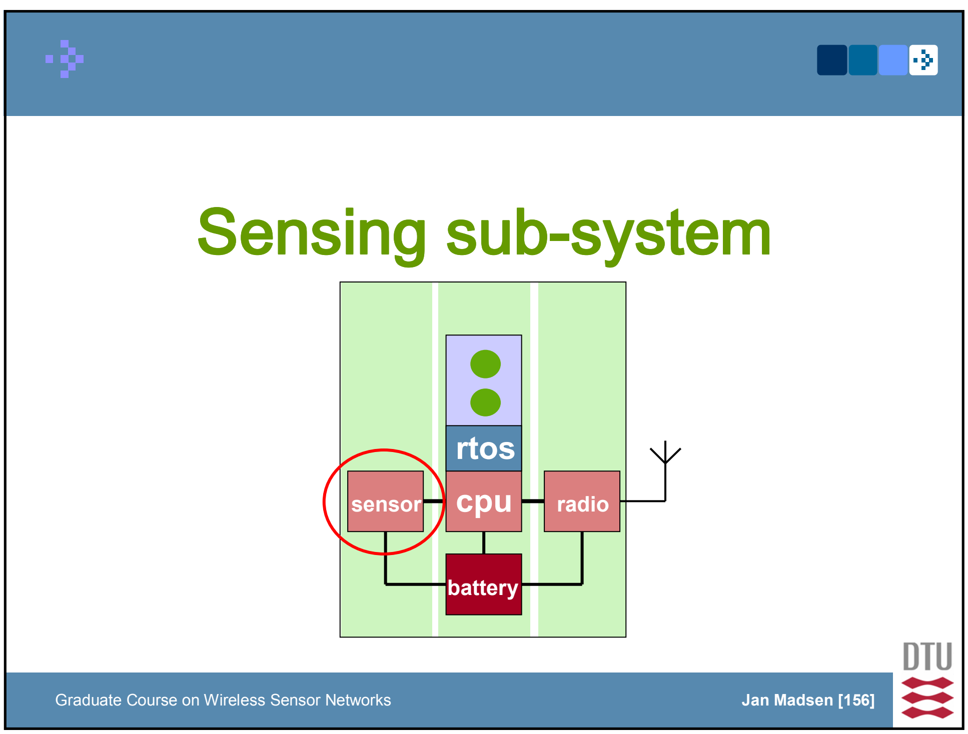
Sensing sub-system
rtos
sensor
cpu
radio
battery
DTU
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Sensor subsystem

- Multiple types of sensors may be used:
  - Environmental: pressure, gas composition, humidity, light...
  - Motion or force: **accelerometers**, rotation, microphone, piezoresistive strain, position...
  - Electromagnetic: magnetometers, antenna, cameras...
  - Chemical/biochemical: **Biochips**
- Digital or analog output
- MEMS enabling size, cost and power miniaturization; nano coming
- Components:
  - Transducer
  - Analog signal conditioning circuits
  - Analog to digital conversion
  - Digital signal processing

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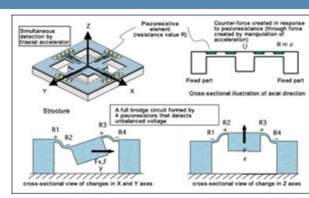
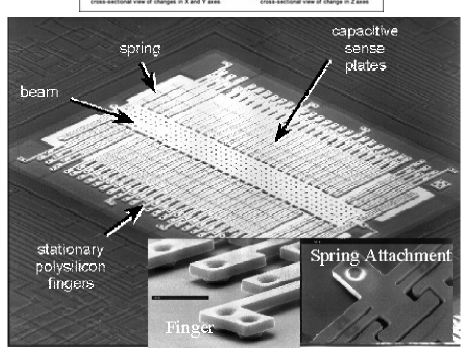
Sensor subsystem

- MEMS 3d accelerometer
  - Ability to simultaneously detect acceleration in three axial directions (X, Y and Z) with a single chip (acceleration rate 3G)
- **Applications**
  - Motion sensors (electronic pets, robots and game controllers)
  - Image control in game machines and other devices with portable terminals with inclining image functions
  - Navigation for portable terminals
  - Inclination, vibration and seismic monitoring





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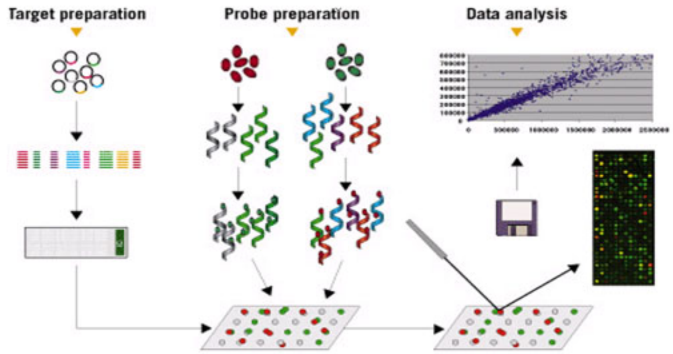
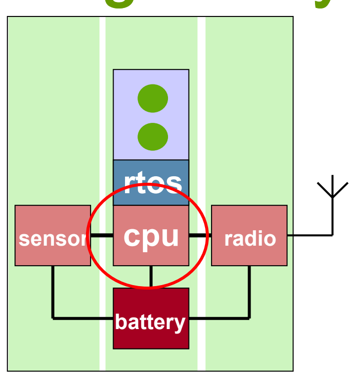
Sensor subsystem

- Biochips



Processing sub-system

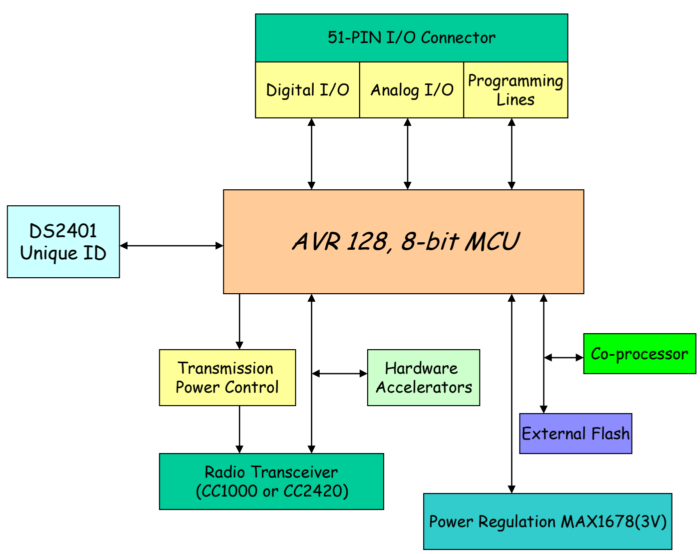


Processing subsystem

- Many flavors of MCU
- From embedded x86 processors 16 and 32-bit processors all the way down to tiny 4-bit processors
- Some of the popular 8-bit families
  - AVR, 8051, Z80, 6502, PIC, Motorola HC11
- 16-bit families
  - Hitachi, Dragon
- Many embedded Java controllers are also emerging

Base Case: The Mica Mote

(The most popular sensing platform today)



Processing Subsystem: Memory

Considerations: Speed, capacity, price, power consumption, memory protection

- SRAM: typical 0.5KB-64MB
  - Typical power consumption
    - retained: ~100ua; read/write: ~10ma if separate chip
    - retained: 2ua-100ua, read/write:~5ma if in core
- DRAM: high power consumption in retained mode
- EEPROM:4KB-512KB, often used as program store
- Flash: 256KB-1GB or beyond
  - Typical power consumption
    - retained: negligible; read/write: ~7/20ma
    - erase operation is expensive
  - Large flashes are outside of core

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Processing Subsystem

Clocks
Hardware Timers
Dividers

Peripheral interfaces
(for sensors, actuators, I/O, power)
(analog and digital)
(multiple busses with bridges between them)

- SPI: Serial Peripheral Interface
- I2C
- UART: Serial communication
- USB
- PCI

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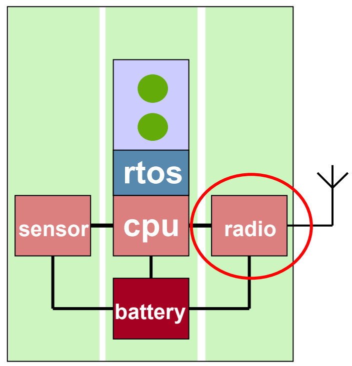
Communication sub-system

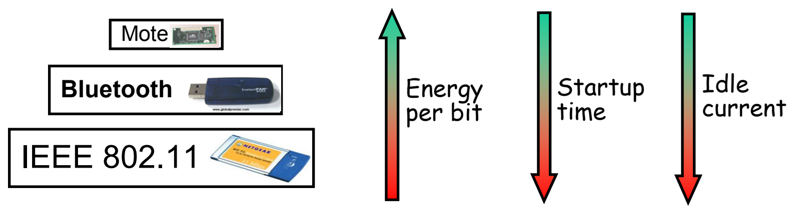


Communication Subsystem

Considerations:

- speed, range, power consumption, startup time
- energy efficiency: joules/bit/m
- signal propagation and interference characteristics
- difference between receive power versus transmit power
- not all devices need a receiver
- choice of power level
- antenna design
  - matching impedance

Communication Subsystem



Technology	Data Rate	Tx Current	Energy per bit	Idle Current	Startup time
Mote	76.8 Kbps	10 mA	430 nJ/bit	7 mA	Low
Bluetooth	1 Mbps	45 mA	149 nJ/bit	22 mA	Medium
802.11	11 Mbps	300 mA	90 nJ/bit	160 mA	High

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Empirical Observations

- Early studies all assumed a simple perfect-connectivity-within-range model for simulations and analysis.
- A number of empirical studies suggest this can be very misleading (Ganesan ‘02; Zhao and Govindan ‘03; Woo, Tong and Culler ‘03).
- A better characterization is that links fall into three regions: connected, transitional and unconnected. The transitional region will contain a large number of unreliable links.

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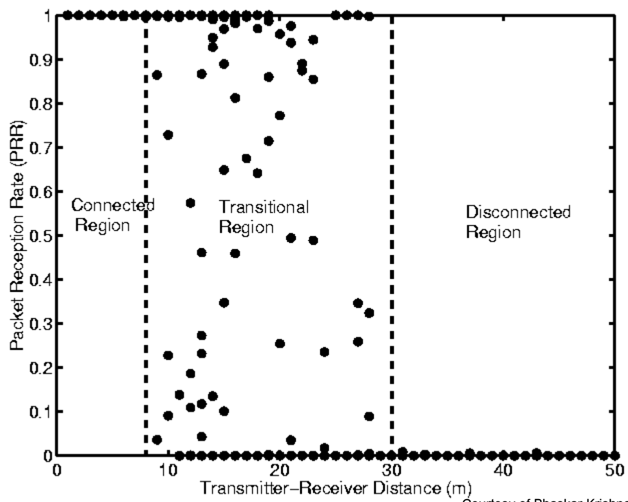
Link Regions



Courtesy of Bhaskar Krishnamachari, UCS

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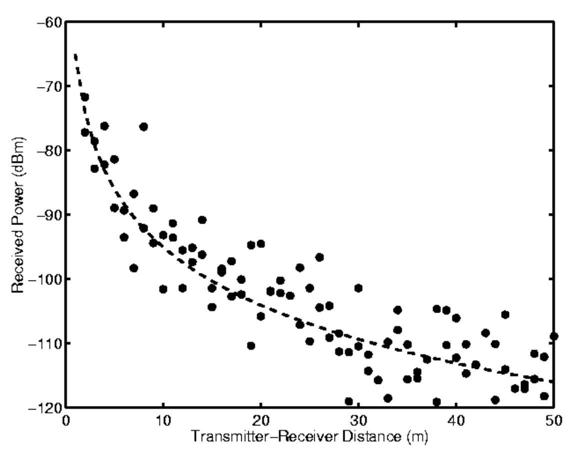
Received Signal Strength



Courtesy of Bhaskar Krishnamachari, UCS

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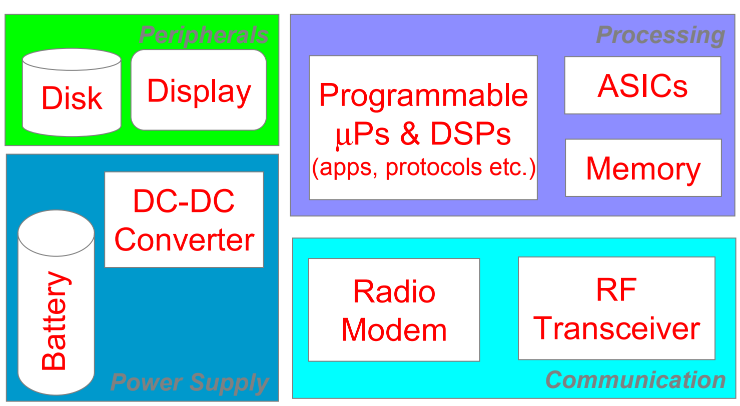
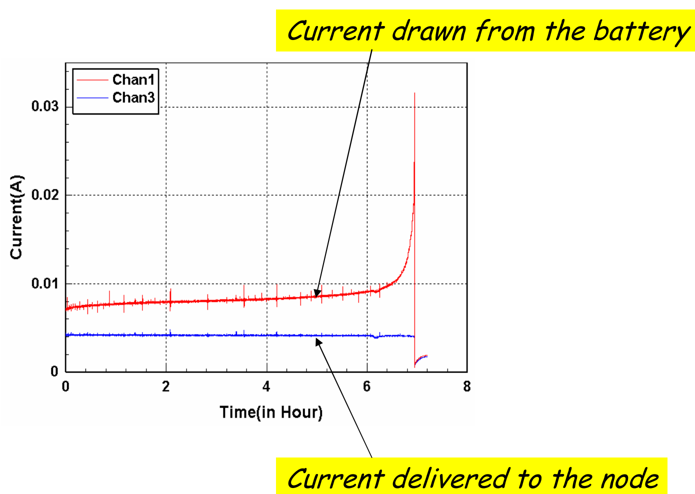
Where does the power go?

Where does the Power Go?



DC-DC Converter Inefficiency



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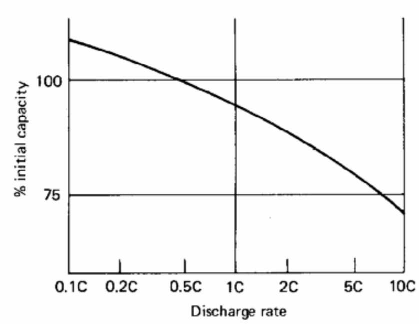
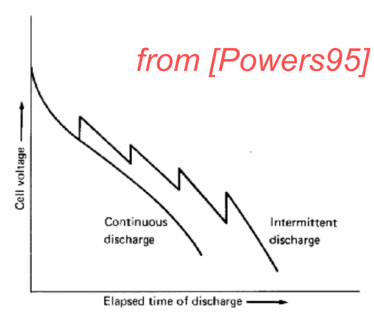
Battery Capacity



from [Powers95]



- Current in “C” rating: load current normalized to battery’s capacity
  - e.g. a discharge current of 1C for a capacity of 500 mA-hrs is 500 mA

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Microprocessor Power Consumption

CMOS Circuits
(Used in most microprocessors)

Static Component
Bias and leakage currents
O(1mW)

Dynamic Component
Digital circuit switching inside the processor

$$P = \underbrace{I_{standby}V_{dd} + I_{leakage}V_{dd} + I_{sc}V_{dd}}_{\text{Static}} + \underbrace{\alpha C_l V_{dd}^{2} f_{clk}}_{\text{Dynamic}}$$

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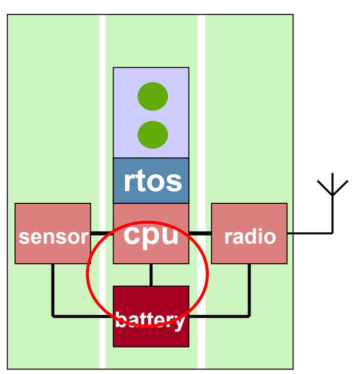
Power management sub-system



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Power Management Subsystem

- Voltage regulator
  - typical ranges: 1.8V, 3.3V, 5V
  - multiple voltages for various subsystem/power levels
- Gauges for voltage or current
  - battery monitor (allows software to adapt computation)
- Control of subsystems wakeup/sleep
  - latency is key in driving down the duty cycle
- Control of platform clock rate, processor voltage

Why energy harvesting?

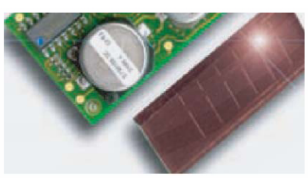
- Cannot use wires
  - "wireless device
  - "practical" issues (interference, robustness, simplicity)
  - economical issues
- Cannot use batteries
  - environmental issues
  - economical issues (disposable)
  - size/weight issues
  - no access to change/recharge

Energy sources

- Light
- Vibration
- Liquid or gas flow
- Chemical reactions
- Temperature
- EM fields
- From transceiver
- …..

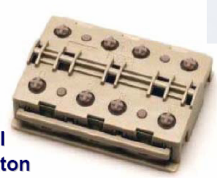
Commercially available energy harvesting

- Harvesting devices from EnOcean



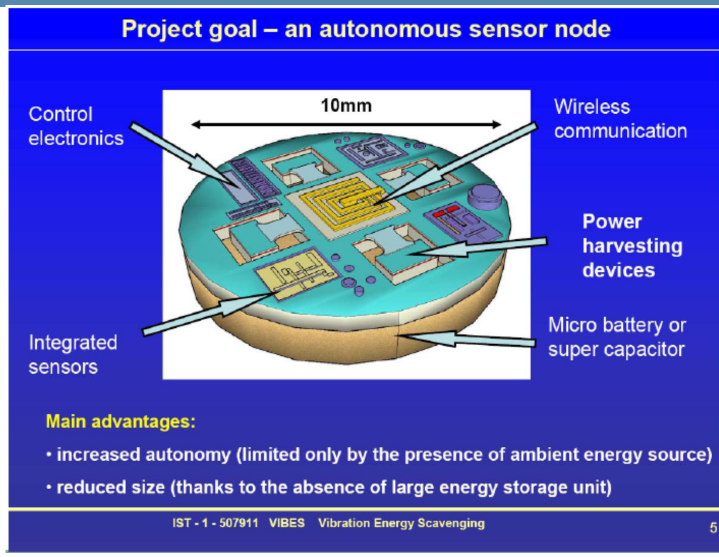
Solar cell, can operate several days in darkness, sleep mode ~25 nA

Push-button, mechanical energy harvesting



Push-button, mechanical energy harvesting, 8-button hand held remote

Vibes: Vibration energy scavenging



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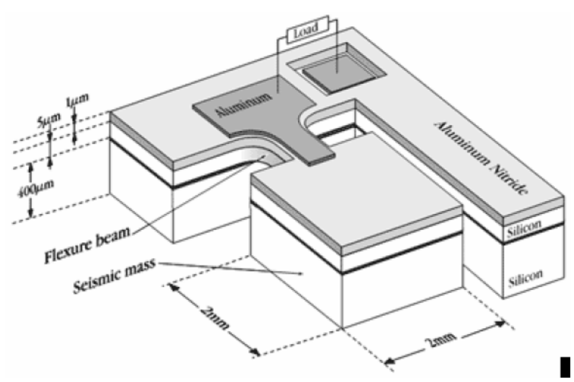
Vibes: Vibration energy scavenging



- Prototype demonstrated with 40 nW power for 0.5 g @ 200 Hz

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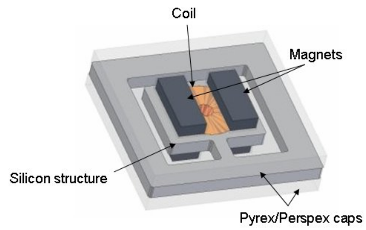
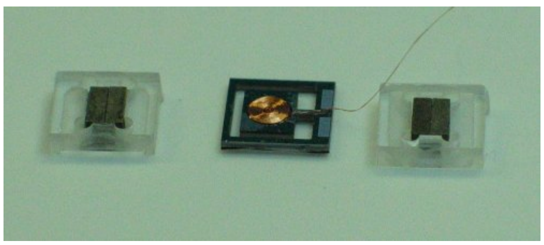
Energy harvesting

- MEMS





Examples of WSN platforms

Popular Nodes Overview

Node	CPU	Power	Memory	I/O and Sensors	Radio	Remarks
Special-purpose Sensor Nodes						
Spec 2003	4–8Mhz Custom 8-bit	3mW peak 3uW idle	3K RAM	I/O Pads on chip, ADC	50–100Kbps	Full custom silicon, traded RF range and accuracy for low-power operation.
Generic Sensor Nodes						
Rene 1999	ATMEL 8535	.036mW sleep 60mW active	512B RAM 8K Flash	Large expansion connector	10Kbps	Primary TinyOS development platform.
Mica-2 2001	ATMEGA 128	.036mW sleep 60mW active	4K RAM 128K Flash	Large expansion connector	76Kbps	Primary TinyOS development platform.
Telos 2004	Motorola HCS08	.001mW sleep 32mW active	4K RAM	USB and Ethernet	250Kbps	Supports IEEE 802.15.4 standard. Allows higher-layer Zigbee stardard. 1.8V operation
Mica-Z 2004	ATMEGA 128		4K RAM 128K Flash	Large expansion connector	250Kbps	Supports IEEE 802.15.4 standard. Allows higher-layer Zigbee stardard.
High-bandwidth Sensor Nodes						
BT Node 2001	ATMEL Mega 128L 7.328Mhz	50MW idle 285MW active	128KB Flash 4KB EEPROM 4KB SRAM	8-channel 10-bit A/D, 2 UARTS Expandable connectors	Bluetooth	Easy connectivity with cell phones. Supports TinyOS. Multihop using multiple radios/nodes.
Imote 1.0 2003	ARM 7TDMI 12-48MHz	1mW idle 120mW active	64KB SRAM 512KB Flash	UART, USB, GPIO, I^2C, SPI	Bluetooth 1.1	Multihop using scatternets, easy connections to PDAs, phones,TinyOS 1.0, 1.1.
Gateway Nodes						
Stargate 2003	Intel PXA255		64KNSRM	2 PCMICA/CF, com ports, Ethernet, USB	Serial connection to sensor network	Flexible I/O and small form factor power management.
Inrysnc Cerfcube 2003	Intel PXA255		32KB Flash 64KB SRAM	Single CF card, general-purpose I/O		Small form factor, robust industrial support, Linux and Windows CE support.
PC104 nodes	X86 processor		32KB Flash 64KB SRAM	PCI Bus		Embedded Linux or Windows support.

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MICA

- Current size around 3.2*5.7cm
- Compressed variant with a size of a 2.5cm coin only 0.5cm thick
- Battery lifetime up to several years

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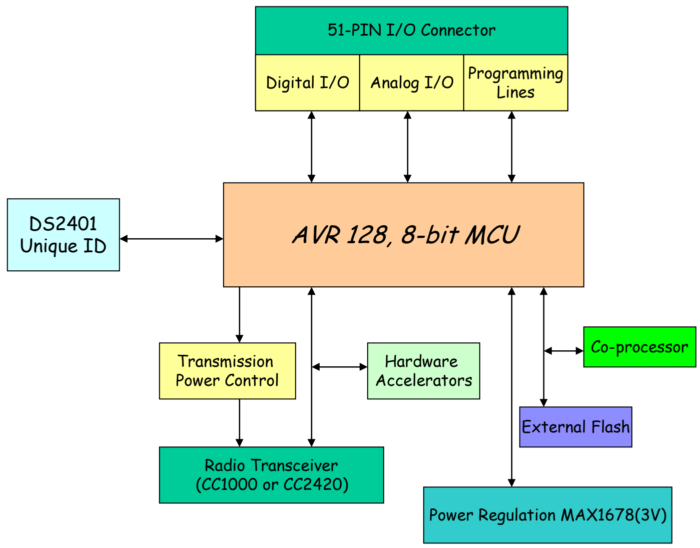
MICA architecture block diagram



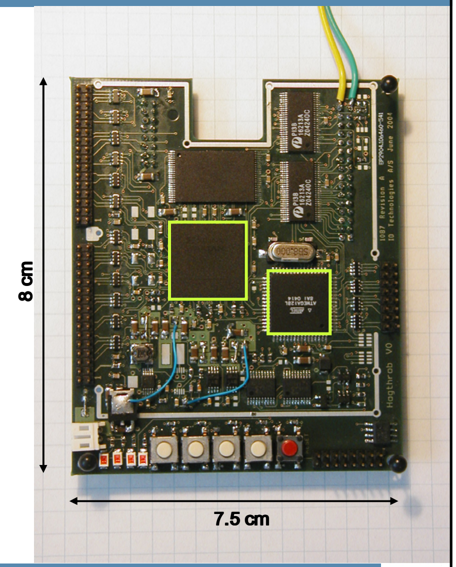
MICA power consumption

Table 1. Breakdown of active and idle power consumption for Mica hardware.

Component	Active (mW)	Idle (μW)
CPU	16.5	30
Radio	21 (transmit mode)	0
	15 (receive mode)	
Silicon ID	0.015	0
External flash	45	30
LEDs	10	0

Hogthrob platform

- AVR Core (8bit, 8 MHz)
  - To ease start-up
  - To be used as timer module (counter of limited size, cannot sleep for hours) and AD converter
- FPGA (Xilinx Spartan3, 90nm)
  - 400.000 gates
  - Co-design Hardware/Software
    - Hardware accelerators (radio, sensors)
  - Different MCUs
    - Clock-based (open core) vs. Asynchronous



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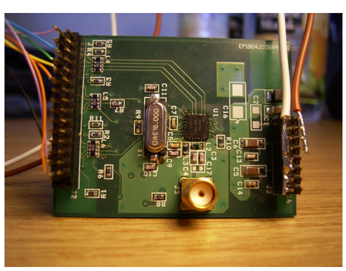
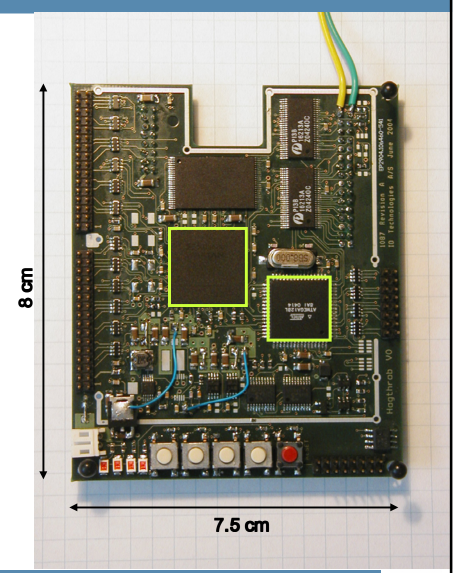
Hogthrob platform

- Add-on radio board
  - 2,4 GHz radio (Nordic VLSI)
  - transmit quickly to avoid interferences
- Add-on sensor board
  - motion detector
  - possibly microphones





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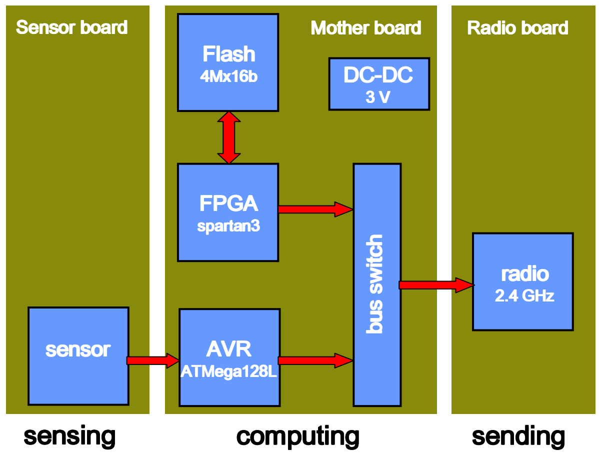
Hogthrob platform



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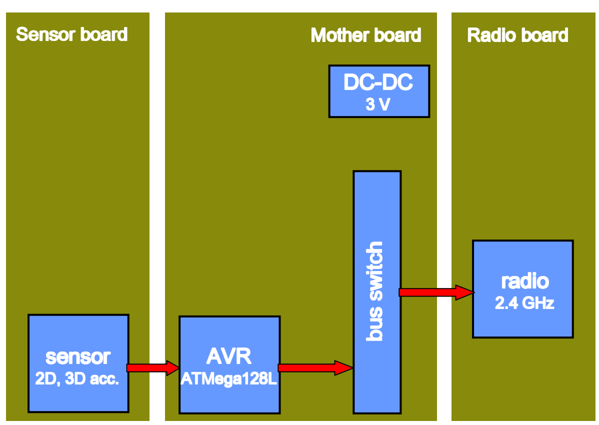
Hogthrob platform

Initial configuration



- Tested in lab
- Range ~80m

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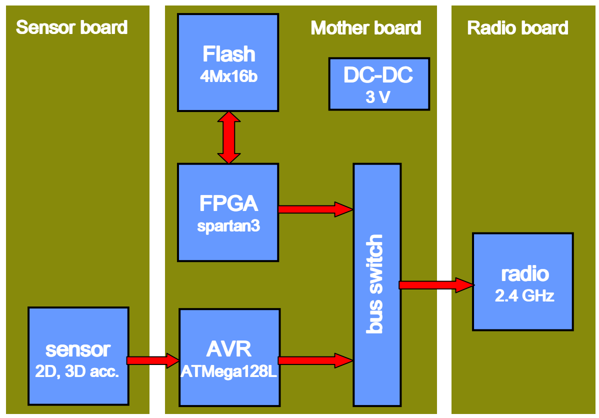
Hogthrob platform

Initial configuration



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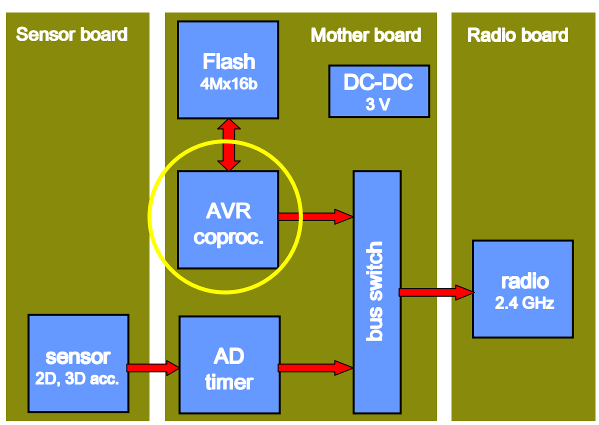
Hogthrob platform

Design space exploration configuration



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Nimbus Processor Core

- AVR instruction set compatible
- Simulated using 0.25 um technology

Power results		
Benchmark	**ATMega128l**	**Nimbus**
nop	47.5 mW	2.26 mW
idle	17.0 uW	1.00 uW
power-save	38.6 uW	1.22 uW
power-down	39.0 uW	0.59 uW
add	30.1 mW	1.38 mW
add-mem	31.9 mW	1.90 mW
hamming	32.3 mW	1.76 mW

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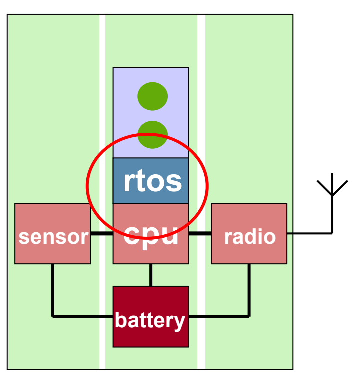
Operating system



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Operating system

- MICA nodes use the TinyOS operating system
- TinyOS is
  - Event based
  - Multithreaded
  - Non-preemptive (preemption from lower layers allowed)
  - Component based
- Most components are implemented in software, this allows for
  - Power saving – Processing is distributed over time to yield a very uniform power consumption without spikes

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TinyOS objectives

- Diversity in design and usage
  > Components
- Low-power consumption
  > Events-based execution
- Robustness
  > Non-concurrent programmation

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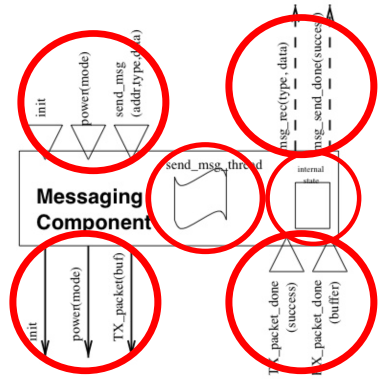
TinyOS Components

- Internal storage: ”frame”, fixed size.
- Set of tasks
  - Called commands
  - Commands handlers
  - Signaled events
  - Event handlers



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TinyOS Components

- Component Graph example

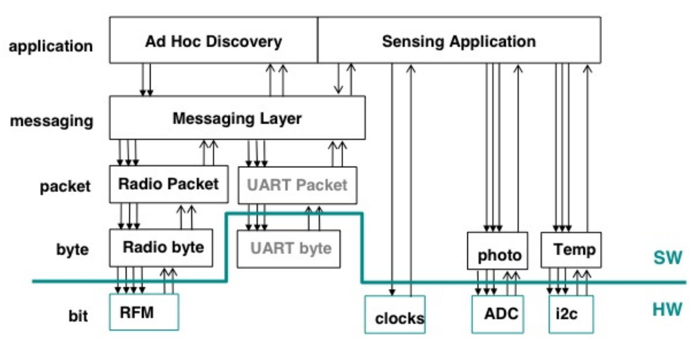

Figure 2. Typical networking application component graph.

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Why an event-based approach?

- A stack-based threaded approach would require:
  - Stack space reserved for each execution context
  - Time costly execution context switches
- An event-based approach provides:
  - Memory gain
  - Robustness for long period runs
    - Hazardous behavior not allowed
  - Energy efficiency
    - Unused CPU cycles spent in sleep mode

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Design specification

Design challenge related to TinyOS

- Component based architecture
  - App's build with OS from system components
  - Dedicated language: nesC
- Task and Event based concurrency
  - Tasks don't preempt tasks
  - Events preempt tasks
  - Events are ties to Interrupts
- Split Phased operations
  - Commands request to execute and returns
  - Events completes

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SOS: Sensor network OS

- Operating system for mote-class sensor nodes
  - consists of dynamically-loaded modules
  - a common kernel, which implements
    - messaging,
    - dynamic memory
    - module loading and unloading
- Achieves dynamic and general-purpose OS semantics without much energy or performance sacrifices.
- Provides significant energy saving over TinyOS and more expressivity than Mate Bombilla.

SOS: Dynamic code

- SOS both expects and support multiple modules executing and interacting on top of the SOS kernel at the same time.
- SOS module updates can not replace the kernel and not force a node to reboot after updates.
- SOS includes a publish-subscribe scheme that is similar to MOAP for distributing modules within a deployed sensor network.

AmbientRT

- AmbientRT is a Real-Time Operating System for embedded devices which has very powerful features like, real-time scheduling, dynamic memory allocation, online reconfigure ability, and support for a data driven architecture based on very limited memory, processing, and energy sources.
  - Brings WSN closer to reality
  - Developed for limited resources
  - Relieve the burden of the developer
  - Efficiently use the resources of the node
  - Concepts used and trade-offs involved in the system
  - Current hardware available for sensor networks, the real time concept is feasible

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AmbientRT: unique aspects

- AmbientRT uses real-time preemptive scheduling and dynamically defines priorities based on the timing properties instead of assigning to tasks.
- Other systems use cooperative scheduling, whose real-time behavior can not be guaranteed.

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AmbientRT: Real time scheduling

- EDF + DI = EDFI
  - EDFI uses deadline inheritance while Priority Ceiling protocol use fixed priorities for inheritance. It allows a considerable simplification of blocking computation during feasibility analysis.
  - EDFI uses static deadline inheritance. It is better than dynamic deadline modification in computation cost.

Comparison

Features	TinyOS	SOS	AmbientRT
Real Time	Soft RT (Poor latency)	Soft RT (Better latency)	Hard RT (Much better latency)
Reconfiguration	Static	Dynamic	Dynamic
Memory Allocation	Static	Dynamic	Dynamic
Preemption	No	No	Yes
Resource Synchronization	Not Required	Not Required	Scheduler
Module Level Error Handling	Compile Time	Execution Time	Not Mentioned

Putting it all together

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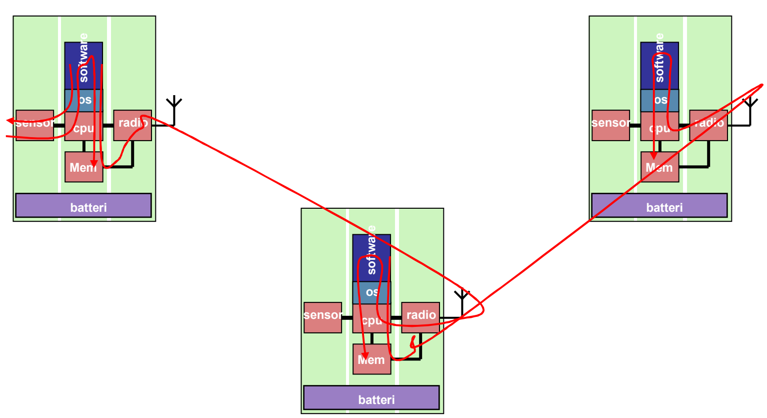
WSN Platform layers



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Sensor node design space

Hardware:

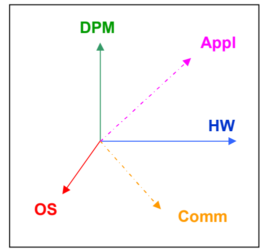
Operating System:

Power Management:

Communication Protocols:

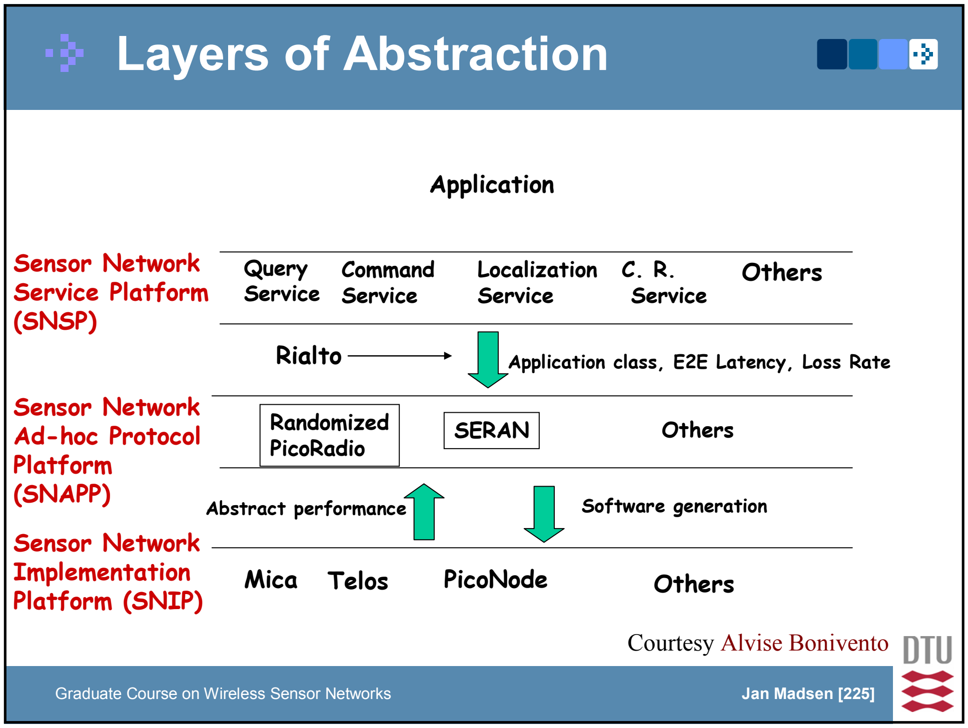
Application:

- Communication/processing trade-off.
  (in-network processing, aggregation)
- Tuning the requirements of the application.
  (measurement rate, performance)



➡ Very large design space and it is difficult to foresee what consequences decision in the different directions affect each other.
System-level sensor network model

WSN Design methods


Layers of Abstraction
Application
Sensor Network Service Platform (SNSP)
Query Service
Command Service
Localization Service
C. R. Service
Others
Rialto
Application class, E2E Latency, Loss Rate
Sensor Network Ad-hoc Protocol Platform (SNAPP)
Randomized PicoRadio
SERAN
Others
Abstract performance
Software generation
Sensor Network Implementation Platform (SNIP)
Mica
Telos
PicoNode
Others
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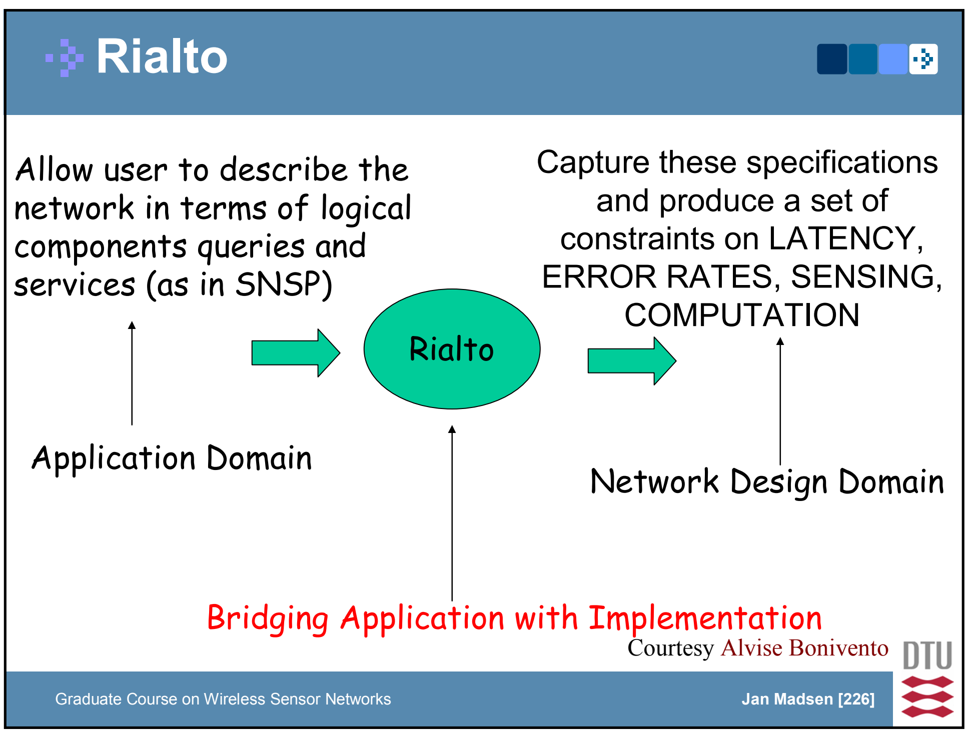
Rialto
Allow user to describe the network in terms of logical components queries and services (as in SNSP)
Capture these specifications and produce a set of constraints on LATENCY, ERROR RATES, SENSING, COMPUTATION
Rialto
Application Domain
Network Design Domain
Bridging Application with Implementation
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Protocol Platform

Modify and combine different Routing and MAC strategies

↓

Derive mathematical model and parametrized MAC+ Routing protocol

→

Refine application constraints

↓

Constrained Optimization Problem

↑

Abstract hardware performance

→

Synthesize parameters

↓

Implement

Courtesy Alvise Bonivento

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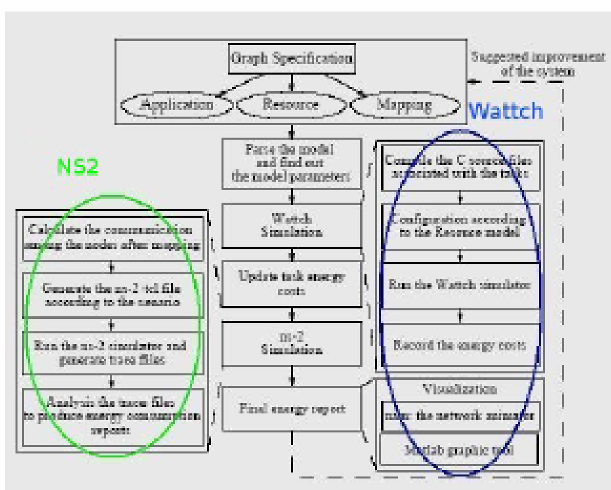

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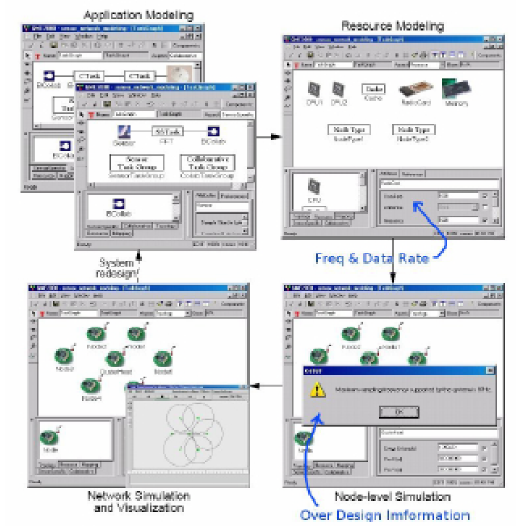

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WSN Summary

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Major System Challenges

- Large numbers of elements
- Limited physical access
- Extreme environmental conditions

- => demand a fundamental reexamination of familiar layers of abstraction, hardware, algorithms

- Suggestion: these are a radically different kind of computing system

Scale

- # of sensors: 10’s to millions
- Size of sensors (cubic feet to millimeters)
- Spatial and temporal sampling rates (miles to mm’s and days to ms)
- Capability (sensors, power, compute, communicate)
- Compose and evolve as a system at scale

- Question: what computing systems do we have that span these ranges? Are they one kind?

Limited Access

- Unwired, unpowered, limited networking (cost)
- Physically remote or harsh enviroments
- Limited human intervention support/administration
- Resource limited

- What are characteristics of our longest running, reliable systems, and techniques?

Extreme Dynamics

- Activity in the physical world happens in bursts
  - Animals are built for this (adrenaline, fear-flight, hunt, taste, smell, etc.)
  - Static network -> things passing, evolving
  - Mobile network -> things encountered
  - Dynamic range of sensory input is orders of magnitude

- Systems must have passive vigilance, efficient triggering, and rapid transformation to high levels of concurrency and effectiveness.
- Not quite “lazy computing”, or something analogous?

Breadth

- Variable design structure – static, dynamic, regular and irregular
- Single sensor type/mode, multiple, single application and multiple-application
- Static or mobile – fast and slow change
- Autonomy and limited access
  - Degree of human involvement in both decision-making/control as well as maintenance of system

State of the Art

- … rambling discussion of some current research activities…
  - Small devices increasing in environmental awareness and networking capability
  - Evolving radio, silicon technology enabling sensor networks
  - Maturing software environments

State of the Art (cont.)

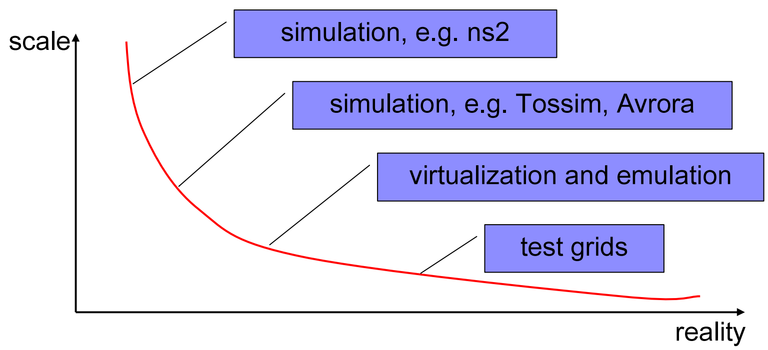
- Outline of several specific challenges (not comprehensive)
  - Sensing and actuation – control loops and variable delays
  - Localization as a key challenge and foundation for coupling with the physical world
  - Self configuration – and reconfiguration

Some “throw ins”

- Data centric architecture and “directed diffusion” Tiered (hierarchical) architectures
  - Different capabilities, heterogeneity
- *Frontier for almost any CS subdiscipline is in this area*

Trend in WSN research

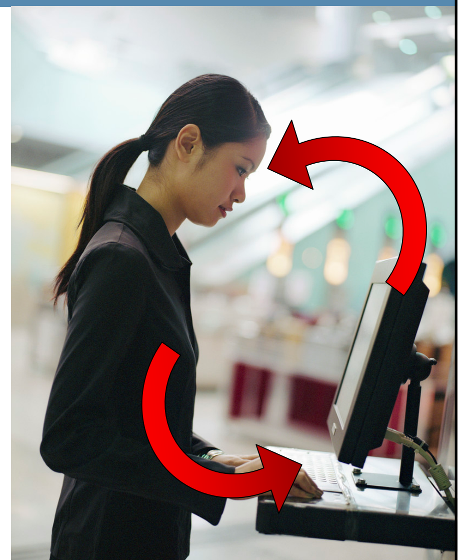
- From theoretical …
- … to practical



Future sensor networks?

Paradigme shift in computing

- From
  - **Inter**active computing
  - People in the loop
- To
  - **Pro**active computing



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PROactive computing

- Get **P**hysical
  - Pervasive contact with the physical world
- Get **R**eal
  - Running faster than human-speed
- Get **O**ut
  - People out of the loop

David Tennenhous, Intel Research

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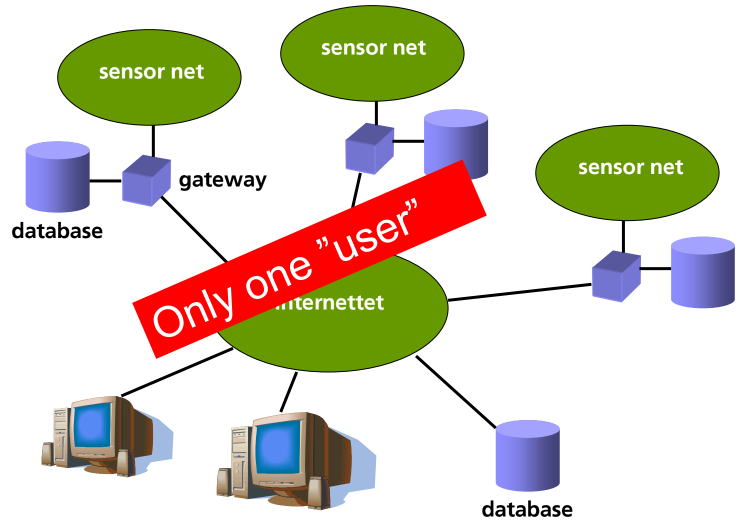
Traditional sensor network



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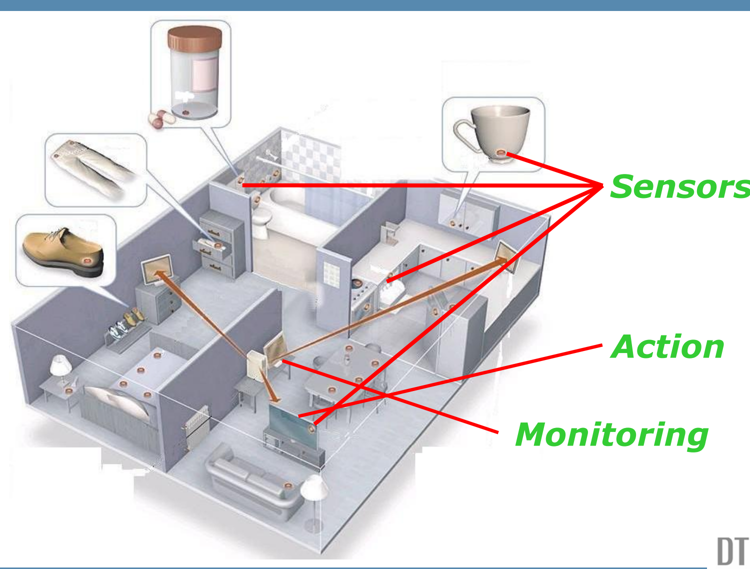
Healthcare: Smart home



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Small Technology, Broad Agenda, Unique Confluence

- **Social factors**
  - security, privacy, information sharing
  - interacting with a computational environment
- **Programming the Ensemble**
  - describe global behavior, synthesis local rules that have correct, predictable global behavior
- **Distributed services**
  - localization, time synchronization, resilient aggregation

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The *Hogthrob* project

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References: Slides

Some slides in this presentation are based, in part or full, on slides from the following tutorial and course presentations.

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- *Building Sensor Networks with TinyOS*, David Culler, Phil Levis, Rob Szewczyk, Joe Polastre, University of California, Berkeley and Intel Research Berkeley. Mobisys Tutorial, San Francisco, 2003.
- *Introduction to Wireless Sensor Networks*, Anish Arora, Ohio State University. Course CSE 788, Spring 2005.
- *Networked Embedded Systems & Sensor Networks*, Andreas Savvides , Yale University. Course EENG 460a
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- Adaptive Protocols for Information Dissemination in Wireless Sensor Networks, W.R. Heinzelman, A. Chandrakasan and H. Balakrishnan. Proceedings of the 5th ACM/IEEE MOBICOM Conference, Seattle, August 1999.

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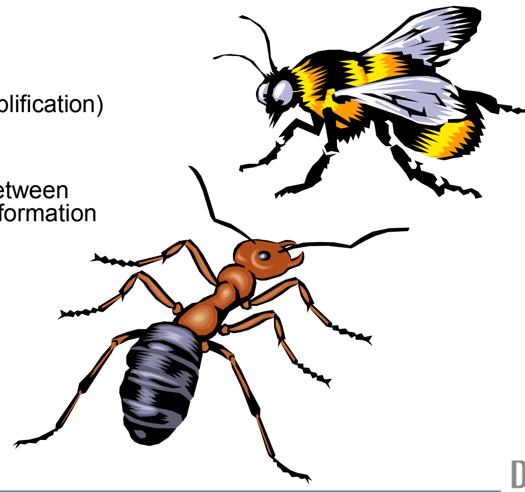
  In proceedings of the 28th EUROMICRO Conference 2002, pages 68-73. 4-6 September 2002, Dortmund, Germany

Appendices

Swarm Intelligence Overview

- Social insect colony
- No central control
- Stimergy
- Self-organization
  - Positive feedback (amplification)
  - Negative feedback
  - Fluctuations
  - Multiple interactions between agents and reuse of information



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Natural Ant Colony Behavior

- Self-organization
- Pheromone trails

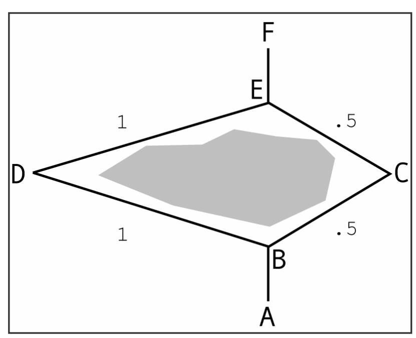

Figure 2. Diagram of experimental setup used to demonstrate self-organization in ants.

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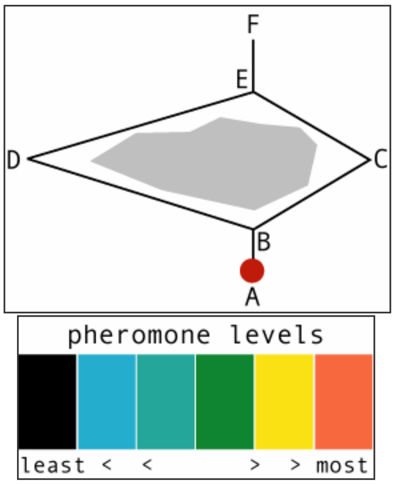
Ants in Action



- Initially, no pheromone on edges

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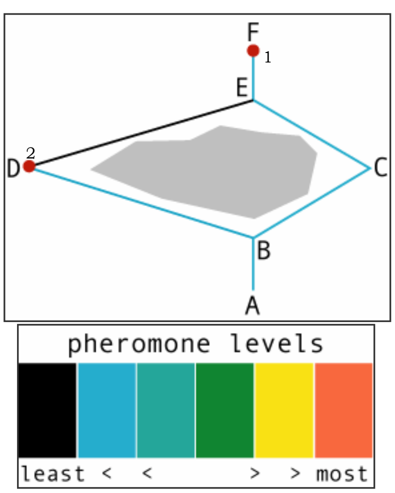
Ants in Action



- Obstacle causes split
- No guiding factor, probable equal split
- Shorter path causes faster travel

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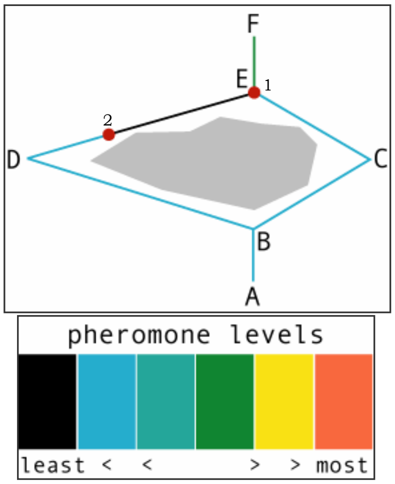
Ants in Action



- Pheromone trails exist; influence decision

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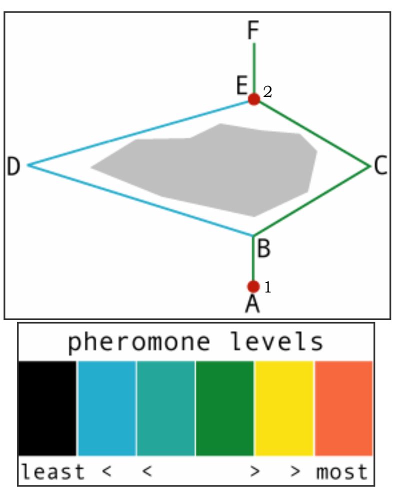
Ants in Action



- Pheromone exists on both trails, but amount differs
- Edge choice is still random, but is weighted towards ECB

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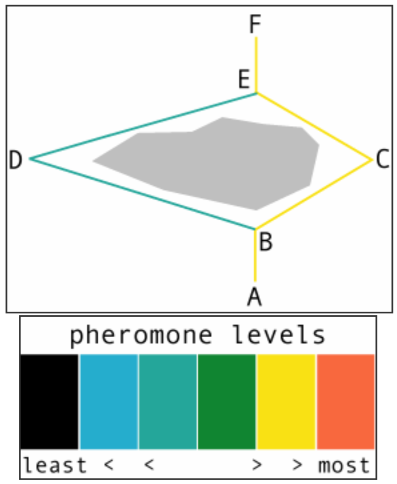
Ants in Action



- A route begins to emerge

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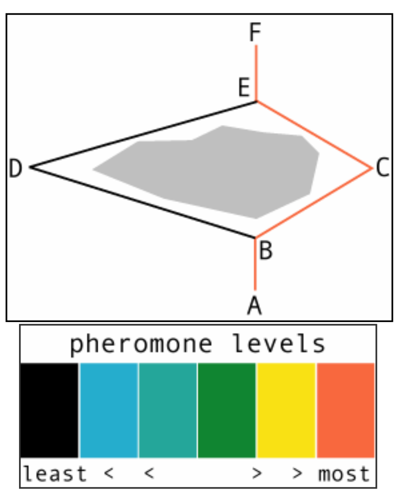
Ants in Action



- A path is established
- Self-organization through *autocatalytic behavior*
- *Negative feedback* through evaporation

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