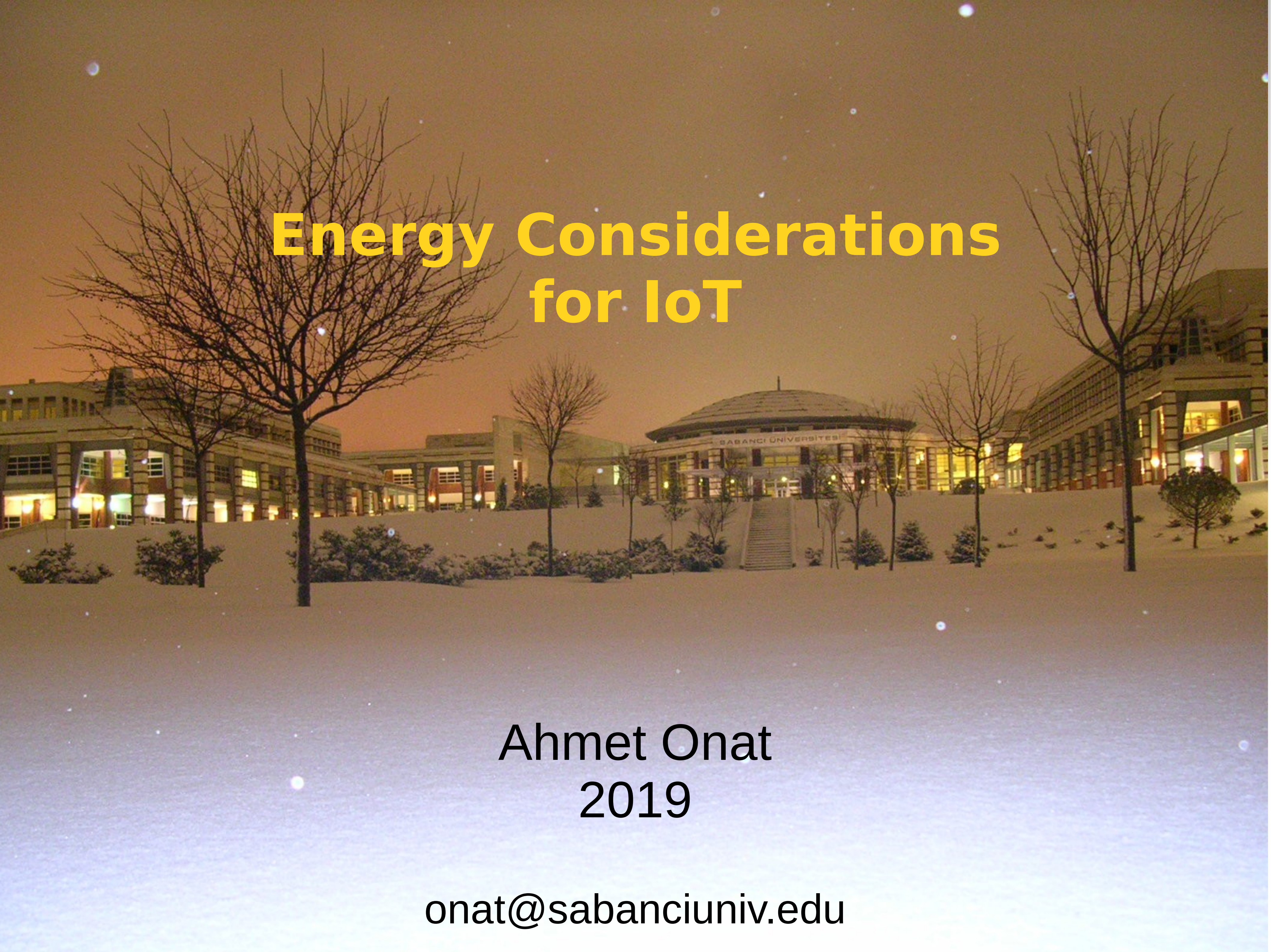

Energy Considerations for IoT

Ahmet Onat
2019

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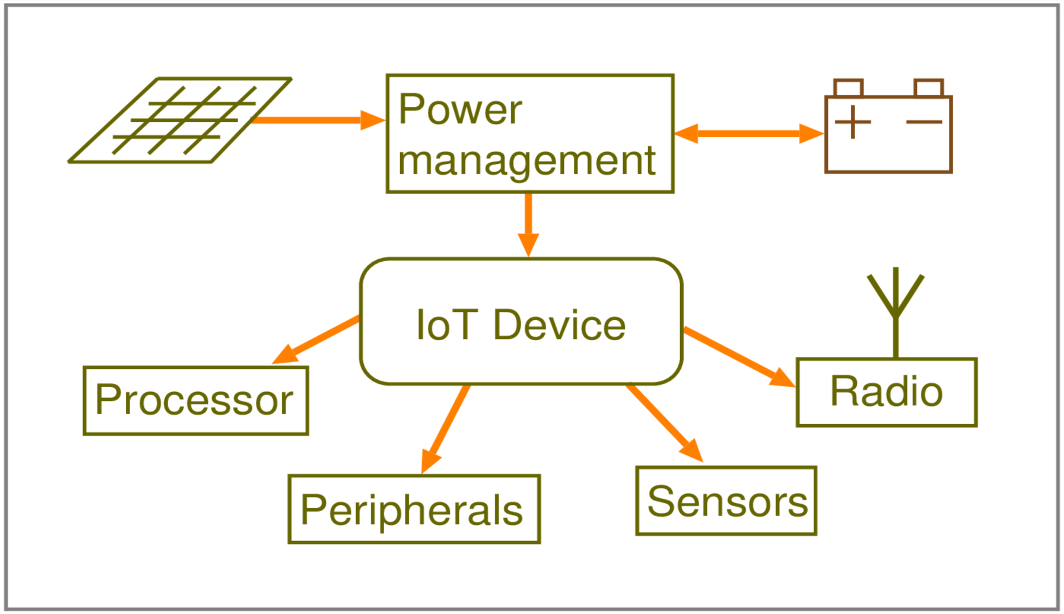
Microcomputer power diet

- Energy source is small
- Battery is inefficient
- Radio , sensors etc. require power



How to manage energy so that the device does its job?

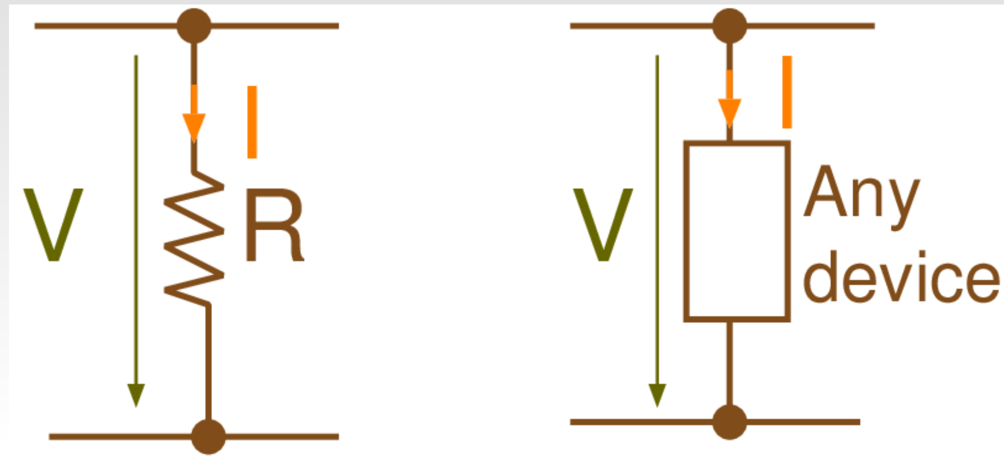
Layout of the Lecture

1. Mechanisms of power loss in digital circuits
2. Methods of minimizing power loss
3. Solar power for IoT devices:

- Calculations of battery and solar cell

Definition of electrical power

- $P = VI$ Watts



- $V = IR$ (Ohm's law)
- $P = I^2R$ W
- $P = V^2/R$ W

V: Volts (V)
I : Amps (A)
R: Ohms (Ω)

Q: What is the resistance of your *1kW* water kettle?

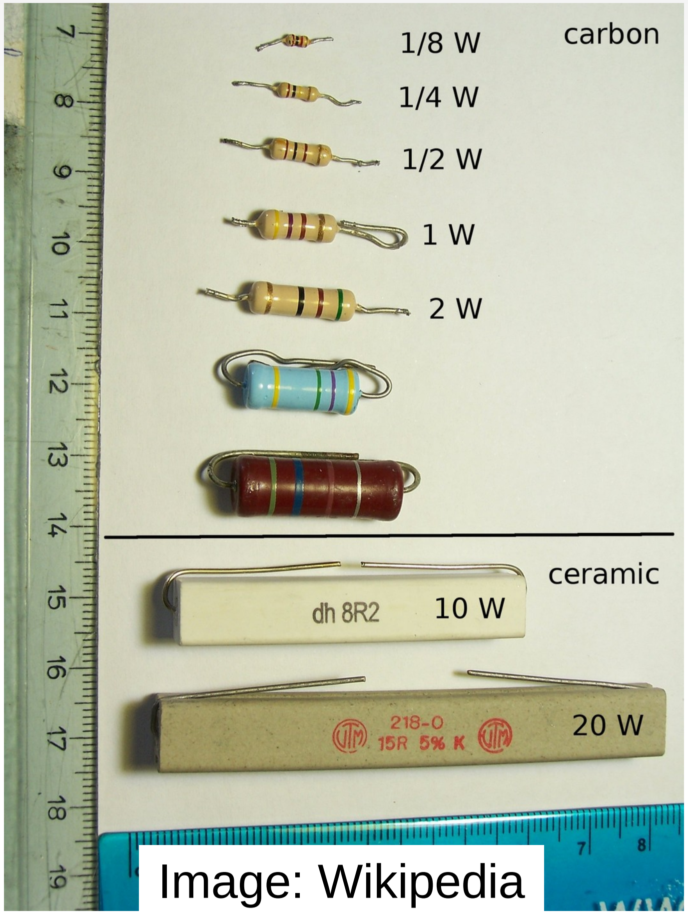
1kW kettle resistance

- $P = V^2/R$ W

  $1000 = (220)^2/R \rightarrow R = 48400/1000 = 48\Omega$

- The resistor dissipates all the electrical power as heat for our tea.

- A high power resistor must be physically large.



Energy

- Energy is the total power spent during a time interval:

$$E(t) = \int_0^t P(\tau)\, d\tau$$

- An IoT device can consume low energy if:

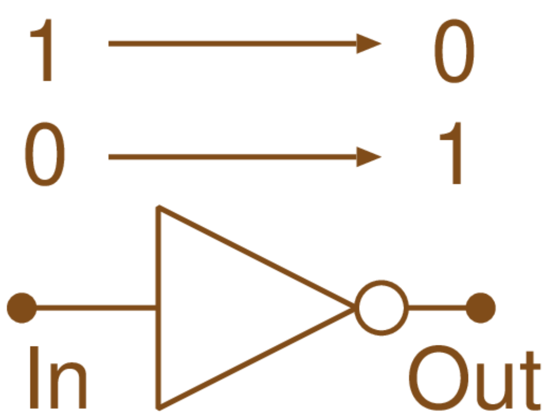
1. It consumes high energy but runs for a short time,
2. It runs for a long time but consumes low energy.

Power Dissipation Mechanisms of Digital Circuits

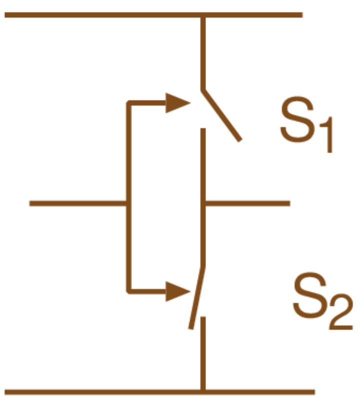
Power dissipation of digital circuits

- Logic inverter gate: simplest digital component

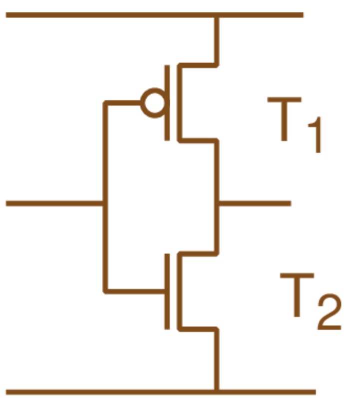
Input	Output
0	1
1	0



Logic symbol



Idealized circuit

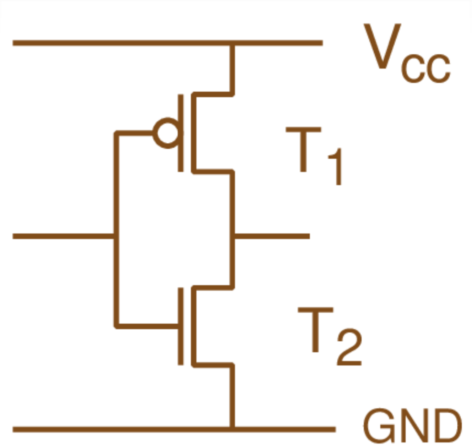


Actual circuit

Power loss in an inverter

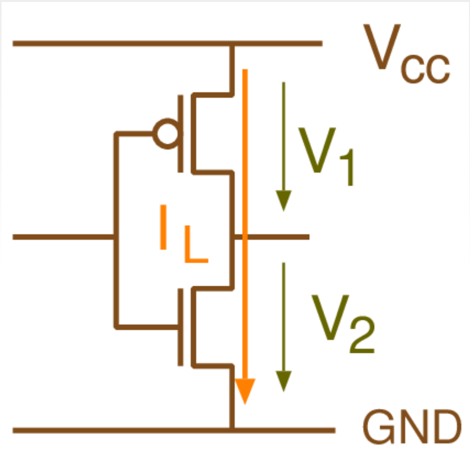
- Two mechanisms:

1. Leakage current
2. Switching loss



Leakage current loss

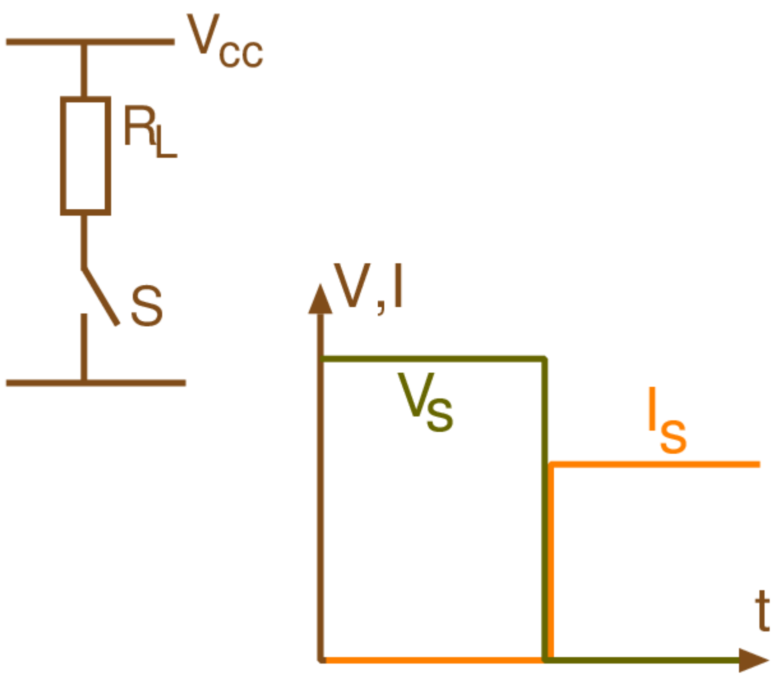
- Some small current always leaks through transistors.
- $P_{T1} = I_L V_1$ W
- $P_{T2} = I_L V_2$ W

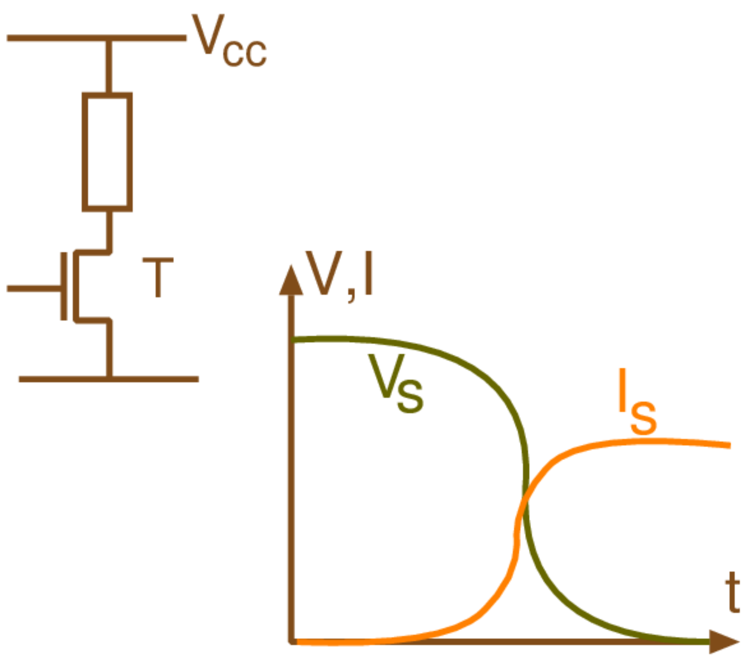


- Leakage current is always there.
- To reduce I_L: reduce supply voltage.

Switching loss

- A switch closes instantaneously. Either the voltage or current are <u>zero</u>. → <u>Power is always zero</u>.
- A transistor slowly "closes". → short duration when both current and voltage are <u>nonzero</u>. Power dissipated during each switch.





Reduce power loss

- To reduce power loss in a digital circuit:

1. Reduce supply voltage. (reduce leakage loss)

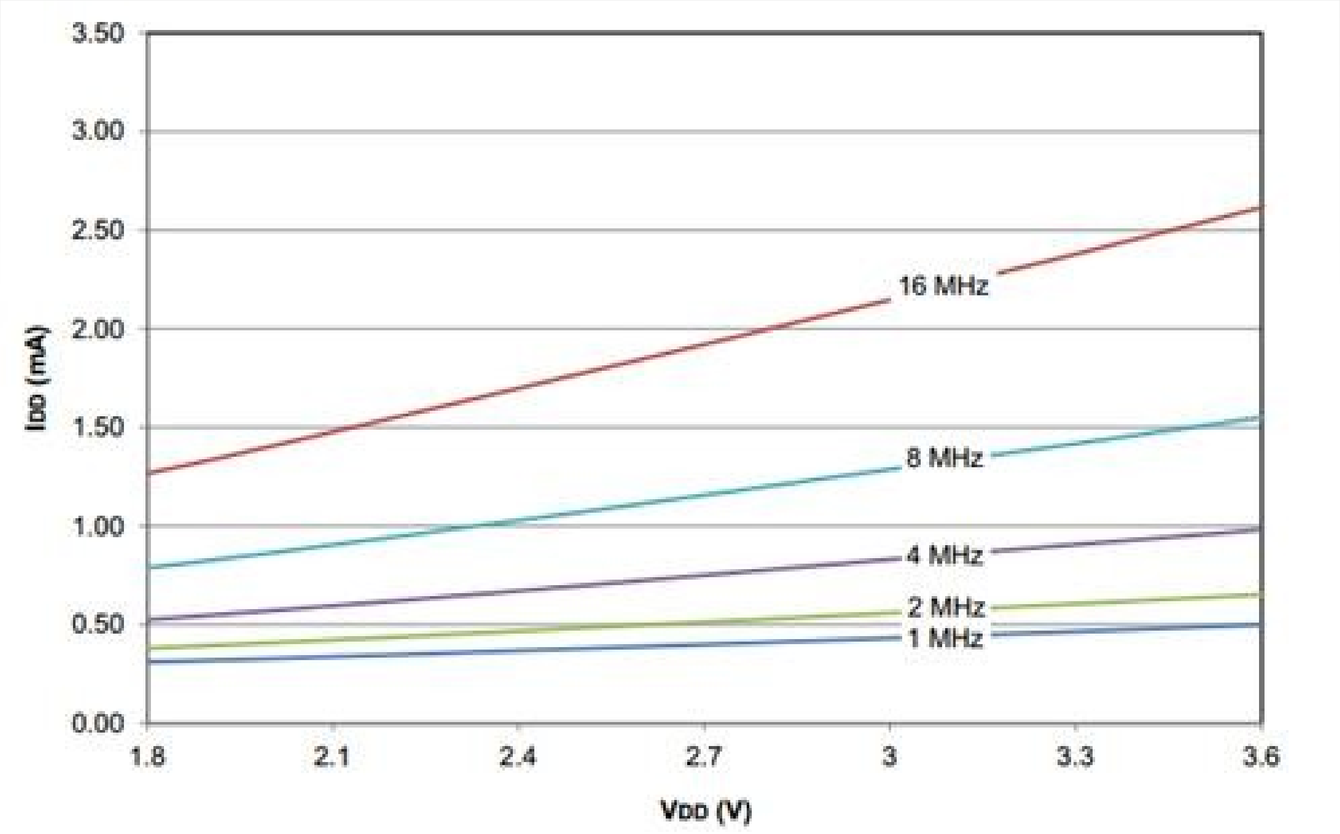
   → But must supply sufficient voltage to external circuits.

2. Reduce clock speed. (reduce switching loss)

   → But must complete calculations on-time.

Low power from low voltage?

- Lowering supply voltage is not very advantageous...



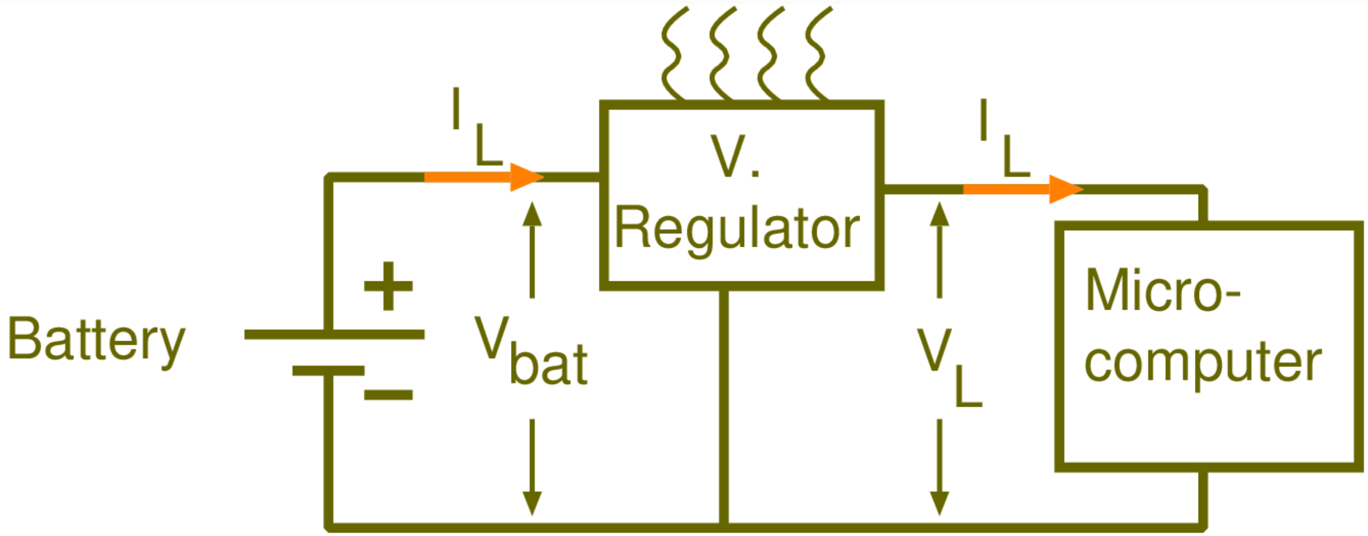
Current increases linearly with supply voltage

Ganssle: Hardware and Firmware Issues in Using Ultra-Low Power MCUs

Low power from low voltage?

- Regulator power loss: $P_R = (V_{bat} - V_L) I_L$

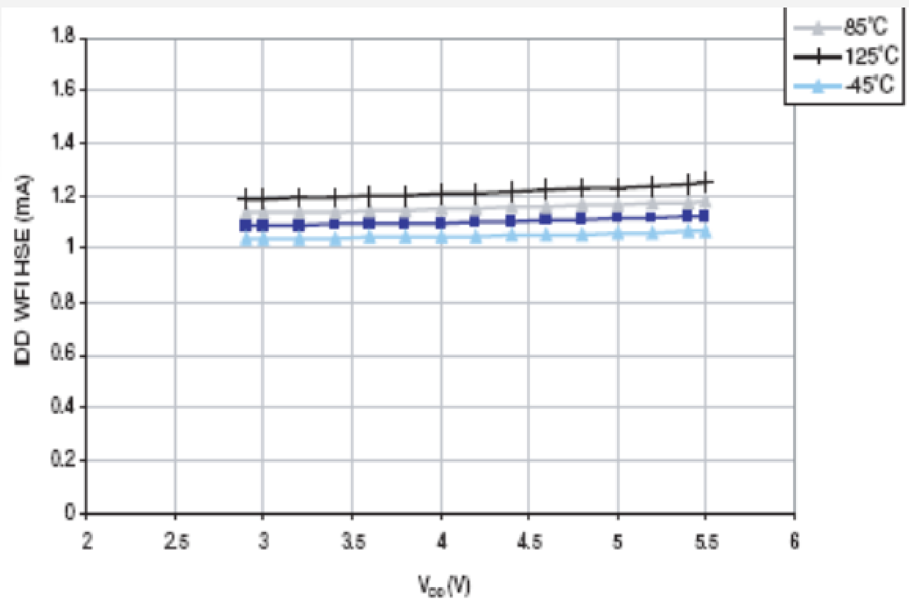
- Linear regulator loss can exceed CPU gain!

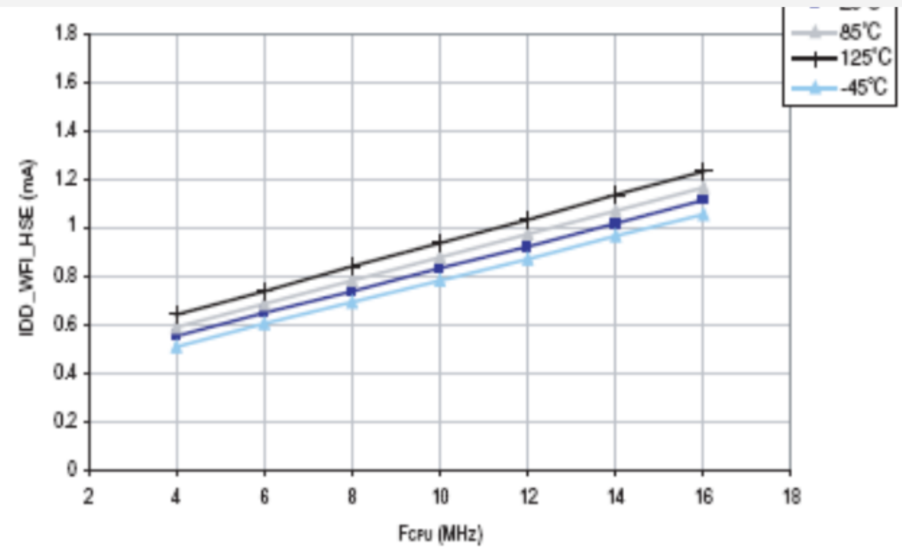


→ Operate system directly from battery with <u>no regulation</u>!

Power loss dependency

- Processor current consumption wrt.
  supply voltage & operating frequency





I_{DD} vs. CPU voltage (f_{osc}=*16*MHz)

I_{DD} vs. CPU frequency (V_{DD}=*5*V)

ST Microelectronics: STM8S103 Datasheet.

Power loss comparison

- Loss from leakage vs. from switching

→ Latest processors are NOT suitable for IoT!

Process technology	Leakage power	Switching power	Voltage
0.35μm	0.5	2.8	3.0V
0.25μm	0.75	2	2.5V
0.18μm	1	1	1.8V
130μm	1.5	0.75	1.5V
90nm	2	0.44	1.2V

Microchip App Note: AN1416

Power Saving Features on Modern Microprocessors

Power saving methods

- Major power saving methods:

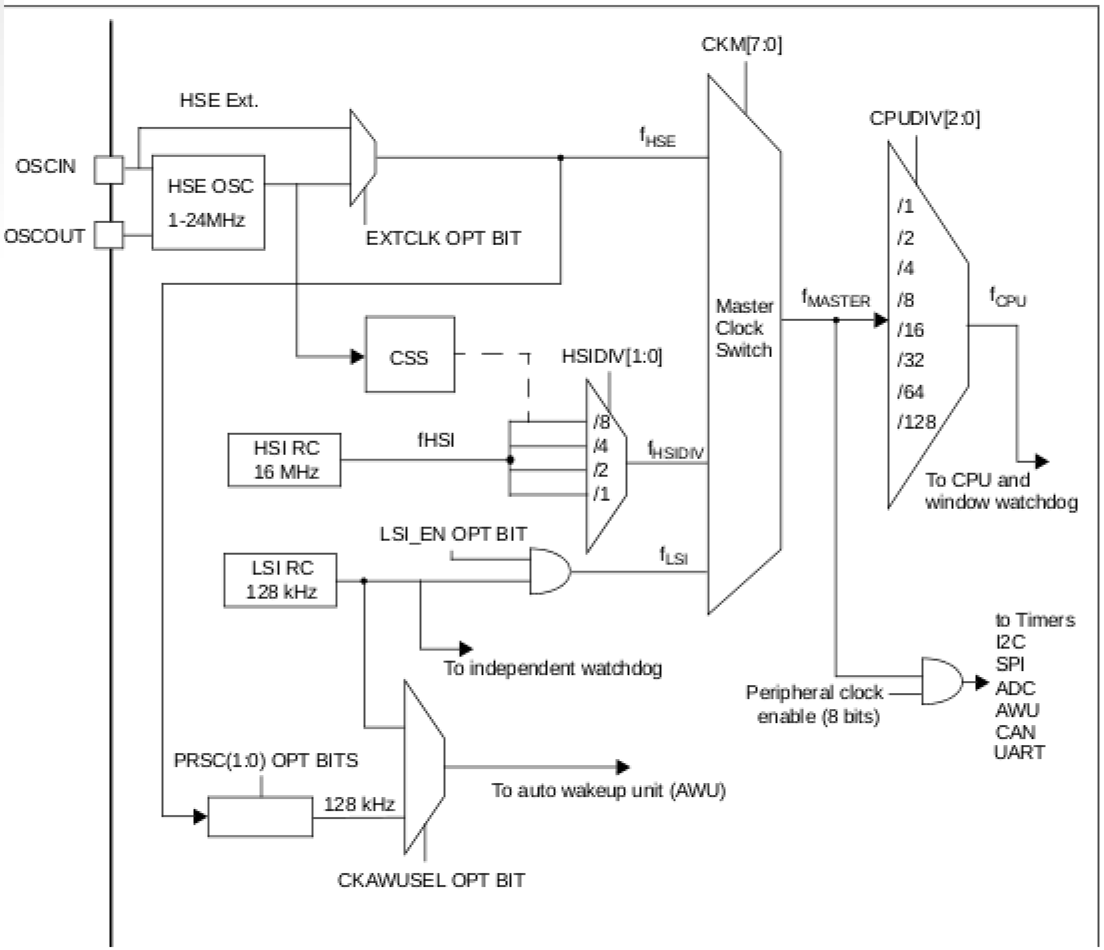
1. Processor clock speed throttling
2. Sleep modes
3. Power off
4. Peripheral device power down

Examples on STM8S103F3 processor

- Manufacturer: SGS Thompson
- http://www.st.com → stm8s103F3
- Modern 8 bit processor
- Widely used
- Structure simple enough to comprehend.
- $0.7 in single quantity (lower in bulk)

Clock tree on STM8S

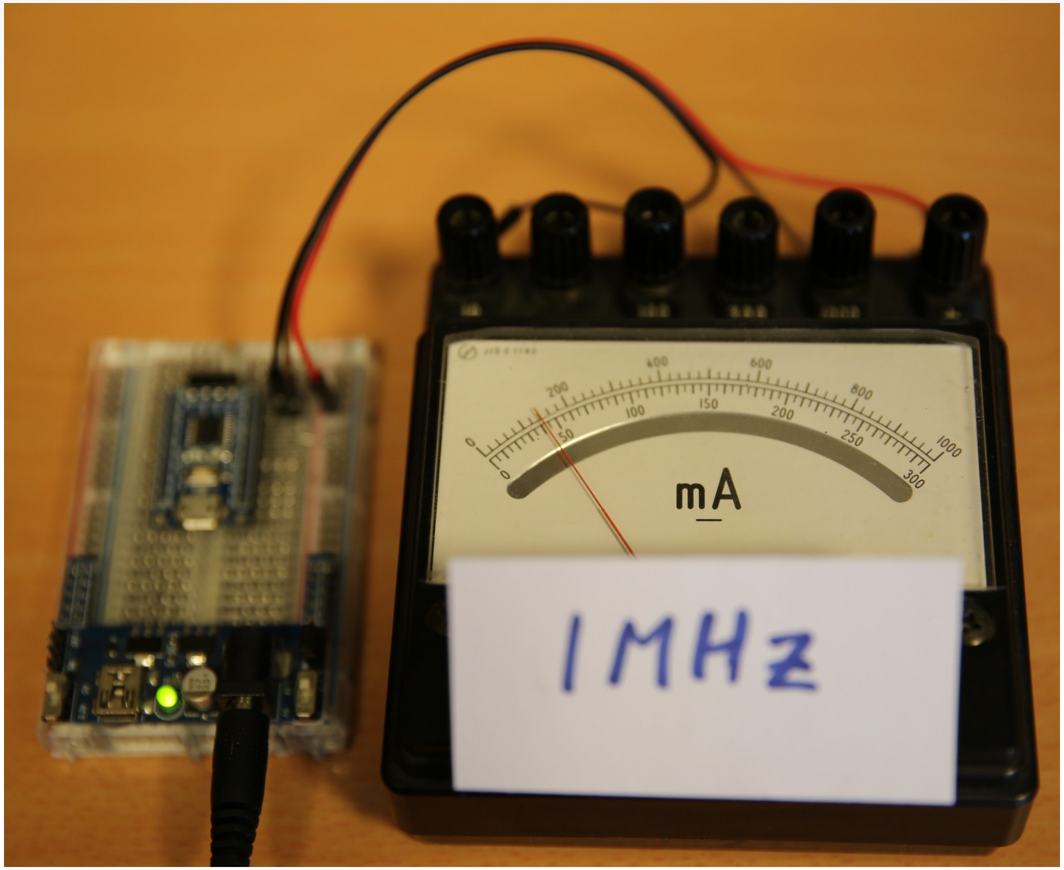
- Many ways of controlling the speed of the processor and peripherals.
- Speed can be precisely controlled
- Speed can be changed on-the-fly.



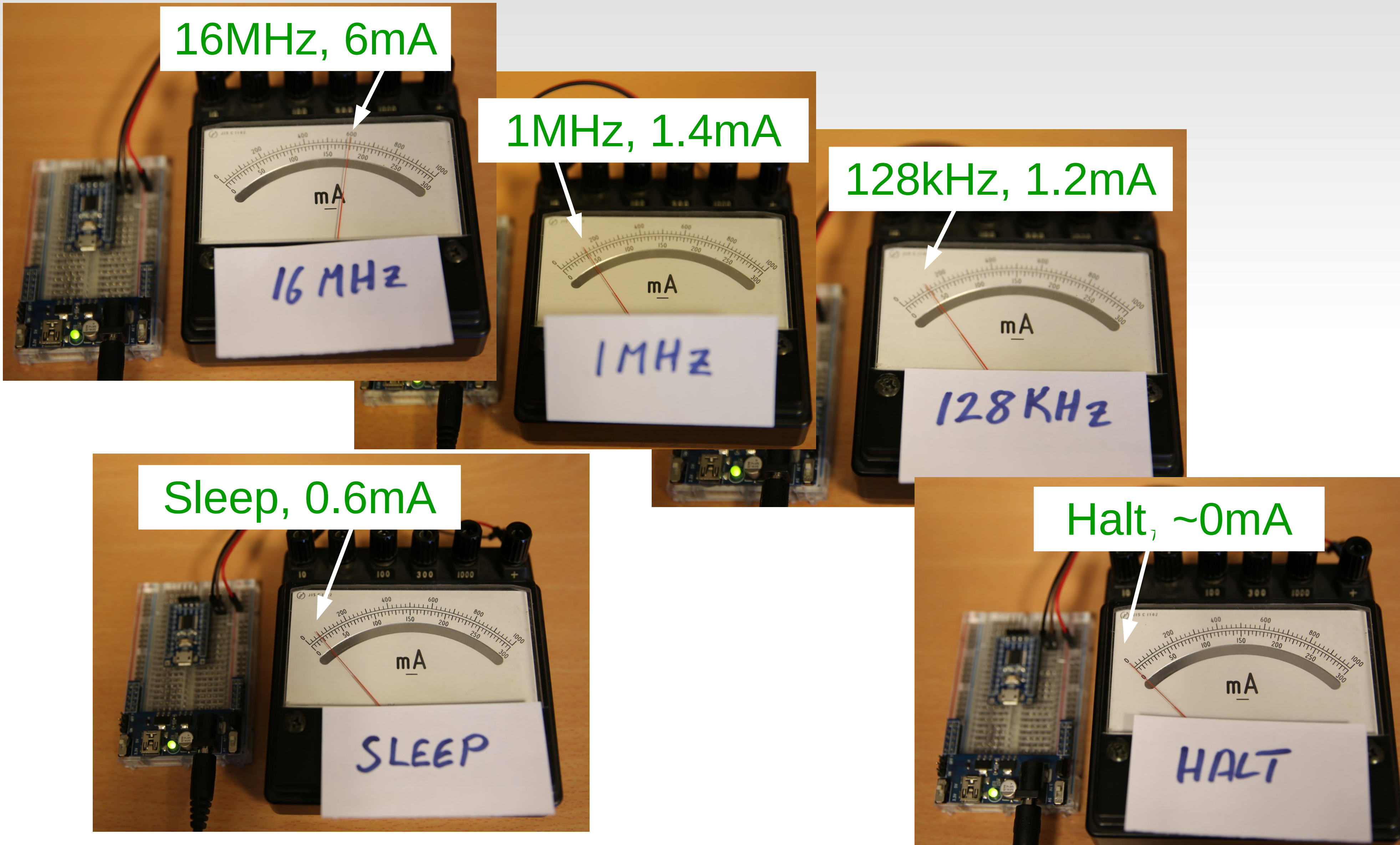
Clock speed vs. power consumption

- Current consumption for different clock speeds were measured at 3.3V supply voltage.
- Drastic change with lower clock frequencies.

Clock speed	Current
16MHz	6mA
1MHz	1.4mA
128kHz	1.2mA
Sleep	0.6mA
Halt	~0mA

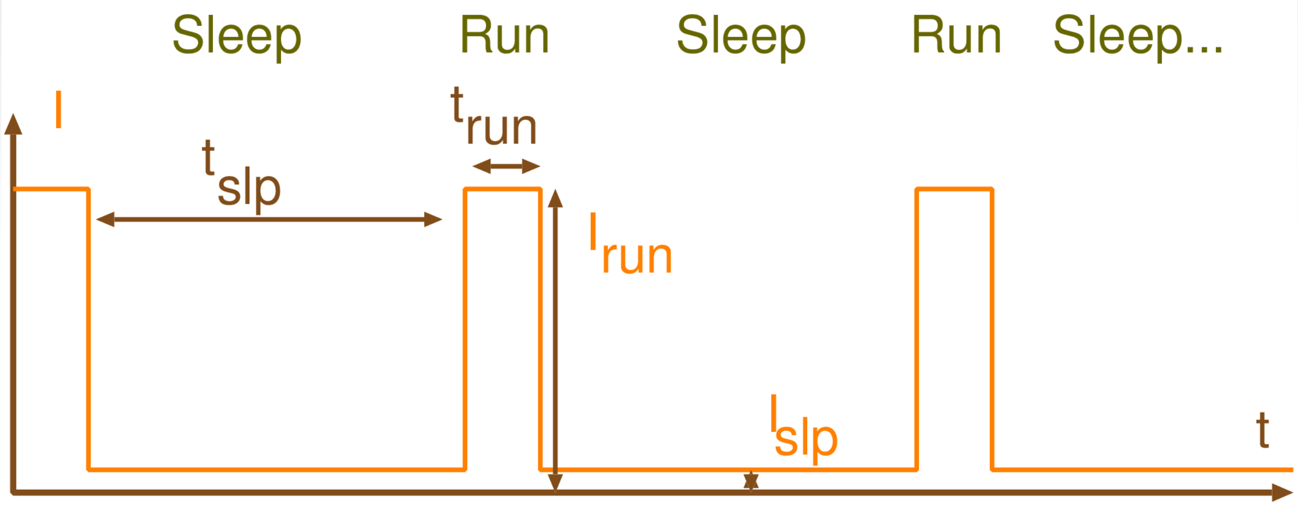


Clock speed vs. power consumption



Sleep mode

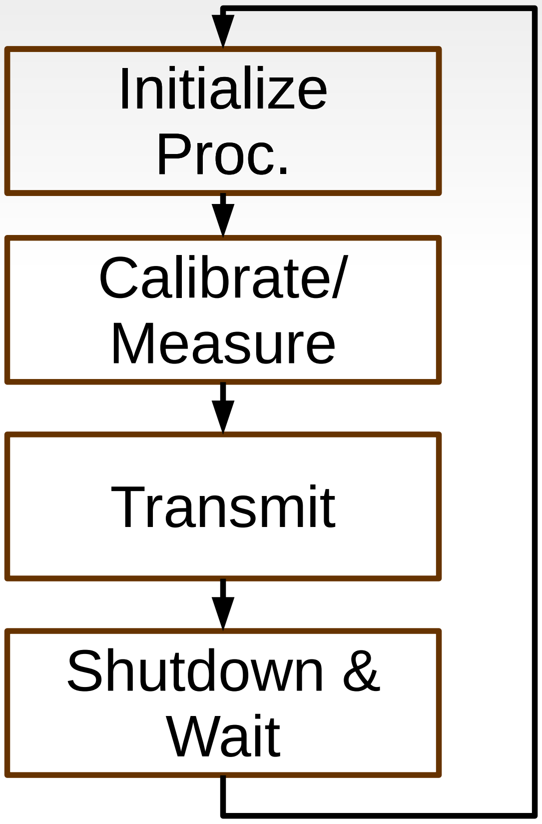
- Stop processor when not needed.



- Average current: $$I_{avg} = \frac{I_{slp} t_{slp} + I_{run} t_{run}}{t_{slp} + t_{run}}$$

FLOPs per Watt

- Processor clock can be actively throttled.
- Low clock speed:
  - Low power consumption
  - Long active time
- High clock speed:
  - High power consumption
  - Short active time
- Most suitable FLOPS/W depends on mode, active peripherals etc.

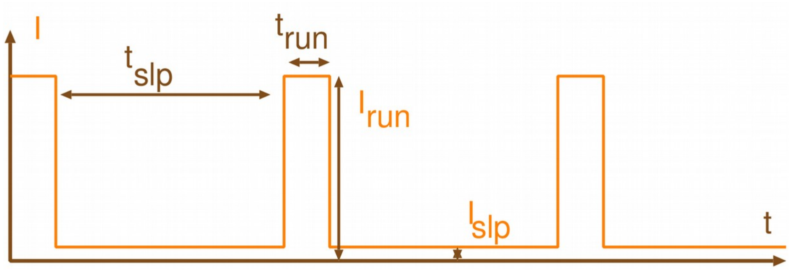


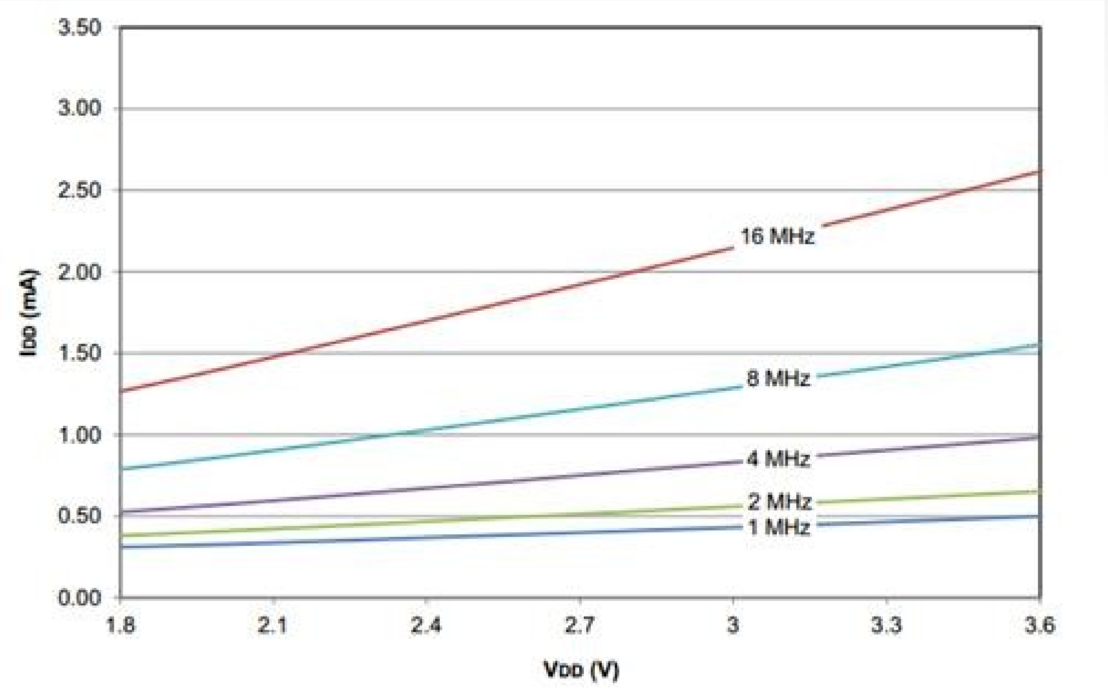
Speed- power tradeoff

- Fast clock & short run time?

OR

- Slow clock & long time?





Fast clock & short time → Better (in general)

Power budget

- For each design:

Mode	Time in Mode (mS)	Current (mA)		Charge Current * Time (mA * Sec)
		By Device	Mode Total	
Sleep MCU Sleep Sensor Off EEPROM Off	1989	0.00005 0 0	5.00E-05	9.95E-05
Initialize MCU Sleep Sensor On EEPROM Off	1	0.00005 0.0165 0	1.66E-02	1.66E-05
Sample Sensor MCU Run Sensor On EEPROM Off	1	0.048 0.0165 0	6.45E-02	6.45E-05
Scaling MCU Run Sensor Off EEPROM Off	1	0.048 0 0	4.80E-02	4.80E-05
Storing MCU Run Sensor Off EEPROM On	8	0.048 0 1	1.05E+00	8.38E-03
Total	2000	—	—	8.61E-03

Battery	Capacity (mAh)	Life			
		Hours	Days	Months	Years
CR1212	18	4180	174	5.8	.48
CR1620	75	17417	726	24.2	1.99
CR2032	220	51089	2129	71.0	5.83
Alkaline AAA	1250	290276	12095	403.2	33.14
Alkaline AA	2890	671118	27963	932.1	76.61
Li-ion*	850	197388	8224	274.1	22.53

Capacities of common cells

Sample power calculation

- CR2032 operated IoT device must run for 5 years, at 1ms operation for every 2sec and sleep current $I_{slp}=1\mu A$.
  → Determine <u>allowable I_{run}</u>?

  $t_{OPR}=5\times 365\times 24=43800\text{h}$

  $t_{slp}=1.999s,\ \ t_{run}=0.001s$

  CR2032 capacity → $C=0.225\text{Ah}$

CR2032

$I_{avg}=C/t_{OPR}\ \ = 0.225\text{Ah}/43800\text{h}= 5.1\mu\text{A}$

$I_{run}=\ \ (I_{avg}(t_{slp}+t_{run})\text{-}I_{slp}t_{slp})/t_{run}= (5.1\mu\text{A}\times 2\text{-}\ 1\mu\text{A}\times 1.999)/0.001$
$= \underline{8.2\text{mA}}.$

- Max 8.2mA runtime current consumption allowed.

$$I_{avg}=\frac{I_{slp}t_{slp}+I_{run}t_{run}}{t_{slp}+t_{run}}$$

Sample power calculation

- IoT device must run for 5 years, at $I_{run}=20\text{mA}$, with 1ms operation for every 2sec and sleep current $I_{slp}=1\mu A$.
  → Determine required battery capacity?

$t_{OPR}=5\times 365\times 24=43800\text{h}$

$t_{slp}=1.999s$, $t_{run}=0.001s$

$C=0.225\text{Ah}$

$$I_{avg}=\frac{I_{slp}t_{slp}+I_{run}t_{run}}{t_{slp}+t_{run}}$$

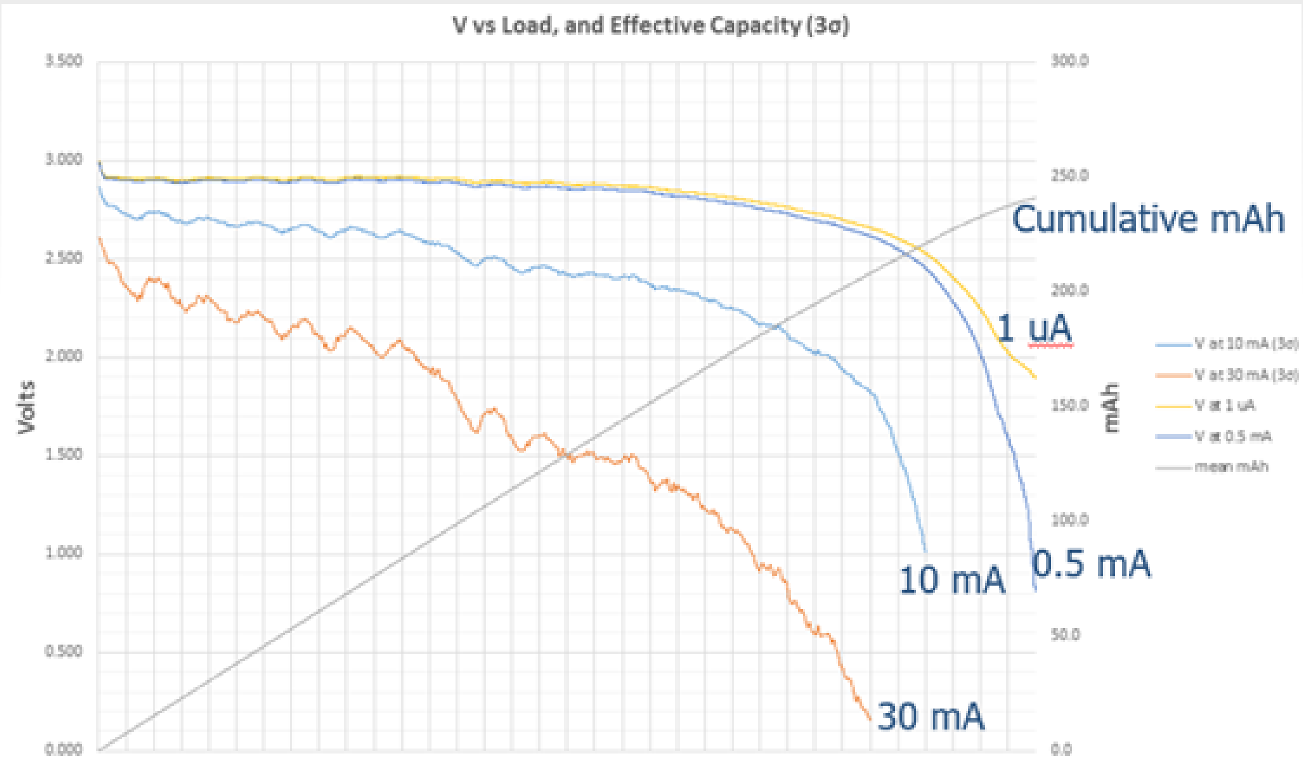
$I_{avg}=(I_{run}t_{run}+I_{slp}t_{slp})/t_{slp+}t_{run}= (20\text{mA}\times 0.001+1\mu\text{A}\times 1.999)/2=11\mu\text{A}$

$C= 11\mu\text{A}\times 43800\text{h}=\underline{481\text{mAh}} \rightarrow 500\text{mAh}$

→ Use a cell of 500mAh capacity.

Battery current capacity

- High current degrades cell performance. <u>Select</u>: $I_{run} < I_{max}$

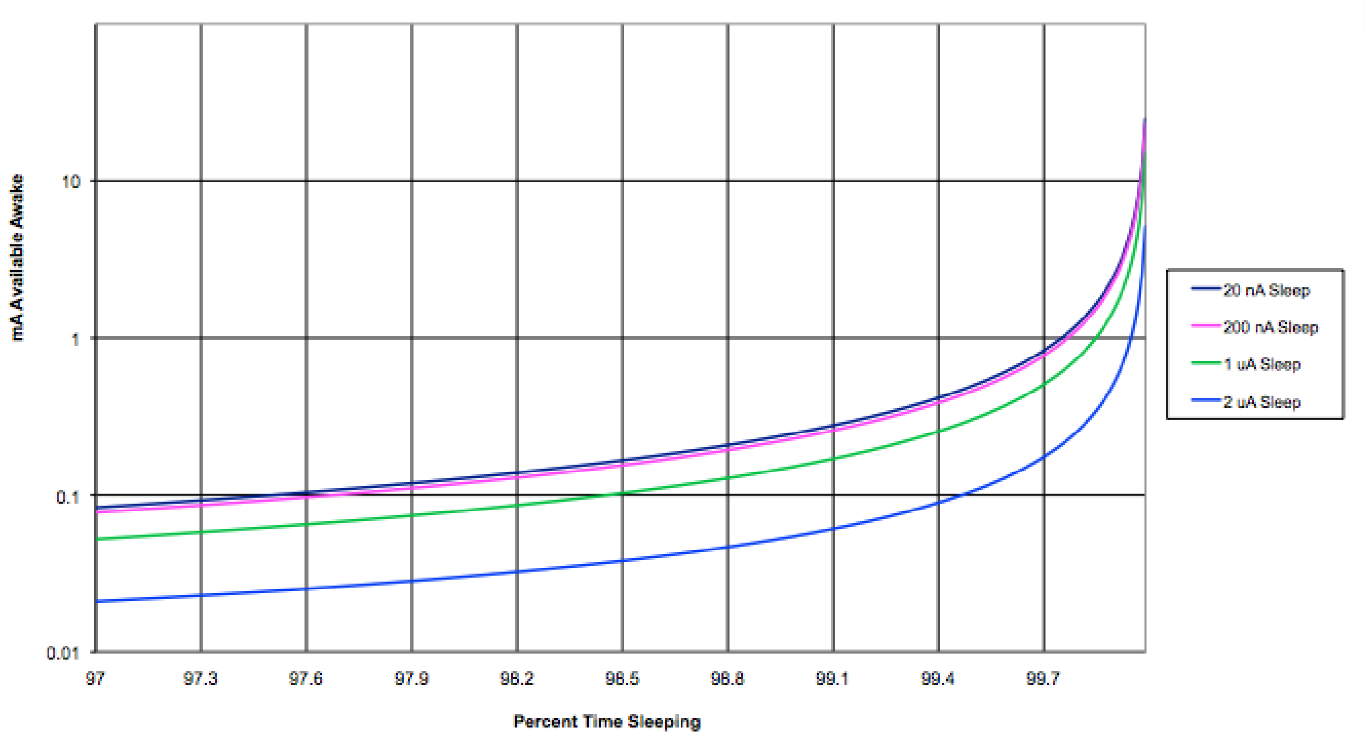


CR2032 discharge curves for different currents

Ganssle: Hardware and Firmware Issues in Using Ultra-Low Power MCUs

Duty ratio vs. energy

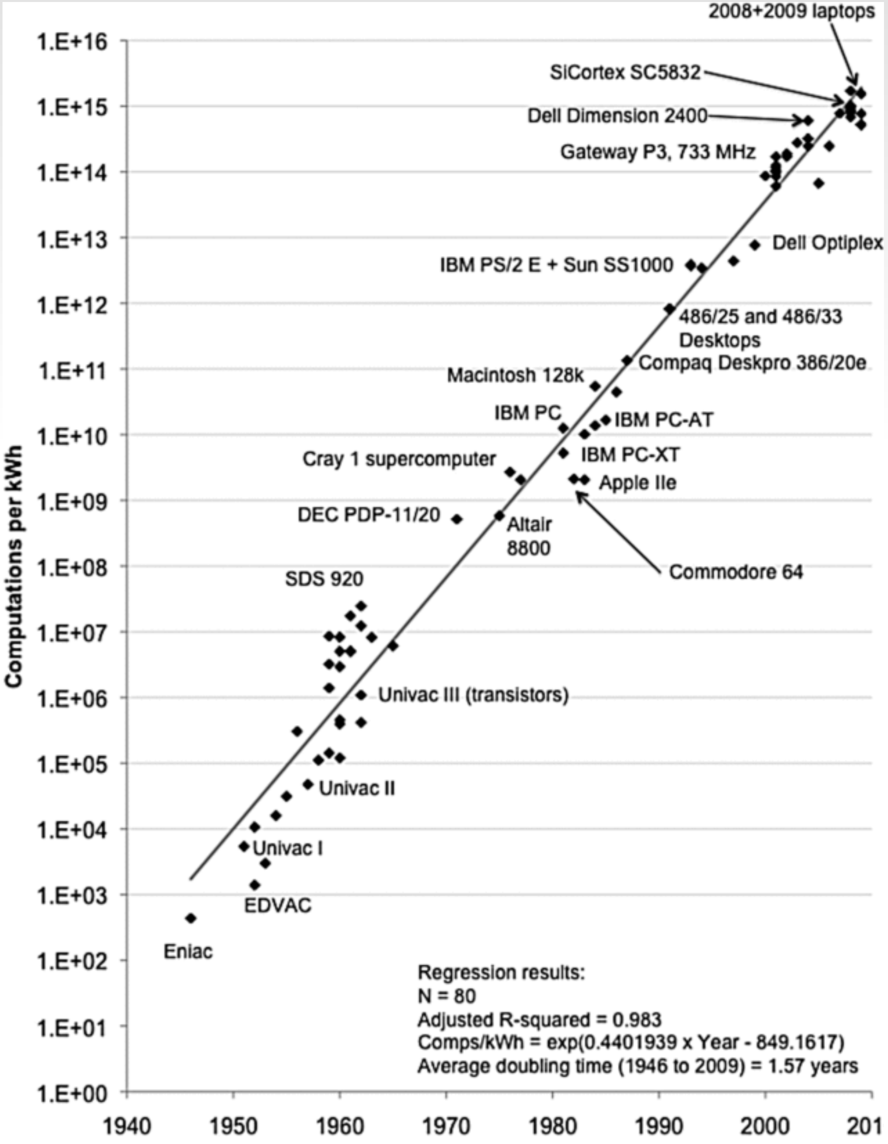
- CR2032 I_{run} vs. duty ratio.
- Lower duty ratios are superior!
- Sleep consumption does not have great impact!



Koomey's Law

- "...the power needed to perform a task requiring a fixed number of computations will fall by half every 1.5 years,"

J.Koomey, S.Berard et al, "Implications of Historical Trends in the Electrical Efficiency of Computing", IEEE Annals Hist. Comp, V33-3, pp. 46~54, 2011



LoRa IoT device

- Detailed models of LoRa power consumption available:

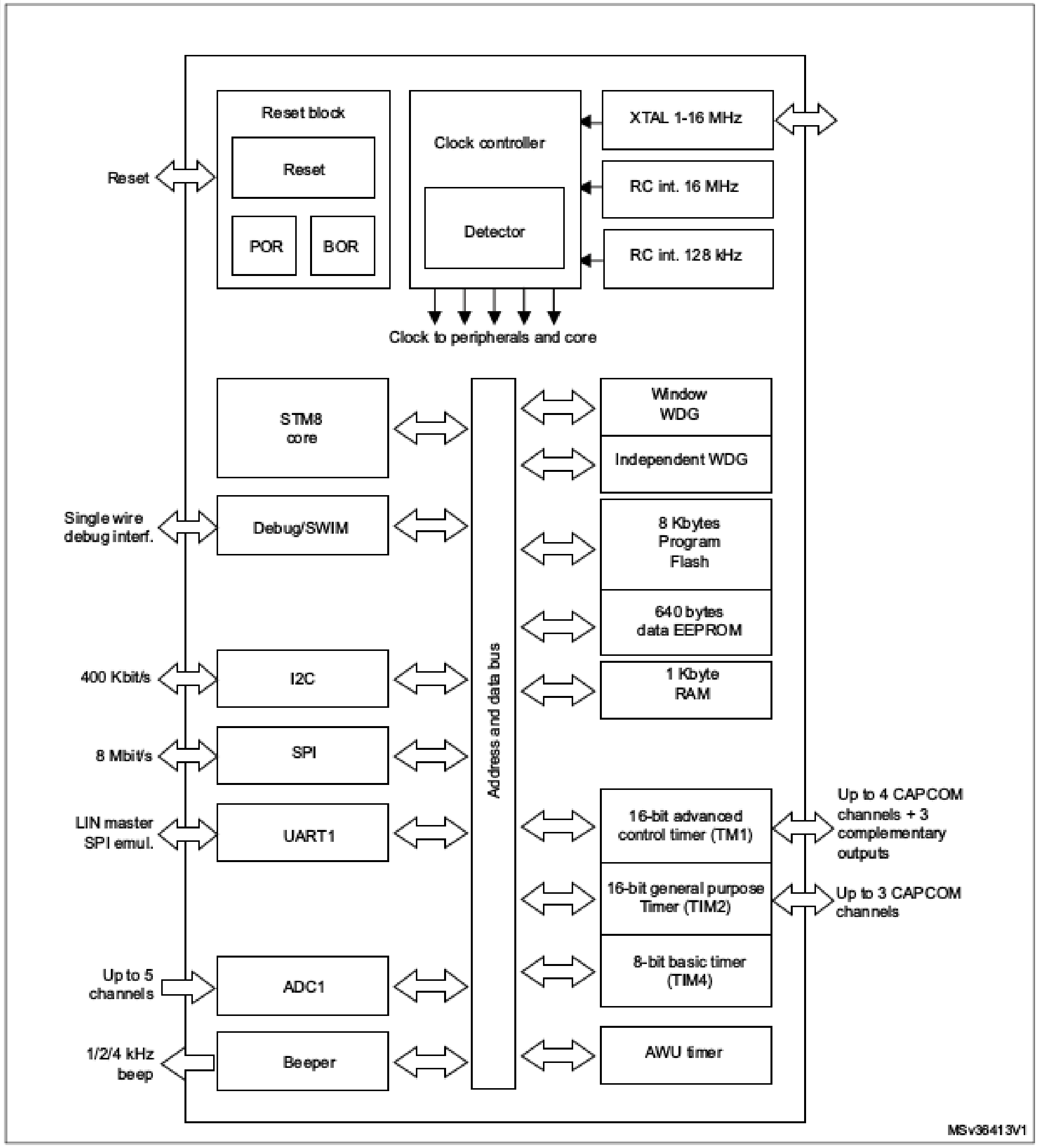
L. Casals et.al., “Modeling the Energy Performance of LoRaWAN”, Sensors, 2364, 2017,

T. Bouguera et.al, “Energy Consumption Model for Sensor Nodes Based on LoRa and LoRaWAN”, Sensors, 2104, 2018 etc.

Power management of peripherals

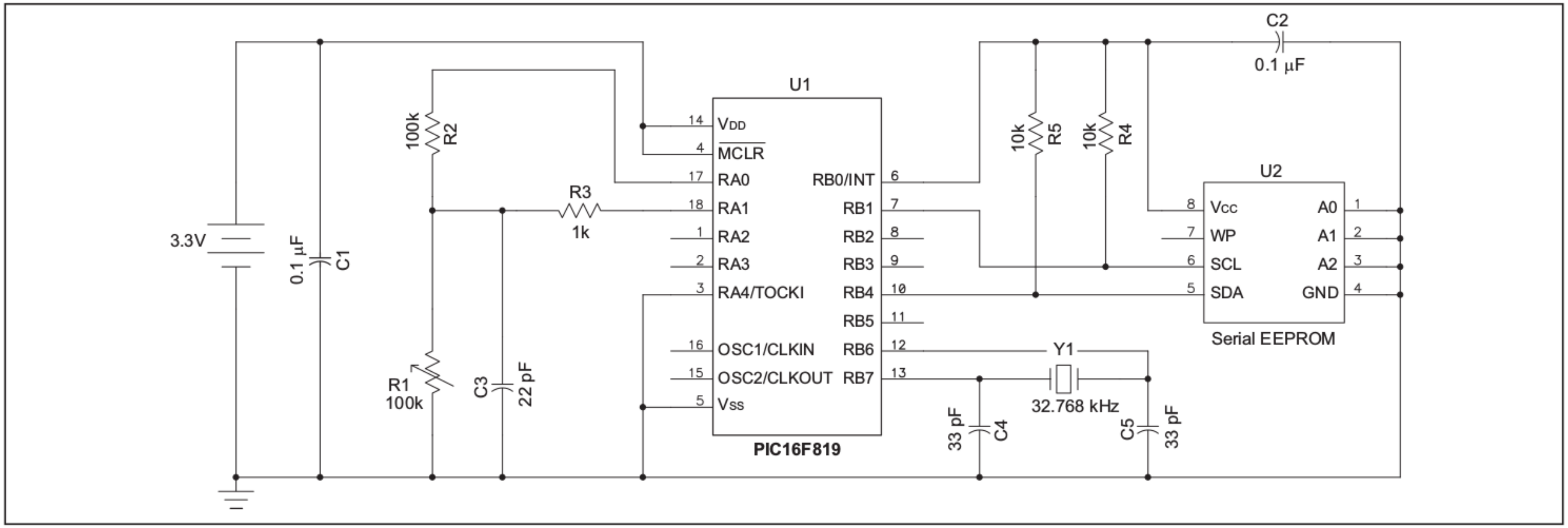
- Microcontrollers have many peripheral devices.
- Powered off when not needed.
- Note clock controller at the top center!

Figure 1. STM8S103F2/x3 block diagram



External devices

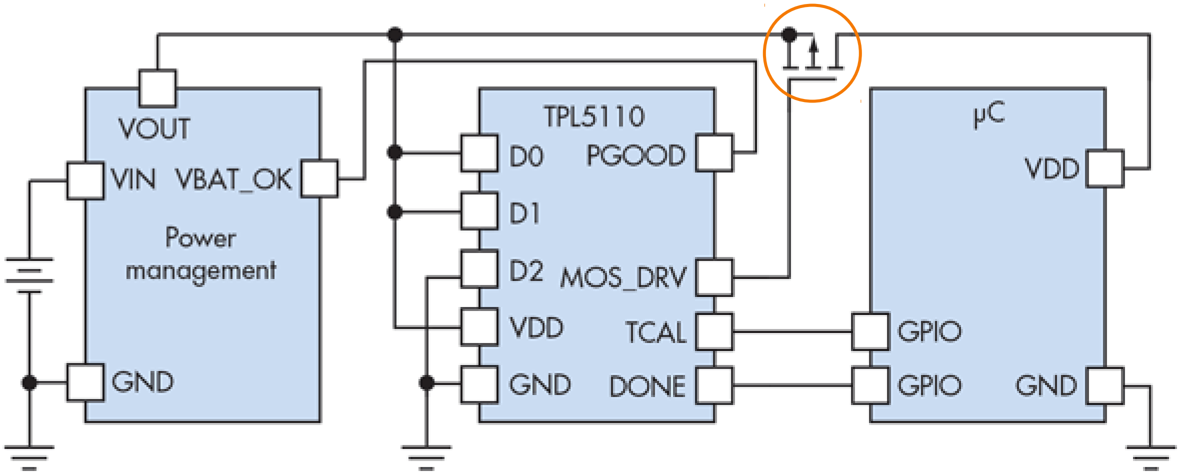
- Should also be powered down.
- Using power switches (transistor)
- Even processor pins:



Microchip App Note: AN1416

External timing of processor power

- Most processors have sleep timers.
  - Processor consumes power during sleep
  - I/O pins used to power down sensors may keep consuming power.
- Many power management chips are on the market.

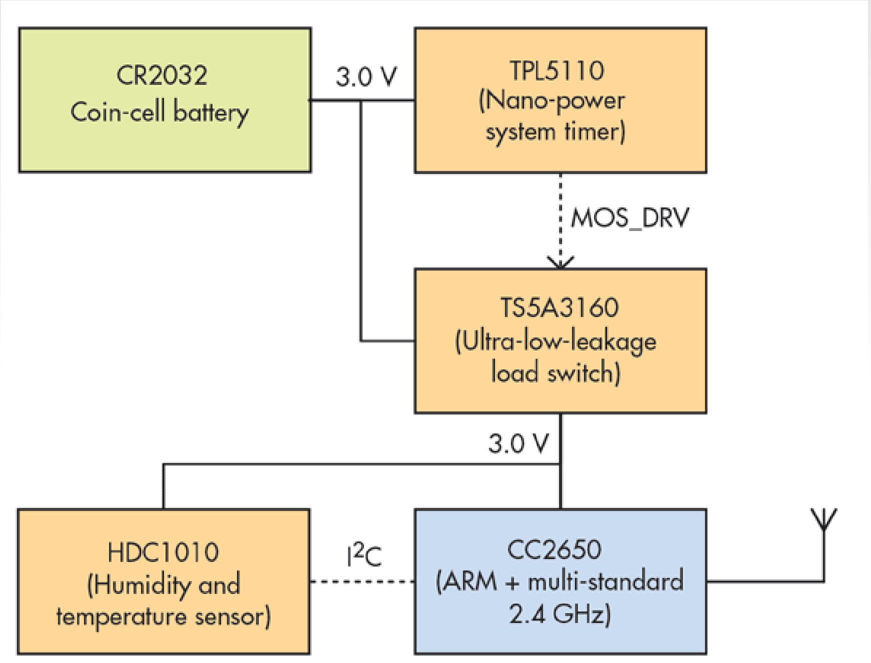


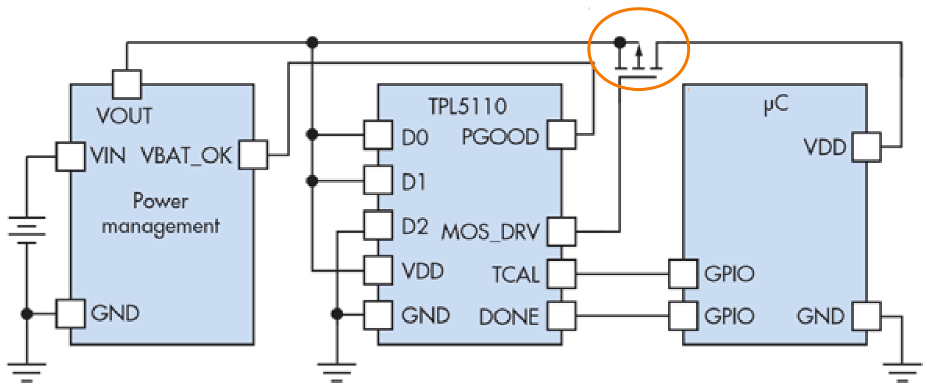
TI TPL5110 System timer

External timing of processor power

- Processor sets sleep time
- Timer turns off power:
  Whole system is switched off.

- Processor sleep mode: 1µA
- Timer sleep mode: 35nA





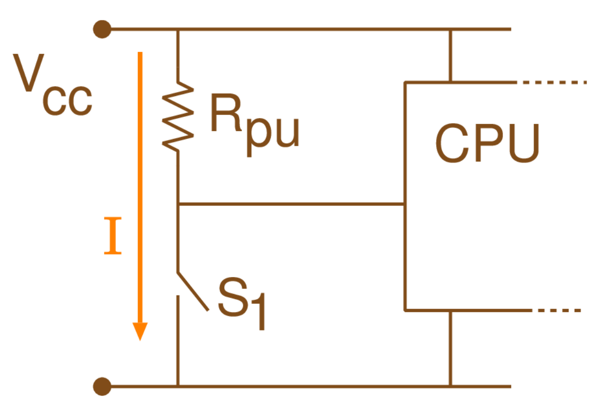
Leakage of insignificant components

- Capacitors across power rails for stabilization

Capacitor| type	Leakage current (nA)
Electrolytic	5000
Tantalum	1000
Ceramic	20
Film	5

- Pull up resistors:

  $I = V_{cc}/R_p$ flows as long as switch pressed.



Power Sources for IoT

What is available?

- Solar power *$O(1000W/m^2)$*
- Wind power– Large scale: *$O(400W/m^2)$*
- Human scavenging: *$O(0.1W/m^2)$*
- Grid connected

- Low power, portable applications:

  → Solar energy is the most common.

(Following slides greatly inspired by Ermanno Pietrosemoli, ICTP)

How much solar energy to expect?

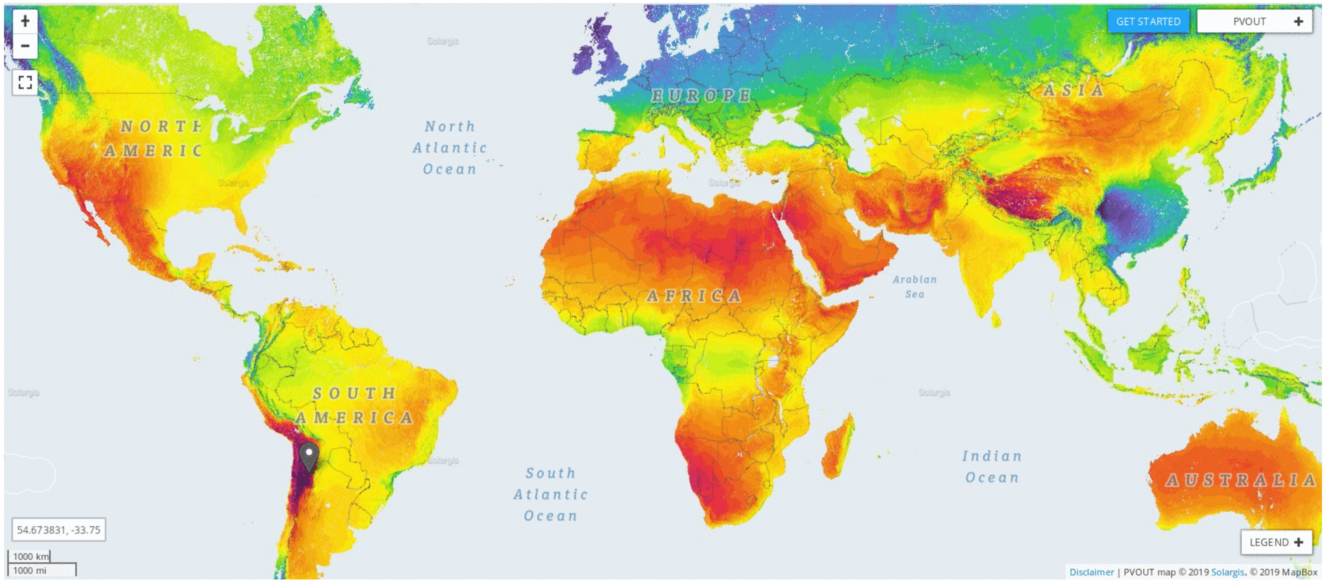
- Indoor solar: $10{\sim}1000\mu W/cm^2$
- Outdoor solar (peak): $1kW/m^2$

- For a general application,
  how much solar power to expect?

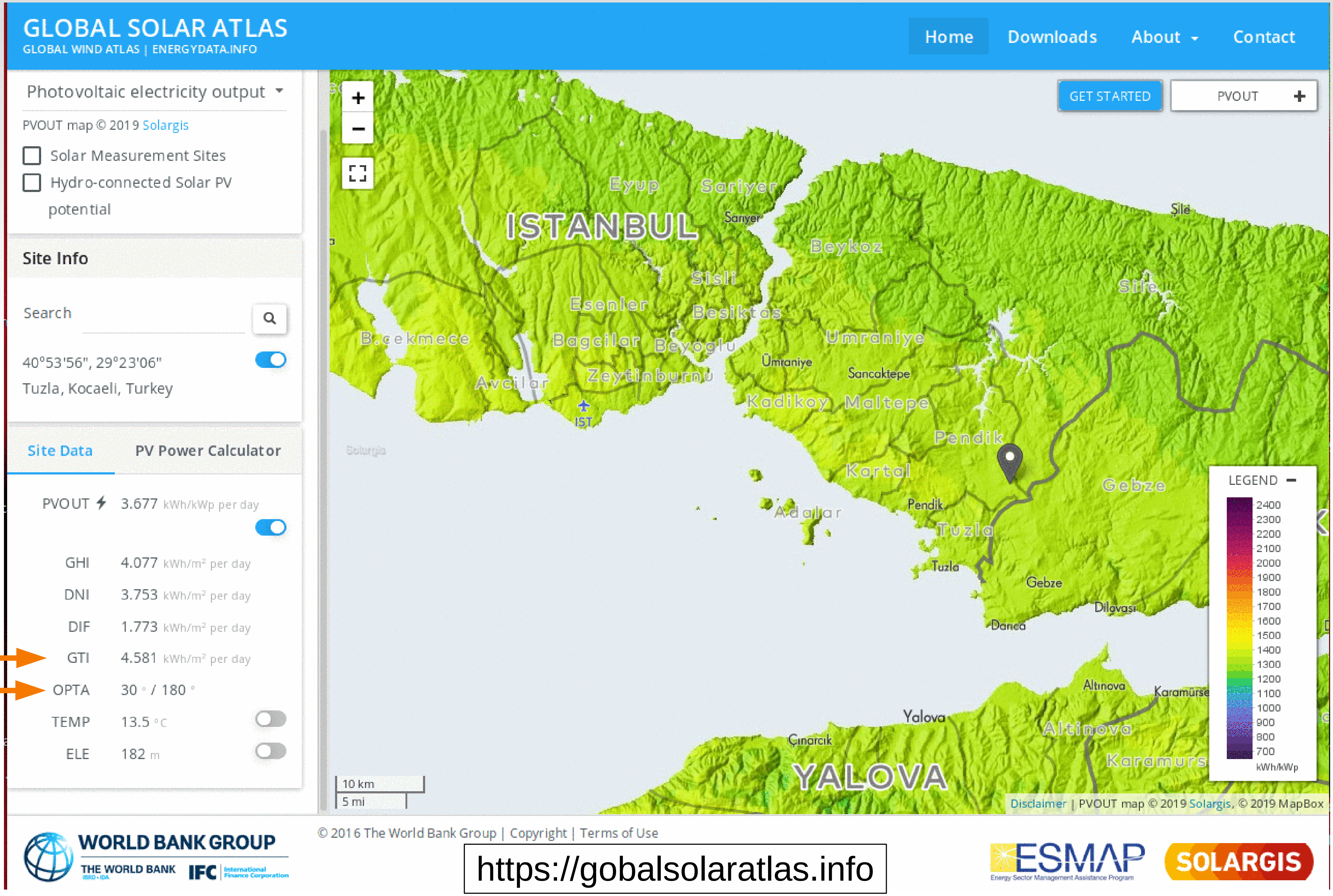
  → Depends on the location.

  Chile: $8.0kWh/day$

  Oslo: $3.3kWh/day$



Sample location: Tuzla, Istanbul



https://gobalsolaratlas.info

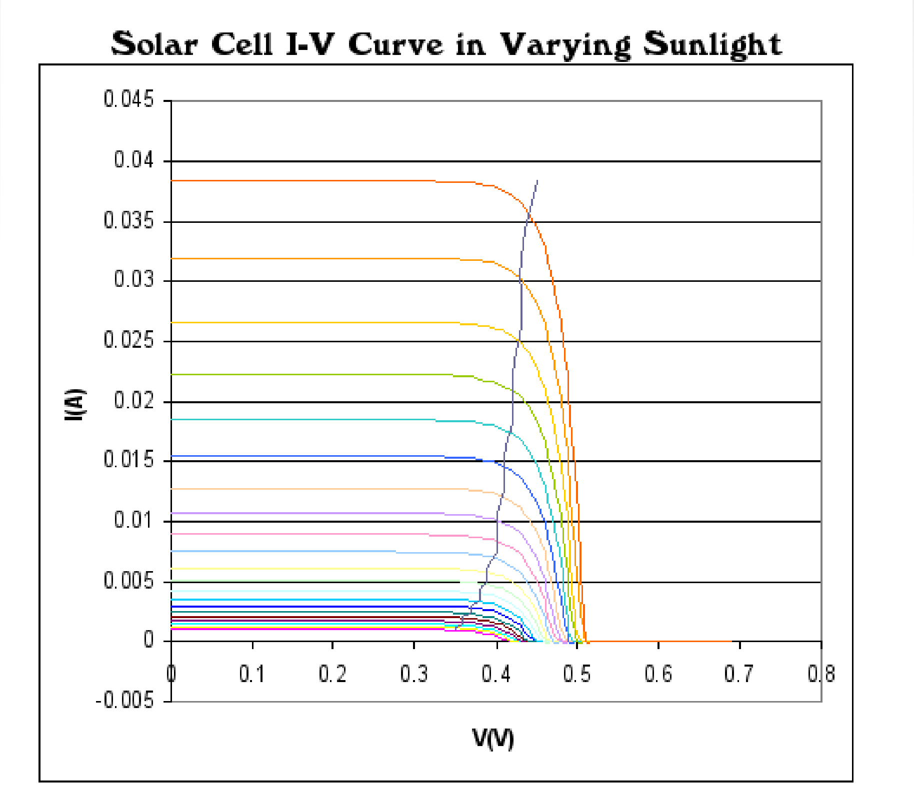
Solar Cell Basics

- Efficiency η_s=8%~45%.
- General commercial: η_s=15%
- Power output:
  - More current draw, less voltage.

$$P = V \times I$$

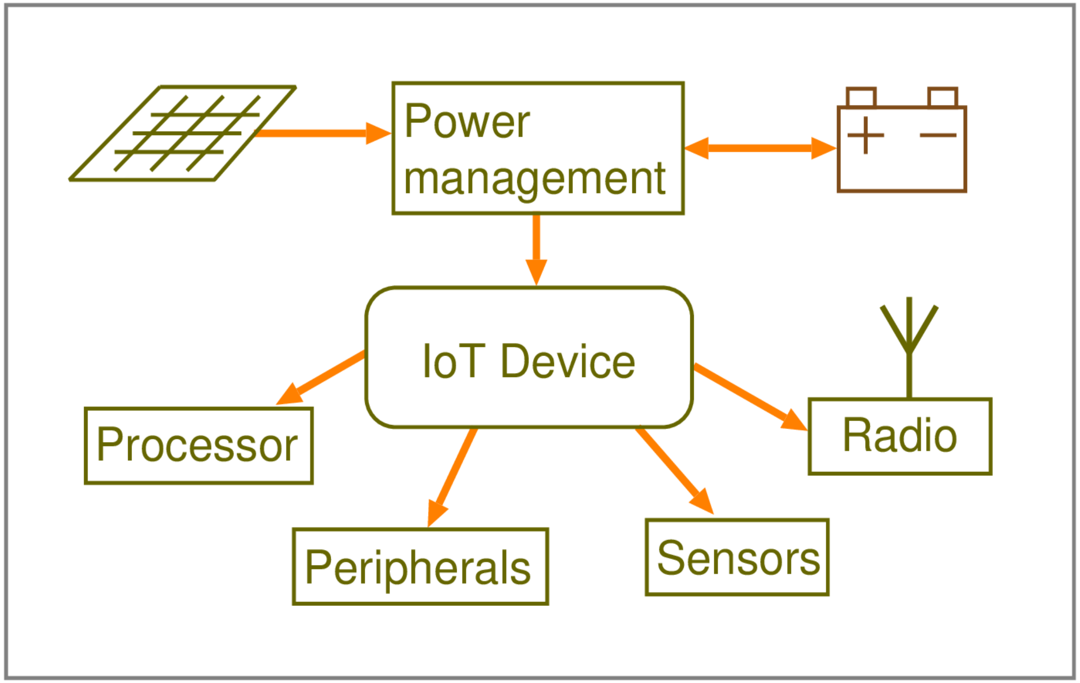
- <u>Must track the best V~I ratio</u>.
- Control charge current
  to maximize power.

→ Buck/boost converter- regulator OR
→ Linear charge controller.



Sizing solar cell systems

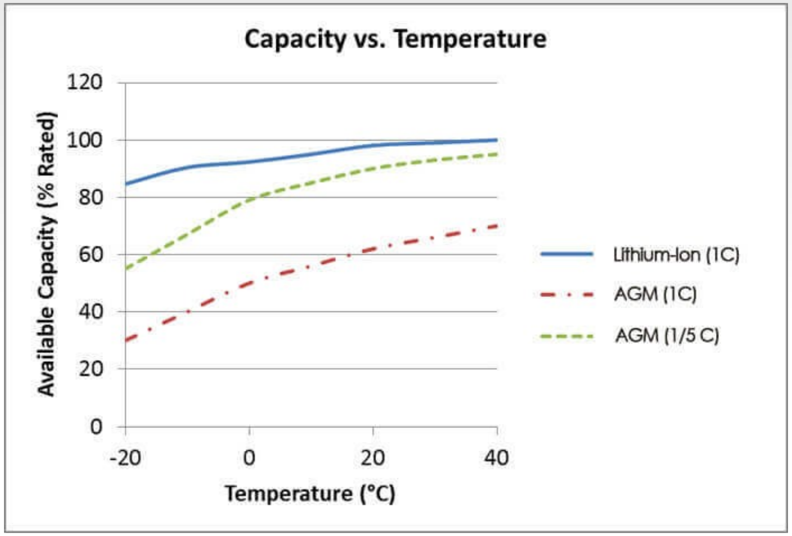
- We know IoT device power consumption →
- What size battery?
- What size solar cell?



Battery capacity

- Determine: I_{avg},
  - Charge efficiency η_C, (=97% for LiPo)
  - Useable capacity C_U, (=90% for LiPo)
  - Temperature dependent capacity C_T
  - Days without solar irradiation D
  - Safety factor S_B (Take e.g. 1.2)

$$C_B = 24\,D\,I_{avg}\,S_B / \eta_C\,C_U\,C_T$$



C_T relationship

- Example: $I_{avg} = 20mA$, 3 days, $C_T = 0.95$ (room temp.)

  $C_B = 2100$mAh →Buy a 2100mAh battery of required voltage.
- Voltage is the same as application requirement.

Solar cell area

- Determine:
  - Local daily Irradiation GTI (from map)
  - Required full charge time t_F (n days)
  - Solar cell rated voltage V_S ($V_S > V_L$. $6V$ for $3.3V$ system)
  - Solar cell efficiency η_S (15%)
  - Battery capacity C_B (from previous)
  - Safety factor: S_S (Take e.g. 1.2)
- Calculate required solar energy: $E_R = C_B V_S S_S / \eta_s t_f$
- Calculate cell area: $A_S = E_R / GTI$

Solar cell area

- Example:
  - Location: Tuzla Istanbul. GTI=$4581 Wh/day\ m^2$
  - Required full charge time t_F= 2 days
  - Solar cell rated voltage $V_S=6V$
  - Solar cell efficiency η_S=15%
  - Battery capacity $C_B=2100mAh$
  - Safety factor: $S_S=1.2$
- Required solar energy:
- Calculate cell area:
- →Buy a solar cell of about 11cm×10cm, at 6V

$$E_R = C_B V_S S_S / \eta_s t_f$$

$$A_S = E_R / GTI$$

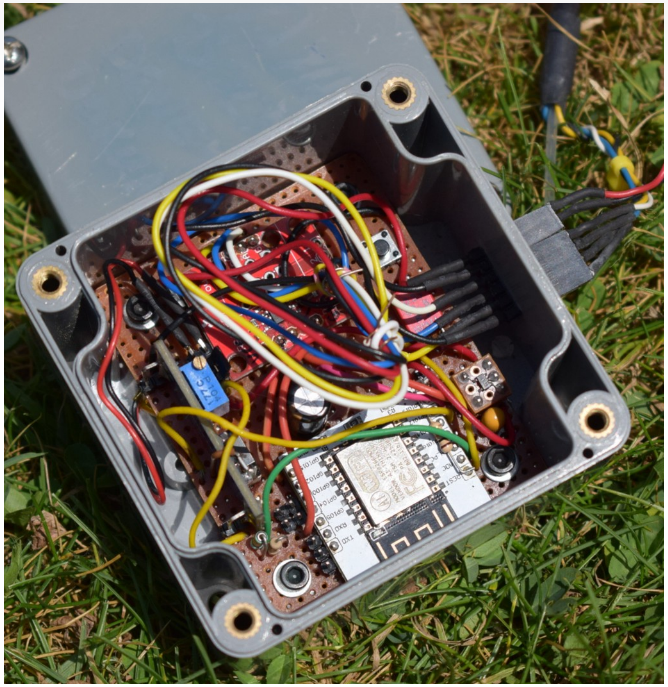
$$E_R = 50.4\,Wh$$

$$A_S = 0.011\,m^2 = 110\,cm^2$$

Example project

- Water depth transmitter built according to the described design rules.
- Pond water depth gage (~2017)

Before deployment at field



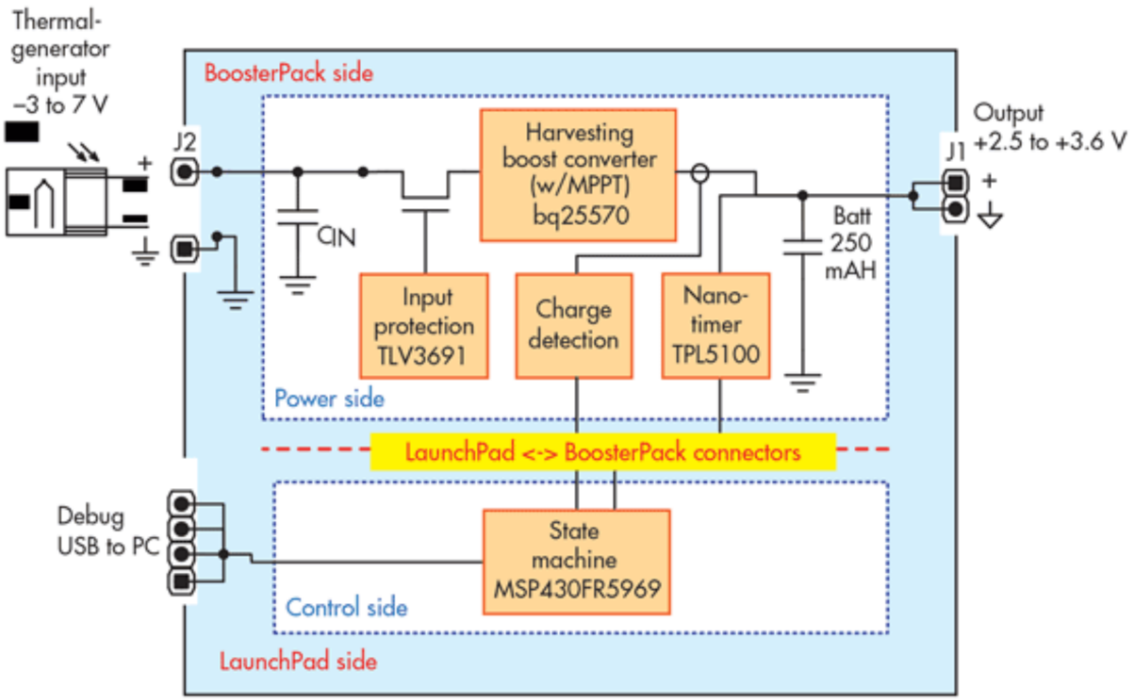
Case contents

Energy Harvesting

- Solar cells, piezo devices, thermoelectric generators etc.
- Maximum power must be derived from the generator.

$$P = V \times I$$

- Stored in a battery.



(Some) References

- L. Casals et.al., “Modeling the Energy Performance of LoRaWAN”, Sensors, 2364, 2017,
- T. Bouguera et.al, “Energy Consumption Model for Sensor Nodes Based on LoRa and LoRaWAN”, Sensors, 2104, 2018 etc.
- Paul Pickering, “Designing Ultra-Low-Power Sensor Nodes for IoT Applications”, Texas Instruments, 2006
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Contact Information

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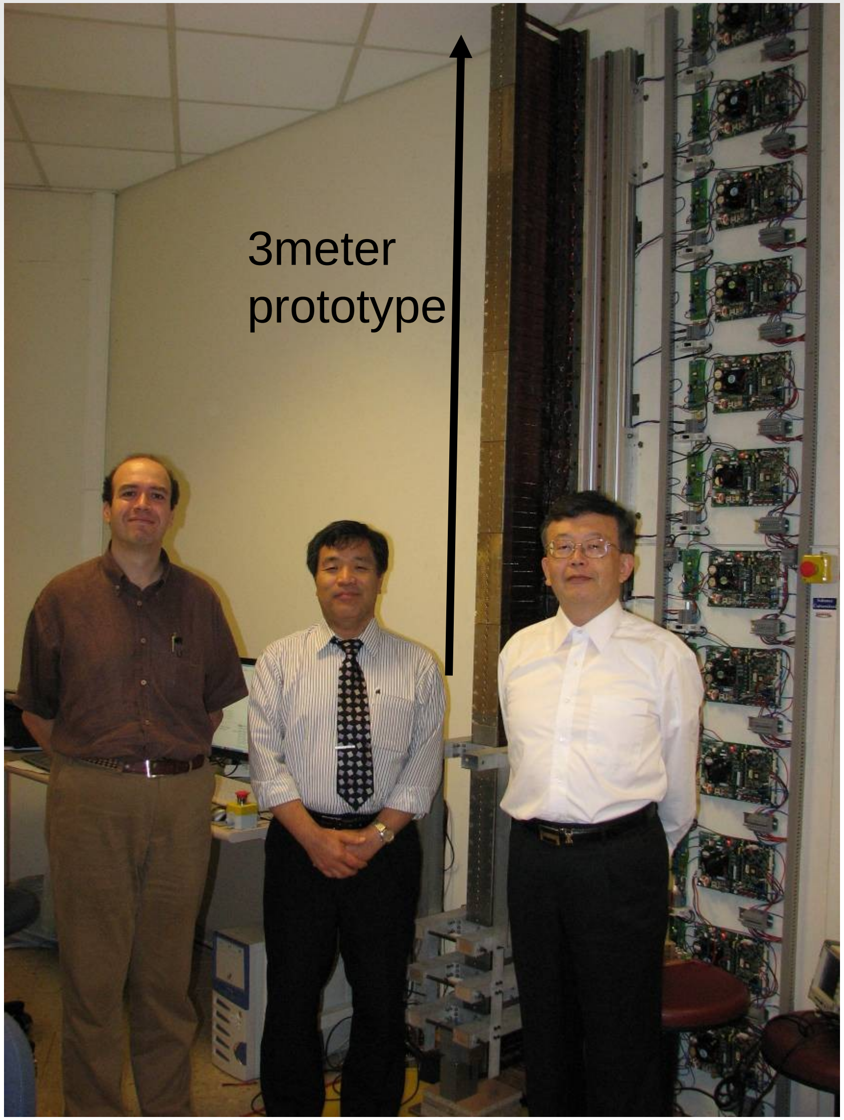
Research projects

- I am carrying out projects in
  - Reinforcemet learning for dynamic systems
  - Networked real-time systems. Internet of Things IoT
  - Haptic interfaces for 3D displays
  - Linear motor design
  - Underwater autonomous robots
- See:
  - http://people.sabanciuniv.edu/onat
  - https://aviatorahmet.blogspot.com

- Enthusiastic students are welcome to help!

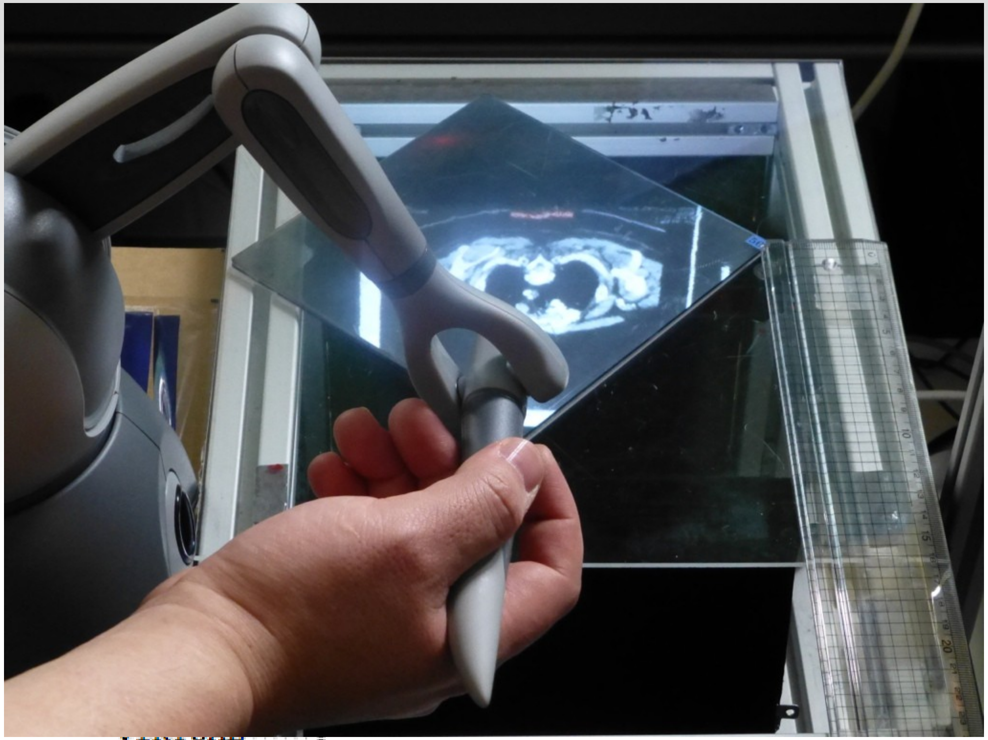
Linear motor elevators

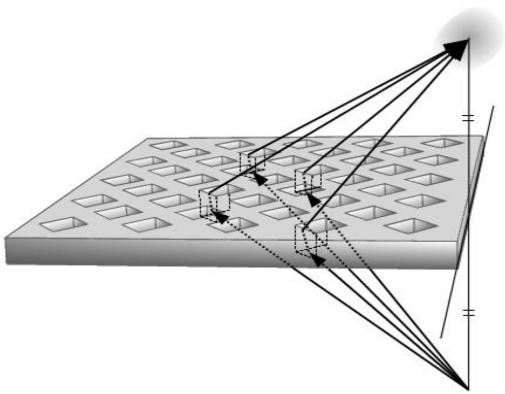
- Vertical linear motor design
- Project funded by Fujitec, Japan
- 2007-2013
- 450kg payload, 1000m length
- Prototype, patents, publications
- Magnetic, electronic, control, safety design

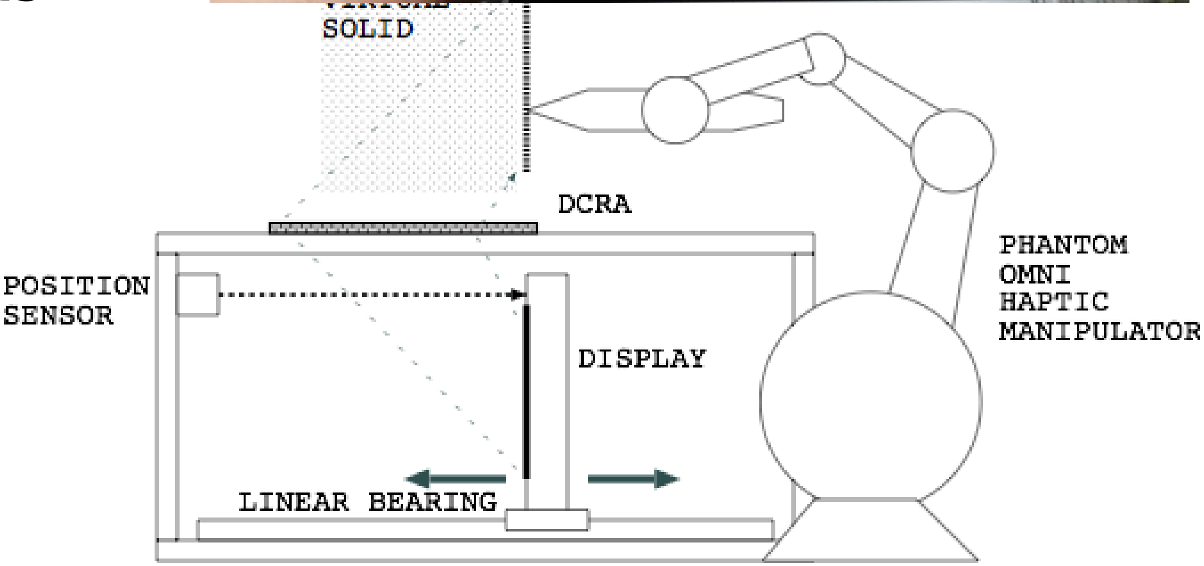


Dihedral Corner Reflector Array (DCRA)

- A passive optical device
- That can create **real reflections** to form **floating images in the air**
- Haptic feedback for projected solid objects

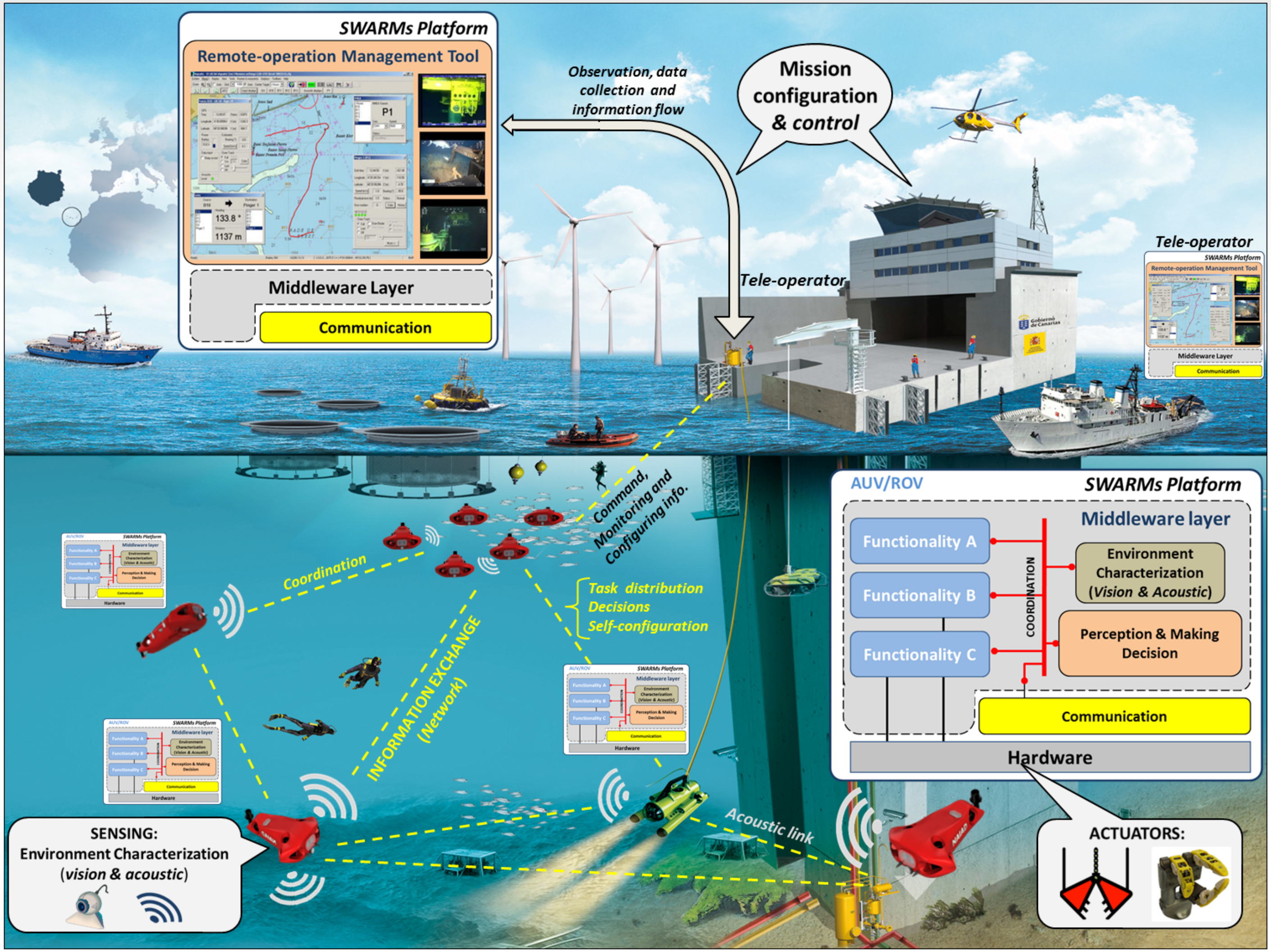






SWARMS

- Modeling of underwarter autonomous vehicles (IoT)



Networked control systems

- A novel method for control over networks with
  unpredictable delay & data loss
- Stability analysis, simulation & prototype
- Tolerant of large amounts of delay
- Also wireless Ethernet application
- Publications & prototype control systems