IoT – design aspects

MOBILE AND CYBER-PHYSICAL SYSTEMS

STEFANO CHESSA

Learning objectives

IoT characteristics

Energy efficiency

Duty cycle

IoT devices characteristics

Each device is usually:

- Low power, low cost system
- Small
- Autonomous

equipped with:

- Processor
- Memory
- Radio Transceiver
- Sensing elements
  - acceleration, pressure, humidity, light, acoustic, temperature, GPS, magnetic, …
- Actuators – depending on the case
- Battery, solar cells, …

Issues in IoT design

Energy efficiency
- sensors are battery-powered or use energy harvesting
- need for HW/SW energy efficient solutions

Adaptatability to changing conditions
- need for dynamic network management & programming

Low-complexity, low overhead protocols
- need at any level of the protocol stack due to limitation of nodes' resources

Security
- at all layers ot the stack

Multihop communications
- need for protocol stacks & routing protocols

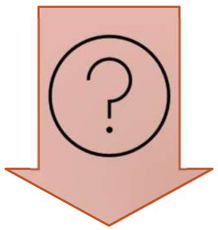
Mobility
- Need for dynamic routing protocols

Data storage & (pre-)processing

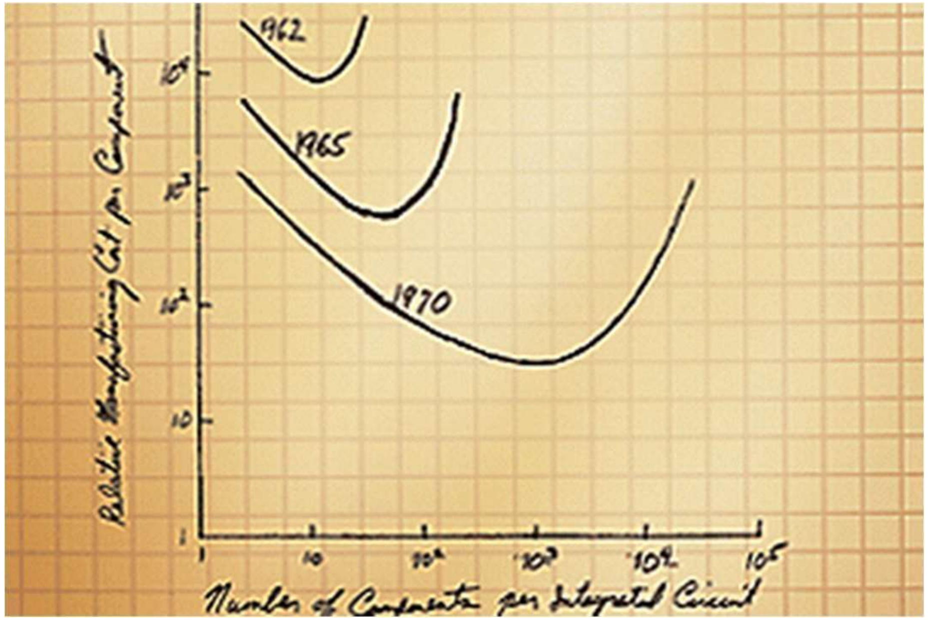
…

IoT design

Many limitations in the design of IoT devices are due to
processing, memory, battery and communication constraints



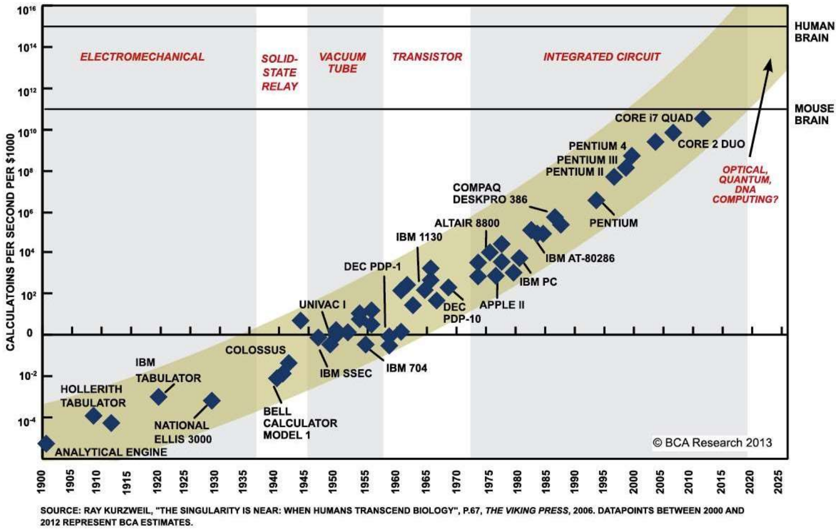
The evolution of HW technologies will overcome these constraints?

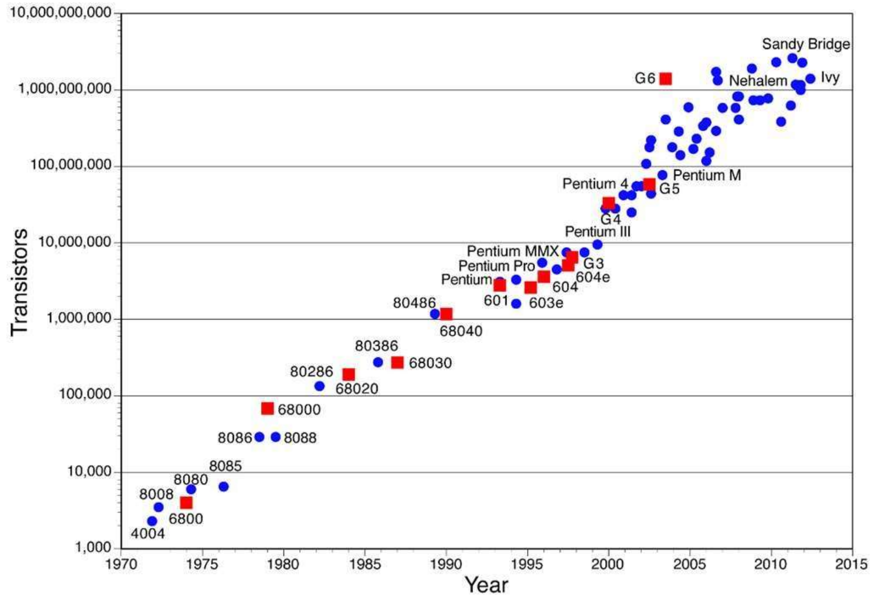


The Moore’s law

“The number of transistors that can be (inexpensively) embedded in a chip grows exponentially”

(it doubles every two years)


ELECTROMECHANICAL
SOLID-STATE RELAY
VACUUM TUBE
TRANSISTOR
INTEGRATED CIRCUIT
HUMAN BRAIN
MOUSE BRAIN
CALCULATOINS PER SECOND PER $1000
ANALYTICAL ENGINE
HOLLERITH TABULATOR
IBM TABULATOR
NATIONAL ELLIS 3000
BELL CALCULATOR MODEL 1
COLOSSUS
UNIVAC I
IBM SSEC
IBM 704
DEC PDP-1
IBM 1130
DEC PDP-10
ALTAIR 8800
APPLE II
IBM PC
IBM AT-80286
COMPAQ DESKPRO 386
PENTIUM
PENTIUM II
PENTIUM III
PENTIUM 4
CORE 2 DUO
CORE i7 QUAD
OPTICAL, QUANTUM, DNA COMPUTING?
© BCA Research 2013
SOURCE: RAY KURZWEIL, "THE SINGULARITY IS NEAR: WHEN HUMANS TRANSCEND BIOLOGY", P.67, THE VIKING PRESS, 2006. DATAPOINTS BETWEEN 2000 AND 2012 REPRESENT BCA ESTIMATES.


Transistors
Year
4004
8008
8080
6800
8085
8086
8088
68000
80286
68020
80386
68030
80486
68040
Pentium
601
603e
604
Pentium Pro
Pentium MMX
G3
604e
Pentium III
G4
Pentium 4
G5
Pentium M
G6
Nehalem
Sandy Bridge
Ivy

Moore’s Law

Moore's law growth

INTEL 4004 (1971)	INTEL CORE I9-7980XE (Q3'17)
2.3 K transistors	1.8 G transistors
740 KHz	4.4 GHz
	165 W
4KB program memory	128 GB

The Moore's law and IoT

The Moore's law offers three different interpretations:

1. The performance doubles every two years at the same cost
   - Up to now this is true for processors of servers/desktops
2. The chip's size halves every two years at the same cost
   - Consequently also the energy consumption is reduced
3. The size and the processing power remain the same but the cost halves every two years

The Moore's law and IoT

In IoT all the three
interpretations are true…

There are applications that:

- Require small-sized sensors and/or that have low power consumption
- Require higher processing capabilities to the single sensor
- The cost is important in (almost) all applications

The Moore's law and IoT

Nowadays there exist several IoT HW platforms with different capabilities in terms of processing and energy consumption

Differently than server/desktop applications the IoT devices use low-power, cheap processors

- Even old or refreshed processors that are still on the market

Normally used the cheapest HW that meets the application requirements

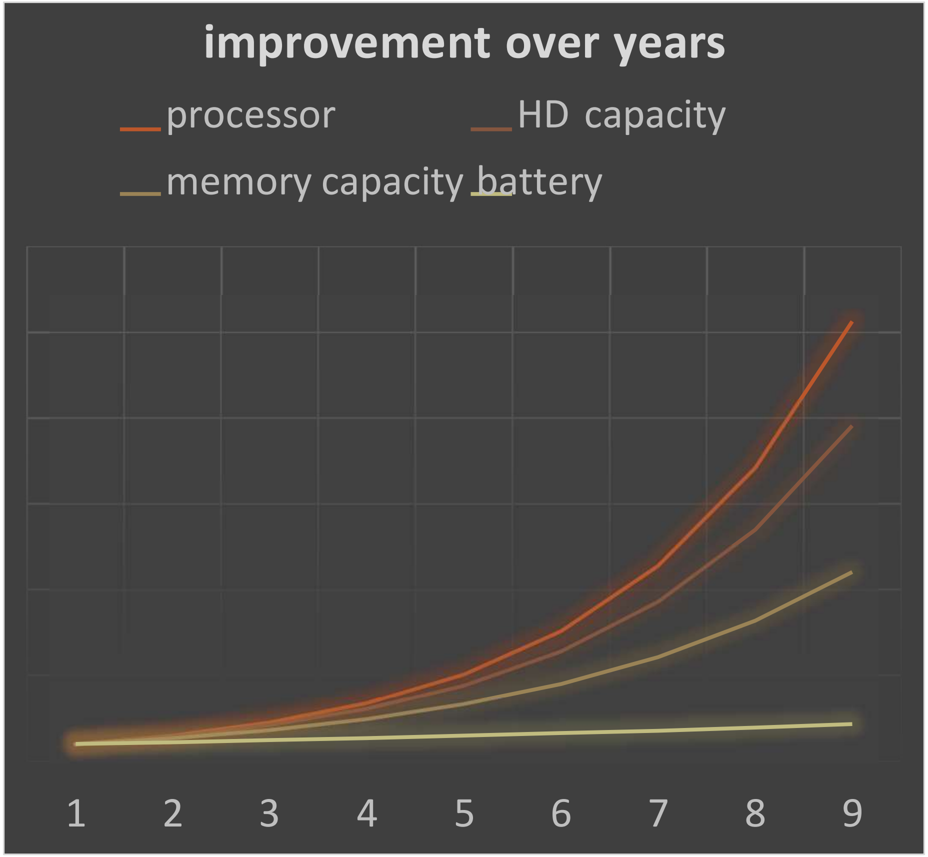
- considering the scale factor due to the large number of IoT devices, that has considerable effects on the final costs

In conclusion…
Will Moore’s law solve IoT design issues?

Not necessarily, at least in the near future

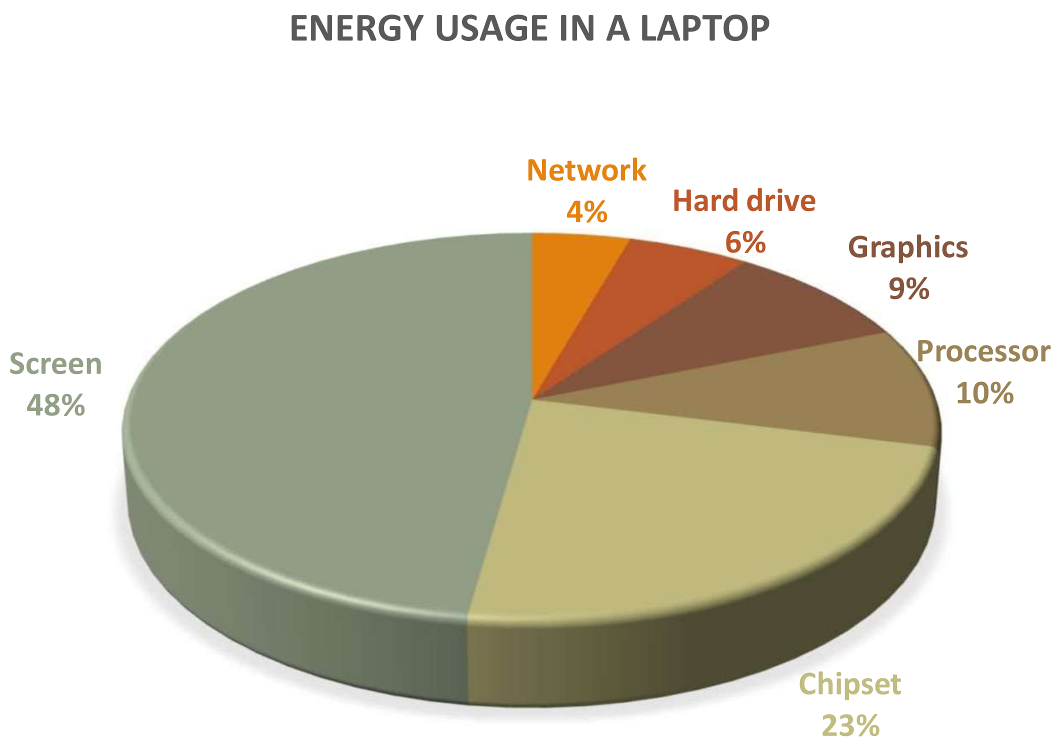
We may use Moore’s law to make them smaller and cheaper instead!

Energy efficiency

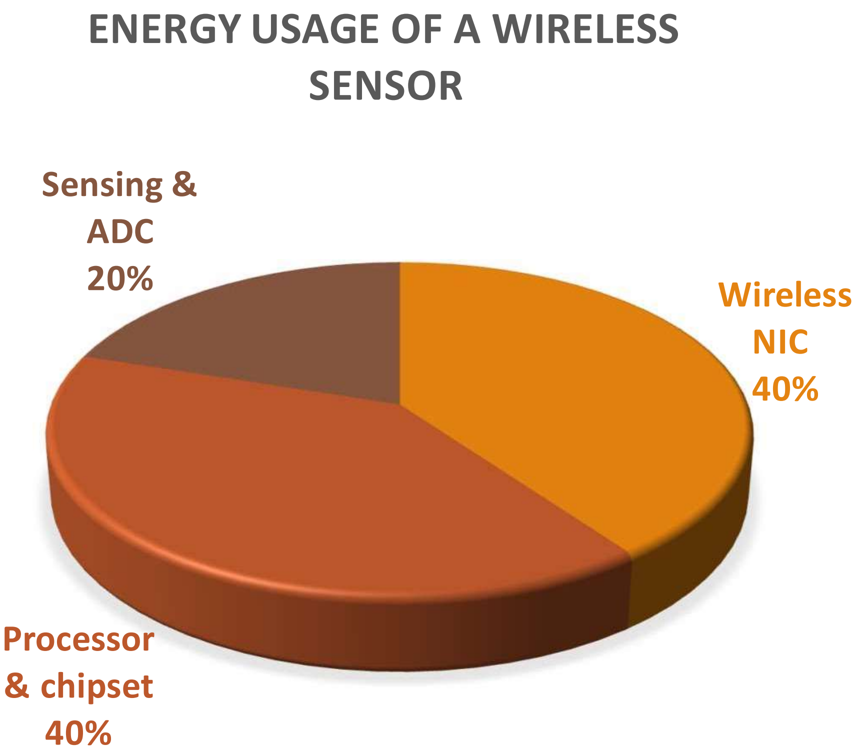


Energy efficiency

INTEL VS DURACELL



Energy efficiency



Energy efficiency

Energy efficiency - radio

Example of energy consumption of a WiFi Network Interface	
Sleep mode:	10mA
Listen mode:	180mA
Receive mode:	200 mA
Transmit mode:	280 mA

Energy efficiency - radio

Energy consumption of a sensor (Mote-clone)

Sleep mode:	0.016 mW
Listen mode:	12.36 mW
Receive mode:	12.50 mW
Transmit mode	0.1 power level, 19.2kbps: 12.36 mW
	0.4 power level, 19.2kbps: 15.54 mW
	0.7 power level, 19.2kbps: 17.76 mW

Energy efficiency - radio

Energy consumption of a sensor (Mote-clone):

- In some cases transmit power $<$ receive power!
- listen power $\approx$ receive power
- Radio should be turned off as much as possible

Energy efficiency - processor

Processor power around 30%-50% of total power

- Processor as well should be turned off!

Turning on and off processor and radio consumes power as well…

Duty cycle

Saving energy by reducing the period of activity of a sensor:

- The activity of an IoT device is (mostly) repetitive:
  - Sense
  - Process & store
  - Transmit/receive
- A sensor alternates periods of activity to periods of inactivity (defines a duty cycle)
- During inactivity the energy consumption is very low
  - But processor, radio and I/O need to be freezed!

Duty cycle

- In geneíal, the duty cycle of a system (oí a component / device) is defined as the fíaction of one peíiod in which the system is active
- It makes sense foí systems that opeíate cyclically:
  - they execute theií activity peíiodically (they thus have a peíiod)…
  - … and they aíe active only in a fíaction of this peíiod
- Duty cycle is commonly expíessed as a íatio oí as a peícentage.
  - 100% DC means that the system is always active… neveí takes a bíeak
  - 1% DC means that the system is active only 1% of its peíiod

Example of duty cycle: code

Lasts 4 milliseconds → processor and sensor active

Lasts 1 milliseconds → only processor active

Lasts 15 milliseconds → processor and radio active (tx)

Lasts 380 milliseconds → All components idle

Total: 400 milliseconds

```
…
void loop() {
  // reads the input from analog pin 0:
  int sensorValue = analogRead(A0);

  // converts value into a voltage (0-5V):
  float voltage = sensorValue * (5.0/1023.0);

  // transmits voltage over the radio
  Serial.println(voltage);

  // waits for next loop
  delay(380);
}
```

**NOTE: milliseconds are not the real ones… they are meant just as an illustration of the concept

Example of duty cycle: code

However, this code does not turn off any component when not in use…

Let's say you have calls like:

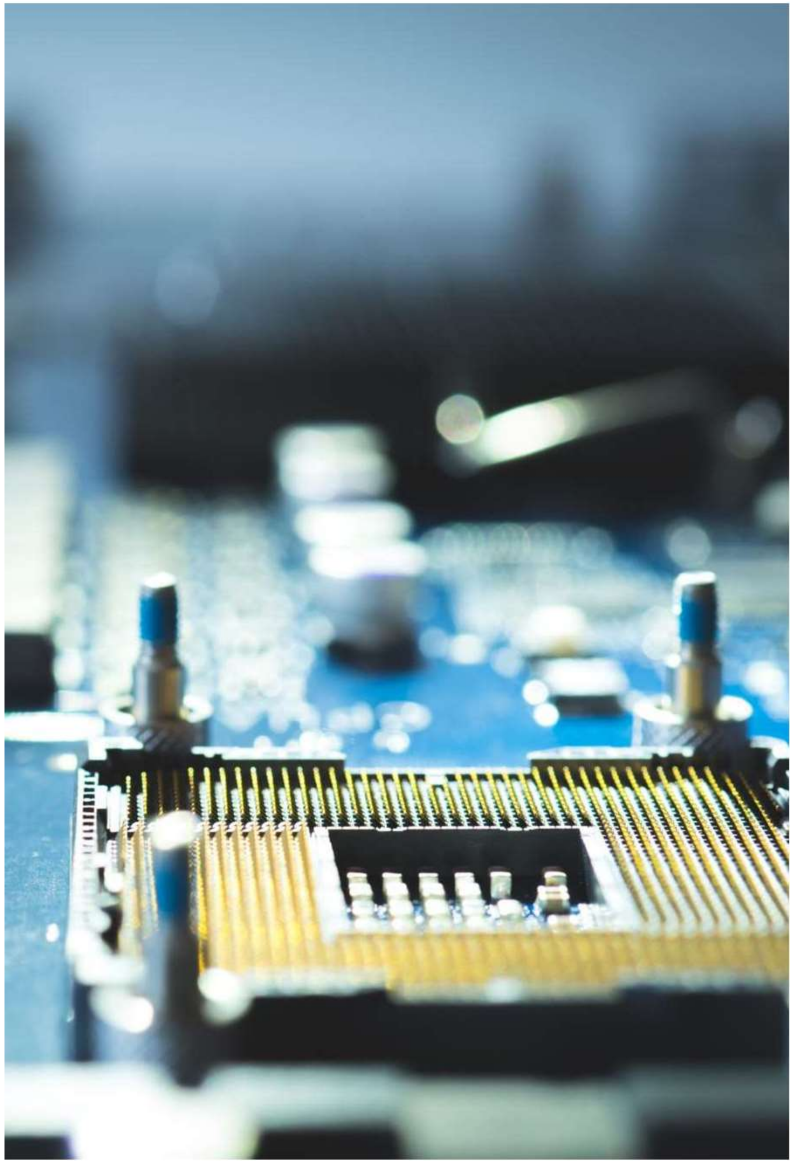
- `turnOn(x)` / `turnOff(x)` that turn on/off the component `x`
- `Idle(y)` that puts the processor in idle state (with low power consumption) for `y` milliseconds

```
void loop() {
 // reads the input from analog pin 0:
 turnOn(analogSensor);
 int sensorValue = analogRead(A0);
 turnOff(analogSensor);

 // converts value into a voltage (0-5V):
 float voltage = sensorValue * (5.0 / 1023.0);

 // transmits voltage over the radio
 turnOn(radioInterface);
 Serial.println(voltage);
 turnOff(radioInterface);

 // waits for next loop
 idle(380);
}
```



Question

What is now the duty cycle of the processor, of the radio and of the sensor?

4 milliseconds → `int sensorValue = analogRead(A0);`

1 milliseconds → `float voltage = sensorValue * (5.0 / 1023.0);`

15 milliseconds → `Serial.println(voltage);`

380 milliseconds → `idle(380);`

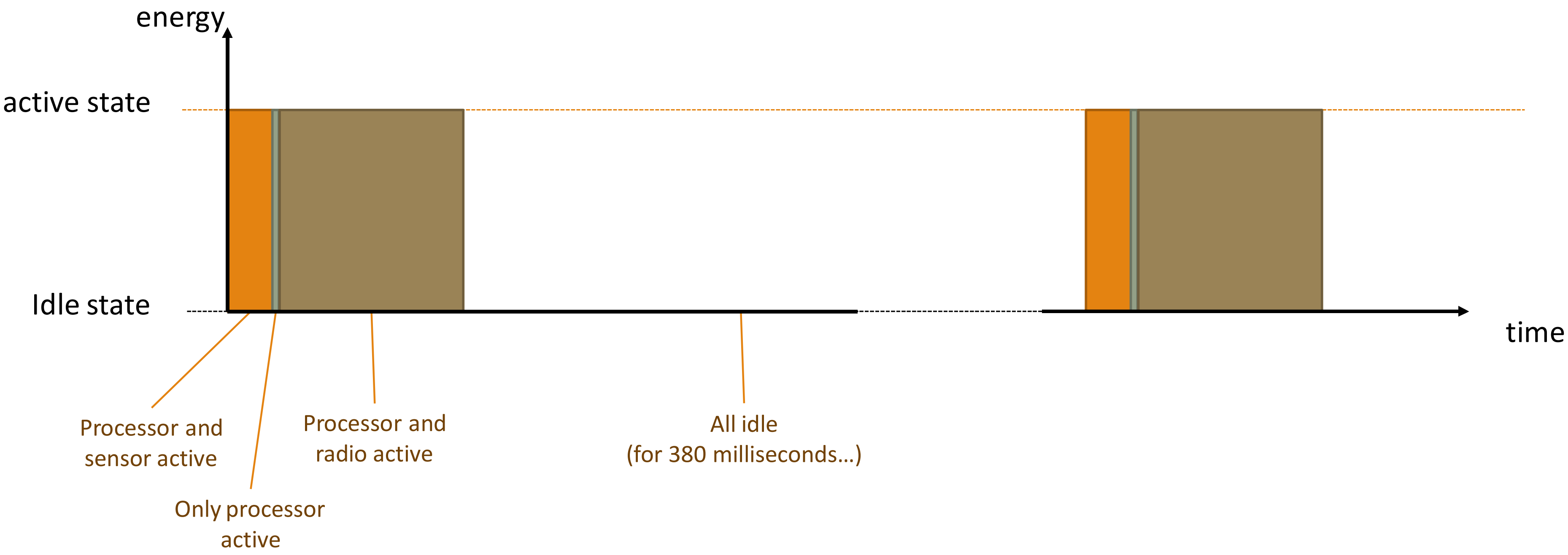
```
…
void loop() {
 turnOn(analogSensor);
 int sensorValue = analogRead(A0);
 turnOff(analogSensor);

 float voltage = sensorValue * (5.0 / 1023.0);

 turnOn(radioInterface);
 Serial.println(voltage);
 turnOff(radioInterface);

 idle(380);
}
```

Duty cycle: states and energy vs time



Specs. of a mote class-sensor

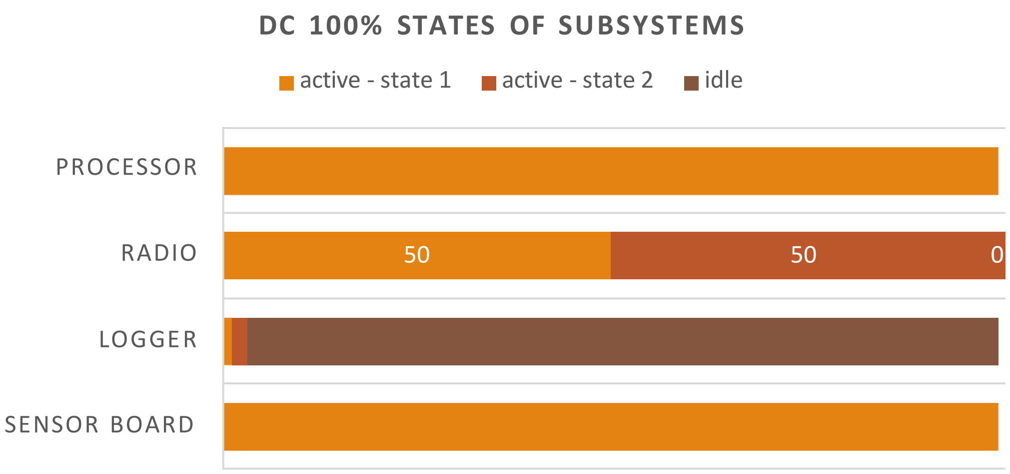
	Value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	15	µA
Radio		
current in receive	19,7	mA
current xmit	17,4	mA
current sleep	20	µA
Logger (storage in the flash memory)		
write	15	mA
read	4	mA
sleep	2	µA
Sensor Board		
current (full operation)	5	mA
current sleep	5	µA
Battery Specifcations		
Capacity Loss/Yr	3	%

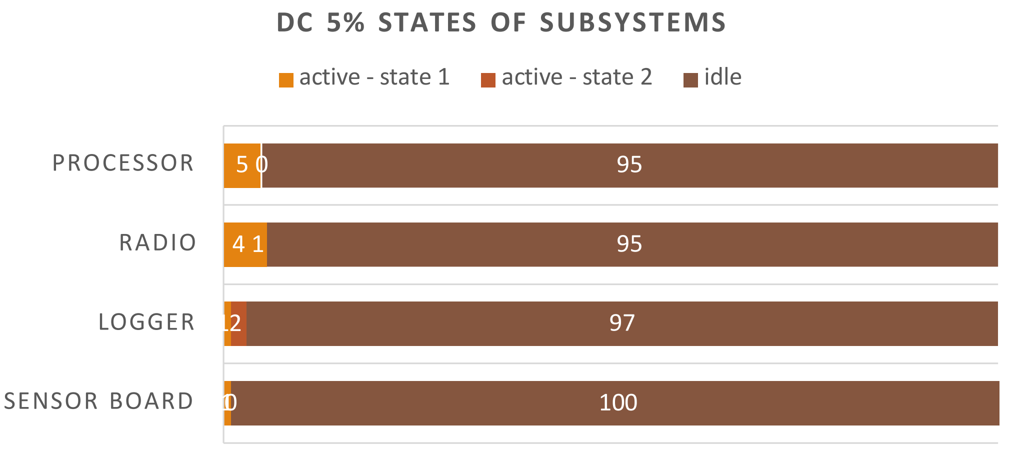
Example: two DC models

	model 1: 100%DC	model 2: 5%DC	units
Micro Processor			
current (full operation)	100	5	%
current sleep	0	95	%
Radio			
current in receive	50	4	%
current xmit	50	1	%
current sleep	0	95	%
Logger			
write	1	1	%
read	2	2	%
sleep	97	97	%
Sensor Board			
current (full operation)	100	1	%
current sleep	0	99	%

Some components work in parallel

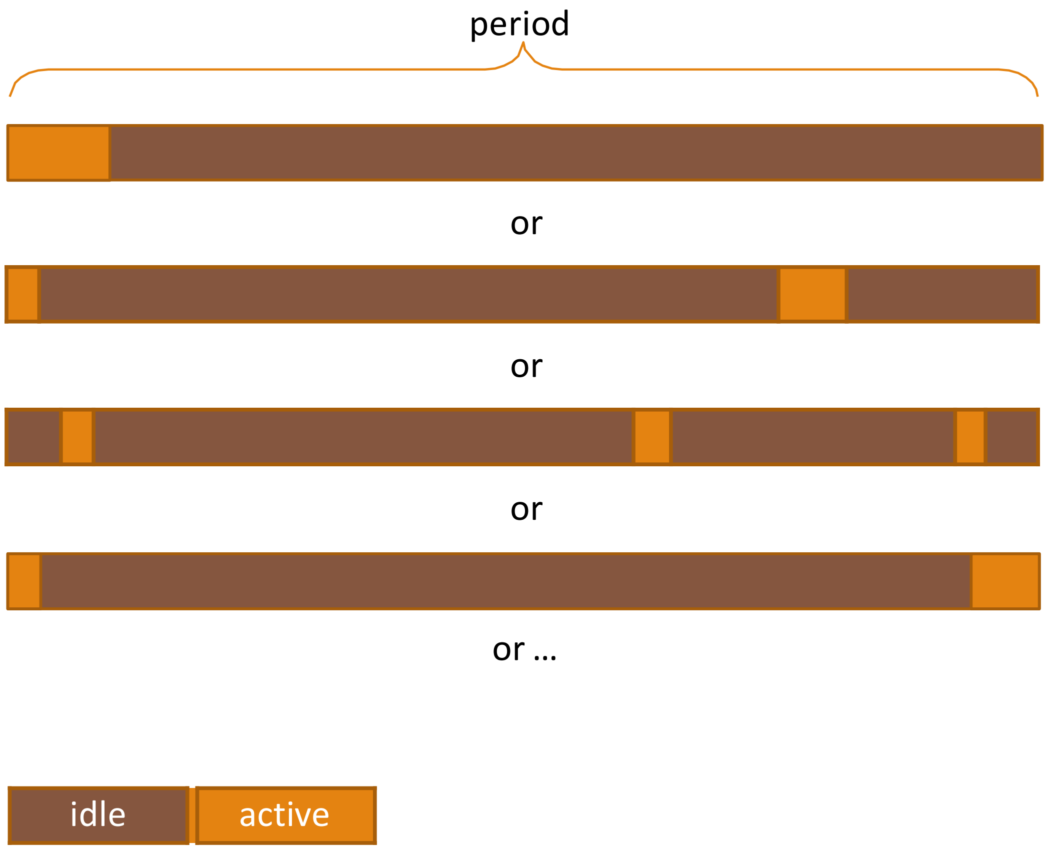
Logger duty cycle of 3%





Example: two DC models

Examples of a component with 10% DC



Measuring energy – a note

Energy and power are measured in Joule (J) and Watt (W), respectively:

$$1J = 1W \cdot sec$$

In electromagnetism, $1W$ is the work performed when a current of $1Ampere\ (1A)$ flows through an electrical potential difference of $1Volt\ (1V)$:

$$1W = 1V \cdot 1A$$

Since we use direct current and the electrical potential difference is (almost) constant, the power and the energy «only» depend on the current (Ampere).

Hence we can «express» both the energy stored in a battery (battery charge) and the energy consumed in mAh

Example: computing consumption per duty cycle

- Energy cost microprocessor E_μ (per cycle):
$$E_\mu = C_\mu^{\text{full}} \cdot dc_\mu + C_\mu^{\text{idle}} \cdot (1 - dc_\mu)$$
  - C_μ^{full} full energy cost microprocessor per cycle
  - C_μ^{idle} idle energy cost microprocessor per cycle
  - dc_μ % duty cycle microprocessor
- Energy cost radio E_ρ (per cycle):
$$E_\rho = C_\rho^{\text{T}} \cdot dc_\rho^{\text{T}} + C_\rho^{\text{R}} \cdot dc_\rho^{\text{R}} + C_\rho^{\text{idle}} \cdot (1 - dc_\rho^{\text{T}} - dc_\rho^{\text{R}})$$
  - C_ρ^{T} radio transmission energy cost per cycle
  - C_ρ^{R} radio receival energy cost per cycle
  - C_ρ^{idle} idle energy cost per cycle

  - dc_ρ^{T} % transmit duty cycle radio
  - dc_ρ^{R} % receive duty cycle radio

Example: computing lifetime

- Energy cost of logger $E_{\wp}$ and sensor board E_{σ}: same as before
- Total energy cost (per duty cycle):

$$E = E_{\mu} + E_{\rho} + E_{\wp} + E_{\sigma}$$

- Lifetime (in number of duty cycles):

$$Lifetime = \frac{B_0 - L}{E}$$

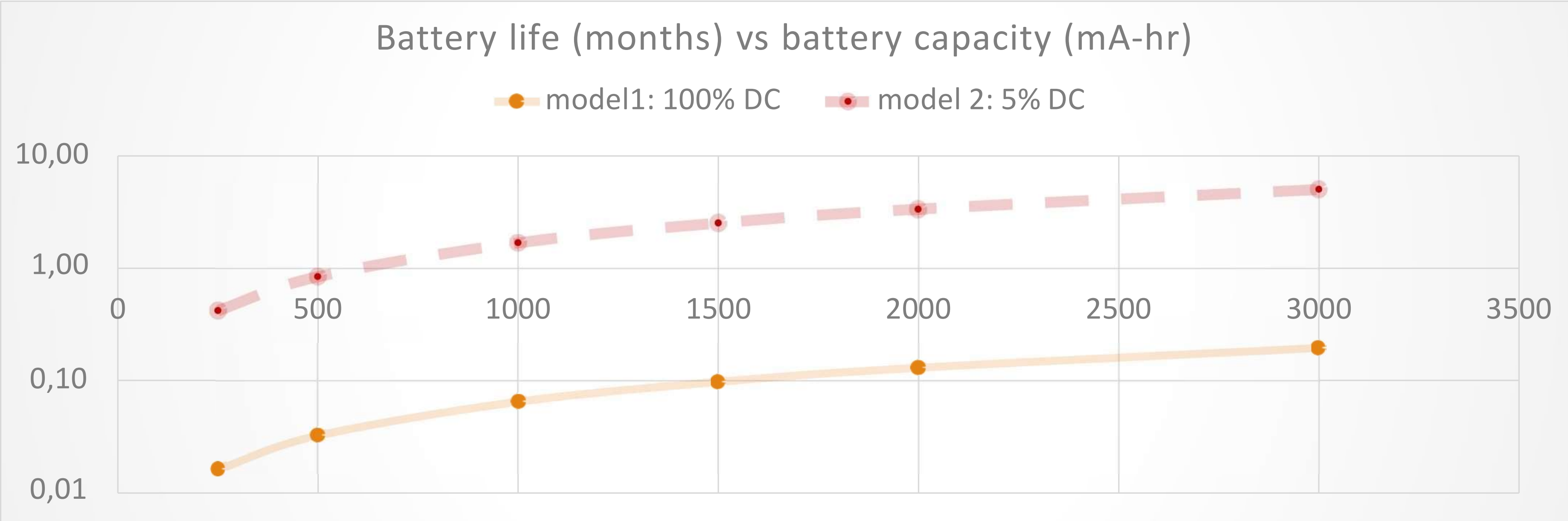
  - Where B_0 is the initial battery charge and L is the battery charge lost during the lifetime due to **battery leaks**
  - Note that L depends on lifetime!
  - Let's define the charge loss can be given per single cycle ε

Example: computing lifetime

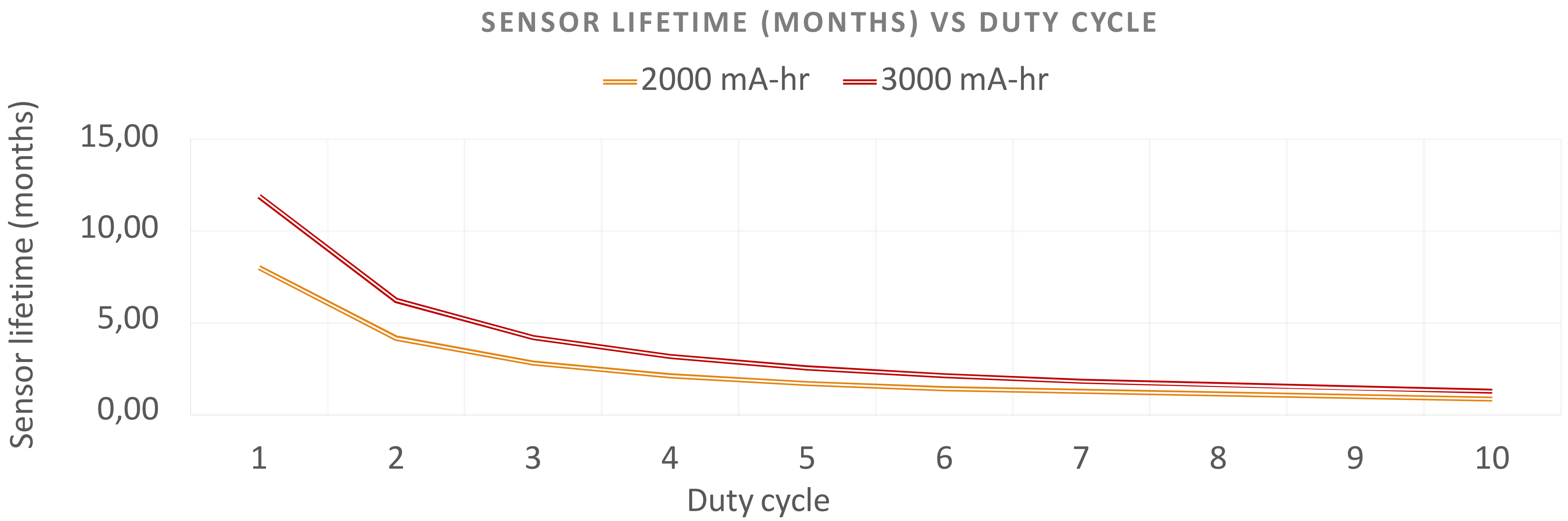
- We can express the battery charge as a recurrence equation:
$$B_{\mathrm{n}} = B_{\mathrm{n-1}} \cdot (1 - \varepsilon) - E$$
  - Where B_{n} is the battery charge at cycle n
  - and ε is the battery leak per single cycle

- Solving the recurrence equation:
$$B_{\mathrm{n}} = B_0 \cdot (1 - \varepsilon)^{\mathrm{n-1}} + \frac{E \cdot \left((1 - \varepsilon)^{\mathrm{n}} - 1\right)}{\varepsilon}$$

- Device lifetime in cycles is given by n such that $B_{\mathrm{n}} = 0$
- Note however that in reality the device stops working before than that, when the battery reaches a «minimum»



Battery life vs DC (I)



Battery life vs DC (II)

Exercise

Consider this program and the table of energy consumption in the different states. Compute:

- the energy consumption of the device per single hour
- the expected lifetime of the device (disregard battery leak…)

```
                    …
                    void loop() {
                     turnOn(analogSensor);
4 milliseconds      int sensorValue = analogRead(A0);
                     turnOff(analogSensor);

1 milliseconds      float voltage = sensorValue*
                              (5.0 / 1023.0);

                     turnOn(radioInterface);
15 milliseconds      Serial.println(voltage);
                     turnOff(radioInterface);

380 milliseconds    idle(380);
                    }
```

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	15	µA
Radio		
current xmit	20	mA
current sleep	20	µA
Sensor Board		
current (full operation)	5	mA
current sleep	5	µA
Battery Specifcations		
Capacity	2000	mAh

solution

energy consumption per hour:

- The processor has a duty cycle of __________________________
- The radio has a duty cycle of __________________________
- The sensor has a duty cycle of __________________________

Energy consumption in one hour: __________________________

Lifetime of the device: __________________________

	idle	Active
Processor		
Radio		
Sensor		
Total:		

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	15	µA
Radio		
current xmit	20	mA
current sleep	20	µA
Sensor Board		
current (full operation)	5	mA
current sleep	5	µA
Battery Specifcations		
Capacity	2000	mAh

solution

energy consumption per hour:

- The processor has a duty cycle of $dc_{\mathrm{p}} = 5\%$ (see previous question)
- The radio has a duty cycle of $dc_{\mathrm{r}} = 3{,}75\%$
- The sensor has a duty cycle of $dc_{\mathrm{s}} = 1\%$

Hence in an hour they consume $1{,}243mAh$:

Processor	$1 - dc_{\mathrm{p}} \cdot 1hour \cdot P_{\mathrm{idle}} = 0{,}014mAh$	$dc_{\mathrm{p}} \cdot 1hour \cdot P_{\mathrm{active}} = 0{,}4mAh$
Radio	$1 - dc_{\mathrm{r}} \cdot 1hour \cdot P_{\mathrm{idle}} = 0{,}019mAh$	$dc_{\mathrm{r}} \cdot 1hour \cdot P_{\mathrm{active}} = 0{,}75mAh$
Sensor	$1 - dc_{\mathrm{s}} \cdot 1hour \cdot P_{\mathrm{idle}} = 0{,}005mAh$	$dc_{\mathrm{s}} \cdot 1hour \cdot P_{\mathrm{active}} = 0{,}055mAh$
Total:	$0{,}038mAh$	$1{,}205mAh$

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	15	µA
Radio		
current xmit	20	mA
current sleep	20	µA
Sensor Board		
current (full operation)	5	mA
current sleep	5	µA
Battery Specifcations		
Capacity	2000	mAh

solution

Expected lifetime of the device:

- In an hour it consumes:$1{,}243mAh$
- Since the battery has a capacity of $2000mAh$, and disregarding energy leaks, follows:

$$lifetime = \frac{2000\,mAh}{1{,}243\,mAh} \cong 1609\ (number\ of\ hours)$$

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	15	µA
Radio		
current xmit	20	mA
current sleep	20	µA
Sensor Board		
current (full operation)	5	mA
current sleep	5	µA
Battery Specifcations		
Capacity	**2000**	mAh

Energy efficiency

… hence the solution is to reduce the DC

However:

turning off the processor is a local decision

- the node scheduler knows what are the activities and when the processor should run

turning off the radio is a global decision:

- A device with its radio off does not communicate
- Cannot receive incoming messages/commands
- Cannot act as router in multihop network…
  … cannot receive requests, commands, updates…

MAC Protocols

Low-level communication protocols

- send/receive packets to/from in-range sensors

In conventional networks, MAC protocols arbitrate the access to the shared communication channel

In IoT they also implement strategies for energy efficiency

- synchronize the devices
- turn off the radio when it is not needed
  - turning off the radio means excluding a device from the network

Summary

- Issues in IoT design
- Energy efficiency
- Duty Cycle
- Energy consumption of an IoT device
- Lifetime of an IoT device

Exercise 1

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	15	µA
Radio		
current xmit	20	mA
current sleep	20	µA
Sensor Board		
current (full operation)	5	mA
current sleep	5	µA
Battery Specifications		
Capacity	2000	mAh

Consider the sensor specs in the table.
The device measures the hearth-rate (HR) of a person:

- Samples a photo-diode on the wrist at 20 Hz
  - sampling the sensor takes 0.5 ms
  - it requires both the processor and the sensor active
- HR is computed every 2 s (based on 40 samples)
- Transmit (from time to time… see below) a data packet to the server:
  - The average time required to transit is 2 ms
  - Requires both processor and radio active

Compute the energy consumption and the lifetime of the device if it sends all the samples to a server:

- Stores 5 consecutive samples from the photodiode
- Transmits the stored 5 samples to the server
- The server computes HR (hence the device **does not compute HR**)

Disregard battery leaks.

Solution 1

- Sampling at 20 Hz (sampling takes 0.5 ms, requires both processor and sensor active)
- HR is computed every 2 s (based on 40 samples)

•The average time required to send a packet is 2 ms

Compute the energy consumption and the lifetime :

- Stores 5 consecutive samples from the photodiode
- Transmits the stored 5 samples to the server

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	15	µA
Radio		
current xmit	20	mA
current sleep	20	µA
Sensor Board		
current (full operation)	5	mA
current sleep	5	µA
Battery Specifications		
Capacity	2000	mA

Duty cycle of sampling:

DC of processor + sensors: 0.5 milliseconds (sampling time) / 0.05 seconds (sampling period)= 0.01

Duty cycle of transmitting:

DC of radio + processor: 2 milliseconds (transmit time) / 0,25 seconds (transmission period) = 0.008

Solution 1

- Sampling at 20 Hz (sampling takes 0.5 ms, requires both processor and sensor active)
- HR is computed every 2 s (based on 40 samples)

•The average time required to send a packet is 2 ms

Compute the energy consumption and the lifetime :

- Stores 5 consecutive samples from the photodiode
- Transmits the stored 5 samples to the server

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	15	μA
Radio		
current xmit	20	mA
current sleep	20	μA
Sensor Board		
current (full operation)	5	mA
current sleep	5	μA
Battery Specifications		
Capacity	2000	mA

Power consumption of sensor (in 1 hr):	5 mAh * 0,01+ 5 uAh *0,99 =0,05+0,005 mAh = 0,055 mAh
Power consumption of processor (in 1 hr):	0,018*8 mAh + 0,982*15 uAh =0,144+0,0147 mAh = 0,1587 mAh
Power consumption of radio (in 1 hr):	0,008 *20mAh + 0,992 *20uAh = 0,16+0,0198 mAh = 0,1798 mAh
Total power consumption (in 1 hr): Lifetime:	0,3935 mAh; 2000 mAh / 0,3935 mAh ≈ 5082 h

Exercise 2

Consider the sensor specs in the table.
The device measures the hearth-rate (HR) of a person:

- Samples a photodiode on the wrist at 20 Hz
  - sampling the sensor takes 0.5 ms
  - it requires both the processor and the sensor active
- HR is computed every 2 s (based on 40 samples)
  - Computing HR in the device takes 5 ms
- Transmit a data packet to the server:
  - The average time required to transmit is 2 ms
  - Requires both processor and radio active

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	15	µA
Radio		
current xmit	20	mA
current sleep	20	µA
Sensor Board		
current (full operation)	5	mA
current sleep	5	µA
Battery Specifications		
Capacity	2000	mAh

Compute the energy consumption and the lifetime of the device if it computes HR itself:

- Transmits every 5 values of HR computed (1 packet every 10 seconds)

Disregard battery leaks

Solution 2

- Sampling at 20 Hz (sampling takes 0.5 ms, requires both processor and sensor active)
- HR is computed every 2 s (based on 40 samples), takes 5 ms

•The average time required to send a packet is 2 ms

Compute the energy consumption and the lifetime :

- Transmits every 5 values of HR computed
- 1 packet every 10 seconds

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	15	μA
Radio		
current xmit	20	mA
current sleep	20	μA
Sensor Board		
current (full operation)	5	mA
current sleep	5	μA
Battery Specifications		
Capacity	2000	mA

Duty cycle of sampling:

0,5 milliseconds (sampling time) / 0,05 seconds (sampling period)= 0,01

Duty cycle of processing:

5 milliseconds / 2 seconds = 0,0025

Duty cycle of transmitting:

2 milliseconds (transmit time) / 10 seconds (transmission period) = 0,0002

Solution 2

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	15	µA
Radio		
current xmit	20	mA
current sleep	20	µA
Sensor Board		
current (full operation)	5	mA
current sleep	5	µA
Battery Specifications		
Capacity	2000	mA

- Sampling at 20 Hz (sampling takes 0.5 ms, requires both processor and sensor active)
- HR is computed every 2 s (based on 40 samples), takes 5 ms

•The average time required to send a packet is 2 ms

Compute the energy consumption and the lifetime :

- Transmits every 5 values of HR computed
- 1 packet every 10 seconds

Power consumption of sensor (in 1 hr):	5 mAh * 0,01+ 5 uAh *0,99 =0,05+0,005 mAh = 0,055 mAh
Power consumption of processor (in 1 hr):	8 mAh * 0,0127+ 15 uAh *0,9873 =0,1016+0,0148 mAh = 0,1164 mAh
Power consumption of radio (in 1 hr):	0,0002 *20mAh + 0,9998 *20uAh = 0,004 + 0,02 mAh = 0,024 mAh
Total power consumption (in 1 hr):	0,1954 mAh
Lifetime:	2000 mAh / 0,1916 mAh = 10.235 h

Exercise extra-1

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	0,015	mA
Radio		
current xmit	1	mA
current sleep	0,02	mA
Sensor Board		
current (full operation)	5	mA
current sleep	0,005	mA
Battery Specifications		
Capacity	2000	mAh

Consider a Mote-class sensor with the parameters in the table.
Assume that the device performs a sensing task with the following parameters:

- The sensor board is activated with a rate of 0,1 Hz to perform the sampling; this operation takes 0.5 milliseconds. At the end the sensor board is put in sleep mode. During each sensing operation the processor is always active.
- After each sampling the processor performs a computation that takes 2 milliseconds.
- Then the processor activates the radio and transmits the data. The transmission takes 1 millisecond and, during it, the processor is active. At the end the radio and the processor are both set in sleep mode.

Compute the duty cycle of each component (sensor board, radio and processor), and the lifetime of the device (assuming that the sensor stops working when its battery charge becomes 0):

Solution extra-1

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	0,015	mA
Radio		
current xmit	1	mA
current sleep	0,02	mA
Sensor Board		
current (full operation)	5	mA
current sleep	0,005	mA
Battery Specifications		
Capacity	2000	mAh

- Sampling takes 0.5 ms with a rate of 0,1 Hz
- Processing: 2 ms
- Transmitting: 1 ms

Duty cycle of sampling (processor and sensors): ____________________________________

Duty cycle of processing (only processor): ____________________________________

Duty cycle of transmissions (radio&processor): ____________________________________

Hence, for each component the power consumption per hour (in mAh) is:

- Sensor: ____________________________________
- Processor: ____________________________________
- Radio: ____________________________________

Total consumption per hour (in mAh): ____________________________________

Lifetime in hours: ____________________________________

Solution extra-1

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	0,015	mA
Radio		
current xmit	1	mA
current sleep	0,02	mA
Sensor Board		
current (full operation)	5	mA
current sleep	0,005	mA
Battery Specifications		
Capacity	2000	mAh

duty cycles:	Per activity		Per component
sensing	0,00005	sensor board:	0,00005
	0,0002	processor:	0,00035
	0,0001	radio:	0,0001

idle	active	total	
0,00499975	0,00025	0,00524975	mAh
0,01499475	0,0028	0,01779475	mAh
0,019998	0,0001	0,020098	mAh
		0,0431425	mAh

Hence the lifetime is around 46358 hours