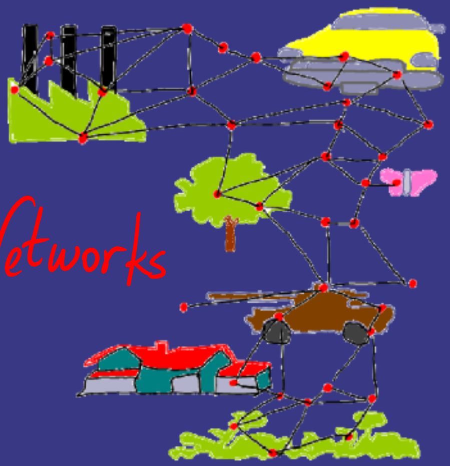
CmpE 58C
Wireless Sensor Networks



Factors That Influence WSN Design

Factors

Fault Tolerance (Reliability)
Scalability
Production Costs
Hardware Constraints
Sensor Network Topology
Operating Environment
Transmission Media
Power Consumption

Fault Tolerance (Reliability)

- Sensor nodes may fail or be blocked due to lack of power, physical damage, or environmental interference
- The failure of sensor nodes should not affect the overall operation of the sensor network
- This is called RELIABILITY or FAULT TOLERANCE, i.e., ability to sustain sensor network functionality without any interruption

Fault Tolerance (Reliability)

- Reliability R (Fault Tolerance) of a sensor node k is modeled:

$$R_k(t)=e^{-\lambda_k t}$$

- So, by Poisson distribution, to capture the probability of not having a failure within the time interval (0,t) with λ_k is the failure rate of the sensor node k and t is the time period.

G. Hoblos, M. Staroswiecki, and A. Aitouche, "Optimal Design of Fault Tolerant Sensor Networks," IEEE Int. Conf. on Control Applications, pp. 467-472, Sept. 2000.

Fault Tolerance (Reliability)

- Reliability (Fault Tolerance) of a broadcast range with N sensor nodes is calculated from:

$$R(t) = 1 - \prod_{k=1}^{N} [1 - R_k(t)]$$

Fault Tolerance (Reliability)

Example:

How many sensor nodes are needed within a broadcast radius (range) to have 99% fault tolerated network if R(t)=0.9?

Assuming all sensors within the radio range have same reliability, previous equation becomes:

$$R(t) = 1 - [1 - R(t)]^N$$

Drop t and substitute f = (1-R) →

0.99 = (1 – f^N) → N=2.

Fault Tolerance (Reliability)

REMARKS:

1. Protocols and algorithms may be designed to address the level of fault tolerance required by sensor networks.
2. If the environment has little interference, then the requirements can be more relaxed.

Fault Tolerance (Reliability)

Examples:

1. House to keep track of humidity and temperature levels → The sensors cannot be damaged easily or interfered by environments → Low fault tolerance (reliability) requirement!!!!
2. Battlefield for surveillance → The sensed data are critical and sensors can be destroyed by enemies → High fault tolerance (reliability) requirement!!!

- Bottomline: Fault Tolerance (Reliability) depends heavily on applications!!!

Scalability

- The number of sensor nodes may reach millions in studying a field/application
- The density of sensor nodes can range from few to several hundreds in a region (cluster) which can be less than 10m in diameter

Scalability

- The Sensor Node Density: i.e., the number of expected nodes within the radio range R:

$$\mu(R) = (N \cdot \pi R^2) / A$$

where N is the number of scattered sensor nodes in region A and R is the radio transmission range.

Basically: μ(R) → is the number of sensor nodes within the transmission radius R of each sensor node in region A.
The number of sensor nodes in a region is used to indicate the node density and depends on the application.

Scalability

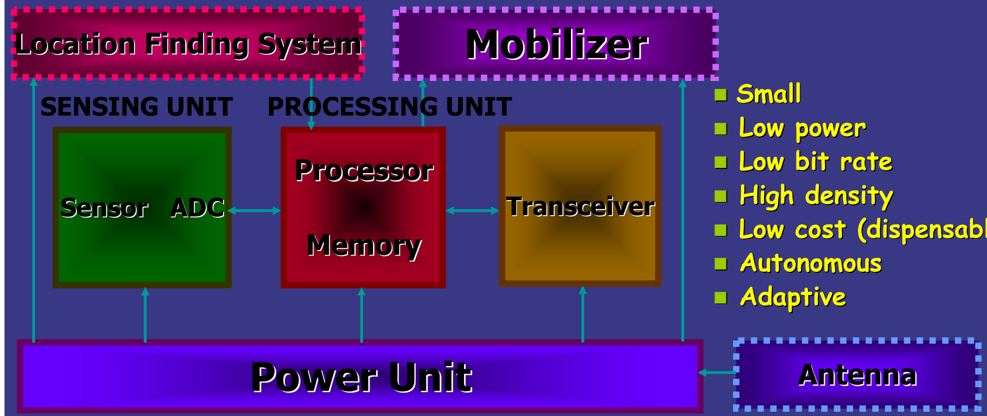
Examples:

1. Machine Diagnosis Application: less than 300 sensor nodes in a 5 m x 5 m region.
2. Vehicle Tracking Application: Around 10 sensor nodes per cluster/region.
3. Home Application: 2 dozens or more.
4. Habitat Monitoring Application: Range from 25 to 100 nodes/cluster
5. Personal Applications: Ranges in tens, e.g., clothing, eye glasses, shoes, watch, jewelry.

Production Costs

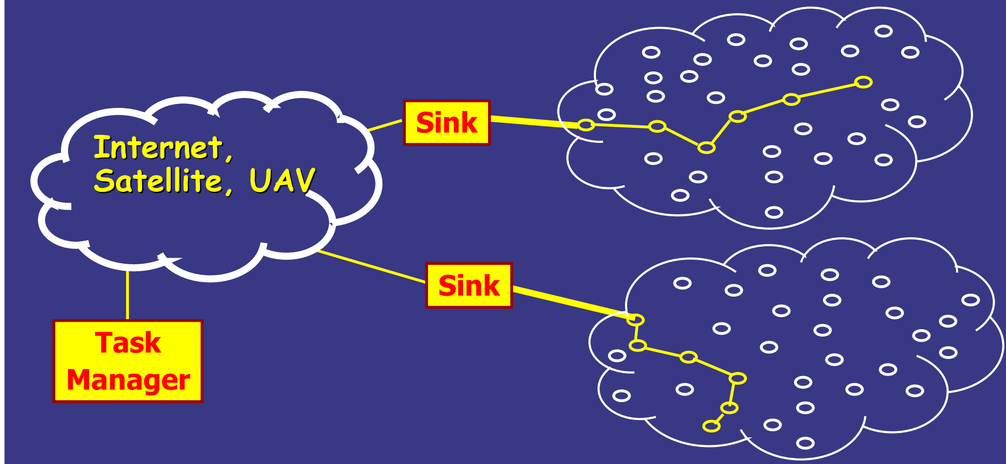
- Cost of sensors must be low so that the sensor networks can be justified!!!
- PicoNode: less than $1
- Bluetooth system: around $10,-
- THE OBJECTIVE FOR SENSOR COSTS must be lower than $1!!!!!!!
- Currently: COTS Dust Motes ranges from $25 to $172 (Still expensive!!!!)

Sensor Node Hardware



- Small
- Low power
- Low bit rate
- High density
- Low cost (dispensable)
- Autonomous
- Adaptive

Sensor Network Topology



Sensor Network Topology

- Topology maintenance and change:
  - Pre-deployment and Deployment Phase
  - Post Deployment Phase
  - Re-Deployment of Additional Nodes

Sensor Network Topology

Pre-deployment and Deployment Phase

- Sensor networks can be deployed by:
  - Dropping from a plane
  - Delivering in an artillery shell, rocket or missile
  - Throwing by a catapult (from a ship board, etc.)
  - Placing in factory
  - Being placed one by one by a human or a robot

Sensor Network Topology

Initial deployment schemes must

- Reduce installation cost
- Eliminate the need for any pre-organization and pre-planning
- Increase the flexibility of arrangement
- Promote self organization and fault tolerance

Sensor Network Topology

Post-deployment Phase

- After deployment, topology changes are due to change in sensor nodes'
  - position
  - reachability (due to jamming, noise, moving obstacles, etc.)
  - available energy
  - malfunctioning

Operating Environment

Sensor networks may work

- in busy intersections
- in the interior of a large machinery
- at the bottom of an ocean
- inside a twister
- at the surface of an ocean
- in a biologically or chemically contaminated field in a battlefield beyond the enemy lines
- in a house or a large building
- in a large warehouse
- attached to animals
- attached to fast moving vehicles
- in a drain or river, moving with current
- SEE ALL THE APPLICATIONS discussed before

Transmission Media

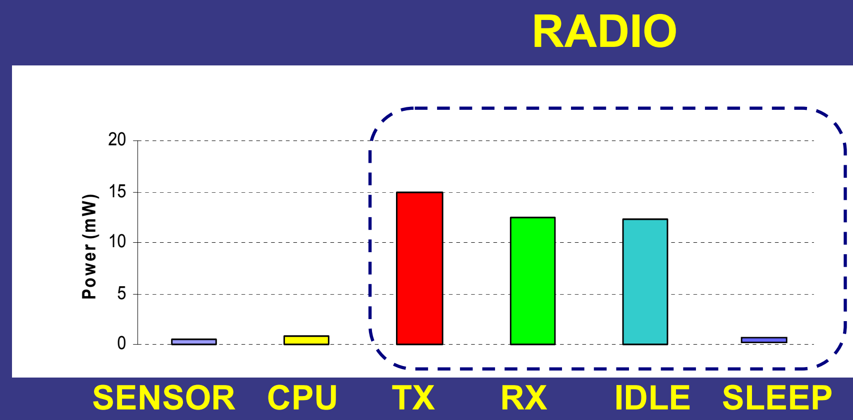
- Radio or Infrared or Optical Media
  - ISM (Industrial, Scientific and Medical) Bands
  - (433 MHz ISM Band in Europe and 915 MHz as well as 2.4 GHz ISM Bands in North America)
- Reasons: Free radio, huge spectrum allocation and global availability

Power Consumption

- Sensor node has limited power source
- Sensor node lifetime depends on battery lifetime
- Sensors can be a DATA ORIGINATOR or a DATA ROUTER
- Power conservation and power management are important

  → POWER AWARE PROTOCOLS must be developed

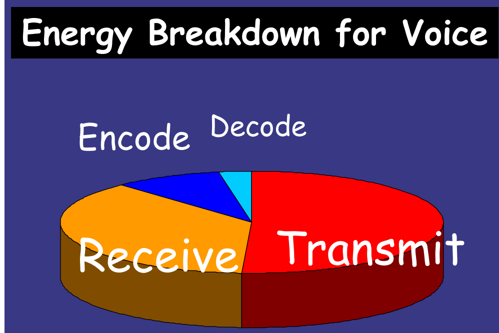
Power Consumption

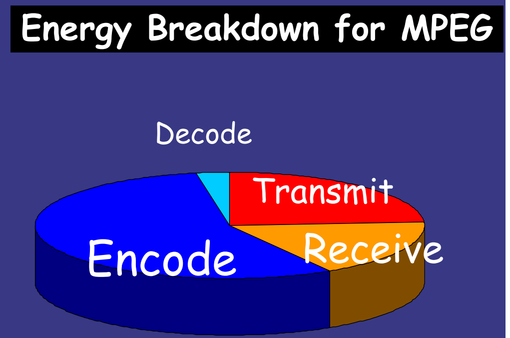


Power Consumption

- Power consumption in a sensor network can be divided into three domains
  - Communication
  - Data Processing
  - Sensing

Computation and Communication





Radio: Lucent WaveLAN at 2 Mbps

Power Consumption

- Communication
  - A sensor expends maximum energy in data communication (both for transmission and reception)

NOTE:

- For short range communication with low radiation power (~0 dbm), transmission and reception power costs are approximately the same, (e.g., modern low power short range transceivers consume between 15 and 300 milliwatts of power when sending and receiving)
- Transceiver circuitry has both active and start-up power consumption

Power Consumption

- Power consumption for data communication (P_c)

$$P_c = P_{te} + P_{re} + P_0$$

$P_{te}/_{re}$ is the power consumed in the transmitter/receiver electronics (including the start-up power)

P_0 is the output transmit power

Energy Supply of Sensor Nodes

- Goal: Provide as much energy as possible at smallest cost/volume/weight/recharge time/longevity
  - In WSNs, recharging may or may not be an option
- Options
  - Primary batteries – not rechargeable
  - Secondary batteries – rechargeable, only makes sense in combination with some form of energy harvesting

Battery Examples

- Energy per volume (Joule per cubic centimeter):

Primary batteries			
Chemistry	Zinc-air	Lithium	Alkaline
Energy (J/cm^3)	3780	2880	1200
Secondary batteries			
Chemistry	Lithium	NiMHd	NiCd
Energy (J/cm^3)	1080	860	650

Energy Scavenging

- Ambient Energy Sources
  - Light Solar Cells – between 10 μW/cm² and 15 mW/cm²
  - Temperature Gradients – 80 μ W/cm² @ 1 V
  - Vibrations – between 0.1 and 10000 μ W/cm³
  - Pressure Variation (piezo-electric) – 330 μ W/cm² from the heel of a shoe
  - Air/liquid flow (MEMS gas turbines)

Energy Scavenging

Energy source	Energy density
Batteries (zinc-air)	1050 – 1560 mWh/cm³
Batteries (rechargable lithium)	300 mWh/cm³ (at 3 – 4 V)
Energy source	**Power density**
Solar (outdoors)	15 mW/cm² (direct sun)
	0.15 mW/cm² (cloudy day)
Solar (indoors)	0.006 mW/cm² (standard office desk)
	0.57 mW/cm² (< 60 W desk lamp)
Vibrations	0.01 – 0.1 mW/cm³
Acoustic noise	$3 \cdot 10^{-6}$ mW/cm² at 75 Db
	$9,6 \cdot 10^{-4}$ mW/cm² at 100 Db
Passive human-powered systems	1.8 mW (shoe inserts)
Nuclear reaction	80 mW/cm³, 10^6 mWh/cm³

Energy Consumption

- Number of instructions
  - Energy per instruction: 1 nJ
  - Small battery ("smart dust"): 1 J = 1 Ws
  - Corresponds: 10^9 instructions!
- Lifetime
  - Or: Require a single day operational lifetime = 24*60*60 =86400 s

Multiple Power Consumption Modes

- Way out: Do not run sensor node at full operation all the time
  - If nothing to do, switch to ***power safe mode***
  - Question: When to throttle down? How to wake up again?
- Typical modes
  - Controller: Active, idle, sleep
  - Radio mode: Turn on/off transmitter/receiver, both

Multiple Power Consumption Modes

- Multiple modes possible, “deeper” sleep modes
  - Strongly depends on hardware
  - TI MSP 430, e.g.: four different sleep modes
  - Atmel ATMega: six different modes

Some Energy Consumption Figures

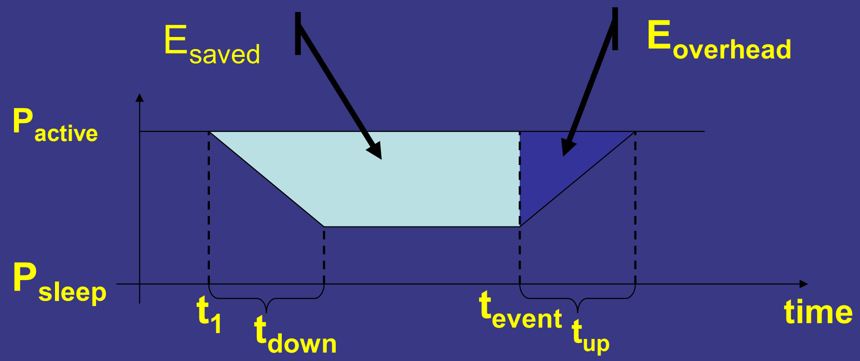
- Microcontroller
  - TI MSP 430 (@ 1 MHz, 3V):
    - Fully operation 1.2 mW
    - Deepest sleep mode 0.3 μW – only woken up by external interrupts (not even timer is running any more)
  - Atmel ATMega
    - Operational mode: 15 mW active, 6 mW idle
    - Sleep mode: 75 μW

Switching Between Modes

- Simplest idea: Greedily switch to lower mode whenever possible
- Problem: Time and power consumption required to reach higher modes not negligible
  - Introduces overhead
  - Switching only pays off if $E_{saved} > E_{overhead}$

Switching Between Modes

- Example: Event-triggered wake up from sleep mode
- Scheduling problem with uncertainty



Alternative: Dynamic Voltage Scaling

- Switching modes complicated by uncertainty of how long sleep time is available
- Alternative: Low supply voltage & clock
  - Dynamic Voltage Scaling (DVS)
- Rationale:
  - Power consumption P depends on
    - Clock frequency
    - Square of supply voltage
    - $P / f V^2$

Memory Power Consumption

- Crucial part: FLASH memory
  - Power for RAM almost negligible
- FLASH writing/erasing is expensive

Controlling Transceivers

- Low duty cycle is necessary
  - Easy to do for transmitter: When is it worthwhile to switch off?
  - Difficult for receiver: Not only time when to wake up not known, it also depends on ***remote*** partners

  ! Dependence between MAC protocols and power consumption is strong!

Controlling Transceivers

- Only limited applicability of techniques analogous to DVS
  - Dynamic Modulation Scaling: Switch to modulation best suited to communication – depends on channel gain
  - Dynamic Coding Scaling: Vary coding rate according to channel gain
  - Combinations

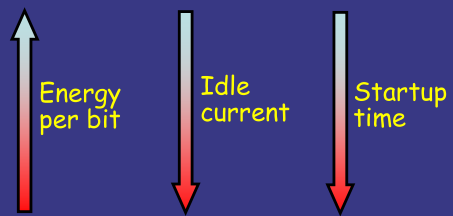
Computation vs. Communication Energy Cost

- Tradeoff?
  - Directly comparing computation/ communication energy cost not possible
  - But, put them into perspective!
  - Energy ratio of "sending one bit" vs. "computing one instruction": Anything between 220 and 2900 in the literature
  - To communicate (send & receive) one kilobyte
    = computing three million instructions!

Computation vs. Communication Energy Cost

- Hence, try to compute instead of communicate whenever possible
- Key technique in WSN: ***in-network processing!***
  - Exploit compression schemes, intelligent coding schemes, …

Comparison



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

Many Ways to Optimize Power Consumption

- Power-aware computing
  - Ultra-low power microcontrollers
  - Dynamic power management HW
    - Dynamic voltage scaling (e.g Intel's PXA, Transmeta's Crusoe)
    - Components that switch off after some idle time
- Energy-aware software
  - Power-aware OS: Dim displays, sleep on idle times, power-aware scheduling
- Power management of radios
  - Sometimes listen overhead larger than transmit overhead

Many Ways to Optimize Power Consumption

- Energy-aware packet forwarding
  - Radio automatically forwards packets at a lower level, while the rest of the node is asleep
- Energy aware wireless communication
  - Exploit performance energy tradeoffs of the communication subsystem, better neighbor coordination, choice of modulation schemes

Putting it All Together: Power-Aware Sensor Node