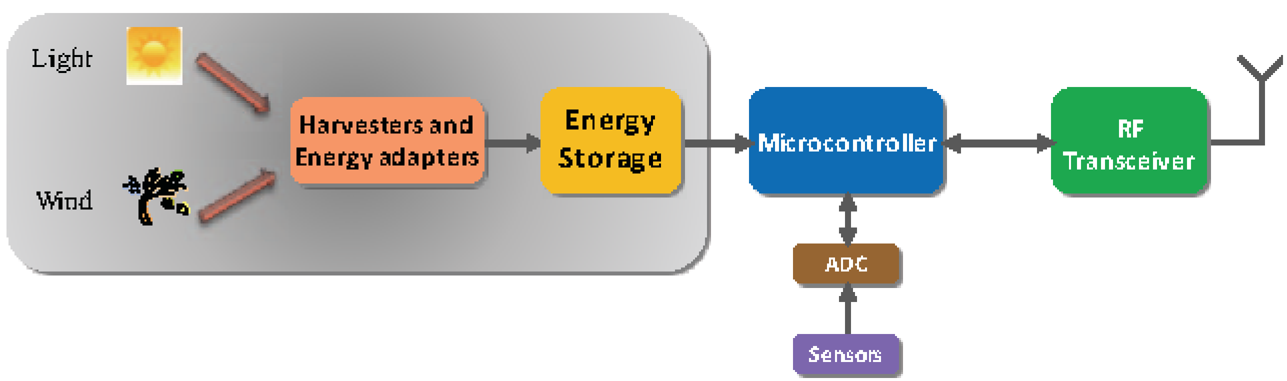
Internet of Things
Design Decisions & Power Calculation

Power supply

- Energy is the most critical resource in a battery operated device (sensor node, “thing”)
- Energy supply has two tasks
  - Provision of electrical energy
    - Typically with batteries
  - Conversion of other energy forms
    - Extraction of energy from the environment
    - Energy harvesting

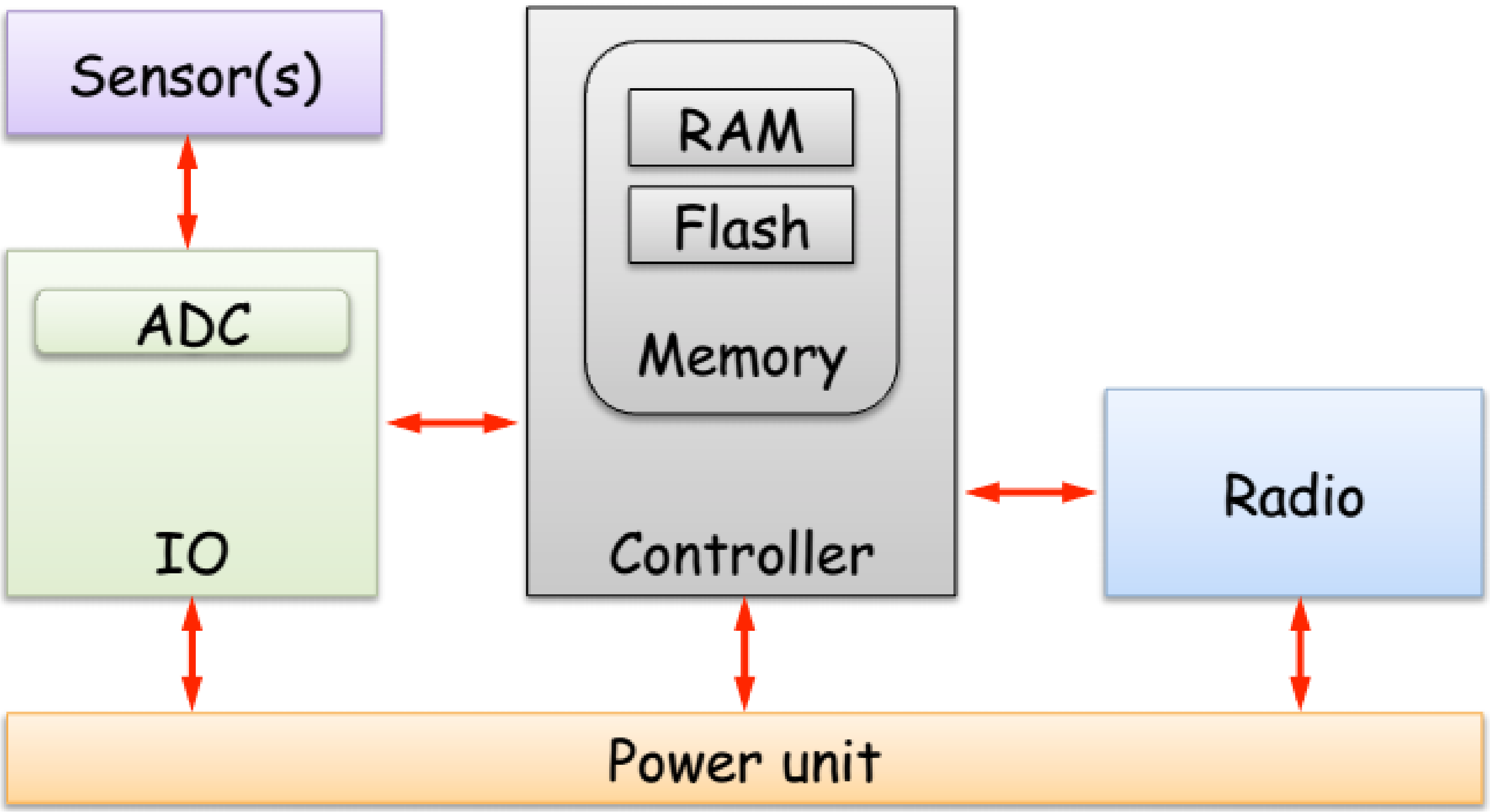


Energy consumption of sensor nodes

- Energy characteristic of the components
  - Radio interface consumes the most energy
  - Ratio of energy requirements of CPU / radio interface

    E(1 Instruction of CPU) : E(Sending of 1 bit) ≈1:1500 – 1:2900
  - Send and receive operations are roughly equal expensive
  - Best energy consumption reduction: switch-off radio
- Flash-Memory has high energy requirements
  - Write operation ~900 times more expensive than read operation
- Processor not so critical
  - Typically several power modes available
- Sensors / Actors
  - Varies between components and difficult to predict

Hardware Node



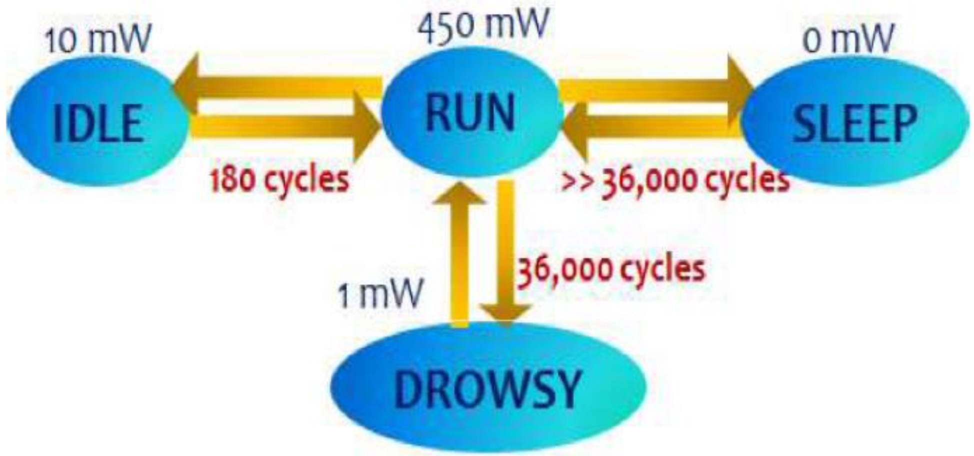
Energy Consumption Estimation in Embedded Systems

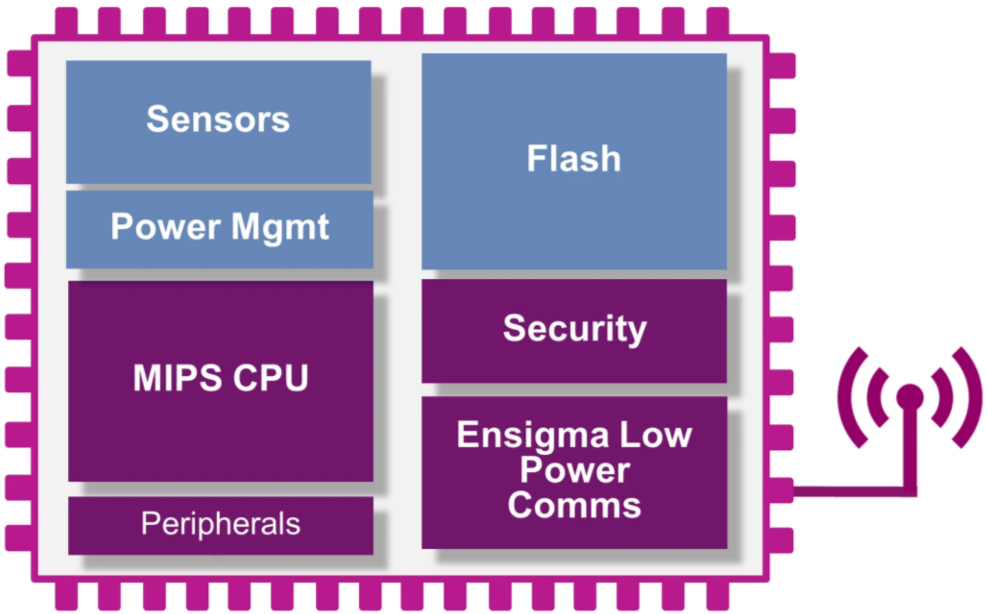
$$E_{node} = E_{microcontroller} + E_{Sensor+ADC} + E_{radio}$$

- Estimate the energy used per operation cycle

$$E_{microcontroller} = cp1.\#instructions1\text{-}cycle + cp2.\#instructions2\text{-}cycles + cp3.\#instructions3\text{-}cycles + cp4.\#instructions4\text{-}cycles + cp5.\#instructions5\text{-}cycles$$

Power Management





Communication interfaces

- Communication interface is required to exchange data with other devices
- Typical communication media
  - Radio
  - Infrared (IR)
- Communication interface has high energy consumption
- Radio interface consumes the most energy usually

ISM Frequencies Worldwide

Frequency Range		Bandwidth	Center Frequency
6.765 MHz	6.795 MHz	30 kHz	6.78 MHz
13.553 MHz	13.567 MHz	14 kHz	13.56 MHz
26.957 MHz	27.283 MHz	326 kHz	27.12 MHz
40.66 MHz	40.70 MHz	40 kHz	40.68 MHz
433.05 MHz	434.79 MHz	1.84 MHz	433.92 MHz
902 MHz	928 MHz	26 MHz	915 MHz
2.4 GHz	2.5 GHz	100 MHz	2.45 GHz
5.725 GHz	5.875 GHz	150 MHz	5.8 GHz
24 GHz	24.25 GHz	250 MHz	24.125 GHz
61 GHz	61.5 GHz	500 MHz	61.25 GHz
122 GHz	123 GHz	1 GHz	122.5 GHz
244 GHz	246 GHz	2 GHz	245 GHz

Low Power Modules Available

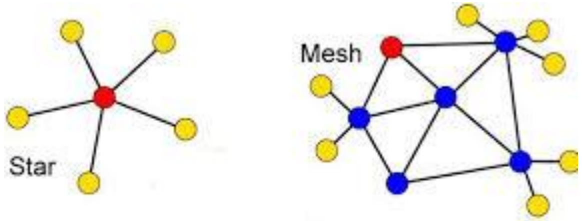
- **Bluetooth low energy:** Bluetooth® low energy (LE) started life as a project in the Nokia Research Centre with the name Wibree. (2.4 GHz)
- **ANT**: is a low-power proprietary wireless technology which operates in the 2.4 GHz spectrum
- ZigBee: is a low-power wireless specification based on IEEE Standard 802.15.4-2003
- **RF4CE:** Radio Frequency for Consumer Electronics (RF4CE) is based on ZigBee and was designed by four consumer electronics companies: Sony, Philips, Panasonic, and Samsung.

Low Power Modules Available

- **WiFi**
- **IRDA**: Infrared Data Association (IrDA) has recently announced an ultra-high-speed connectivity version, yielding 1 Gbps. However, it only works over a distance of **less than 10 cm**. One of the main problems with infrared (IR) is its line-of-sight requirement
- **Nike+:** is a proprietary wireless technology developed by Nike and Apple to allow users to monitor their activity levels while exercising.

Network topologies

- **Broadcast:** A message is sent from a device in the hope that it is received by a receiver within range. The broadcaster doesn't receive signals.
- **Mesh:** A message can be relayed from one point in a network to any other by hopping through multiple nodes.
- **Star:** A central device can communicate with a number of connected devices — Bluetooth is a common example.
- **Scanning:** A scanning device is constantly in receive mode, waiting to pick up a signal from anything transmitting within range.
- **Point-to-Point:** In this mode, a one-to-one connection exits, where only two devices are connected, similar to a basic phone call.



Supported Topologies

	LA	A	A+	Zi	RF	Wi	Ni	Ir
Broadcast	√	√	√	x	x	x	x	x
Mesh	√	√	√	√	√	x	x	x
Star	√	√	√	√	√	√	x	x
Scanning	√	√	√	√	√	x	√	x
Point-to-Point	√	√	√	√	√	√	√	√

Range

- IrDA – 10 cm
- Nike+ – 10 m
- ANT(+) – 30 m
- ZigBee – 100 m
- RF4CE based on ZigBee – 100 m
- Wi-Fi – 150 m
- LE – 280 m

Throughput

- IrDA ~1 Gbps
- Wi-Fi (lowest power 802.11b mode) ~6 Mbps
- LE ~305 kbps
- ZigBee ~255 kbps
- RF4CE (same as ZigBee)
- ANT+ ~20 kbps
- Nike+ ~272 bps

Latency

- ANT ~zero
- Wi-Fi ~1.5 ms
- LE ~2.5 ms
- ZigBee ~20 ms
- IrDA ~25 ms
- Nike+ ~1 second

Power efficiency

- Power efficiency is often queried by customers who are interested in prolonging the battery life of their devices while still achieving good user experience. (Amps./BIT)
- **ANT**
  An ANT device is configured to transmit 32 bytes/second and consumes 61 μA.
  - A byte consists of 8 bits, therefore 32 x 8 = 256 bits/second
  - Power = VI = 3 V x 61 μA = 0.183 mW
  - Power per bit = 0.183 mW / 256 bits = 0.71 μW/bit
- Always on, no sleep mode ?!!!

Power efficiency

- **Bluetooth low energy**
  Power consumption = 49 µA x 3 V = 0.147 mW
  - Bytes per second = 20 x (1 second/500 ms) x 3 channels = 120 bytes/second
  - Bits per second = 120 bytes/second x 8 = 960 bits/second
  - Power per bit = 0.147 mW/960 = 0.153 µW/bit
- **IrDA**
  - Power = 0.163 mW
  - Bits = 14
  - Power per bit = 0.163 mW/14 bits = 11.7 µW/bit

Power efficiency

- **Nike+**
  A foot pod lasts 1000 hours and transmits its payload every second. The payload is 34 bytes. A typical CR2032 has 225 mAh.
- Current drawn = 225 mAh/1000 hours = 0.225 mA
- Power = 3 x 0.225 mA = 0.675 mW
- Bits per second = 34 x 8 = 272 bits/second
- **Power per bit = 0.675 mW / 272 = 2.48 µW/bit**

Power efficiency

- **Wi-Fi**
  - Power = 116 mA x 1.8 V = 0.210 W
  - Power per bit = 0.210/40,000,000 = 0.00525 µW/bit
- **Zigbee**
  A Zigbee device consumes 0.035706 W when transferring 24 bytes of data.
  Bits per second = 24 x 8 = 192 bits
  Power per bit = 0.035706/192 = 185.9 µW/bit

Peak Power Consumption

- IrDA peak current draw ~ 10.2 mA
- Nike+ peak current draw ~ 12.3 mA
- LE peak current draw ~ 12.5 mA
- ANT peak current draw ~ 17 mA
- RF4CE and Zigbee peak current draw ~ 40 mA
- Wi-Fi peak current draw ~ 116 mA

E_{radio} Calculations

E_{radio} = (P(per Bit)* Number of Bits)+ (I_{sleep}* V * T)

Total Energy used for this module

What kind of a battery needed then?!

Battery (Short Review)

Duracell batteries

Two cells

9v battery

A real battery

6v dry cell

Another battery

More precisely

Batteries

- Cheap, easy to use
- Rechargeable batteries available
- Lithium Ion batteries with high capacity
- Charging is simple and easy
- Size of batteries is a problem
- AA battery defines the size of many devices
- Environment (temperature) has influence on the capacity

D, C, AA, AAA, AAAA cells, and a 9-volt battery

Battery Characteristics

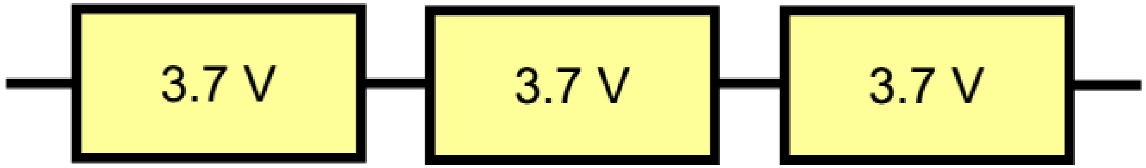
- Size
  - Physical: button, AAA, AA, C, D, ...
  - Energy density (watts per gram or cm^3)
- Longevity
  - Capacity (Ah, for drain of C/10 at 20°C)
  - Number of recharge cycles
- Discharge characteristics (voltage drop)

Further Characteristics

- Cost
- Behavioral factors
  - Temperature range (storage, operation)
  - **Self discharge**
  - **Memory effect**
- Environmental factors
  - Leakage, gassing, toxicity
  - Shock resistance

Battery Organization

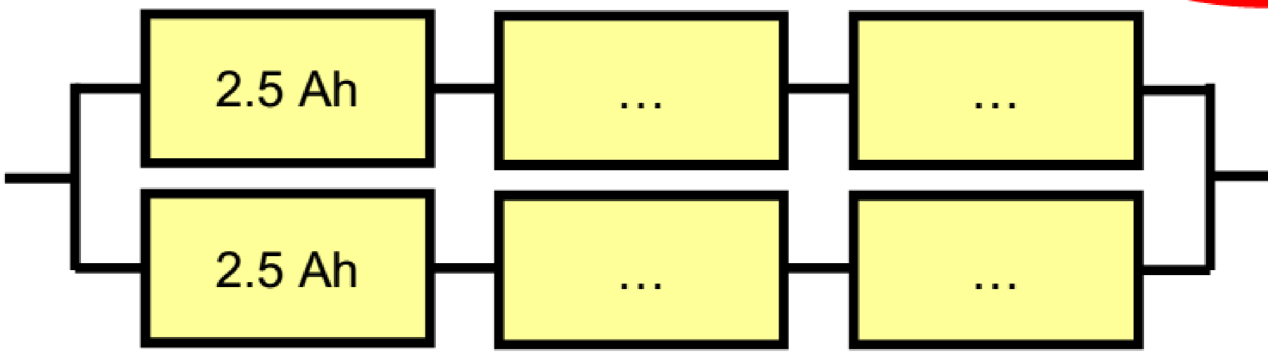
Battery Connections



→ 3 times 3.7 V gives you 11.1 V (you get the voltage you need)

→ Connect your battery (3.7 V, **2.5 Ah**) in parallel

6 cell 3S2P



→ 2 times 2.5 Ah gives you 5 Ah (you get the capacity you need)

Energy harvesting

- Capacity of battery limits the lifetime of the device
- Battery depletion -> Device cannot work -> (Sensor) network cannot work
- Idea: recharge the batteries during operation
- Use energy from the environment
- Current approaches
  - Photovoltaics: Solar modules for sensor nodes
  - Thermoelectric generators
    - Conversion of temperature differences to energy
  - Kinetic energy conversion
    - Piezo-electric principle already tested for shoes
  - MEMS gas turbines
    - Convert air- or fluid streams

Questions?