TIWSNE – Wireless Sensor Networks and Electronics – (2015-Q4)

Lecture 3

HW nodes & Energy consumption

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Lecture plan

- Two lectures about HW modes & Energy
  - Today – theory (part 1)
    - Sensor node (mote) HW/Architecture
      - Survey of the main components
    - Energy (power) supply and consumption
      - Understand energy consumption aspects for these components
    - Energy sources incl. harvesting methods
    - Power management
  - Lab exercise (part 2)
    - Tuesday 28/4 – group 1 to n
    - Tuesday 5/5 – group n+1 to N

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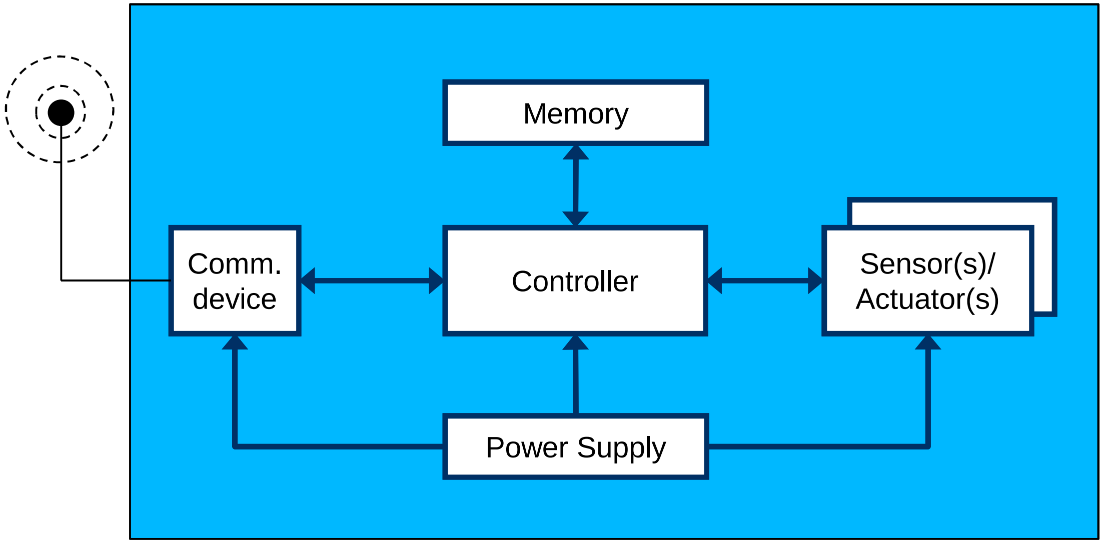
Sensor node architecture

- Three characteristics:
  - Sensing/controlling
  - Processing
  - Communication
- Five major components:



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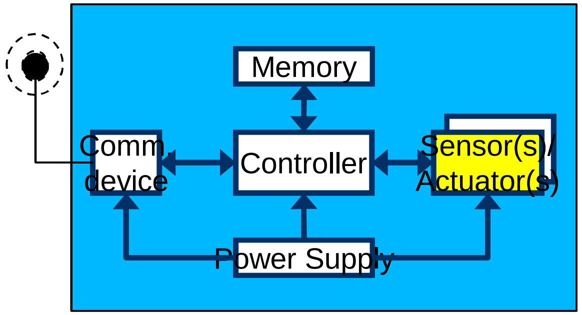
Sensors

- Purpose is to sense (control) some physical or environmental condition, such as temperature, and turn it into a signal for reading and/or further processing
- There exist “thousands” of different kind of sensors
  - Own interface specifications
    - No general interface
- Characteristics
  - Any energy radiated ?
  - Passive or active ?



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Sensors - Categories

- Main categories
  - Passive, omnidirectional
    - Ex: Thermometer, microphones
  - Passive, narrow-beam
    - Ex: Camera
  - Active
    - Ex: Radar
- Use of integrated electronics provides outputs easy to interface to microprocessor e.g.
  - A digital interface
  - An (analog) low impedance voltage

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Sensors – Ex. Temperature

- An analog temperature sensor consists of a chip that tells what the ambient temperature is!
  - Utilize that voltage across a diode change with temperature
  - Precisely amplifying the voltage change generates an analog signal that is directly proportional to temperature
- **Ex. ADI TMP36**
  - **Temp in °C = [(Vout in mV) - 500] / 10**
  - **What is temperature if Vout = 1V ?**
  - **What is ΔVout if ΔTemp = 1°C ?**

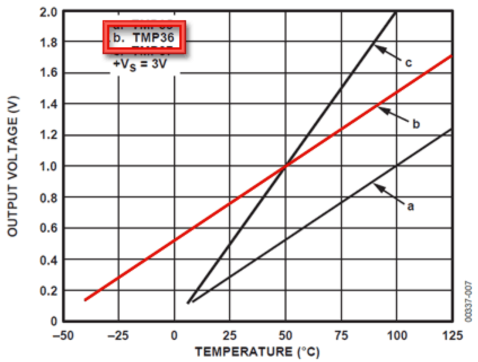
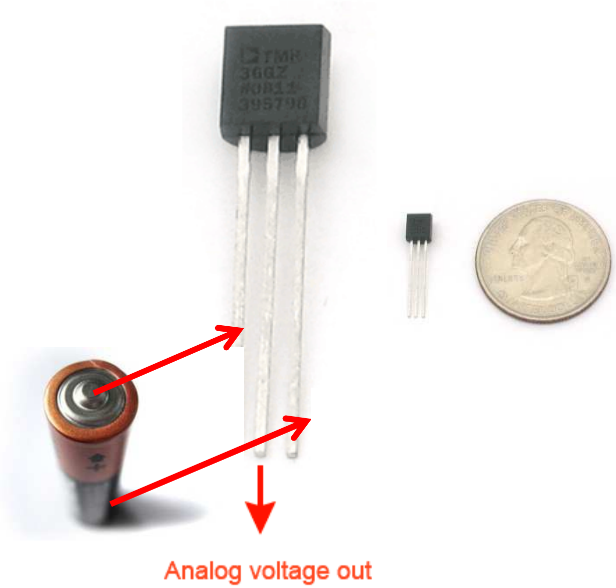


Figure 6. Output Voltage vs. Temperature



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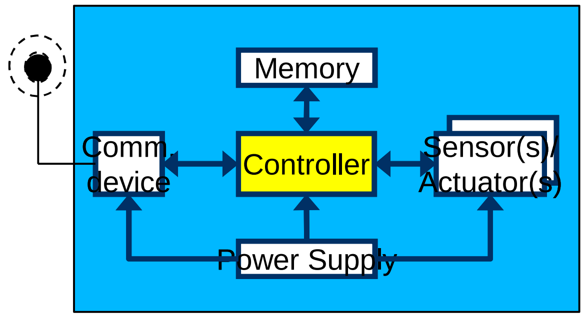
Controller

- Purpose of the controller is to process (all) tasks:
  - Collecting and processing data from sensors, and prepare data for communication
  - Execute programs
    - Start-up and initialization
    - Time critical signal processing
    - Communication protocols
    - Applications
      - Aggregate data (e.g. avg temperature measurements)

“CPU” of the node



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Controller - Options

- Various architectures - trade-offs between:
  - Flexibility
  - Performance
  - Energy efficient
  - Costs
- Main options (HW implementations - chips)
  - Microcontrollers – “Slim” general purpose processor
  - DSPs – Optimized signal processor
  - FPGAs – Re-programmable (soft application specific) IC
  - ASICs – Application specific IC

Controller - Options (cont.)

	Microcontroller	DSP	FPGA	ASIC
Flexibility				
Performance				
Energy efficient				
Cost (development)	N/A	N/A		
Cost (per pcs)				
Comments	Tailored embedded application	Tailored signal processing	Good for testing / small volume	Peak performance / large volume

- To be energy efficient the controller should be able to operate in low power modes, i.e. it should be possible to move efficiently between sleeping and working/active states

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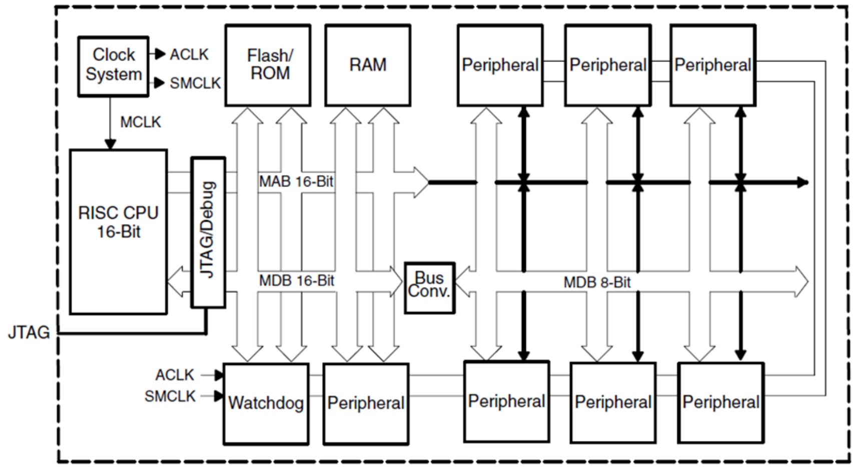
Controller – Examples of Microcontrollers

- Texas Instruments MSP430 (many versions/flavours)
  - 16-bit RISC core, 4-48 MHz, up to 66KB RAM, up to 512KB Flash, several DACs, prices starts at ~0.25 USD
  - 32-bit version (MSP432) based on ARM Cortex M4 core
  - Low power modes of operation (active-to-idle-to-sleep)



- ARM Cortex-Mx (x=0,1,2,3,4,7) based ones
  - 32 bits optimized for energy and mixed-signal appls.

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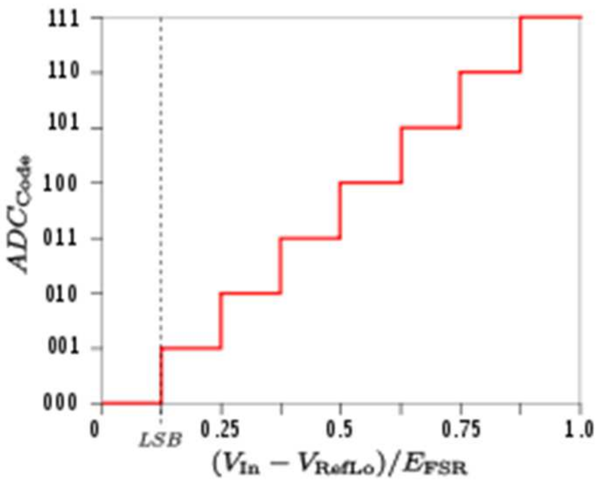
Controller – Ex. Temperature continued.

- Ex.: Temperature Sensor (ADI TMP36) connected to an ADC (Analog-2-Digital Converter) in the Microcontroller
  - Full scale measurement range = 0 to 2 volts
  - ADC resolution is 10 bits: 2^{10} = 1024 quantization levels (codes)
  - What is the ADC voltage resolution ?
  - What is the ADC temperature resolution?



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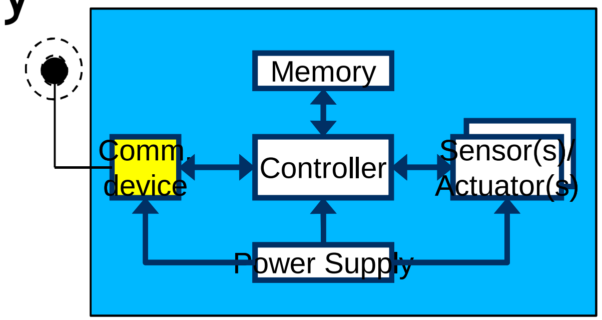
Communication device

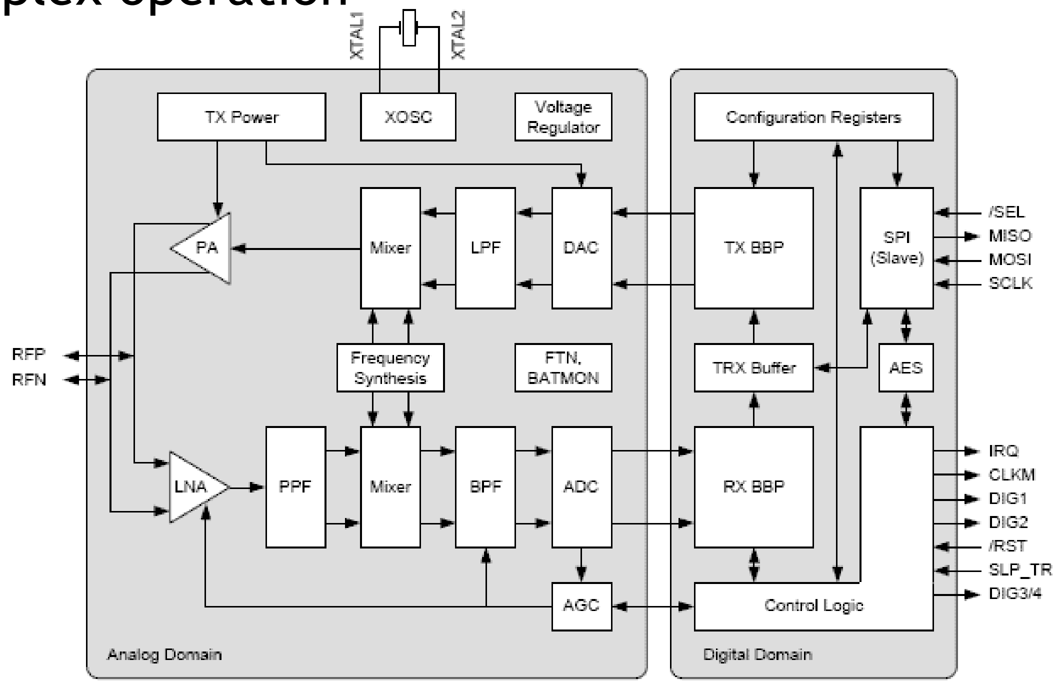
- The purpose of the communication device is to exchange data between individual nodes
- Which transmission medium for wireless?
  - Electromagnetic at radio frequencies ?
  - Electromagnetic, light ?
  - Ultrasound ?
- Radio Frequency (RF)-based communication is the preferred and dominant technology
  - Relatively long range and overcome challenging “corners”
  - High data rates
  - Acceptable bit error rates

All at reasonable energy expenditures



Communication device (cont.)

- The communication device receives (transmit) bit- or byte streams from (to) the controller and convert them to (from) radio waves
- Combined device - Transmit and Receive = Transceiver
- Half Duplex operation



Transceiver states

- Transceivers can be put into different operational ***states***, typically:
  - ***Transmit***
  - ***Receive***
  - ***Idle*** – ready to receive, but not doing so
    - Some functions in hardware can be switched off, reducing energy consumption a little
  - ***Sleep*** – significant parts of the transceiver are switched off
    - Not able to immediately receive something
    - ***Recovery time*** and ***startup energy*** to leave sleep state can be significant

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Transceiver characteristics

- Capabilities
  - Interface: bit, byte, packet level?
  - Supported frequency range?
    - Typically, somewhere in 433 MHz – 2.4 GHz, ISM band
  - Multiple channels
  - Data rates
  - Range
- Energy characteristics
  - Power consumption to send/receive data?
  - Time and energy consumption to change between different states
  - Transmission power control
  - Power efficiency (which percentage of consumed power is radiated?)
- Radio performance
  - Modulation? (ASK, FSK, …?)
  - Noise figure? $NF = SNR_I/SNR_O$
  - Gain? (signal amplification)
  - Receiver sensitivity? (minimum S to achieve a given E_b/N_0)
  - Blocking performance (achieved BER in presence of frequency-offset interferer)
  - Out of band emissions
  - Carrier sensing & RSSI characteristics
  - Frequency stability (e.g., towards temperature changes)
  - Voltage range

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Example radio transceivers

- Almost boundless variety available – two examples:

- TI Chipcon CC2420
  - Implements 802.15.4
  - 2.4 GHz (carrier frequency)
  - 250 kbps (data rate)
  - 16 channels
  - Low power consumption
    - Rx 18.8 mA, Tx 17.4mA (0dBm)
    - Idle 0.4mA, Sleep 0,02mA
- DustNetwork DN2510 (Linear Technology)
  - Similar as CC2420
  - Ultra low power consumption
    - Rx 6mA, Tx 7mA (0 dBm)
  - Next gen 50% reduction

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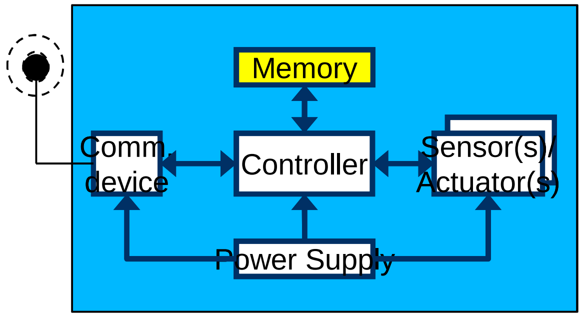
Memory

- Store programs and collected data requiring non-volatile memories, i.e. content not lost when the power is turned off
  - Read-Only Memory (ROM) – Can only be read (slow write)
  - Flash - Can be electrically erased and reprogrammed
  - Both of these have very high density (Mb/mm2)
- Variable data is stored in Static Random-Access Memory (SRAM) which is volatile, i.e. content lost when the power is turned off
  - Faster access than Flash or ROM
  - Lower dynamic power dissipation than Flash or ROM
  - ~10 times lower density that Flash or ROM
- On-chip memories (see microcontroller)
  - Extra external Flash via serial interface



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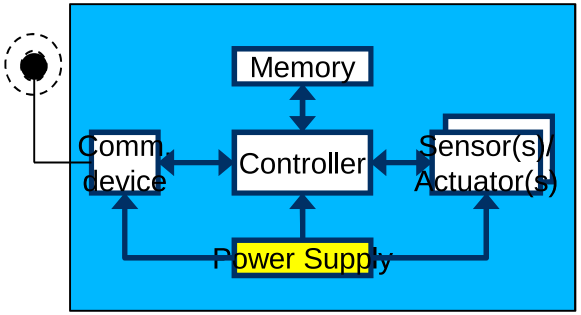
Energy/power supply

- Energy storage (reservoirs)

- Power distribution & management

- Energy harvesting



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Energy/power supply

- Goal: provide as much energy as possible at smallest cost/volume/weight/recharge time/longevity
  - In WSN, 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
- Requirements include
  - Low self-discharge
  - Long shelf live
  - Capacity under load
  - Voltage stability (to avoid DC-DC conversion)
  - ….

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Battery examples

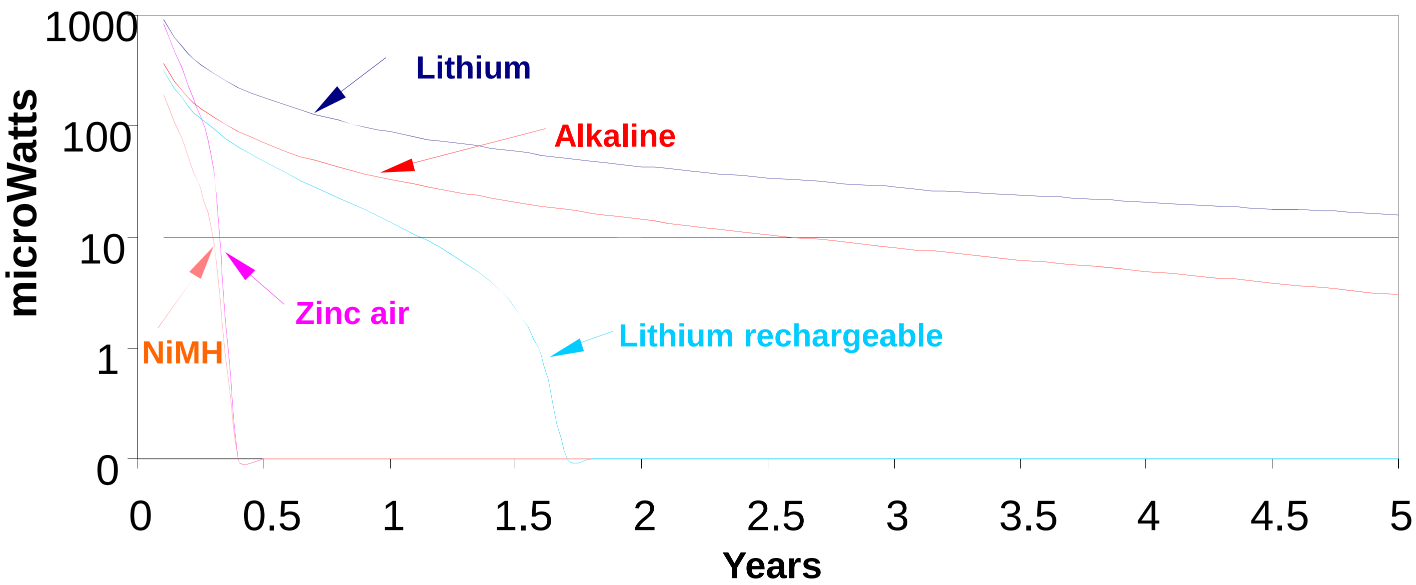
- Energy per volume (J/cm^3) – Energy Density

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

- Familiar alkaline "cylindrical cell" batteries
  - AAA, AA, C
  - Lithium based one as well
- Lithium "coin cell" batteries
  - DT size where D is diameter ([mm]) and T i thickness ([mm/10])
  - Popular 2032, i.e. 20 mm diameter and 3.2 mm thickness ~1 cm^3

Battery examples

- Additional info:
  - Lithium batteries flat discharge profile , i.e. constant voltage over most of their life time
  - Alkaline batteries linear decrease in voltage – limit lifetime
  - Lithium batteries has lowest internal leakage /self-discharge
  - Lithium most expensive
- Continuous Power / cm3 vs. Life



Power Problem

- **Example 1**
  - At an average power consumption of *100* μ*W*, we need slightly more than *1 cm3* of lithium battery volume for *1 year* of operation, assuming we can use 100% of the charge in the battery.
  - Energy density of rechargeable batteries is less than half that of primary batteries.
  - So, someone needs to either replace batteries in every node every ~ 9 months, or recharge every battery every 3 to 4 months.
  - In most cases, this is not acceptable.

Power Problem

- Example 2:
  - Number of instructions
    - Energy per instruction: 1 nJ
    - Small battery (“smart dust” – cubic-mm): 1 J = 1 Ws
    - Corresponds: 10^9 instructions!
  - Lifetime
    - Or: Require a single day operational lifetime = 24x60x60 =86400s
    - 1 Ws / 86400s ≈ ***11.5 μW*** as max. sustained power consumption!
      - Ex. MSP 430 ~1mW when active! (rougly 100 times more ~864s ~15mins operation)
  - Not feasible! (today)

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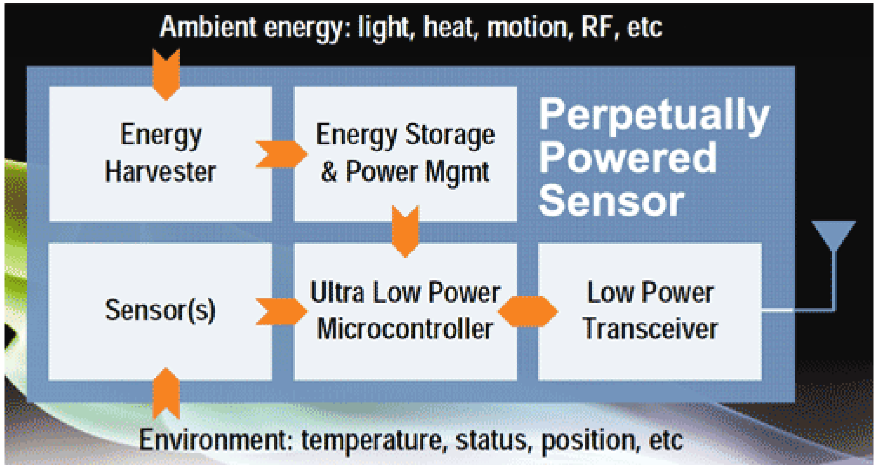
Energy harvesting

- How to recharge a battery?
  - A laptop: easy, plug into wall socket in the evening
  - A sensor node? – Try to ***harvest*** energy from environment



- Ambient energy sources
  - Light ! solar cells
  - Temperature gradients difference
  - Vibrations
  - Pressure variation (piezo-electric) from the heel of a shoe
  - ……

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Energy harvesting – overview

Energy source	Energy density
Batteries (zinc-air)	$1050 - 1560\,\mathrm{mWh/cm^3}$
Batteries (rechargable lithium)	$300\,\mathrm{mWh/cm^3}$ (at $3 - 4\,\mathrm{V}$)

Energy source	Power density
Solar (outdoors)	$15\,\mathrm{mW/cm^2}$ (direct sun)
	$0.15\,\mathrm{mW/cm^2}$ (cloudy day)
Solar (indoors)	$0.006\,\mathrm{mW/cm^2}$ (standard office desk)
	$0.57\,\mathrm{mW/cm^2}$ (< 60 W desk lamp)
Vibrations	$0.01 - 0.1\,\mathrm{mW/cm^3}$
Acoustic noise	$3 \cdot 10^{-6}\mathrm{mW/cm^2}$ at $75\,\mathrm{Db}$
	$9,6 \cdot 10^{-4}\mathrm{mW/cm^2}$ at $100\,\mathrm{Db}$
Passive human-powered systems	$1.8\,\mathrm{mW}$ (shoe inserts)
Nuclear reaction	$80\,\mathrm{mW/cm^3}$, $10^6\,\mathrm{mWh/cm^3}$

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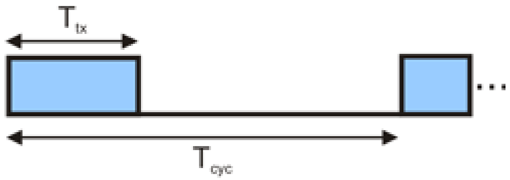
Power Problem “solution”

- What can we do?
  - Utilize that most of the time the Sensor node has nothing to do!
  - Turn it off, i.e. go into sleep (less power) when nothing to do and wake up again when required
    - External stimuli
    - Timer
  - Known as Duty-Cycling
    - Active (e.g. 1%)
    - Sleep (e.g. 99%)
  - Combine this if possible with energy harvesting, i.e. recharge battery continuously even when system is sleeping

$$\text{Duty cycle} = \frac{T_{tx}}{T_{cyc}}$$



T_{tx} = transmission period
T_{cyc} = total cycle period

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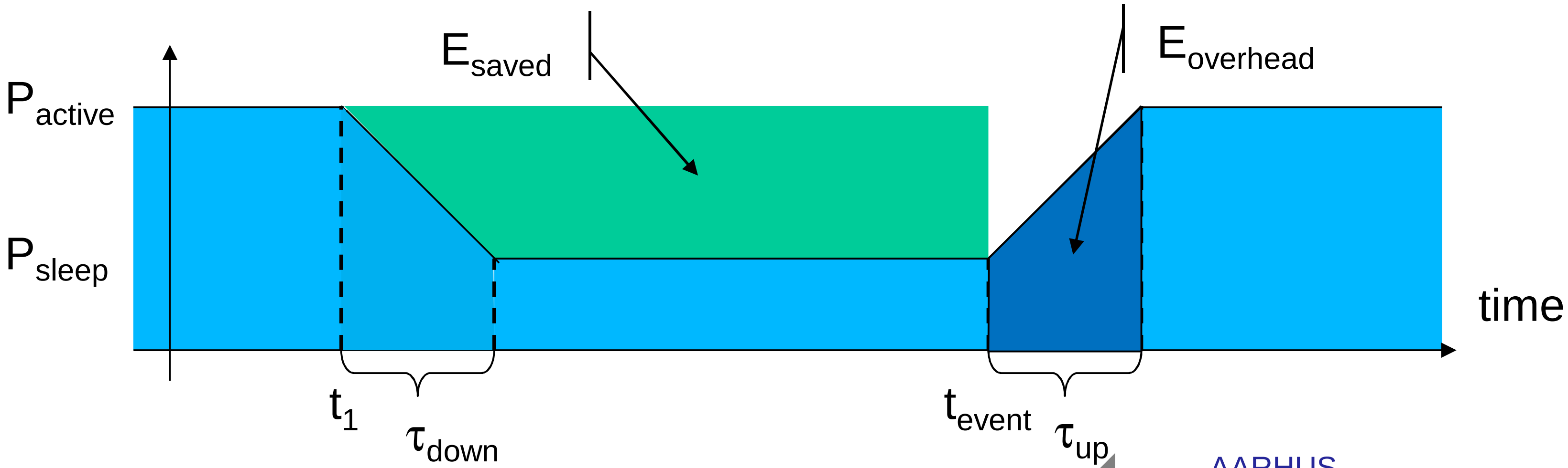
Switching between operation (consumption) modes

- 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 ?

- Example: Event-triggered wake up from sleep mode



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Some energy consumption figures

- Microcontroller
  - TI MSP 430 (@ 1 MHz, 3V):
    - 300 µA active (~1mW)
    - 0.5 µA standby/idle (~1.5µW)
    - 0.1 µA power down /deep sleep(~0.3µW)– only woken up (1µS) by external interrupts (not even timer is running any more)
  - Atmel ATMega
    - Operational mode: 15 mW active, 6 mW idle
    - Sleep mode: 75 µW

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Memory power consumption

- Crucial part: FLASH memory
  - Power for SRAM almost negligible (but leakage)

- FLASH writing/erasing is expensive
  - Example: FLASH on Mica motes
  - Reading: ≈ 1.1 nAh per byte
  - Writing: ≈ 83.3 nAh per byte

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Controlling transceivers

- Similar to controller, low duty cycle is necessary
  - Easy to do for transmitter – similar problem to controller: 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

- Example
  - TI CC2420
    - Rx 18.8 mA, Tx 17.4mA (0dBm)
    - Idle 0.4mA, Sleep 0,02mA

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

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2-and-2 exercise

- Radio
  - Data rate 250kbps, TX current 25mA (I)
- Sample a sensor once per sec. and send the 8 bit result
- Calculate the average current over time (charge Q) per sample in the following scenarios: (Note: I = dQ/dt, i.e. dQ = Idt)

  a) No energy consumed to acquire the sample. No startup time for the radio – just wake up and transmit sample and go back to sleep immediately after transmission.

  b) As in (a) except the radio burns an average of 10 mA during a 1ms startup period.

  c) As in (b) except we collect samples for two minutes at a time, and send all 120 samples at the end of each two minute period.

     a) How much longer can the radio/mote run when supplied from a battery?

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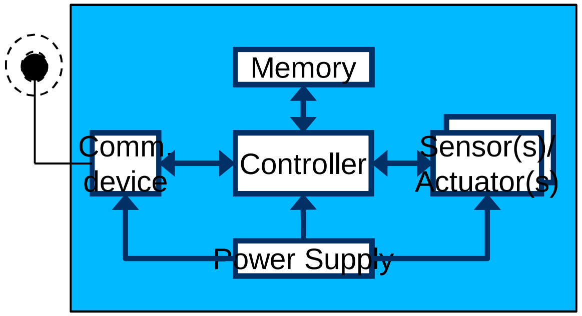
Summary

- For WSN, the need to build cheap, low-energy, (small) devices has various consequences for system design
  - Radio frontends and controllers are much simpler than in conventional mobile networks
  - Power management (switching off or throttling down devices) is crucial
  - Energy supply and harvesting are still (and for the foreseeable future) a premium resource
  - Try to compute instead of communicate whenever possible



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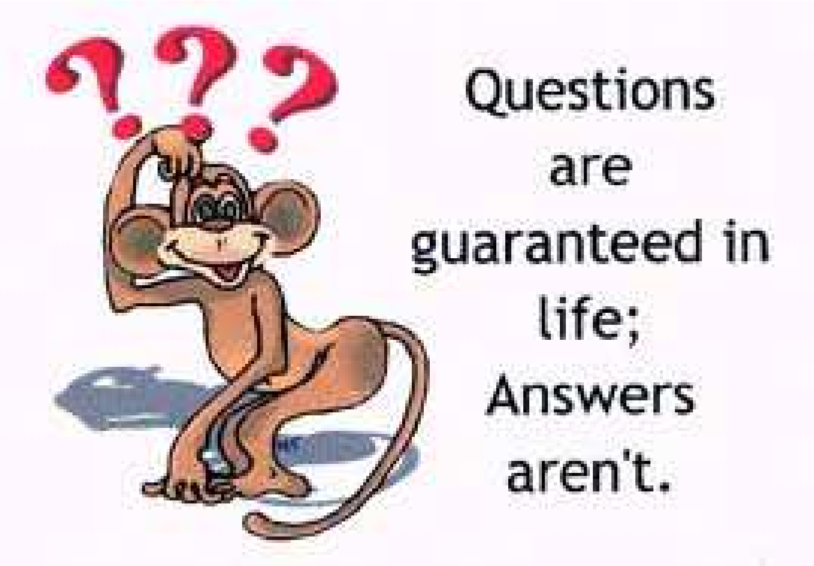

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