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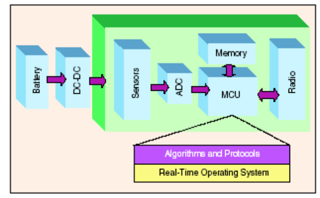
Wireless Sensor Networks

- Sensor Nodes: Energy Consumption
- Routing
- Localization

Where does the energy go?



- Processing
  - excluding low-level processing for radio, sensors, actuators
- Radio
  - Transmit, receive, idle
- Sensors & Actuators
- Power supply

Processing

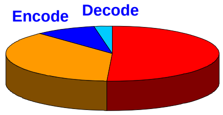
- Common sensor node processors:
  - Atmel AVR, Intel 8051, StrongARM, XScale, ARM Thumb, SH Risc
- Power consumption all over the map, e.g.
  - 16.5 mW for ATMega128L @ 4MHz
  - 75 mW for ARM Thumb @ 40 MHz
- But, don't confuse low-power and energy-efficiency!
  - Example
    - 242 MIPS/W for ATMega128L @ 4MHz (4nJ/Instruction)
    - 480 MIPS/W for ARM Thumb @ 40 MHz (2.1 nJ/Instruction)

Radio

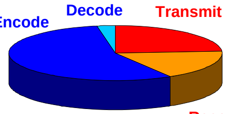
- Energy per bit in radios is a strong function of desired communication performance and choice of modulation
  - Range and BER for given channel condition (noise, multipath and Doppler fading)
- Watch out: different people count energy differently
  - E.g.
    - Mote's RFM radio is only a transceiver, and a lot of low-level processing takes place in the main CPU
    - While, typical 802.11b radios do everything up to MAC and link level encryption in the "radio"
- Transmit, receive, idle, and sleep modes
- Variable modulation, coding
- Currently around 150 nJ/bit for short ranges

Computation & Communication

Energy breakdown for voice



Energy breakdown for MPEG



Radio: Lucent WaveLAN at 2 Mbps

Processor: StrongARM SA-1100 at 150 MIPS

- Radios benefit less from technology improvements than processors
- The relative impact of the communication subsystem on the system energy consumption will grow

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Sensing

- Several energy consumption sources
  - Transducer
  - Front-end processing and signal conditioning
    - analog, digital
  - ADC conversion
- Diversity of sensors: no general conclusions can be drawn
  - Low-power modalities
    - Temperature, light, accelerometer
  - Medium-power modalities
    - Acoustic, magnetic
  - High-power modalities
    - Image, video, beamforming

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Actuation

- Emerging sensor platforms
  - Mounted on mobile robots
  - Antennas or sensors that can be actuated
- Energy trade-offs not yet studied
- Some thoughts:
  - Actuation often done with fuel, which has much higher energy density than batteries
    - E.g. anecdotal evidence that in some UAVs the flight time is longer than the up time of the wireless camera mounted on it
  - Actuation done during boot-up or once in a while may have significant payoffs
    - E.g. mechanically repositioning the antenna once may be better than paying higher communication energy cost for all subsequent packets
    - E.g. moving a few nodes may result in a more uniform distribution of node, and thus longer system lifetime

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Power Analysis of RSC's WINS Nodes

Table 1. Power Analysis of Rockwell's Wins Nodes.

MCU Mode	Sensor Mode	Radio Mode	Power (mW)
Active	On	Tx (Power: 36.3 mW)	1080.5
		Tx (Power: 19.1 mW)	986.0
		Tx (Power: 13.8 mW)	942.6
		Tx (Power: 3.47 mW)	815.5
		Tx (Power: 2.51 mW)	807.5
		Tx (Power: 0.96 mW)	787.5
		Tx (Power: 0.30 mW)	773.9
		Tx (Power: 0.12 mW)	771.1
Active	On	Rx	751.6
Active	On	Idle	727.5
Active	On	Sleep	416.3
Active	On	Removed	383.3
Sleep	On	Removed	64.0
Active	Removed	Removed	360.0

- Summary
- Processor
  - Active = 360 mW
    - doing repeated transmit/receive
  - Sleep = 41 mW
  - Off = 0.9 mW
- Sensor = 23 mW
- Processor : Tx = 1 : 2
- Processor : Rx = 1 : 1
- Total Tx : Rx = 4 : 3 at maximum range
  - Comparable at lower Tx

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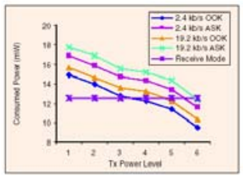
Power Analysis of Mote-Like Node

Table 2. Power Analysis of Medusa II Nodes.

MCU Mode	Sensor Mode	Radio Mode	Mod. Scheme	Data Rate	Power (mW)
Active	On	Tx(Power: 0.7368 mW)	OOK	2.4 kb/s	24.58
		Tx(Power: 0.0979 mW)	OOK	2.4 kb/s	19.24
		Tx(Power: 0.7368 mW)	OOK	19.2 kb/s	25.37
		Tx(Power: 0.0979 mW)	OOK	19.2 kb/s	20.05
		Tx(Power: 0.7368 mW)	ASK	2.4 kb/s	26.55
		Tx(Power: 0.0979 mW)	ASK	2.4 kb/s	21.26
		Tx(Power: 0.7368 mW)	ASK	19.2 kb/s	27.46
		Tx(Power: 0.0979 mW)	ASK	19.2 kb/s	22.06
Active	On	Rx	Any	Any	22.20
Active	On	Idle	Any	Any	22.06
Active	On	Off	Any	Any	9.72
Idle	On	Off	Any	Any	5.92
Sleep	Off	Off	Any	Any	0.02



Some Observations (1)

- Using low-power components and trading-off unnecessary performance for power savings can have orders of magnitude impact
- Node power consumption is strongly dependent on the operating mode
  - E.g. WINS consumes only 1/6-th the power when MCU is asleep as opposed to active
- At short ranges, the Rx power consumption > T power consumption
  - Multihop relaying not necessarily desirable
- Idle radio consumes almost as much power as radio in Rx mode
  - Radio needs to be completely shut off to save power as in sensor networks idle time dominates
    - MAC protocols that do not "listen" a lot

Some Observations (2)

- Processor power fairly significant (30-50%) share of overall power
- In WINS node, radio consumes 33 mW in "sleep" vs. "removed"
  - Argues for module level power shutdown
- Sensor transducer power negligible
  - Use sensors to provide wakeup signal for processor and radio
  - Not true for active sensors though…

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Wireless Sensor Networks

- Sensor Nodes: Energy Consumption
- **Routing**
- Localization

Routing in Sensor Networks

- Multihop Routing with the following constraints and features
  - Power efficiency
  - Attribute-based addressing
  - Location awareness
  - Data-centric (communication is for named data)

Routing Protocols

- Flooding
- Directed Diffusion
- SPIN
- Low Energy Adaptive Clustering Hierarchy (LEACH)
- Rumor Routing

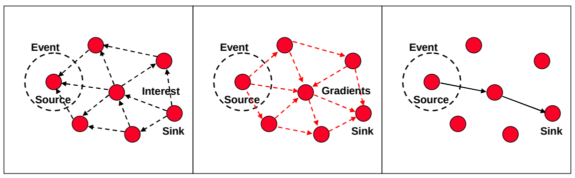
Flooding

- Flooding is the simplest form of routing
- Each node broadcast the packets to all its neighbors and the process repeat until a maximum number of hops or the packet reaches its destination
- Problems:
  - Implosion (multiple copies of messages are sent to the same node)
  - Overlap (Neighbor nodes receive duplicate messages because of overlap in observing region)
  - Resource Blindness (Unaware of resources, energy)

Directed Diffusion [Intanagonwiwat'00]

- Data-centric routing where sink broadcasts the request
- The sink sends out requirements in terms of attribute-value pairs called as *interest*
- This dissemination sets up gradients within the network designed to draw events
- Events start flowing towards the originators of interests along multiple paths
- The sensor network reinforces one or a small number of these paths.

Directed Diffusion



a) Interest Propagation b) Gradients setup c)Data delivery

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SPIN [Heinzelman99]

- Sensor Protocols for Information via Negotiation (SPIN) uses negotiation and resource adaptation to address the deficiencies of flooding
- Propose a family of routing protocols
- Conserves energy by exchanging metadata during negotiation
- Nodes monitor and adapt to changes in their own energy resources to extend the operating lifetime of the system

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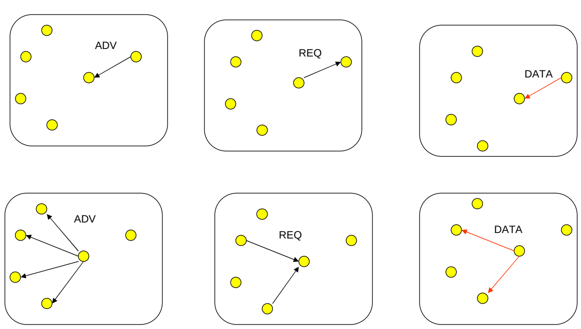
SPIN Protocol



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LEACH [Heinzelman'00]

- LEACH is self-organizing, adaptive clustering protocol
- Randomly selects nodes as cluster-heads to distribute the energy load evenly
- High-energy dissipation in communicating with the base station is distributed among the sensor nodes.
- LEACH performs local data fusion to "compress" the amount of data being sent from the cluster-heads to the base station

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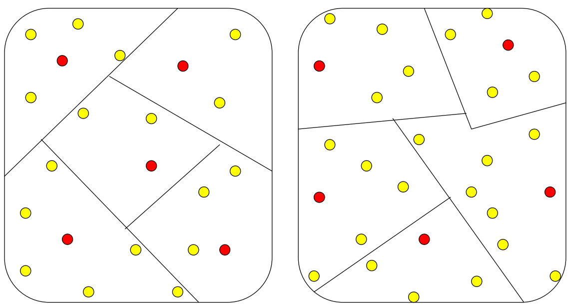
Dynamic Clusters in LEACH



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Rumor Routing [Braginsky'02]

- A logical compromise between flooding queries and flooding event notifications
- Upon witnessing an event, a node probabilistically generates an agent, which travels the network, propagating information about local events to distant nodes.
- A query generated by a node traverses in a random direction until a TTL value or when it finds a node that has the path to the event
- A query can be retransmitted or flooding can be adopted as a last resort.

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Wireless Sensor Networks

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- Routing
- **Localization**

Localization Issues

- What is Localization?
- Why is it important?
- Categorization
- Some Localization Mechanisms
  - GPS
  - Beacon based ranging
  - Range free methods

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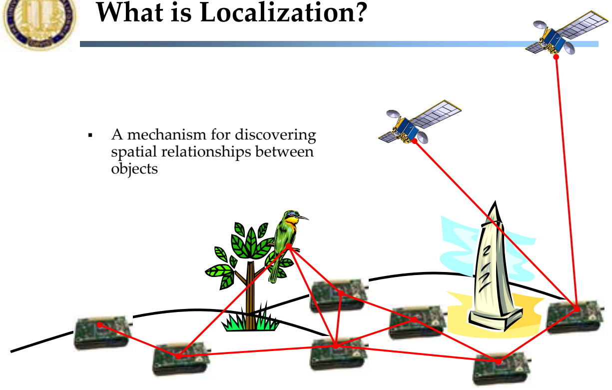
What is Localization?

- A mechanism for discovering spatial relationships between objects



Why is Localization Important?

- Sensor Network Data is typically interpreted based on a sensor's location
  - Report event origins
  - Giving raw sensor readings a physical context
    - Temperature readings ⇒ temperature map
  - Objects tracking
- Enables data-centric network design
  - Assist with routing
  - Evaluate network coverage

Categorization

- Coarse-grained Localization
  - Proximity to a given reference point
  - E.g., Active Badge
- Fine-grained Localization
  - Coordinates estimation
    - E.g., Distance to a given reference point

Fine-Grained Localization

- Ranging based methods
  - Timing, e.g., GPS
  - Signal Strength, e.g., Beacon based ranging
  - Directionality Based, e.g., Angle of Arrival (AoA) measured with directional antennas or arrays

- Ranging free methods
  - E.g.: Centroid based, DV-hop

Timing

- Time-based Method
  - Time of Arrival (ToA), TDoA
    Time of flight of communication signal
  - Used with radio, IR, acoustic, ultrasound
- Signal Pattern
  - Global Positioning System
  - Local Positioning System
  - Pinpoint's 3D-iD

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Signal Strength

- Uses received signal strength indicator (RSSI) readings and wireless propagation model
- Attenuation of radio signal increases with increasing distance
- RADAR
  - Wall Attenuation Factor based Signal Propagation Model
  - RF mapping

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Directionality Based Fine-Grained Localization

- Small Aperture Direction Finding
  - Used in cellular networks
  - Requires complex antenna array
- Disadvantages
  - Costly
  - Not a receiver based approach

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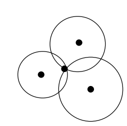
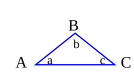
Basic Concepts in Ranging

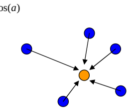
Trilateration
Triangulation
Multi-lateration
- Considers all available beacons





Sines Rule $\frac{A}{\sin a} = \frac{B}{\sin b} = \frac{C}{\sin c}$

Cosines Rule
$$C^2 = A^2 + B^2 + 2AB\cos(c)$$
$$B^2 = A^2 + C^2 - 2BC\cos(b)$$
$$C^2 = B^2 + C^2 - 2BC\cos(a)$$



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Global Positioning System (GPS) [Getting'93]

- Started in 1973, built in 1993
- Wide-area radio positioning system
- Ranging-based method
  - Using Timing of Arrival (ToA)

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GPS System Architecture

- Constellation of 24 NAVSTAR satellites made by Rockwell
  - Altitude: 10,900 nautical miles
  - Orbital Period: 12 hours
- At least five satellites in view from every point in the Globe

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How GPS Works

- The basis of GPS is "trilateration" from satellites
- Distance measuring based on ToA
  - Accurate timing is important
- Along with distance, you need to know exactly where the satellites are in space
  - High orbits and careful monitoring are the secret
- Finally you must correct for any delays the signal experiences as it travels through the atmosphere
  - A Fourth satellite used for correction purpose

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Differential GPS

- Ground-based Station with known location information can estimate the GPS measure errors
- These error estimations are made available to other GPS users in the area
  - Allow them to mitigate errors in their measurements
  - Such "differential corrections" are transmitted in real time over a FM radio link

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GPS Not Always Applicable

- Many contexts you cannot have GPS on every node
  - Form factor
  - Energy
  - Cost
  - Obstructions

- Beacon based approaches for sensor networks
  - Ranging based v.s. ranging free

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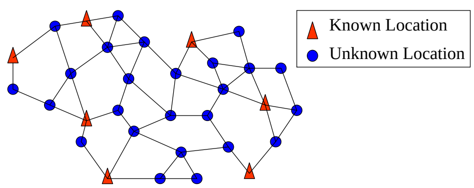
Beacon Based Location Discovery [Savvides'01]



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Beacon Based Location Discovery

- No need of GPS
- No infrastructure support
  - Ad hoc deployable
- Use RSSI for measuring node separation
  - But how should the beacons be placed?
- Distributed Localization
  - Iterative multilateration

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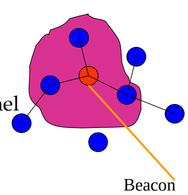
Localization Approach

- Single hop beaconing
- Iterative multilateration
- Dynamic estimate the wireless channel parameters
- Can be done in conjunction with routing



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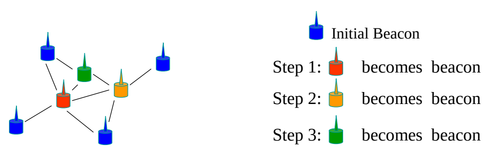
Iterative Multilateration

- Start with a small number of beacons
- Number of beacons increases as more nodes estimate their positions



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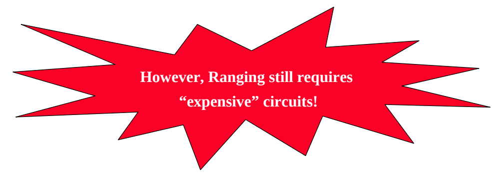
Advantages

- Data packets also act as beacon signals
  - Location discovery is almost free
- Distributed
  - relies on neighborhood information
- Fault tolerant



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Range Free Methods

- Centroid approach [Bulusu'00]
  - Adaptive beacon placement [Bulusu'01]
  - Self-configuring localization [Bulusu'03]
- DV-hop [Niculescu'01]
  - AoA approach [Niculescu'03]

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Centroid Based Approach [Bulusu'00]

- Multiple nodes serve as reference points (Beacons)
- Reference points transmit periodic beacon signals containing their positions
- Receiver node finds reference points in its range and localizes to the intersection of connectivity regions of these points

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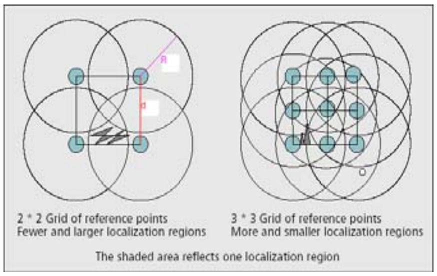
Model



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DV-Hop [Niculescu'01]

- Standard DV propagation
- Never measures node distance
  - Insensitive to signal strength errors
- Basic idea
  - Range = hop_count * hop_size

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DV-Hop: How It Works

- Each node maintains a table {Xi, Yi, hi} by running classic DV
- Each Landmark {Xi, Yi}
  - Compute a correction Ci and flood into the network
- Each node
  - Use the correction from the closest landmark
  - Multiply its hop distance by the correction

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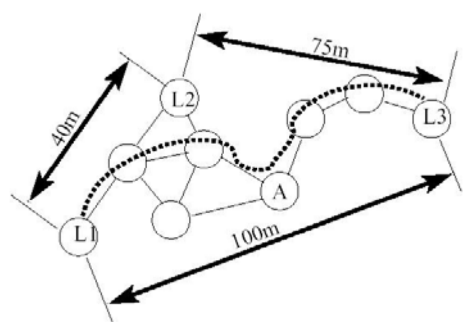
DV-Hop: Example



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DV-Hop: Example (contd.)

- Landmarks compute corrections

L_1 computes the correction $(100 + 40)/(6 + 2) = 17.5$
L_2 computes a correction of $(40 + 75)/(2 + 5) = 16.42$
L3 computes correction of $(75 + 100)/(6 + 5) = 15.90$

- Assume A gets its correction from L2
- A estimates its ranges to the landmarks
  - L1: 3*16.42, L2: 2*16.42, L3: 3*16.42
- A performs trilateration with the above ranges

Localization: Wrap up…

- Localization is important in sensor networks
- GPS is useful, but not always applicable
- Beacons (aka, anchors, landmarks) can help
  - Range based methods
  - Range free methods