Northwestern University

Wireless Sensor Networks and RFIDs

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Outline:

- Enabling technology trends.
- History
- Single Sensor Node Architecture.
  - Hardware
  - Software
- Design considerations

Design considerations

In addition to performance, much of sensor net design is driven by three (often conflicting) factors:

1. **Cost:** less is better
2. **Size:** smaller is (often) better
3. **Energy-efficiency:** longer lifetime is better

Design Considerations

- Cost: Currently $\approx$ \$100
  - Economies of scale could bring this down to < \$10.
  - For some areas $\approx$ \$1 needed to drive adoption.
- Size:
  - MEMS and Nano-tech will likely reduce size of chips.
  - Some designs already at $\approx 1cm^2$.
    - except for batteries/sensors
  - In some cases packaging may dominate chip size.
  - Antenna size can also be important.
- Energy-efficiency:
  - Some applications require 1-5 year lifetimes.
  - One of the most challenging issues for sensor nets.

Energy Efficiency

- Recall 1 Watt = 1 Joules/sec.
- Total energy in joules
  - Lifetime of a node =1/(Watts used)
- Reasonable lifetimes ⇒ operate at low Watts!
- One Christmas tree light = 0.5 W
  - Want Motes to use 1/10,000th of this on average!

Energy Efficiency

- Typical energy sources
  - Non-rechargeable coin-size or AA battery:
    - stores ≈ 3 watt-hours.
    - Shelf life of ≈ 5 years.
  - Lithium-Thionyl Chloride AA battery
    - ≈ 8 watt-hours.
    - More expensive.
- Example energy consumption:
  - Micro-controller: 10mW
  - Short-range radio: 20 mW
- Typical battery at 30mW lasts < 5 days!

Energy efficiency solutions?

1. Find better energy sources
2. Lower energy consumption

Better energy sources

Battery technology is fairly mature.

– current power density is within 1000 of that of nuclear reactions/ within 2-10 of fuel cells.

Renewable sources:

– **solar cells:** power density = 15mW/cm^2 in direct sun. drops to 0.15mW/cm^2 in clouds.
– Other forms of scavenging have even lower power densities.

- In some cases replenishment/energy delivery possible.

Energy efficiency solutions?

1. Find better energy sources
2. Lower energy consumption

Energy Consumption

- Computation and Communication are main energy consumers.
- Excessively writing to FLASH memory can also impact memory.
  - Reading requires less energy.
  - Reading/writing to on-board memory considered part of processing power.
- Most sensors use little energy
  - Exceptions are active sensors.
  - A/D costs can be important for large data streams.

Processing power

- Processing power:
  - Integrated circuits require power each time a transistor pair is flipped.
  - In CMOS:

$$\text{Power} = 0.5\ CV_{dd}^2 f$$

C = device capacitance (related to area)

V_{dd} = voltage swing

f = frequency of transitions (clock speed).

Processing power

$$\text{Power} = 0.5\ CV_{dd}^2 f$$

- Moore's law decreases C.
- What about V_{dd} and f ?
  - Decreasing f slows down processor.
  - Decreasing V_{dd} has similar effect, indeed:

$$\frac{1}{f} \propto \frac{V_{dd}}{(V_{dd} - V_t)^2}$$

  - Dynamic voltage scaling (DVS) – adjust V_{dd} and f in response to computational load.

DVS example

Suppose a processor can be scaled from 700Mhz at 1.65 V to 200 Mhz at 1.1 V.

What is reduction in power and speed?

Energy/instruction?

Processor alternatives

Year	ASIC	FPGA	Microprocessor
1999	1 pJ/op	10 pJ/op	1 nJ/op
2004	0.1 pJ/op	1pJ/op	100pJ/op

- As noted earlier ASICs and FPGAs have better energy efficiencies.
  - Less flexibility/higher costs.
- All “ride Moore’s law” at roughly the same rate.

Dynamic power management

- When “on” processors consume power even if idle (e.g. generating clock signal)
- In most sensor nodes, only need to be “active” a small fraction of the time.
- Can conserve power by putting processor into various “sleep” modes when not active.

Dynamic power management

- Most microcontrollers provide one or more sleep states.
  - Difference is in how much of the chip is shut down.
  - Note some Energy is required to change state
    - Usually more Energy to return to active the deeper the sleep.

Dynamic power management

Example: Intel StrongARM microcontroller

3 modes:

- *Active mode* – all parts powered, consumes up to 400mW
- *Idle mode* – CPU clock stopped, clocks for peripherals are active, power consumption = 100 mW.
- *Sleep mode* – only real-time clock remains active. Wake-up only via timer, power consumption = 50μW

Dynamic power management

Example continued:

Given 5000 Joule battery, controller will operate for

5000 J/400mW = 12500 sec = 208 minutes

If active only 1% of the time, can extend this to ≈ 14 days

Communication Power

Energy consumption in radio transmission:

1. Energy radiated by the antenna.
2. Energy consumed by needed electronic components (oscillators, mixers, filters.)

The second component is also present when receiving. (or even if just “listening”).

Radiated energy

- Amount of radiated energy depends on distance to receiver and target transmission rate.
  - I.e. need to transmit enough energy to get target SNR at receiver.
  - For given rate: $P_r \propto d^{\alpha}$, $\alpha \approx 4$ for most sensor nets.
- Also depends on antenna type/power amplifier.
  - For small sensors, antennas maybe in efficient.
  - Power into power amp often $\approx$ 4 times transmitter power

Communication Energy

- Circuit energy is roughly constant and independent of distance.
  - on the order of 1-10mW
- For large distances, transmission energy dominates.
- For short distance, circuit energy should also be considered.

Communication Energy

Example: For a particular radio the power consumption while on is 2mW. When transmitting at a peak power of 10mW the power amplifier has an energy efficiency of 25%.

What is total power while transmitting?

Communication power and multi-hop

- Are two hops better than one?

Processing vs. transmitting

- For motes transmitting 1-bit costs same as executing $\approx$ 1,000 processor instructions.
- Can save on transmission costs by intelligently processing data before transmitting!
- Data aggregation/fusion.

Data fusion example

- Averaging in network vs. averaging outside.

Dynamic power management

- Dynamic power management also useful for communication power.
- Turn radio off when nothing to send/receive.
- Note while off can not receive.

Dynamic power management

- Taking into account DPM can change transceiver trade-offs.
  - e.g. is it better to send at high rate for short time and sleep or slow rate for longer time?

Hibernation

Key Issue: when to wake-up?

Possibilities:

1. At regular intervals
   - need synchronization
2. Trigger by stimulus
   - e.g. heat sensitive circuit.

Network Size Issues

- Energy efficiency and network size.

Heterogeneous network

- Another way to reduce power is to have nodes with heterogeneous capabilities.

Possible design trade-offs:

- Millennial Net "I-Bean" sensor platform
  - 10-year life at "normal sampling mode" (once per 100 sec.) with coin-size lithium battery.
  - But only limited transmission range (30m)
    - Vs. ≈ 300m with MICA-2