Behind the Device: Where your power goes in IoT devices before you burn it

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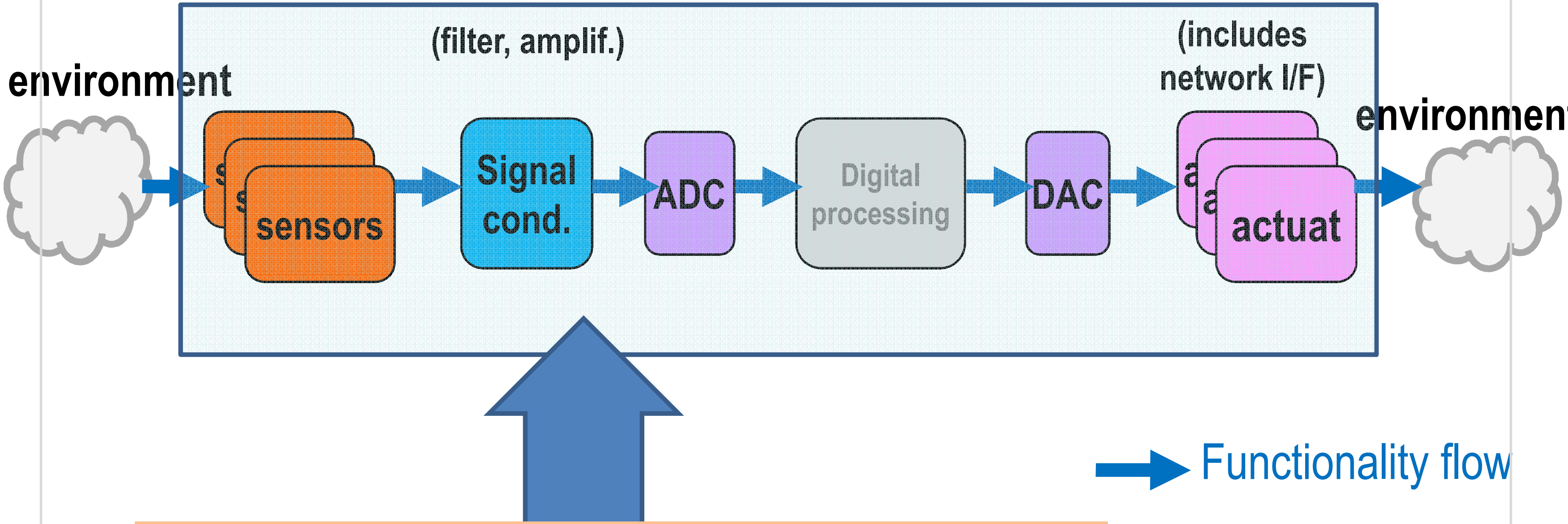
Overview

- What's "behind" your IoT device?
- Optimizing energy usage "behind the device"
  - **Generation**
  - **Conversion and distribution**
  - **Storage**

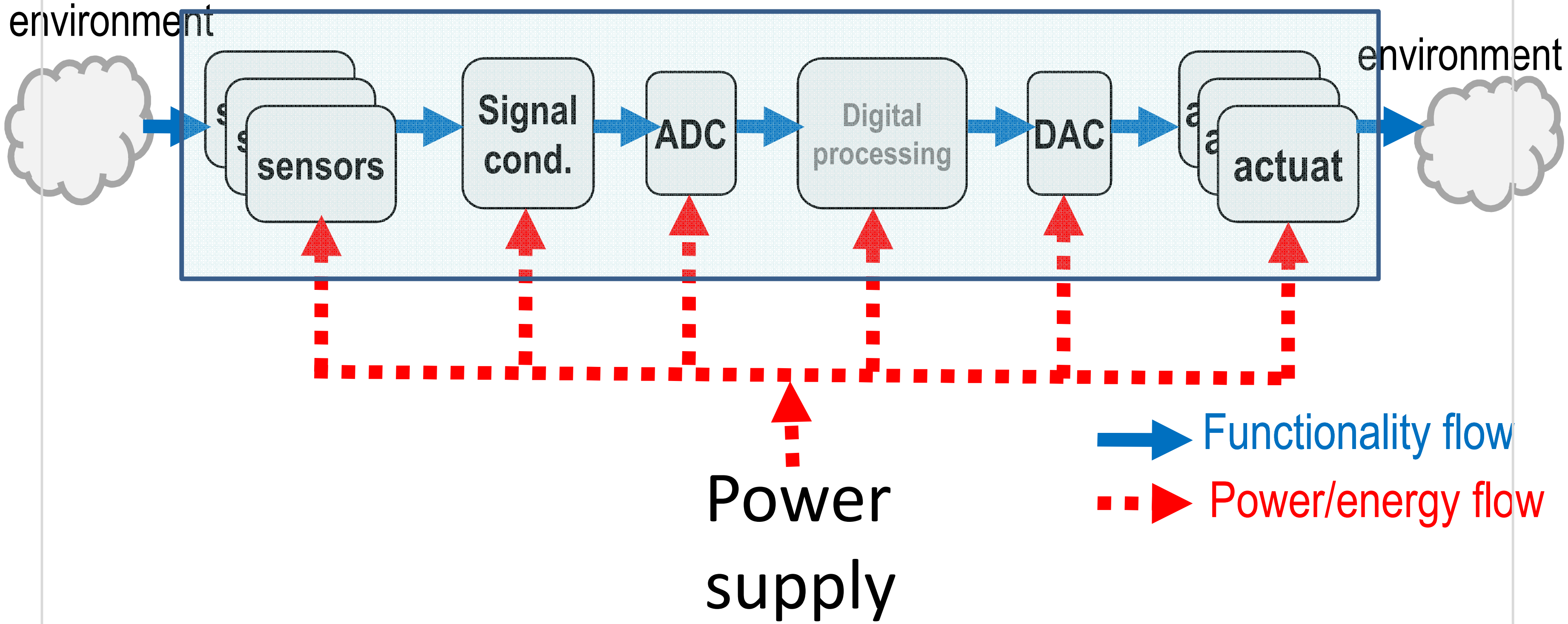
An abstract view of an IoT device



Energy-efficient strategies
work here: the "hardware"

An abstract view of an IoT device

- But there is much more around



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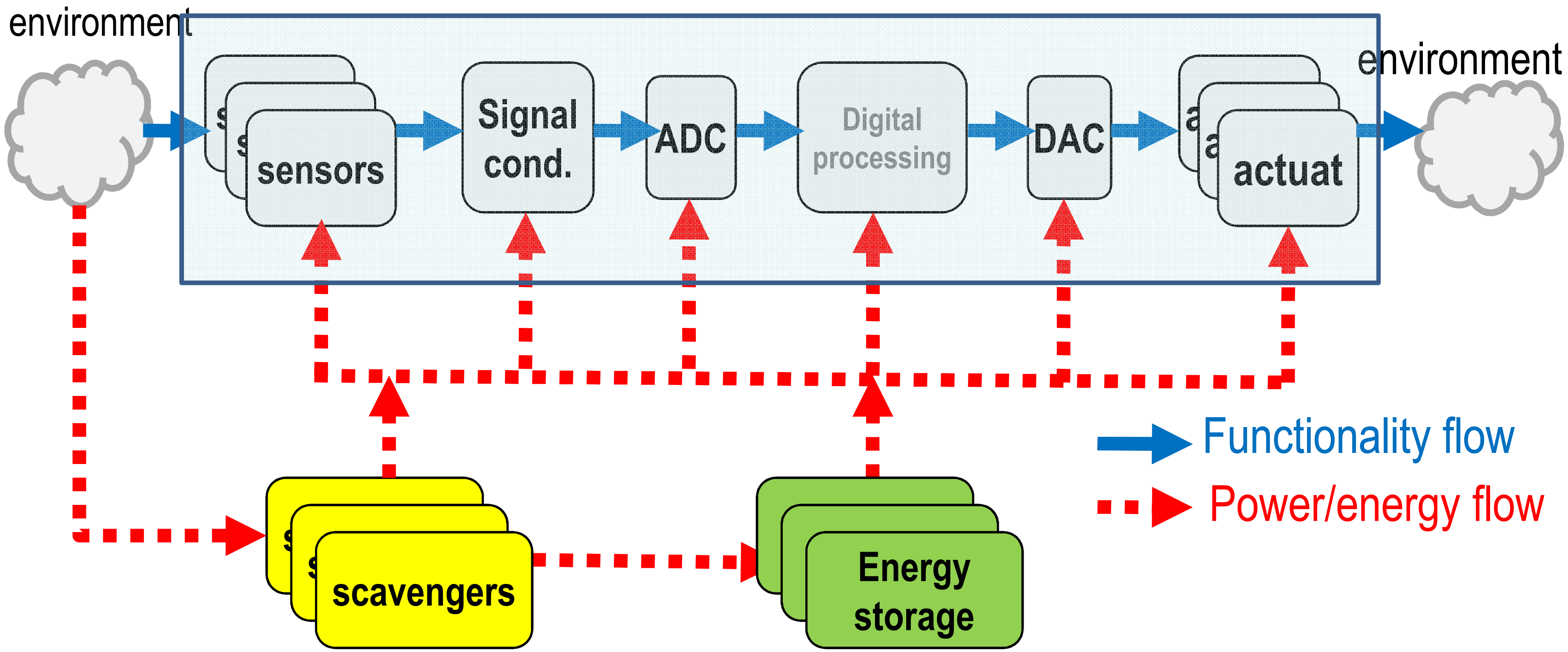

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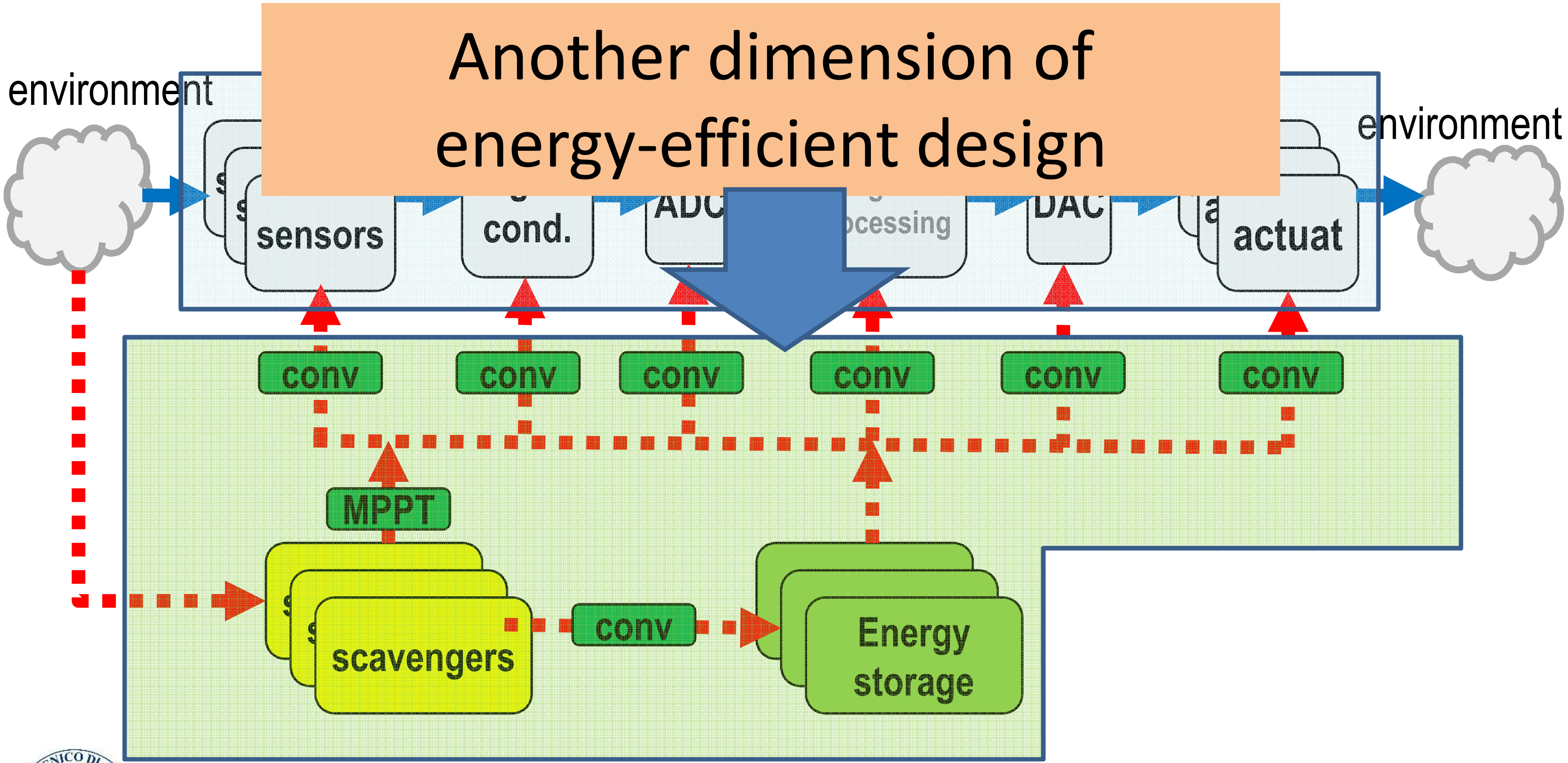


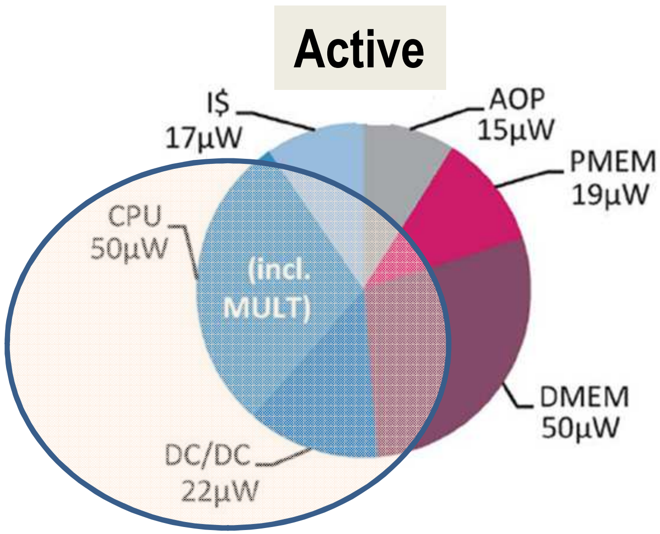
Consuming energy?

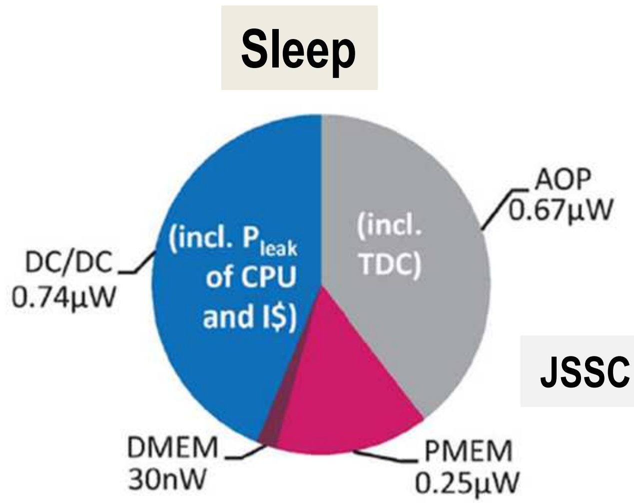
- Digital and non-digital **functional** parts (MCU, accelerators, memories, RF, I/Fs) are **assumed to be power-optimized**
  - Designer picks components, protocols, etc. based on needs and based on their power scores
  - **Functionality (@ low power) as commodity!**

- … But most of the energy is likely to **lost elsewhere** (and not in the loads)

Some figures from an example device

- SleepWalker node from IMEC
  - Actually a ULP µcontroller (7uW/MHz) including a DC/DC converter
- DC/DC losses take from about 12% to 40%
  - Small but even more significant in sleep state…
  - And this is just one converter…





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Managing energy

- In an autonomous system power is
  - **Generated** through various types of energy harvesters (*power sources*)
  - **Distributed/converted** to the various units
  - **Stored** in appropriate energy storage devices (ESDs) to guarantee sustained service

- **We will overview the main sources of energy inefficiencies in these three phases**

Power sources:
background and power issues

Energy harvesting

- = extracting energy from the environment
- We need electrical energy, so any harvester embeds some kind of transducer
- A large variety of physical effects can be exploited
  - Piezo*electric*, photo*electric*,tribo*electric*, thermo*electric*,...
- As users, we are more interested in the “sources” from which we can extract energy…
  - **(solar) radiation**
  - **Vibration**
  - **temperature**
  - friction
  - Ambient radio frequency/noise
  - Ambient airflow

Issues with energy harvesting (1)

1. **Generated power depends on the value of a specific environmental quantity**

How do we guarantee as much extracted power as possible under different environmental conditions?

The "maximum power extraction" problem

Issues with energy harvesting (2)

2. **Extracted power is almost invariably very low…**

Harvesting method	Power density
Solar cells (outdoor at noon)	15 mW/cm^2
Solar cells (illuminated office)	100 µW/cm^2
Piezoelectric (shoe inserts)	330 µW/cm^3
Thermoelectric (10 °C gradient)	40 µW/cm^3
Acoustic noise (100 dB)	1 µW/cm^3

A typical battery cell has 100s-1000s mW/cm^3 !!!

Issues with energy harvesting (2)

2. **Extracted power is almost invariably very low…**

How can we derive acceptable power levels for typical computing blocks?

Power conversion

Scavenger “packing”

Issues with energy harvesting (3)

3. **Extracted power might not be needed "right now"**

How can we accumulate excess energy?

Energy storage design and optimization

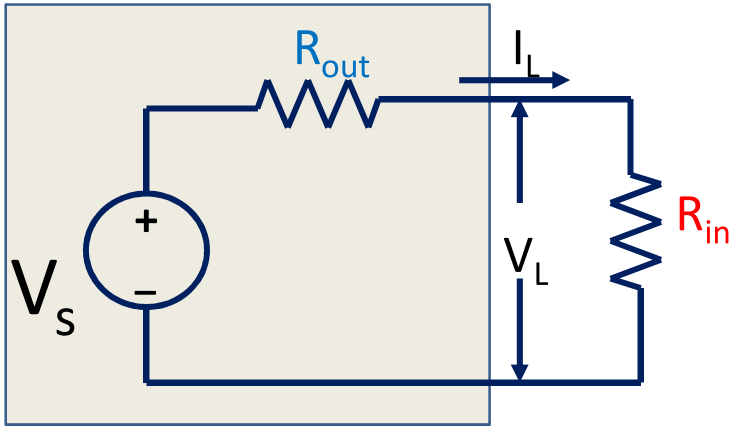
Extracting Maximum Power

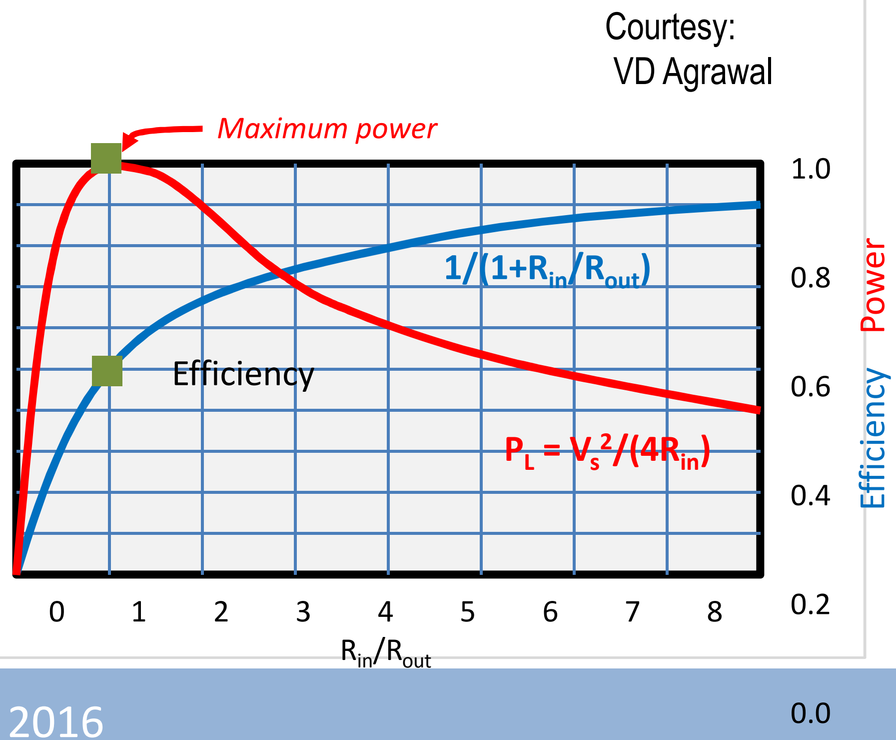
Extracting power

- Almost invariably output voltage (e.g., battery,load) is **not** the ideal value for harvesting the available energy!
- Harvester has low efficiency if storage device is not **impedance-matched** to source !!!
  - Source impedance is variable
  - **Maximum power point tracking (MPPT) problem**
- Need proper circuits
  - Tradeoff between **energy extracted** and **consumed** by MPPT circuit

Impedance matching and maximum power: recap

- **Maximum power theorem:**
  - Power transferred to the load is maximum when output and load resistance are the same (R_{in}=R_{out})

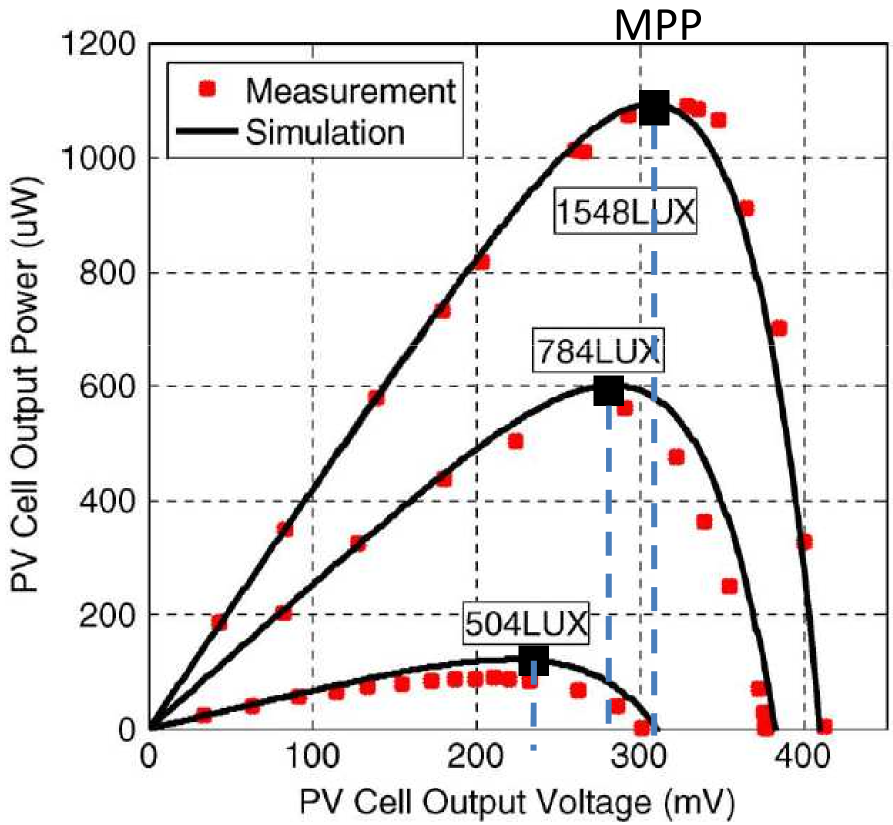




  - Power transferred only 50% (efficiency)

MPP(T): an example

- Power source: solar PV microcell [Raghunathan 2013]



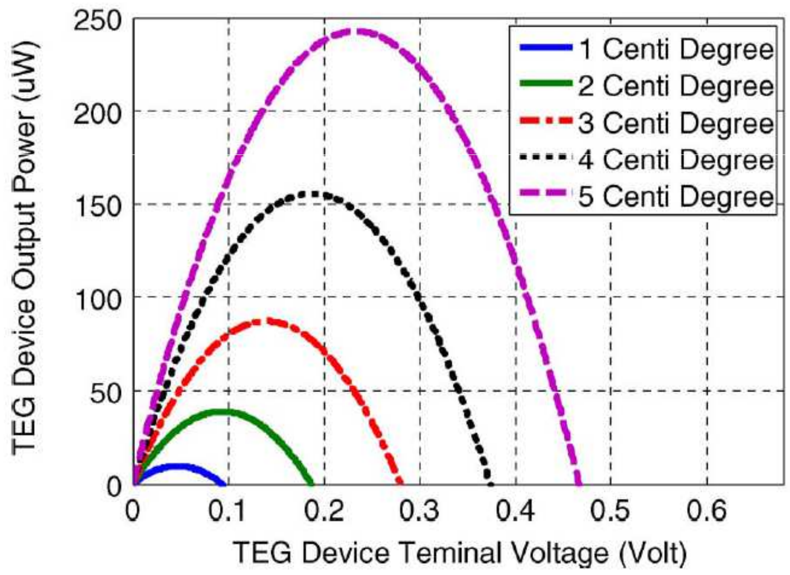
Tracking the MPP

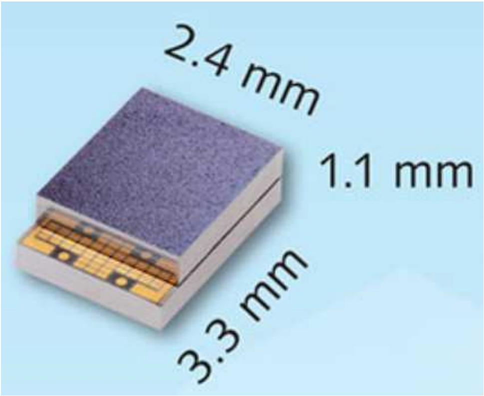
- Done by ad-hoc HW call MPP tracker (MPPT)
- Basically a switching DC-DC converter that tries to match R_{in} and R_{out} by adapting the working point
  - **Double source of inefficiency !**
    1. **Converter efficiency…**
    2. **Failure to perfectly track MPPT**
  - **Plus, some power overhead**

Extracting Low Power Levels

Extracting from Ultra-Low Power sources

- *"Low-power"* here not a value !!!
- Example:
  - TEG device Micropelt MPG-D751





  - MPPT for $\Delta T = 5^oC$ is only 50 uW!!! (@0.25V!)

Extracting from Ultra-Low Power sources

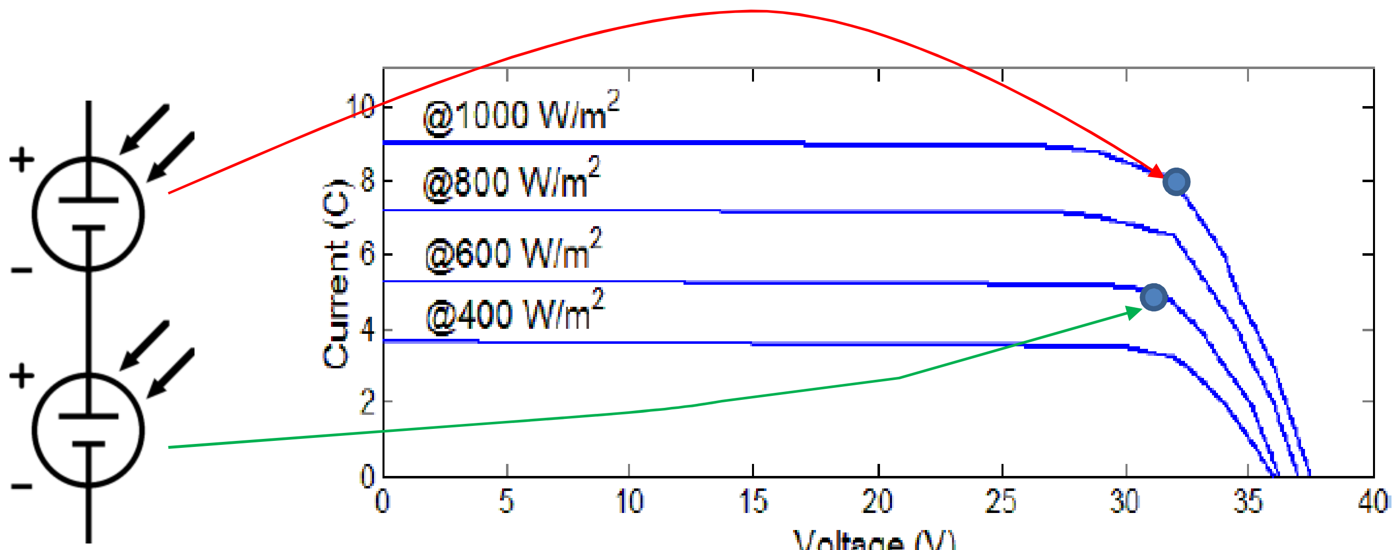
- How to make such a low power level usable for a typical load (e.g., 10mA @ 1V = 1mW?)

1. Use appropriate converters
   – Will discuss later

2. If possible, combine power sources into "modules"
   – scale up both voltage and curretn
     - Series connection ➡ increase voltage
     - Parallel connection ➡ increase current

"Packing" power sources: constraints

- Obviously, space constraints should allow
- Issues with **unmatched devices !!!!**
  - i.e., exposed to different environmental conditions
  - Example:

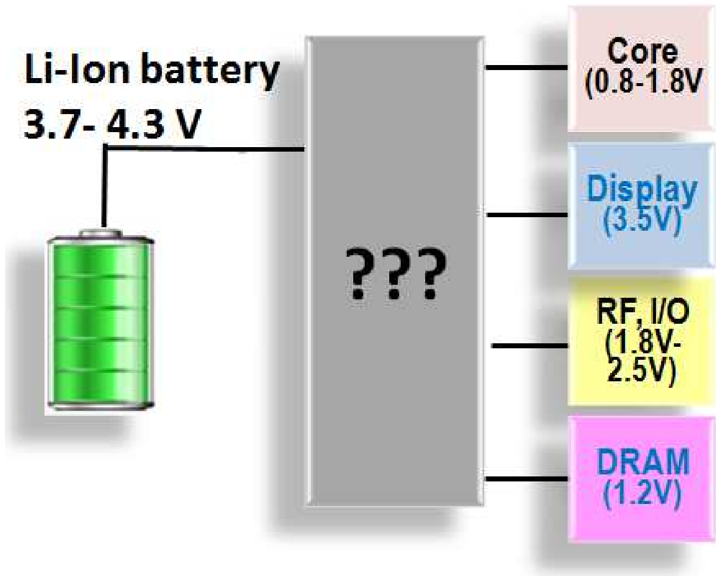


Conversion Issues

Why conversion?

- a.k.a. Voltage regulators
  - **The equivalent of transformers in DC!**
- **INPUT** : an unregulated DC voltage $\mathbf{V_g}$.
- **OUTPUT**: a regulated output voltage **V**, having a magnitude (and possibly polarity) that differs from $\mathbf{V_g}$

- Why do we need to care?
  - Plenty of voltage domains and supplies with disparate values



Characterization: power loss and efficiency

- The conversion process is not “perfect”
- Efficiency = output power/input power

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{in} - P_{losses}}{P_{in}} = 1 - \frac{P_{losses}}{P_{in}}$$

  – $P_{\mathrm{in}} = V_{\mathrm{in}}\, I_{\mathrm{in}}$
  – $P_{\mathrm{out}} = V_{\mathrm{out}}\, I_{\mathrm{out}}$

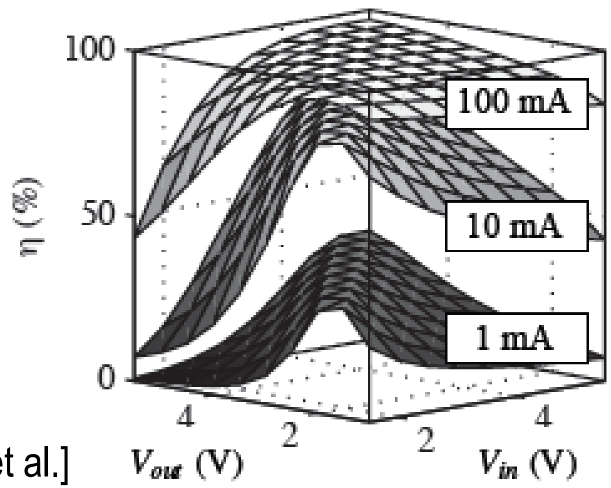
- **Bad news**
  - **Efficiency is not constant**
    - Affected by various involved quantities
  - **Efficiency can be quite low**
    - If used in the “wrong” working point

Converter efficiency

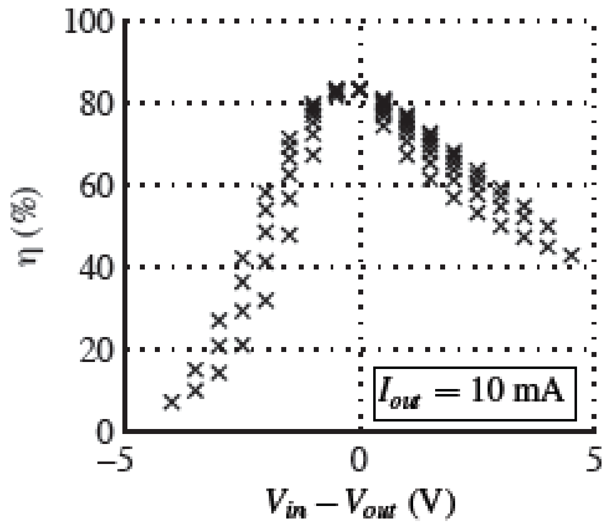
- Factors affecting efficiency depends on the converter **type**
  - **Distance between V_{in} and V_{out} (0 is best)**
    - **$V_{out}>V_{in}$ less efficient than for $V_{in}>V_{out}$**
  - **Absolute values of V_{in} and V_{out}**
  - **Output current (smaller is worse!!!)**

  For switching converters

- Example:



[Kim et al.]



An example

- Assume efficiency proportional to ΔV, e.g.,

$$\eta = 1 - (V_{in} - V_{out})/V_{in}$$

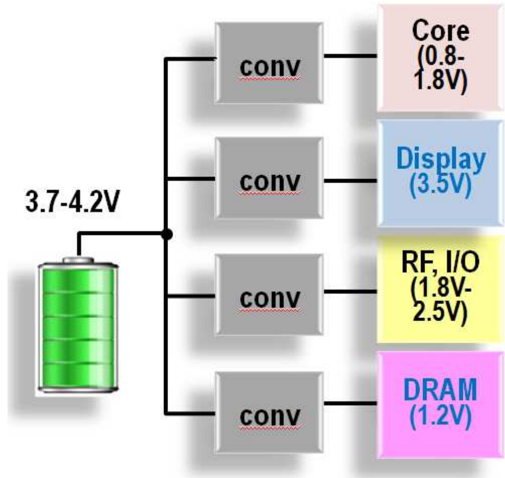
  - $V_{in} = 1.5V$
  - V_{out} $(=V_{dd}) = 1.1V$
  - **η = 73.3%**

- By DVS, we lover V_{dd} to 0.9V
  - **η = 60.0%**

Did we really save power?

Converter efficiency - Insights

- **Efficiency can quite far from 100%**
  - You might waste most of your power in the conversion…!
- **Low output currents are bad for conversion**
  - Especially for inductor-based switching converters
  - … and this is exactly what you are pursuing in low-power design!!!
- **You typically have multiple converters**
  - …Each one with losses



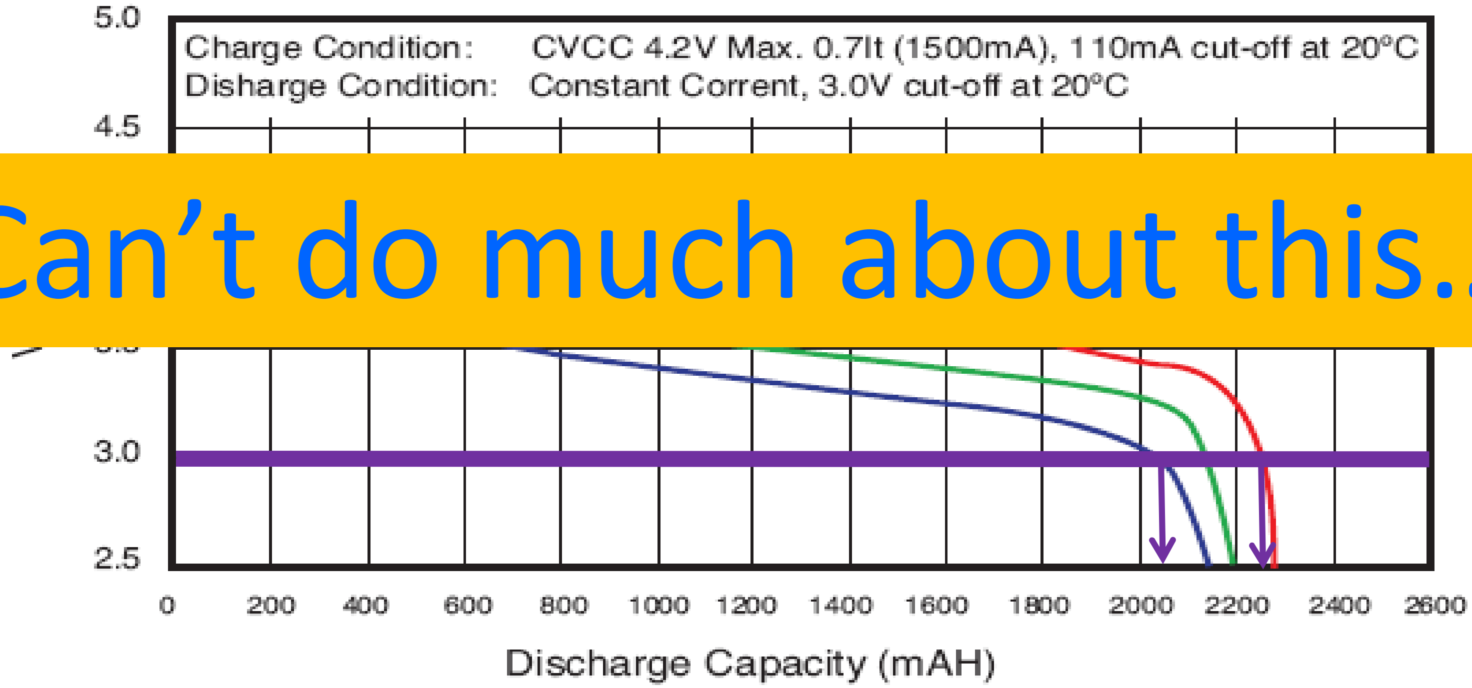
Energy storage: background and issues

Energy Storage Devices

- Two main functions
  - **Buffering:** Accumulate harvested energy to smooth the variations
  - **Power supply**: Power the system (especially if not energy autonomous)
- General view: ESD = battery
  - But they are just one possible choice
  - Many possible alternatives (even at μscale)…
    - *Ultra-capacitors*
    - *Fuel cells*
    - *Flywheels*
    - …

Batteries are not ideal… (1)

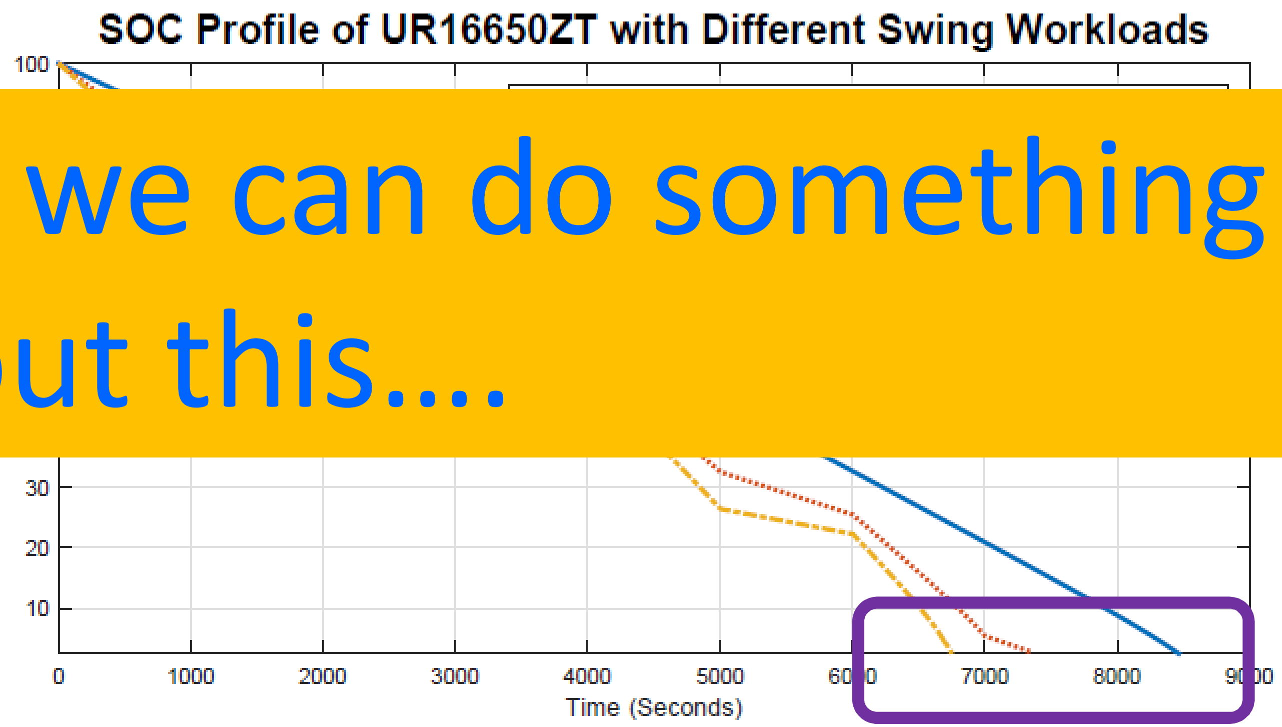
- **Rated-capacity** effect
  - **The amount of energy a battery can provide depends on the current drawn from the battery itself**



Can’t do much about this….

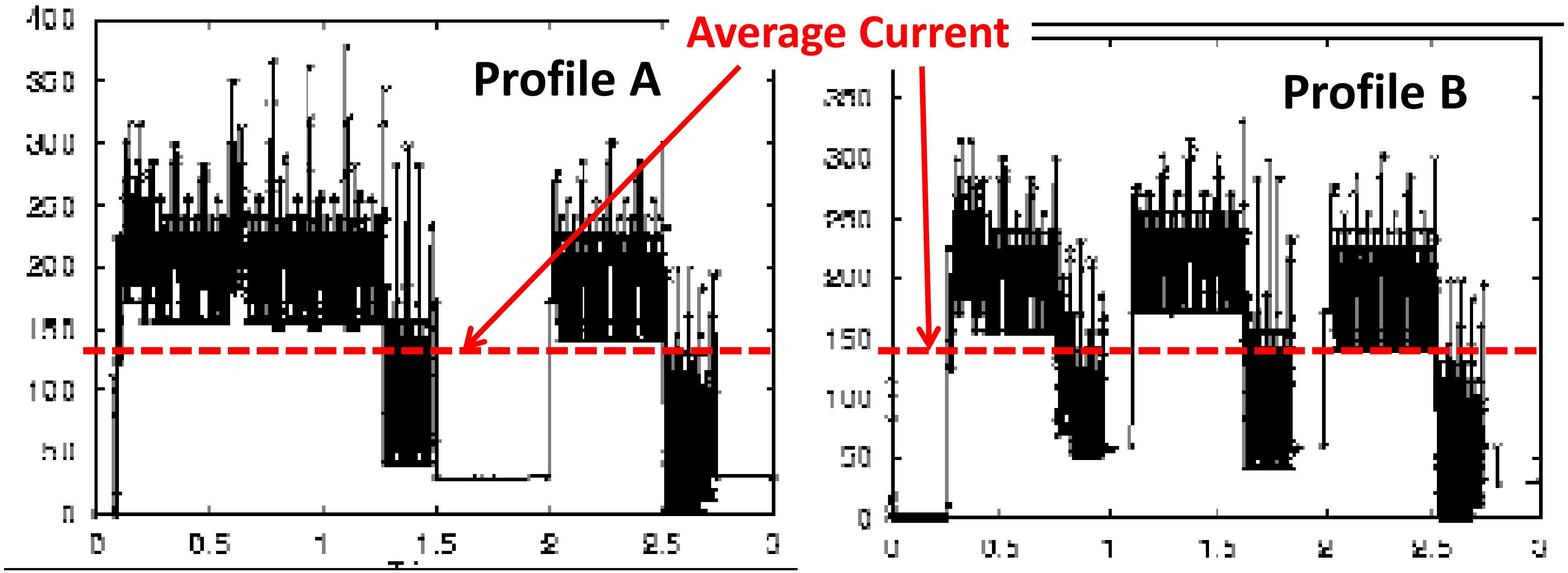
Batteries are not ideal… (2)

- **Dependence on current dynamics**
  - For a given *average current*, the constant profile is the one the battery can serve the best



But we can do something about this….

Minimum avg. current ≠ max battery lifetime!



[Source: Intel]

Profile	Average Current(mA)	Battery Life (ms)	Specific Energy(Wh/Kg)
A	123.8	357053	15.12
B	124.2	536484	18.58

Main impact of non-idealities

- **Current magnitude impacts battery efficiency**
  - Whenever possible use a smaller current
  - Consistent with "low-power design"!
- **Large current variations impact battery efficiency**
  - Smooth current profile as much as possible (filter?)
  - **Average current (power) is not a reliable metric for battery!**
  - Relation with "low-power design"?
    - Duty cycling vs. speed scaling…
- **Idle times can increase battery efficiency**
  - Contrast with smoothing of current variations…?

Concluding…

Conclusions

- Killing the microWatt in the computational part can be useless
- Much more energy is wasted while powering your device…
  - η_{MPPT} for each scavenger
  - η
  - η

Losses, losses, losses,….