Sustainable sensing

Enabling Technology for Computational Sustainability

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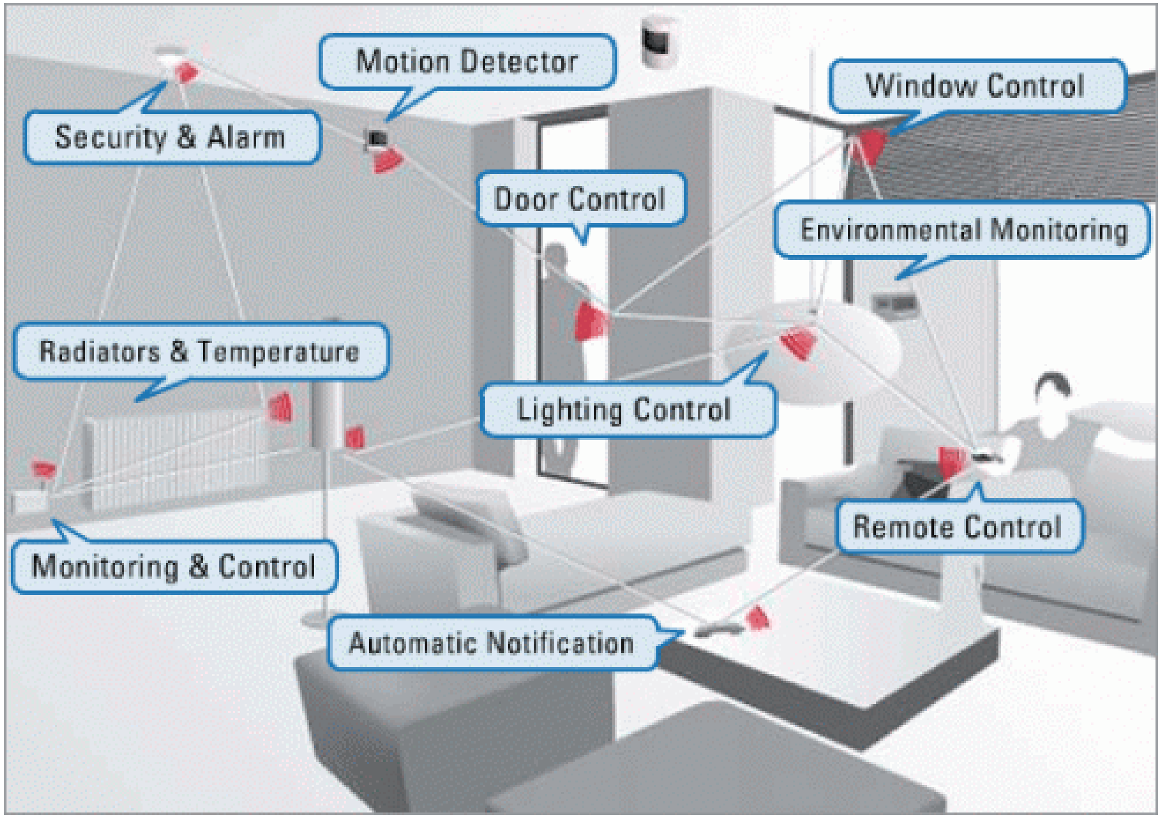
Ambient Intelligence

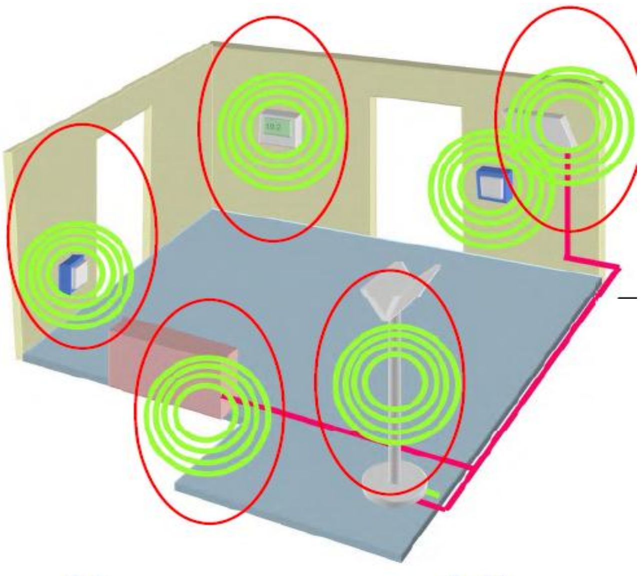


Ambient Intelligence
electronic environments that are sensitive and responsive to the presence of people

AmI = Ubiquitous computing + intelligent social user interfaces

Integration of Environment Network & Body Area Network

Energy-Neutral AmI



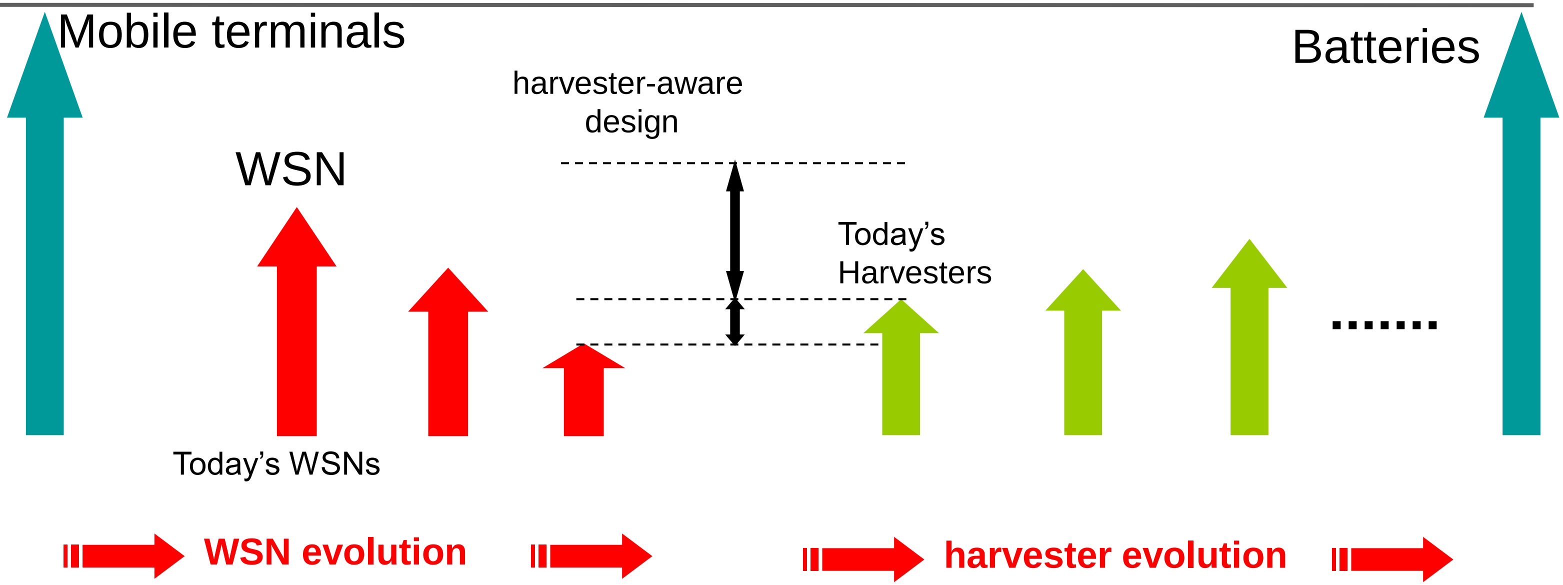
- No power and data cable for sensors and controls
- Easy to install (in the optimal position)
- Retrofitting is feasible and inexpensive
- Battery-powered operation → maintenance

Multiple Scenarios:
Indoor/Outdoor
Stationary/Mobile/Wearable

Energy-neutral → harvest energy *from the surrounding environment and* ***store it*** *locally*

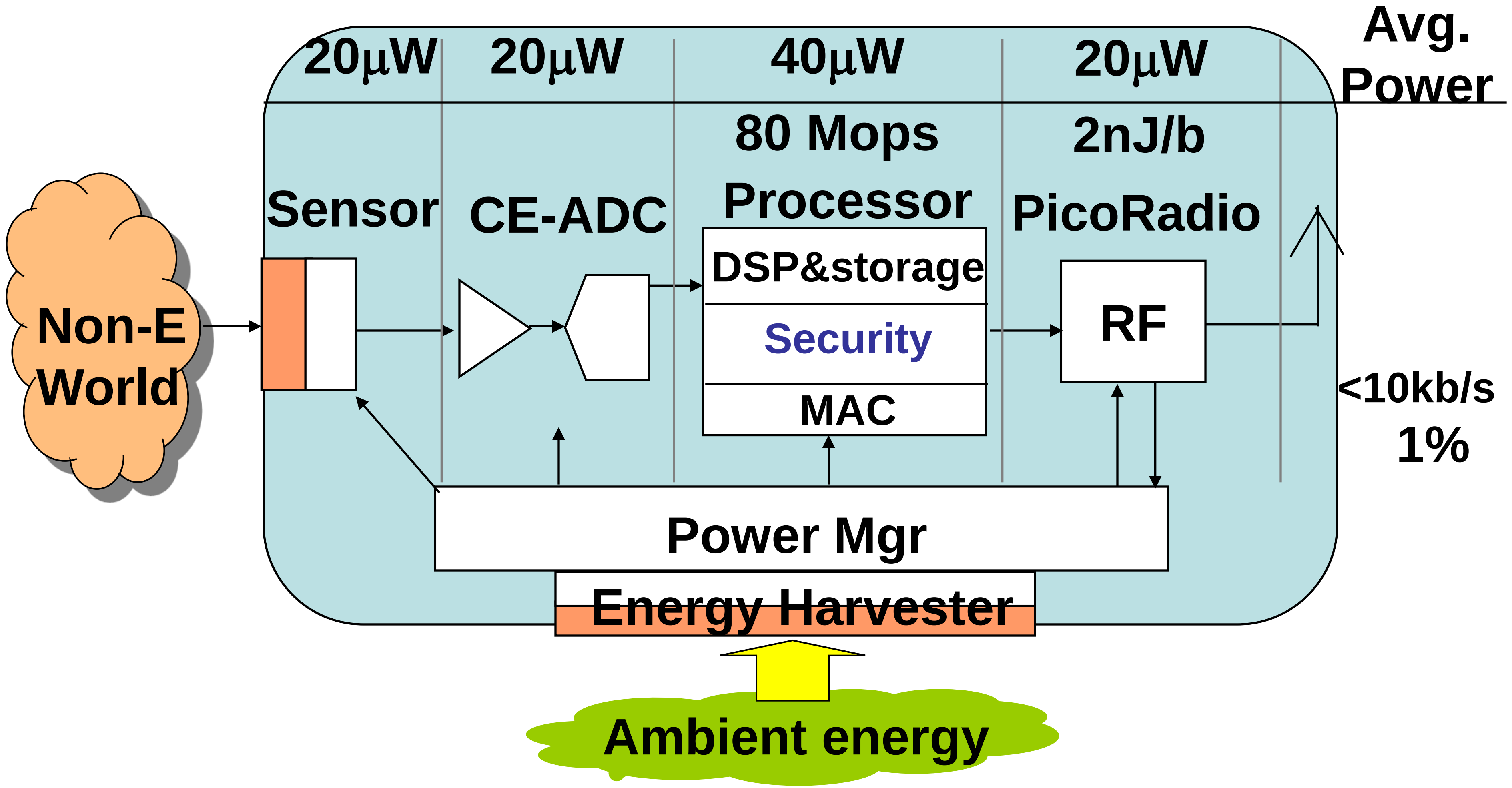
- Photovoltaic (outdoor, indoor)
- Inductive coupling
- RF energy
- Air flow
- Motion, vibration

The Good News



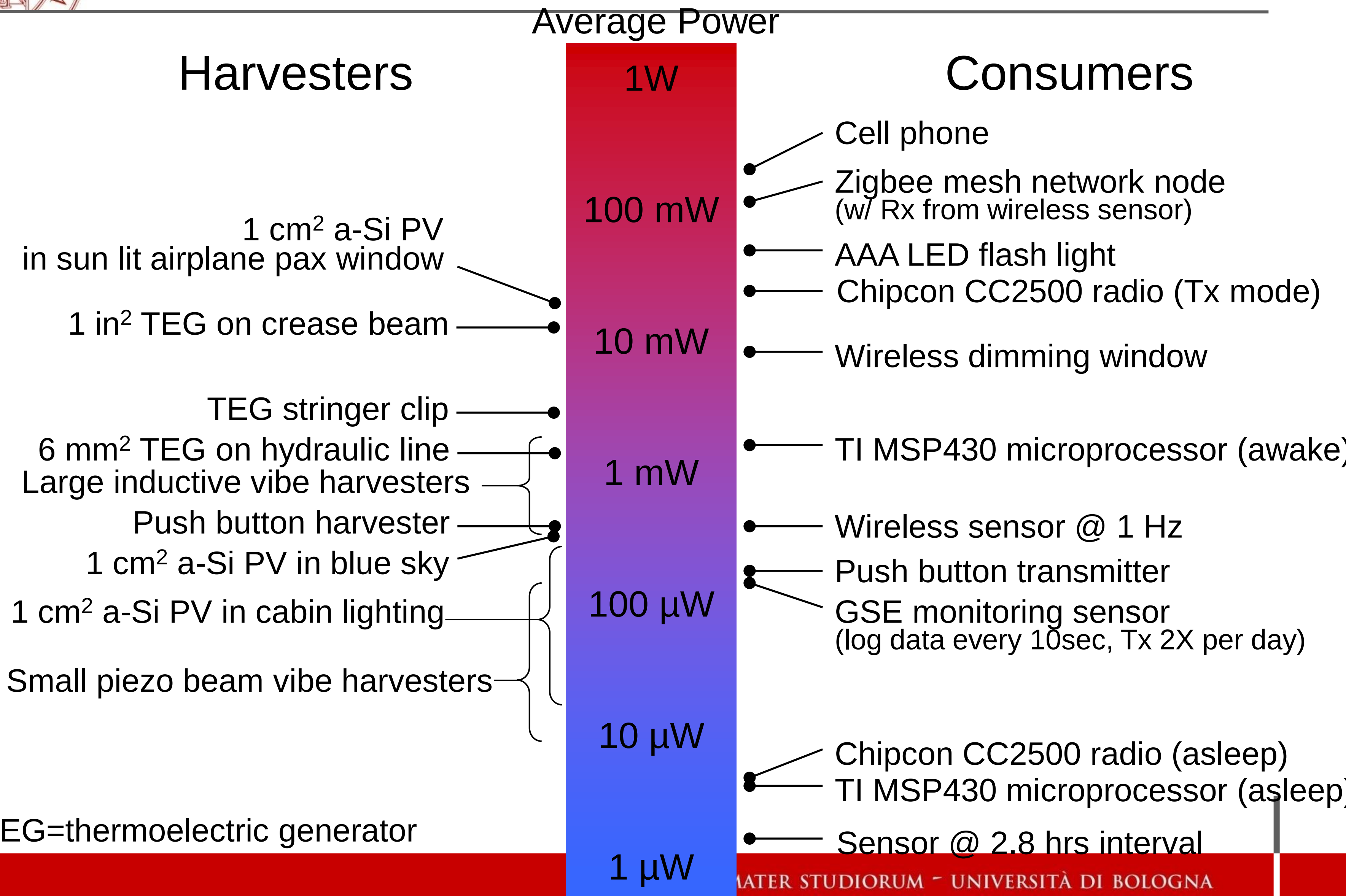
- The gap between scavengers energy and requirements of digital systems is shrinking
- Exploit energy management strategies and improvements in scavenger technology
  - Overcome traditional energy management strategies (battery-driven)
- An new **unified design methodology** is required
  - Smart adaptation
  - Design for unreliability
  - Exploit unpredictable power sources

Sensor Node Evolution



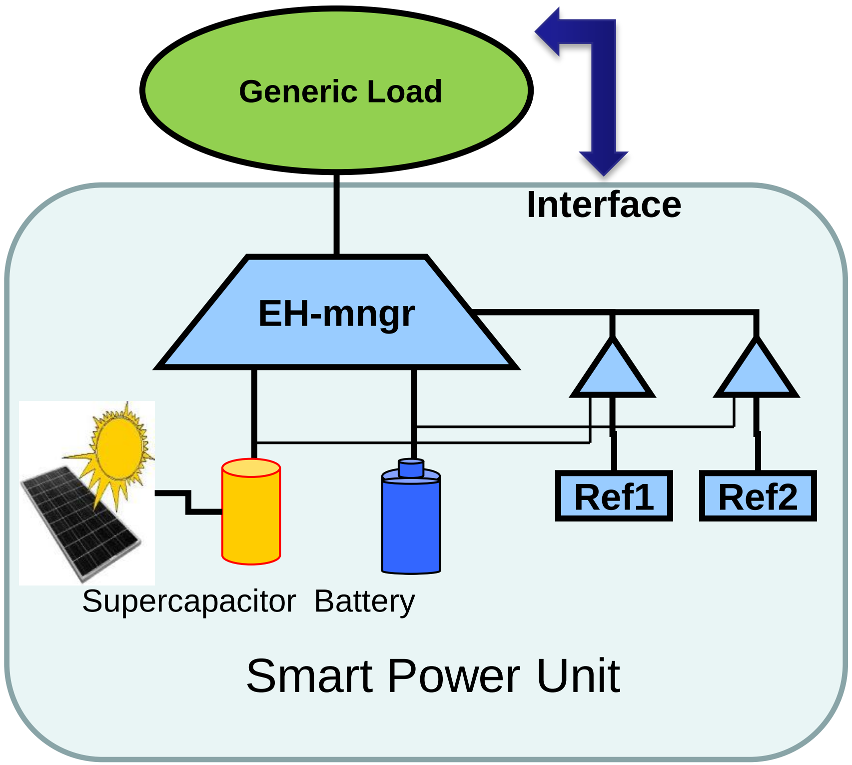
Objective: 100 µW Avg → Energy neutrality becomes "easy"

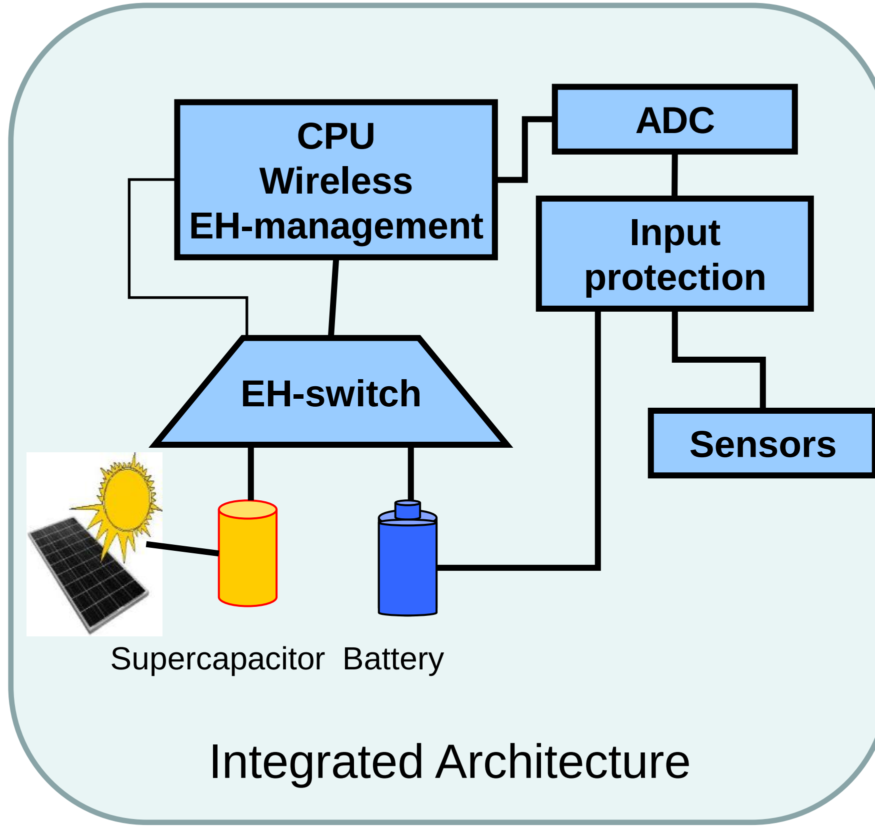
Where are we now?



TEG=thermoelectric generator

EH powered nodes



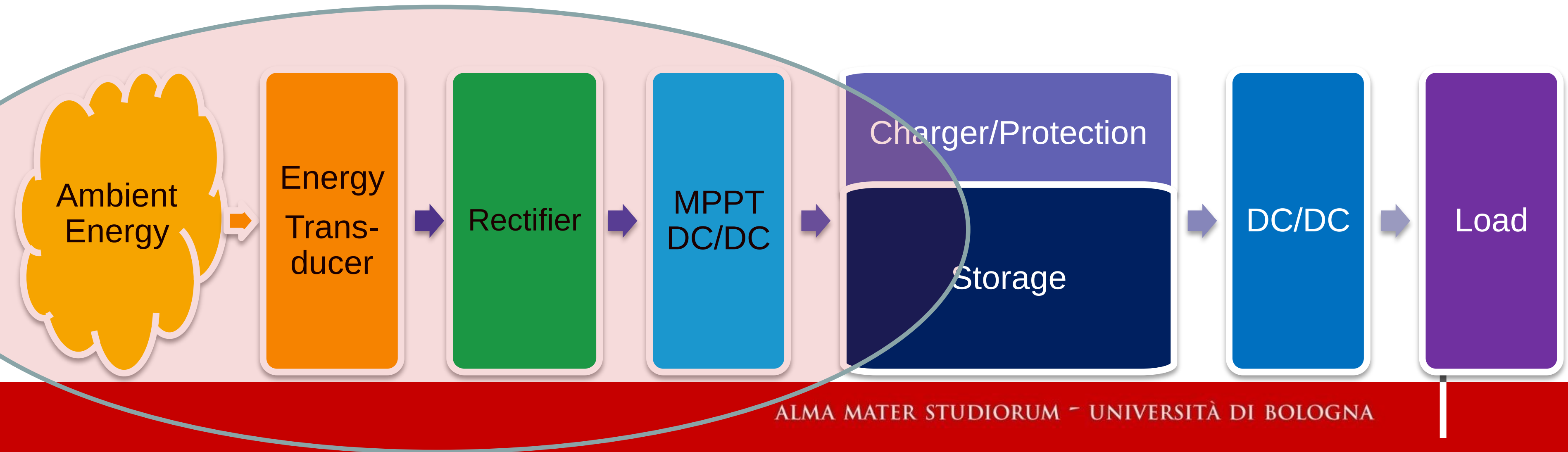


- General purpose
  Optimized for Ambient Source and storage, but not for a specific application/load
- Plug-&-play
- Analog or with Digital Interface for external power management (*standardization*?)

- Usually maximum efficiency
- Tailored on a specific application/load
- Fully integrated (complexity!)

EH Subsystem architecture

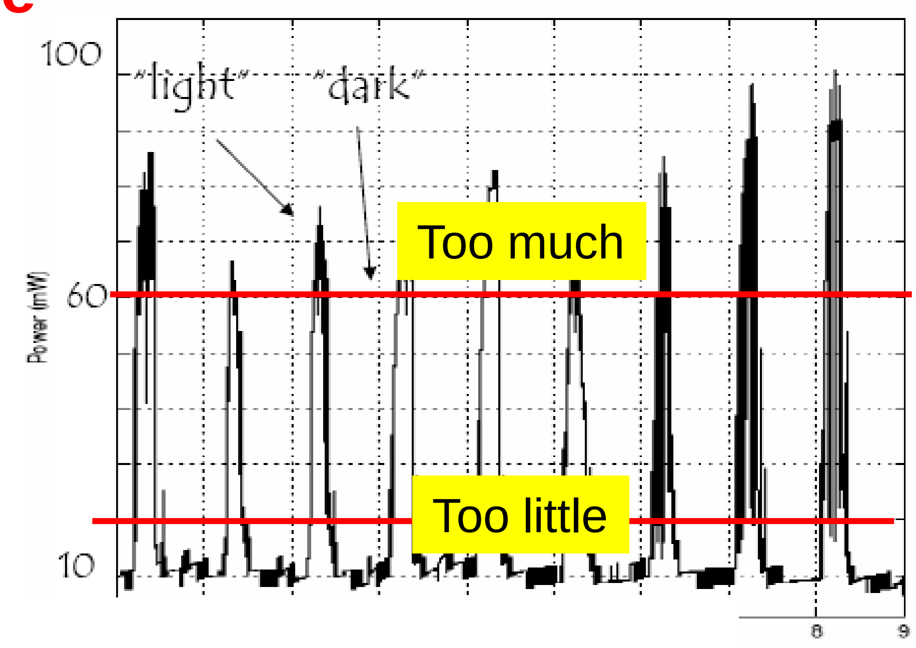
- **Not all are required** for every application and every source
- Rectifier, DC-DC converter and MPPT are the most **challenging** and require a very **accurate design process (coupling)**
- Charger/limiter/protection consumes additional power and are often to some extent redundant.



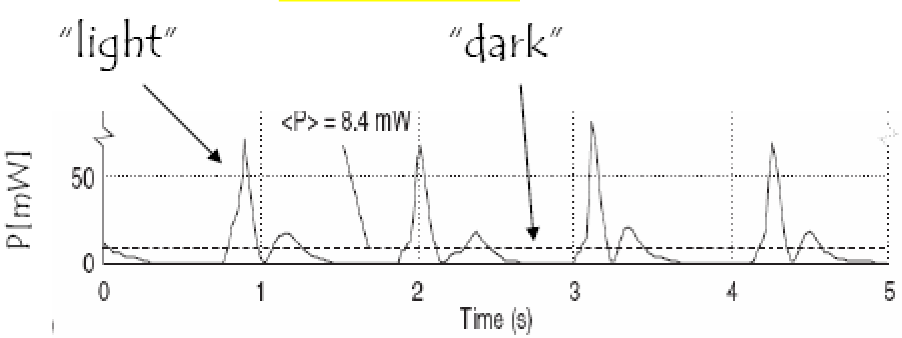
Energy sources

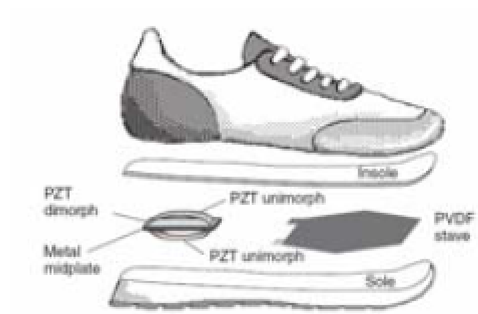
Non-monotonic & Unpredictable

- E.g. solar power (PV-cells)
- E.g. power waveform from human walk (piezo-scavengers)



Aperiodic





[Paradiso05]

Low power design ≠ Design for neutrality

Natural progression of Energy Optimization Techniques

Low Power Design

↓

Power Aware Design

↓

Battery Aware Design

↓

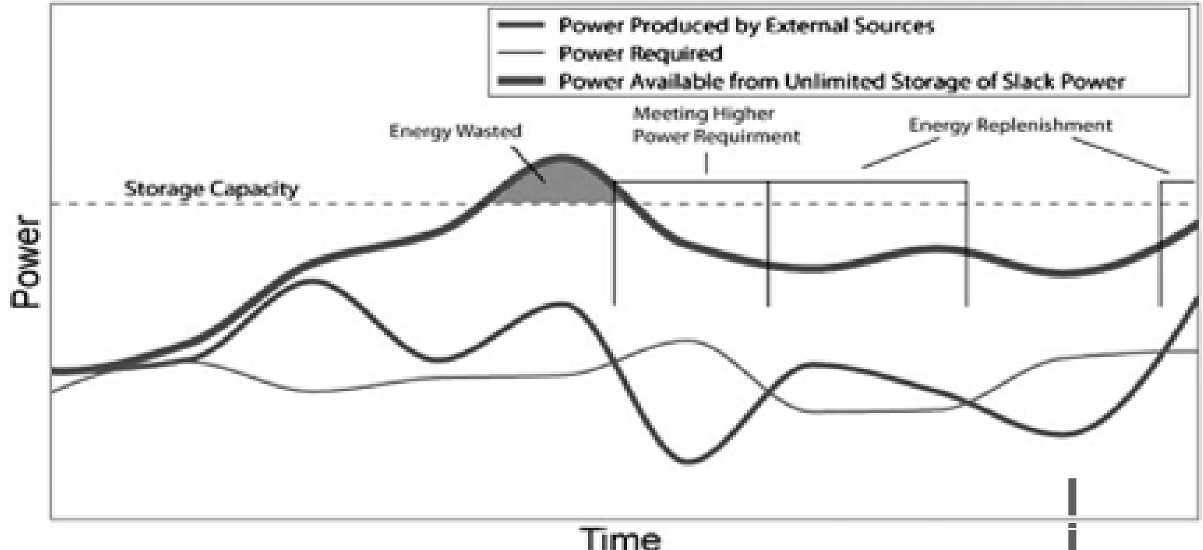
Energy Harvesting Aware Design

Hardware Design

- Conversion efficiency
- Impedance Matching
- Maximum power transferred

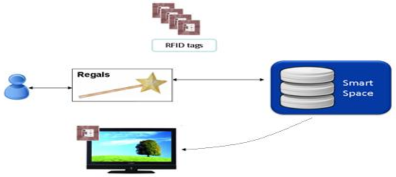
Software Design

- Energy Prediction,
- Scheduling & Allocation
- QoS adaptation



AmI Contexts

- GENESI genesi.di.uniroma1.it
  - Structural monitoring
- SCALOPES www.scalopes.eu
  - Video-surveillance
- SOFIA www.sofia-project.eu
  - Smart objects & spaces
- Sensaction-AAL
  - Auditory Biofeedback
- SMILING www.smilingproject.eu
  - Training active exoskeleton



How hard?

Stationary, Outdoor, low-bandwidth → 'Easy'

Stationary, Indoor/outdoor, high bandwidth→ 'Not Easy'

Mobile, Indoor/outdoor, high bandwidth→ Hard

Wearable, high bandwidth→ Very Hard

Wearable, high bandwidth, high-power→ Undoable?

Wireless Video WSNs

- Features:
  - Video acquisition analysis in real time (detection)
  - Multi Sensor
  - Data Fusion

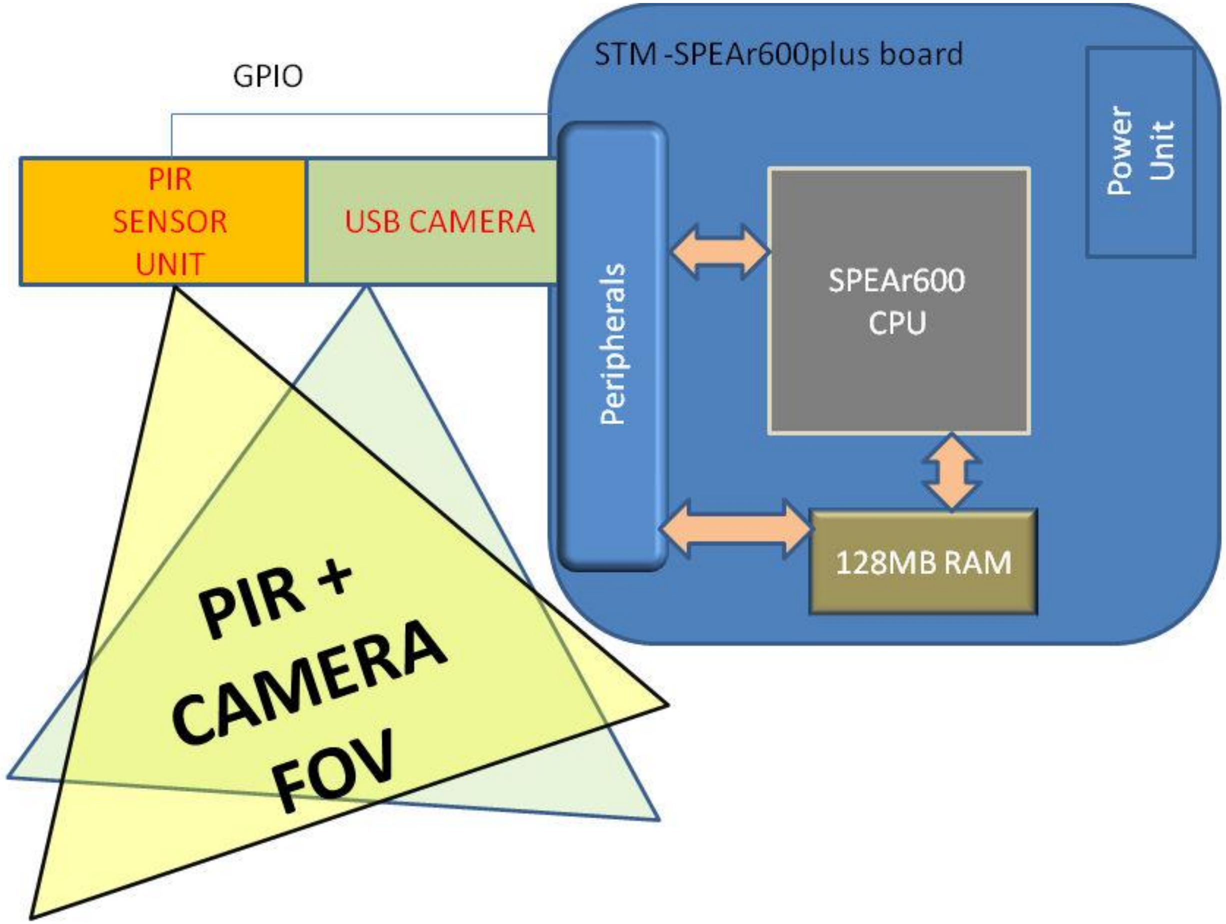
- WSN challenges
  - **High data rate** → needs local processing
  - **High power consumption** due to
    - huge quantity of data produced in by image sensors
    - Useless processing occurring when the scenario doesn’t change

Low Power HW is not enough

Multi-modal Approach

HARDWARE

- STM SPEAr 600plus
  - ARM A9 dual-crore
  - Video HW accelerator
- USB camera
- Infrared pyroelectric sensor (PIR)

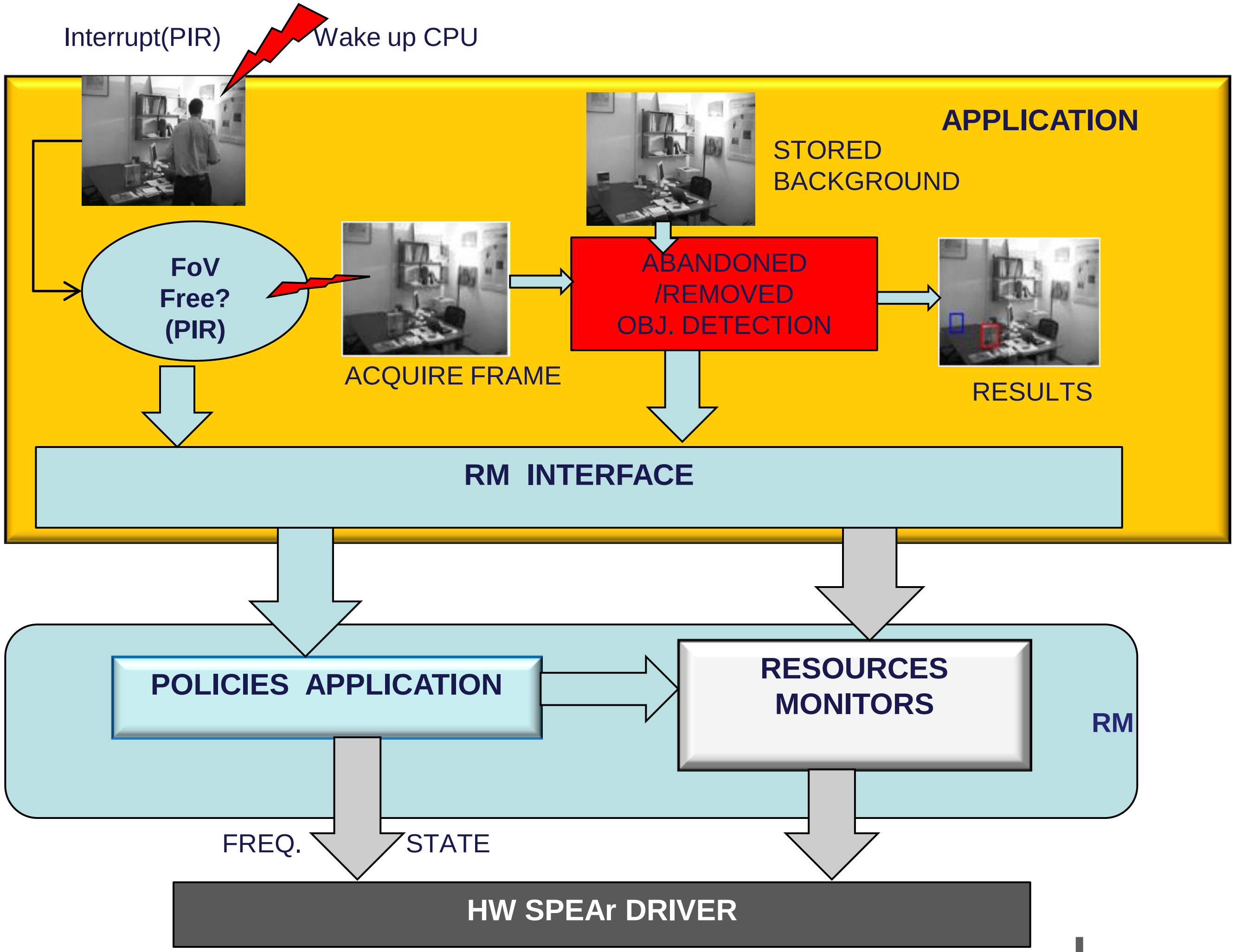


SOFTWARE

- Embedded Linux Kernel 2.6.27(CPUfreq + PM framework)

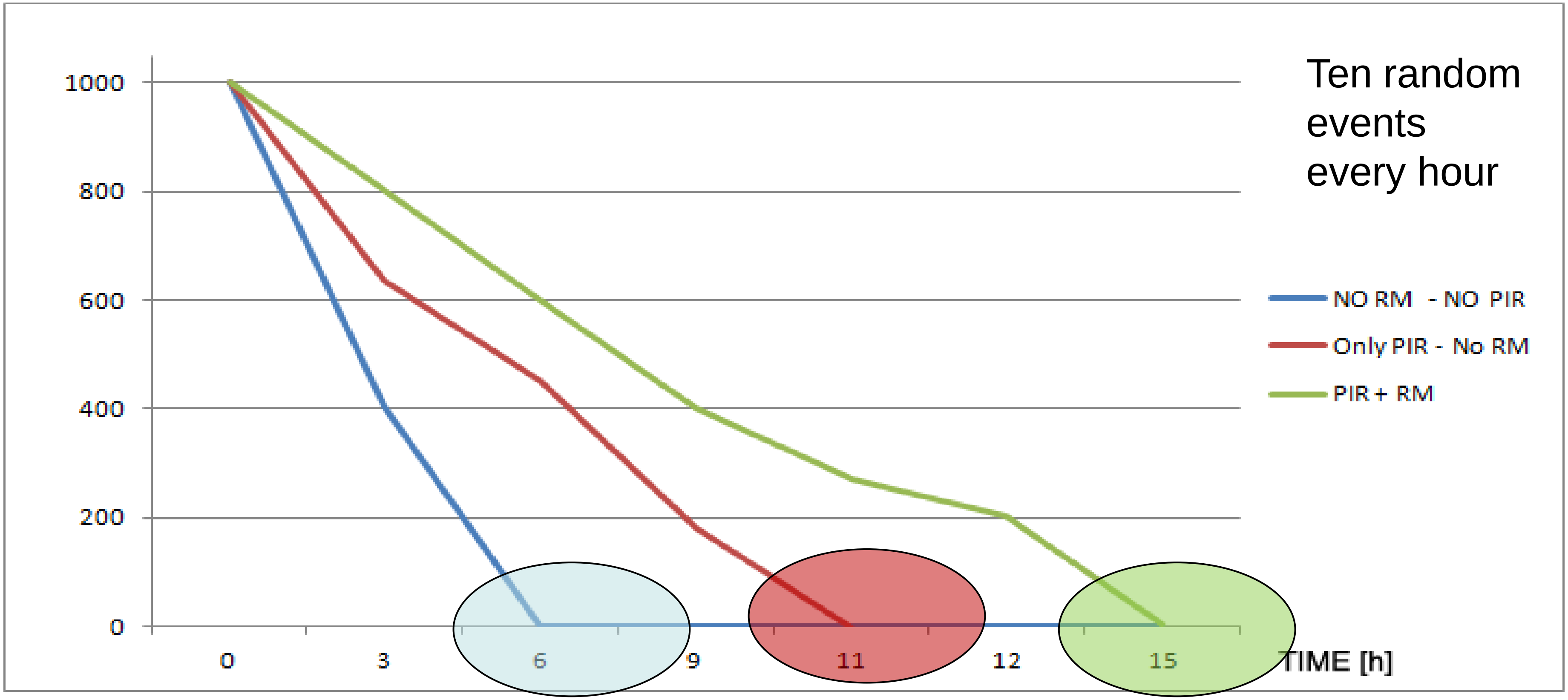
Multi-level + Multi-modal

- Interaction Application / Resource Manager
- Dynamically scales processor frequencies and application features
- Reduction of the power Consumption
- Dynamic tuning of video algorithm and application
- Variable Quality of Service (FR, Accuracy)



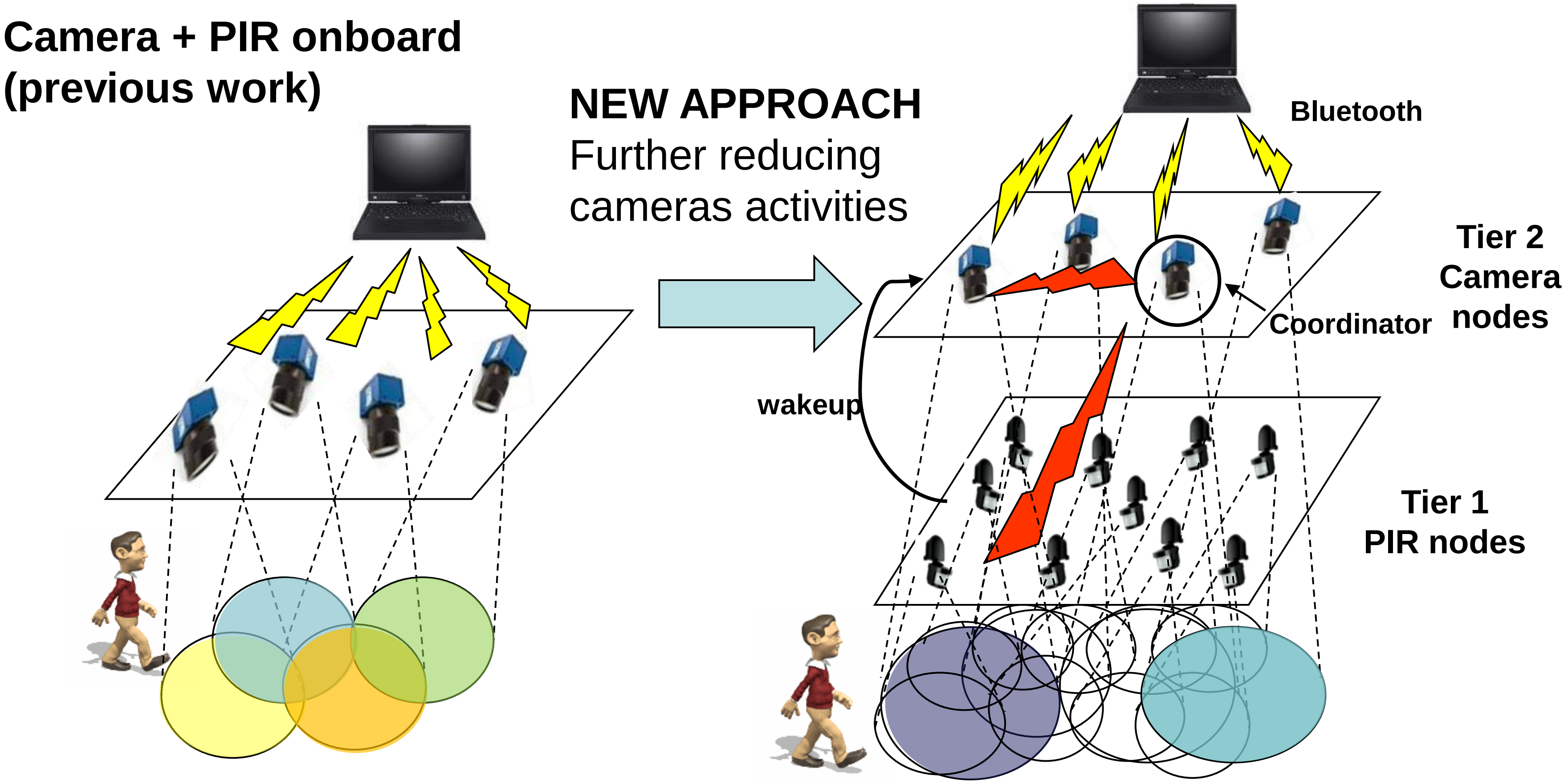
Results

Estimated time life using three approaches (with 1000mAh battery)



Reduction of power consumption up to about 60%

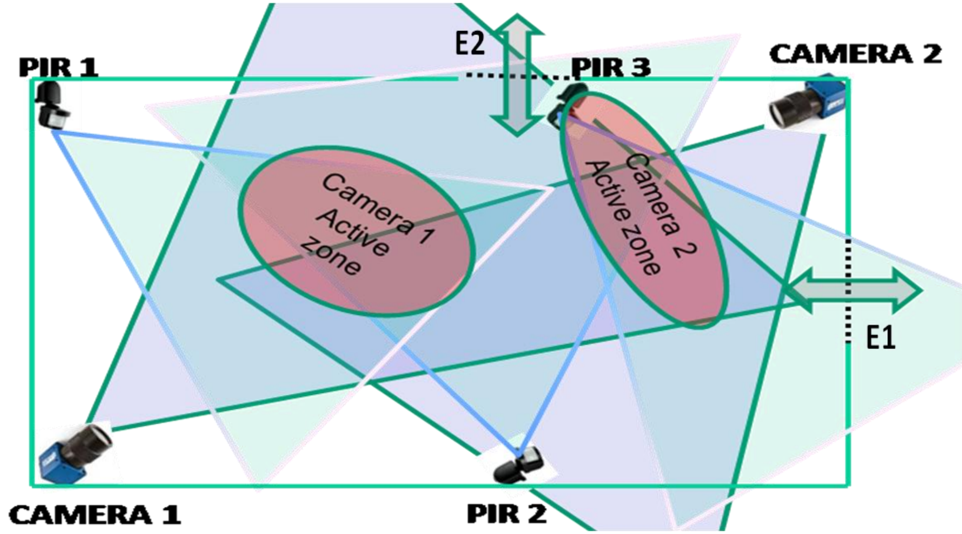
Multi-ML + Distributed



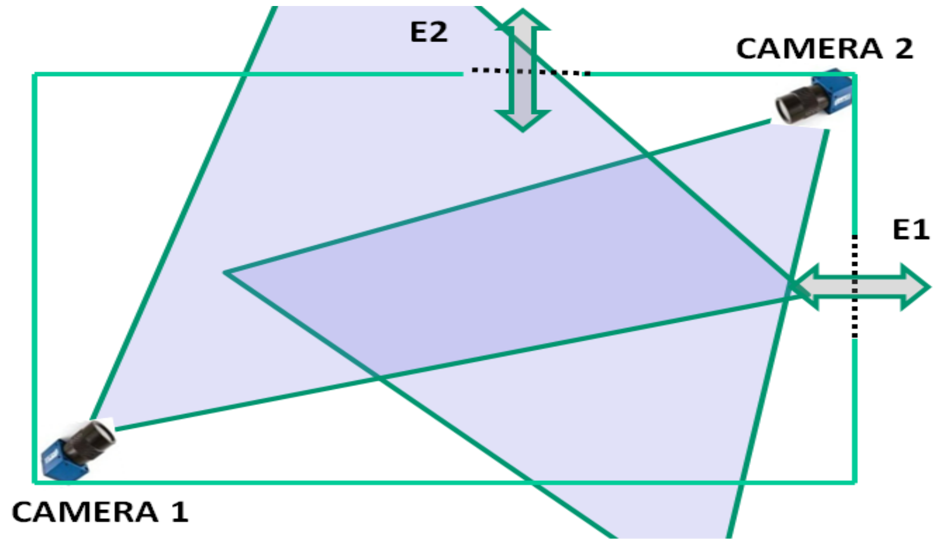
Two-tier network

Example

Scenario with a PIR network



Scenario with onboard PIRs



75% of events in the room both cameras awake →large overhead

Prolongation of network's lifetime!

WAKE-UP RULES:

CAMERA 1 = PIR1 & PIR2

CAMERA 2 = PIR2 & PIR3

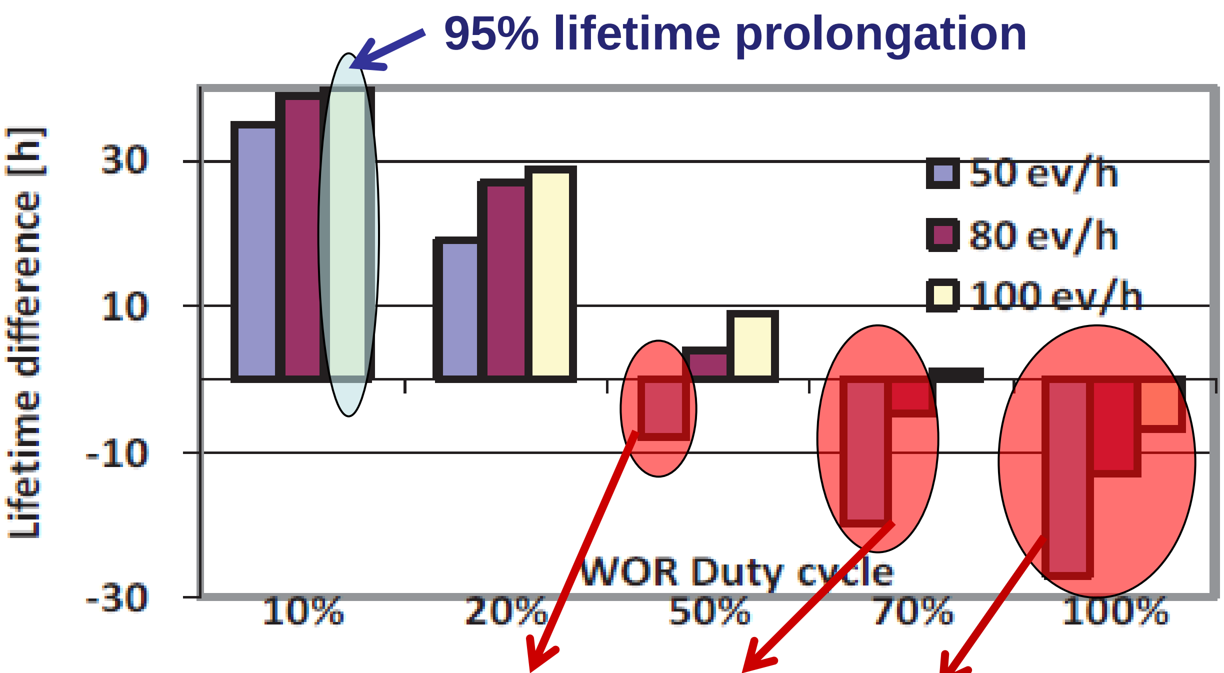
+ energy awareness

IF:

Radio energy < Energy savings from reducing cameras activities!

Results

- Camera's lifetime prolongation for the Scenario with a PIR nework for lower WOR duty cycles



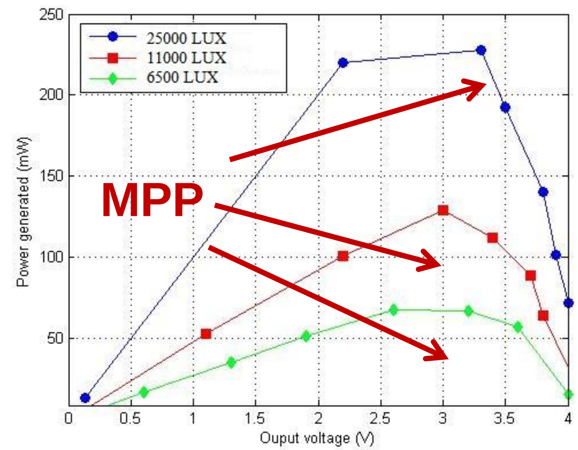
Overhead of transceiver power consumption!

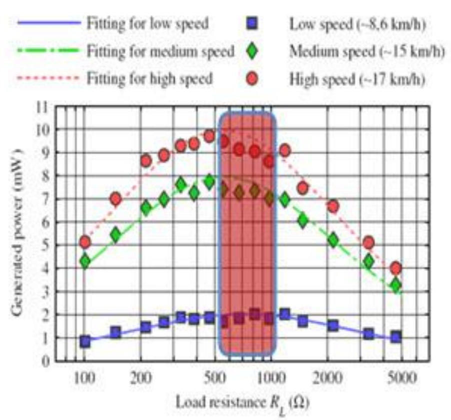
Working on physical-layer Wake-up radio and system implications

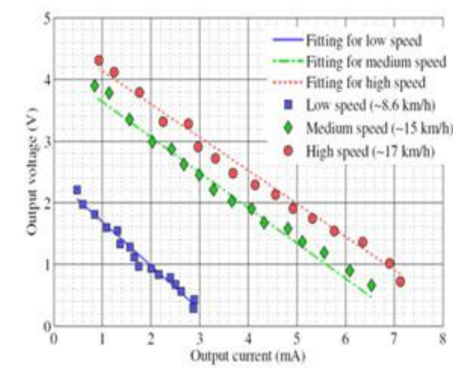
Energy Generation Options

Solar + Wind + High-frequency kinetic ***together*** do the job
+ aggressive network power management

Source	Power Density	
Solar	**1 – 100**	**mW/cm²**
Vibration Capacitive	100	µW/cm³
Vibration Inductive	10 – 15	µW/cm³
Vibration Piezoelectric	300 - 500	µW/cm³
Thermoelectric	6 – 15	µW/cm³
High frequency vibration	100	µW/cm³
Ambient radio frequency	< 1	µW/cm²
Vibrational microgenerators	800 (@ kHz)	µW/cm³
Ambient airflow	**1**	**mW/cm²**







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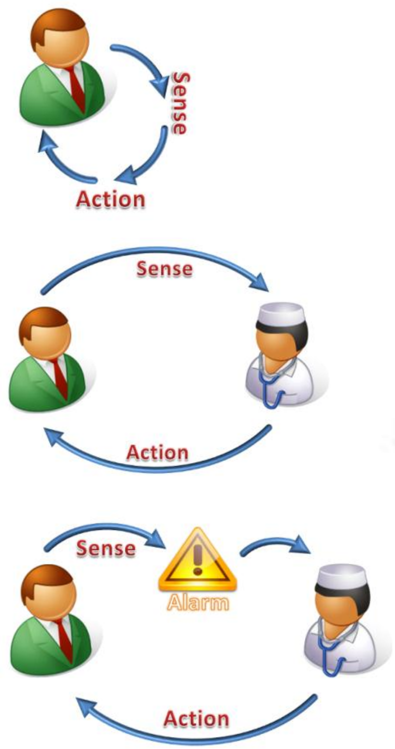
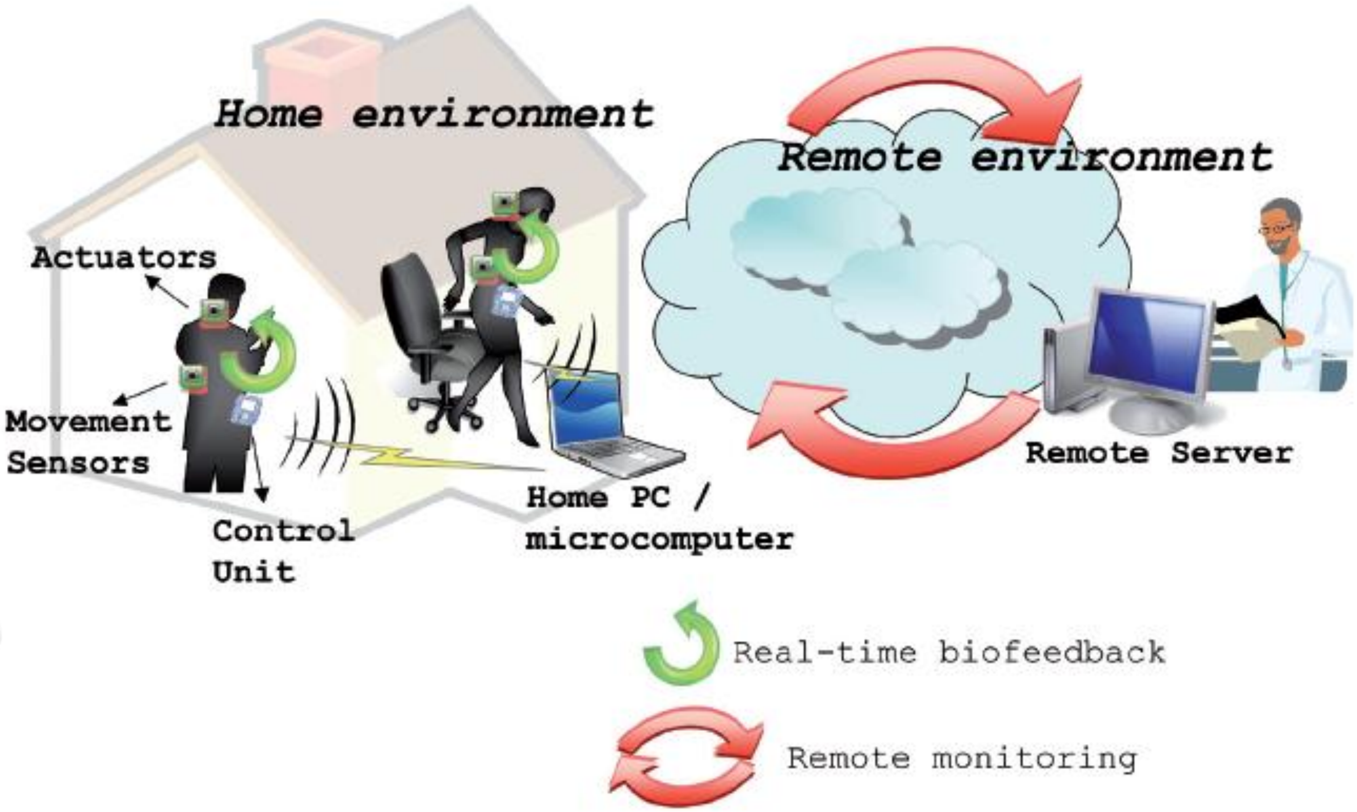
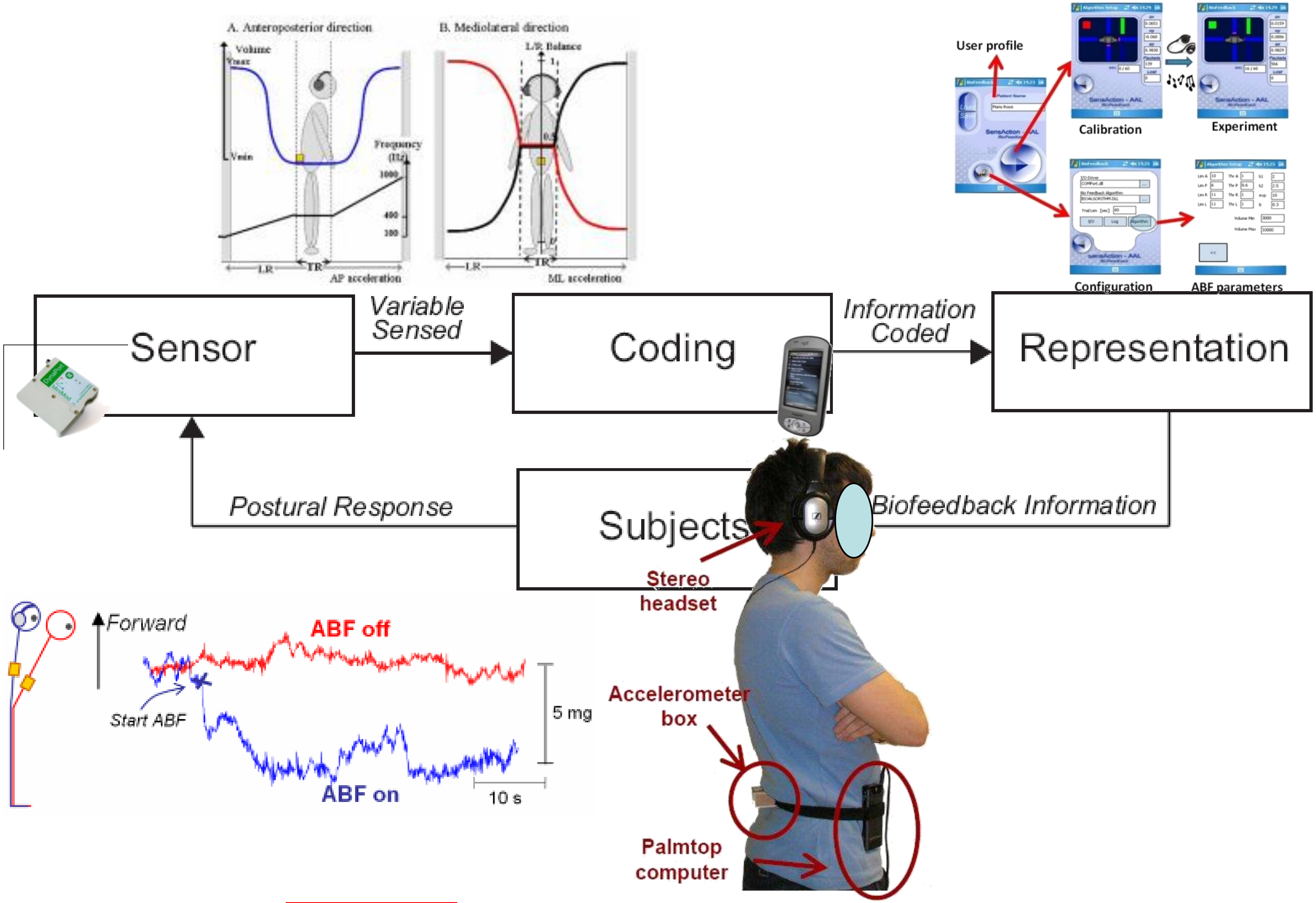
Monitoring, alerting, training



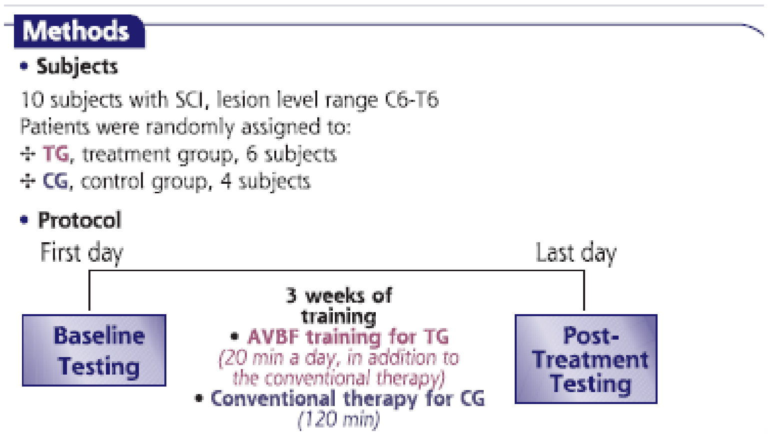


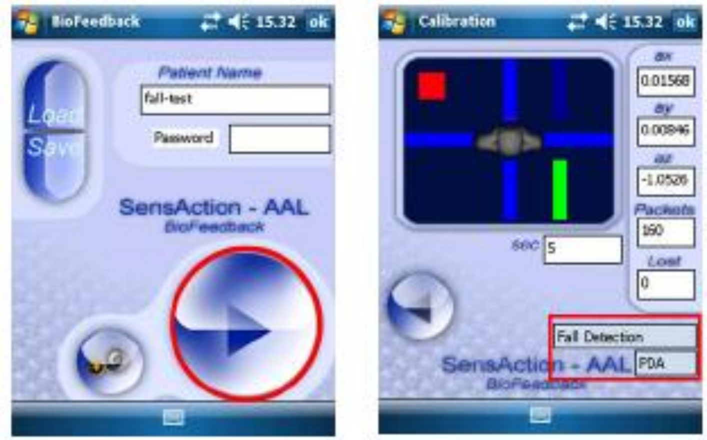
Closed loop scenario: Biofeedback for rehabilitation

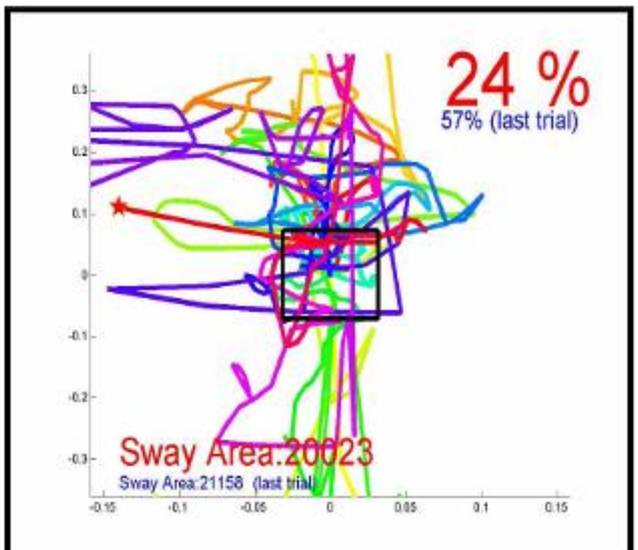


videos

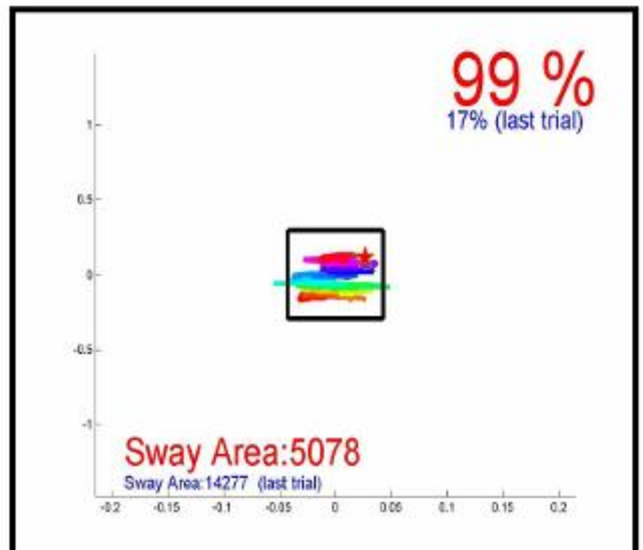
Clinical validation trial







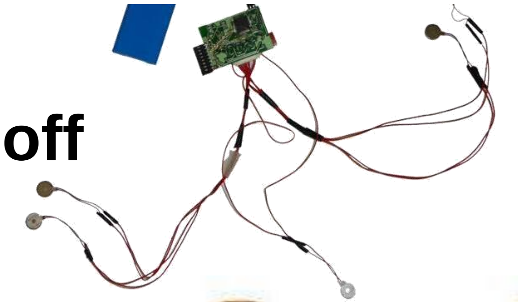
First trial



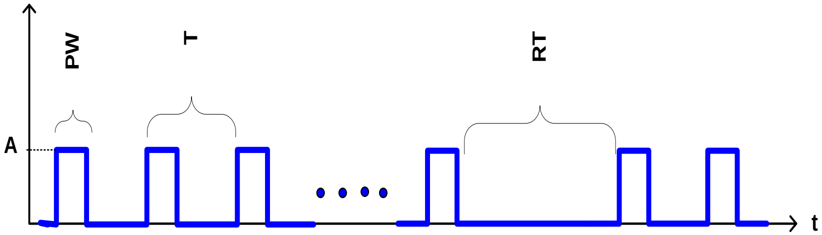
Last trial

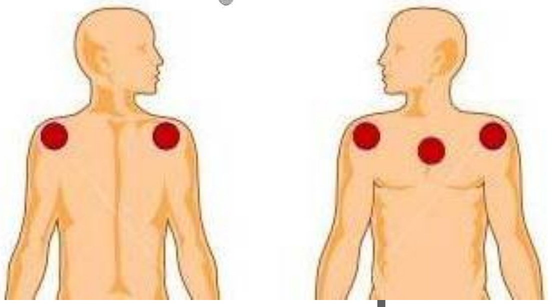
Vibro-tactile navigation system

- Add application specific strategies.
- **Important factors in the perception of a tactile stimulation:**
  - Vibration frequency
  - Vibration amplitude
  - Stimulation location
  - The Adaptation behavior.



- **We produce stimulation through on-off pulses in a square-wave shape.**
  - By changing the duty cycle of these pulses we add another control variable to the system





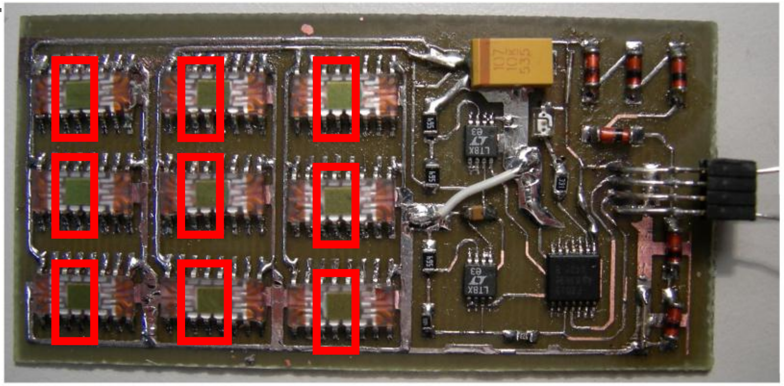
Bring Sensaction-AAL Home

- Extend battery lifetime
- Strategy:
  - Reduction of energy requirements:
    - Low-power node design and component selection
    - On board processing – minimize wireless transmission
    - Context-aware power management
  - Reduce QoS: simplest feedback
  - **Harvest energy**
    - Indoor PV?
    - EM?
    - Kinetic?
    - Thermal?

Miniature PV harvesting

- WSN HW support a wide voltage supply range (usually between 1V and 4V)

Tmote Sky	2,1 – 3,6 V
TinyNode 584	2,4 – 3,6 V
TI Node	1,8 – 3,6V

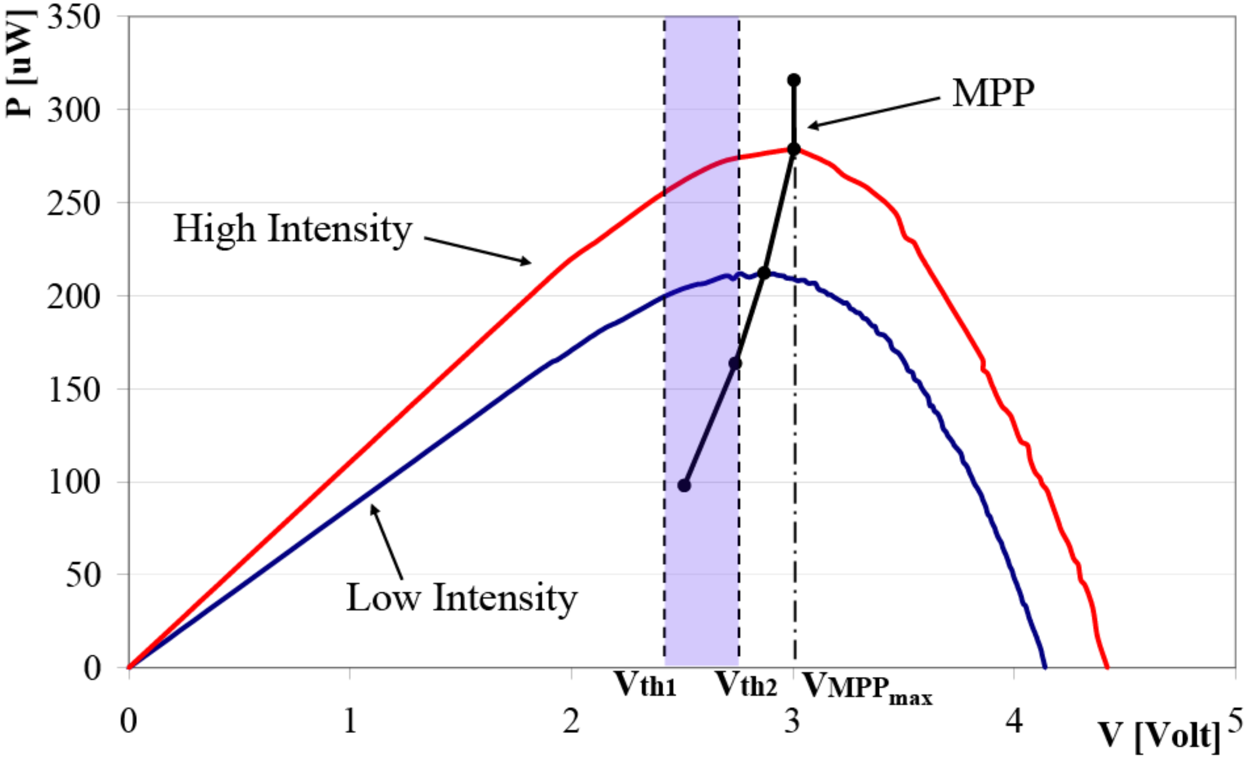


[µsolar scavenger 10mm^2 PV surface: Brunelli, Benini]

- Powering sensor nodes with unregulated and variable voltage supply from the solar cell → ***adaptive Active-Recovery DC***
  - Minimize the energy used for DC/DC or linear regulation
  - Automatically adapt duty-cycle with analog thresholds (comparators) on voltage supply
  - Optimize thresholds for MPP in low-lighting condition (no tracking at high lighting as energy is over-abundant)

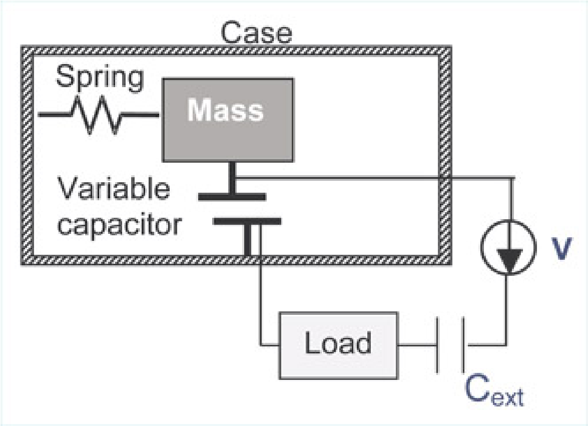
Approach

- Select the desired light intensity and find the solar cell MPP
- A window (Vth1 , Vth2) is defined around the MPP forcing the senor node to operate in this range of values.



Motion and Vibrations

Electrostatic

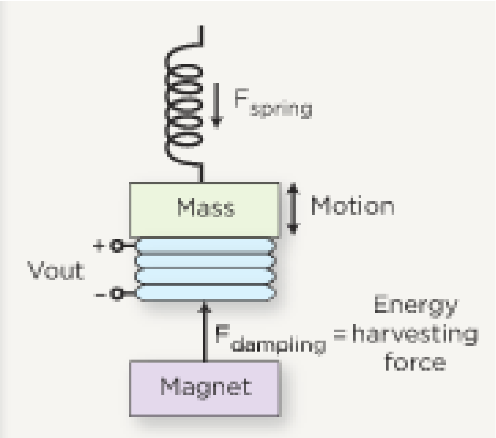


•More easily implemented in standard micro-machining processes

•Requires a separate voltage source (such as a battery) to begin the conversion cycle.

~4 mJ/cm^3

Electromagnetic

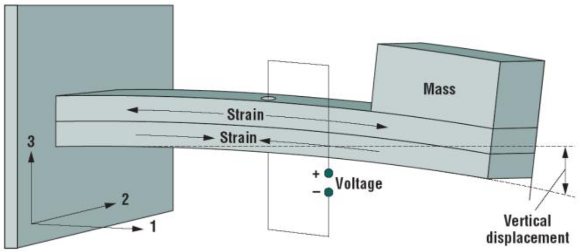


•Typically output AC voltages is below 1 volt in magnitude

•Not easy to implement with MEMS technologies

~12 mJ/cm^3

Piezoelectric



•The output voltage is irregular and depends on the constructions

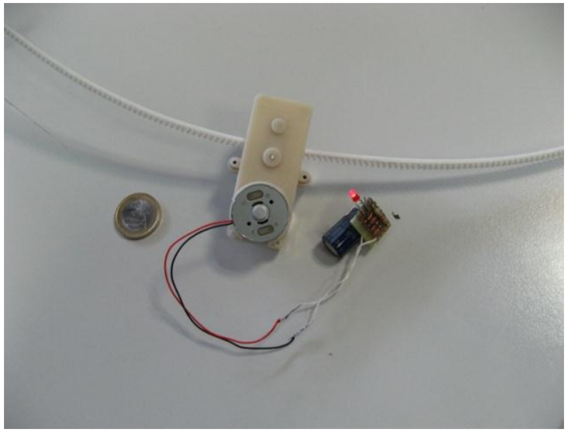
•An overvoltage protection circuits is required

~36 mJ/cm^3

Kinetic Harvester with micro-motors

Micromotors

Kinetron (NL)



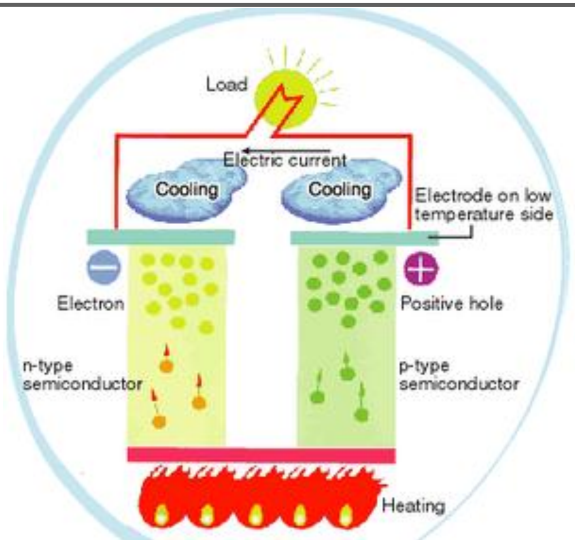
(10x more than piezo!)

Size	6,5 x 2,5 x 2,5 cm
Weight	~80 g
Storage Capacitance	4700 µF
Average power (2 Hz)	206 µW
Energy per minute	12,4 mJ

Major challenge: Mechanical Coupling with the body

Harvesting Thermal Energy

Thermoelectric Seebeck Effect



Temp. gradient drives heat flow

⇩

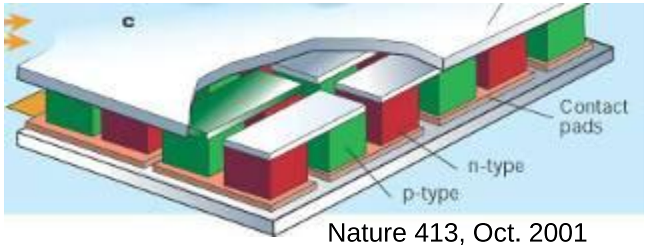
Electrons and holes flow in N-type and P-type lags made of semiconductor materials

⇩

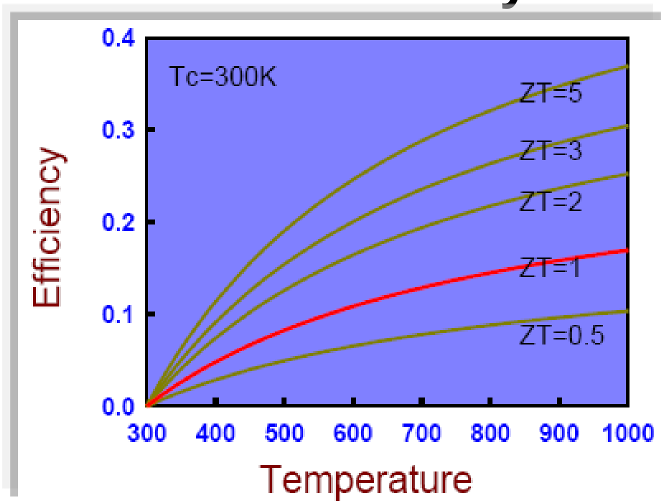
Carnot Efficiency
≡ ΔT/TH

Thermocouple

Low Efficiency



Nature 413, Oct. 2001



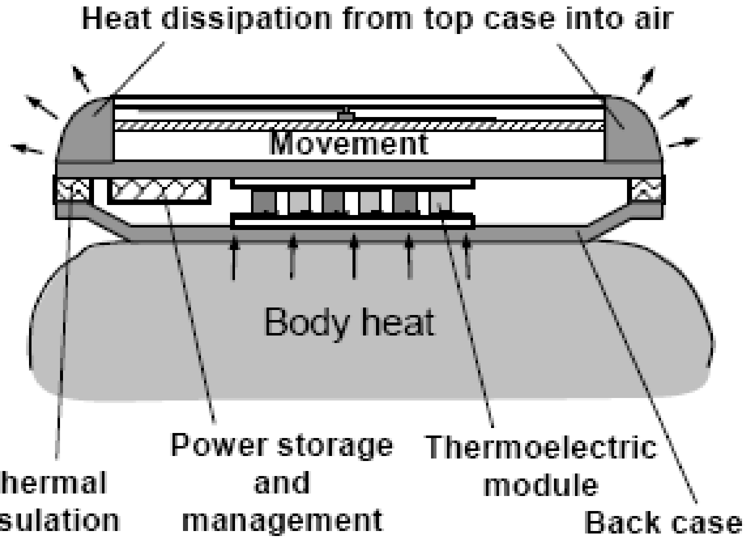
Thermopiles
- thermally in parallel
- electrically in serial

Thermal Harvesting from Human Body

Thermal energy from human body: ~ 6 mW/cm^2

Conversion efficiency at ΔT=5K: ~0.3% (not a problem!)

P ~ 20 μW/cm^2



Quartz Watches: ~40 μW

Seiko (45μW), Citzen (14μW)

In order to obtain an operating voltage of 1.5 V, over 2000 pairs of Bi_2Te_3 thermocouples are required.

very costly using conventional module fabrication technology

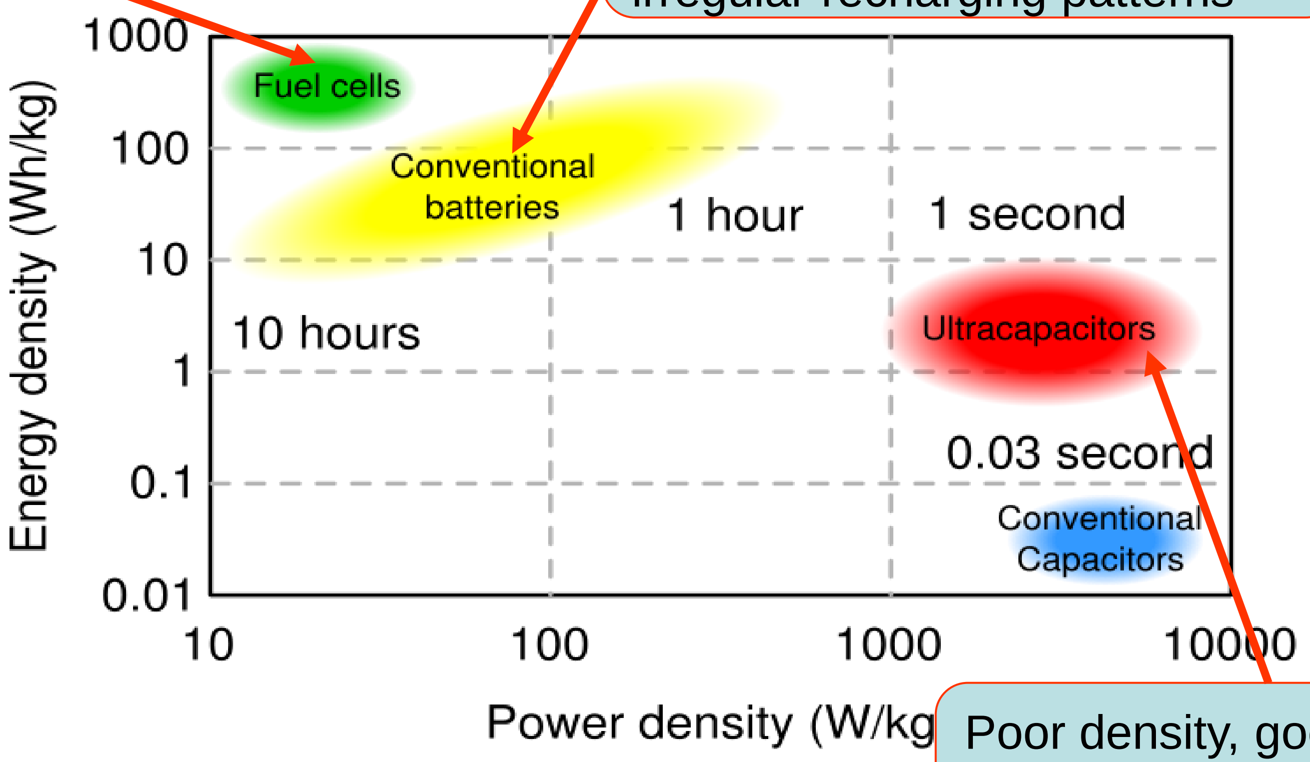
Energy Generation & Storage

- One size does not fit all for generation
  - Environmental energy sources are (intrinsically) highly heterogeneous
  - Their availability strongly depends on application context
- …and for storage
  - Major tradeoffs in density vs. peak current vs. # of recharge cycles vs. cost

Energy Storage Options

Ultimate energy deposit, but difficult to delivery and reload

Good density, easy to recharge, but lifetime is an issue with irregular recharging patterns

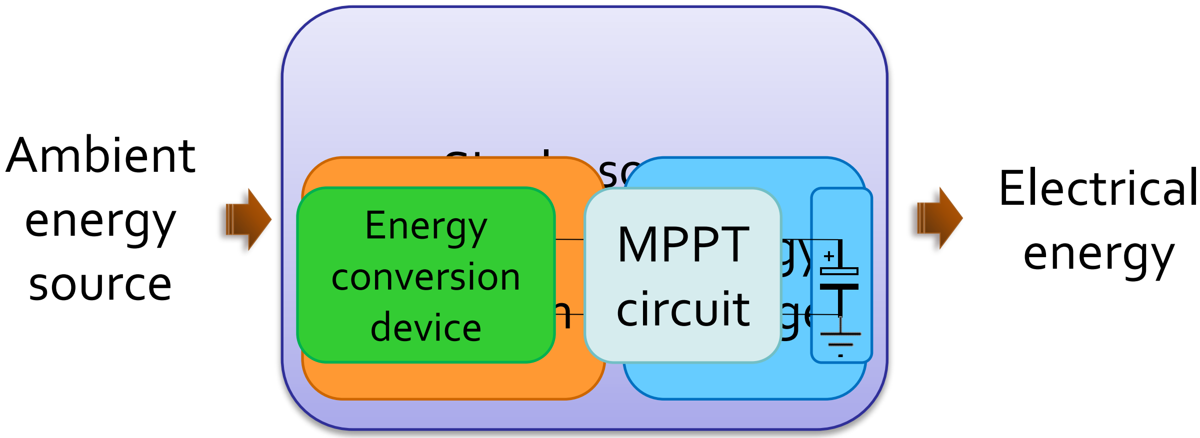


Poor density, good with peaks, but difficult to deliver efficiently, great with recharging

Putting it all together: the Smart EH Unit

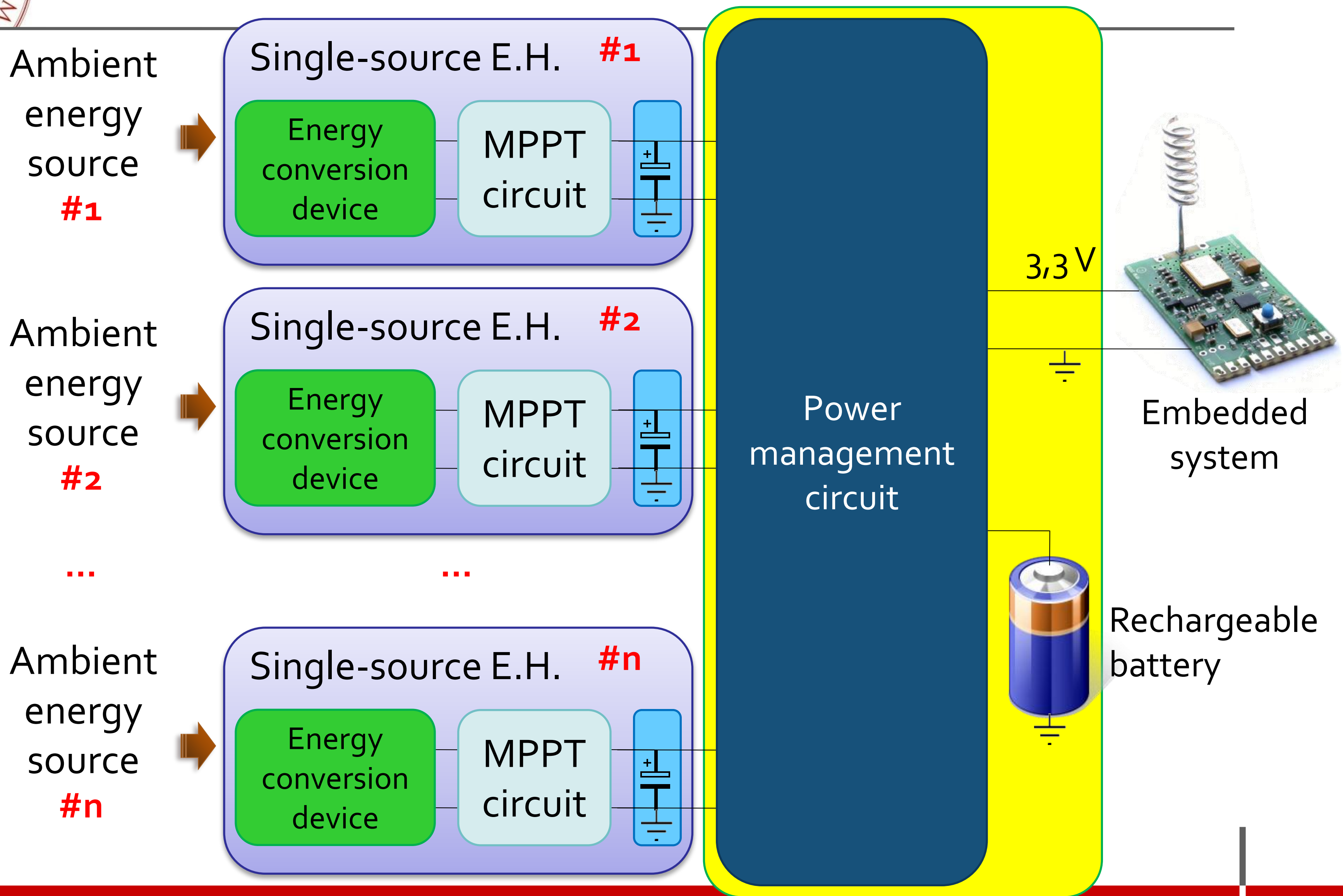
Heterogeneous EH + Storage

Harvester architecture

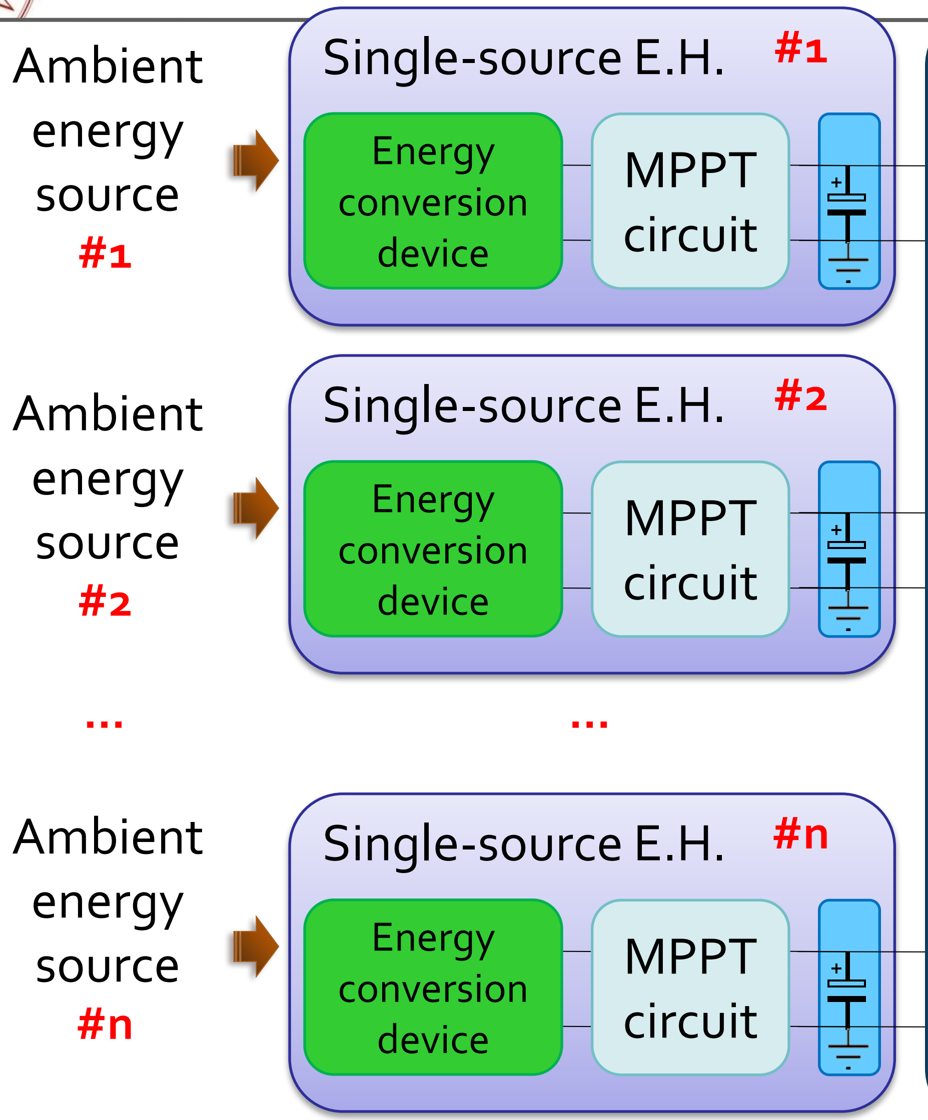


MPPT = Maximum Power Point Tracking

Harvester architecture



Harvester architecture



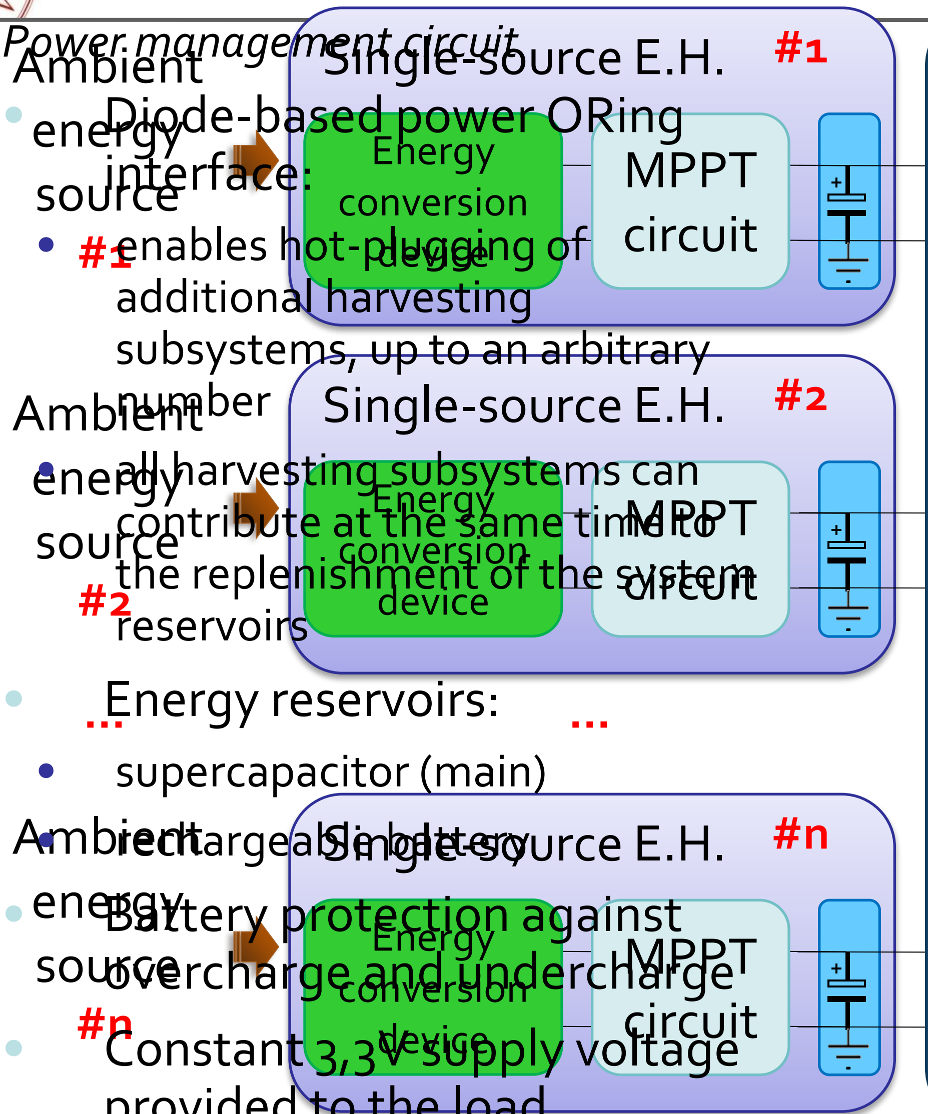
Energy harvesting subsystems

- Operate independently of each other
- Each one performs MPPT
- Each one stores the collected energy in its own supercapacitor (or battery)

Harvester architecture

Power management circuit

- Diode-based power ORing interface:
  - enables hot-plugging of additional harvesting subsystems, up to an arbitrary number
  - all harvesting subsystems can contribute at the same time to the replenishment of the system reservoirs
- Energy reservoirs:
  - supercapacitor (main)
  - rechargeable battery
- Battery protection against overcharge and undercharge
- Constant 3,3V supply voltage provided to the load



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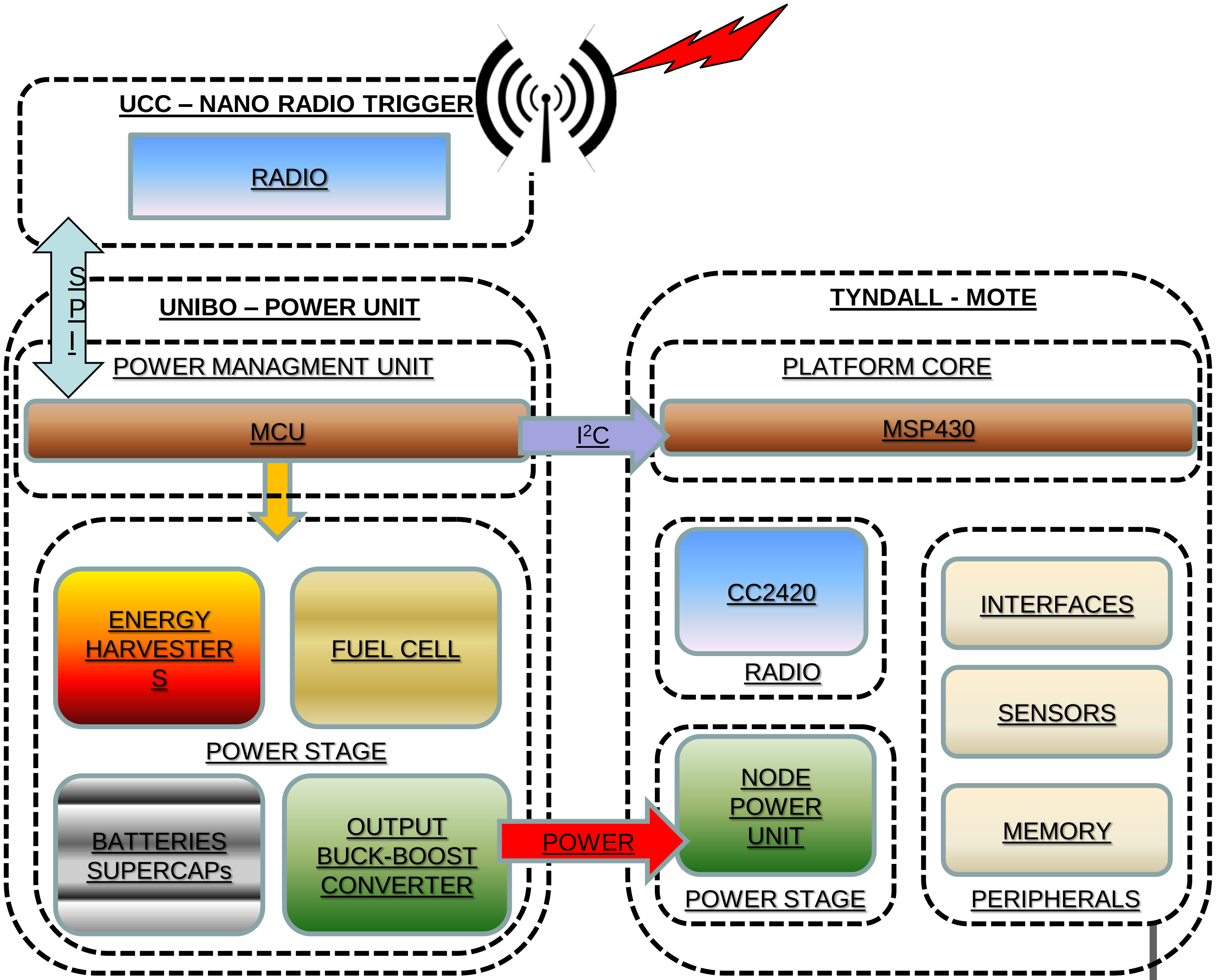
Embedded system

Putting it all together

- Power unit with radio trigger capabilities
- To provide the nodes with a smart power management sub-system
- Policies for power management
- Dynamic duty cycling
- Advanced wakeup/sleep mechanisms



Commercial harvesters

- PV: quite mature, with many products
  - Flexible PV materials are interesting e.g. www.powerfilmsolar.com
- Solution provides
  - www.enocean.com (Piezo, kinetic, solar)
  - www.kinetron.com (EM – kinetic)
  - www.micropelt.com (thermal)
  - www.powercast.com (RF –transmission)
  - www.microstrain.com (Piezo)
- …and many others – EH forum
  - www.energyharvesting.net

Now, let’s make it really hard!

Large power sinks

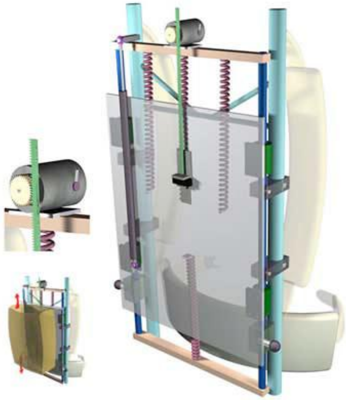
or

Ultra-small for factors

Smart Prosthetics

- Local project with INAIL:
  - Smart node based on electromiographic sensors to drive a prosthetic arm+hand
  - Embedding intelligence on board (pattern recognition)
- Motors involved… that is Watts!

"Big" Harvesters



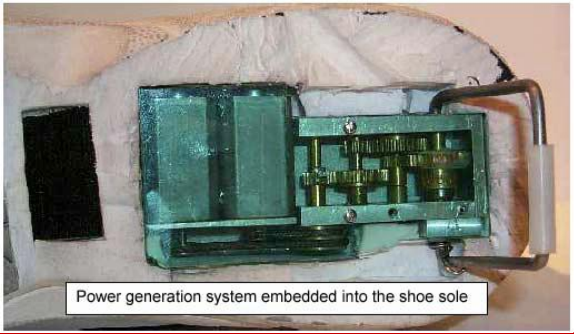
Larry Rome, University of Pennsylvania, 2005

5 cm up-down hip movement from walking reacting with 20-38 kg inertial load generated up to 7 Watts

www.bionicpower.com

8-14W power from comfortable walking pace (2 devices)

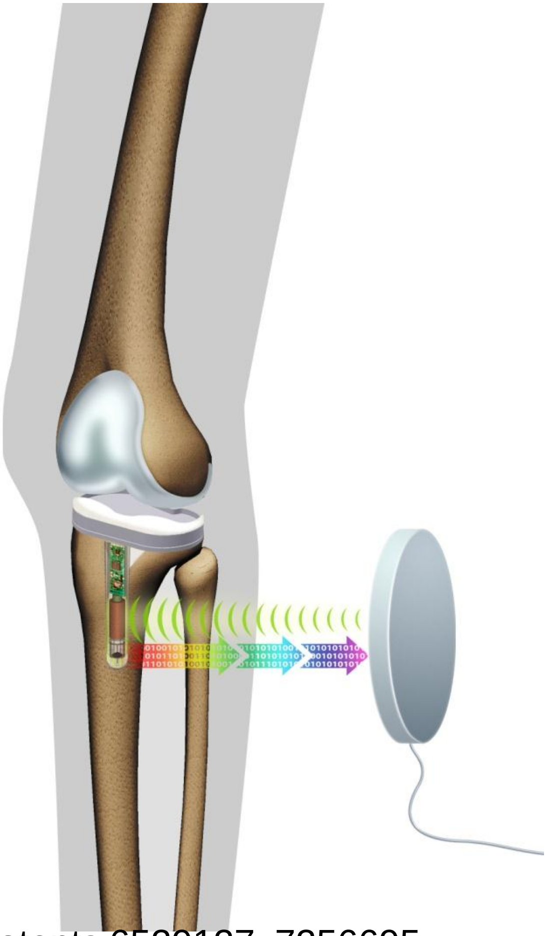
1.5m/s on level ground



Up to 1-2W

Going small – In-vivo WSN

- Embedded coil and microelectronics module are hermetically sealed within a titanium package.
- Implant monitors static & dynamic forces and moments across knee in vivo.



US patents 6529127, 7256695

Current state of the art → Inductive power coupling

Miniaturized, Integrated Storage

Cymbet's EnerChip Permits System-on-Chip Integration and Surface Mount Packaging

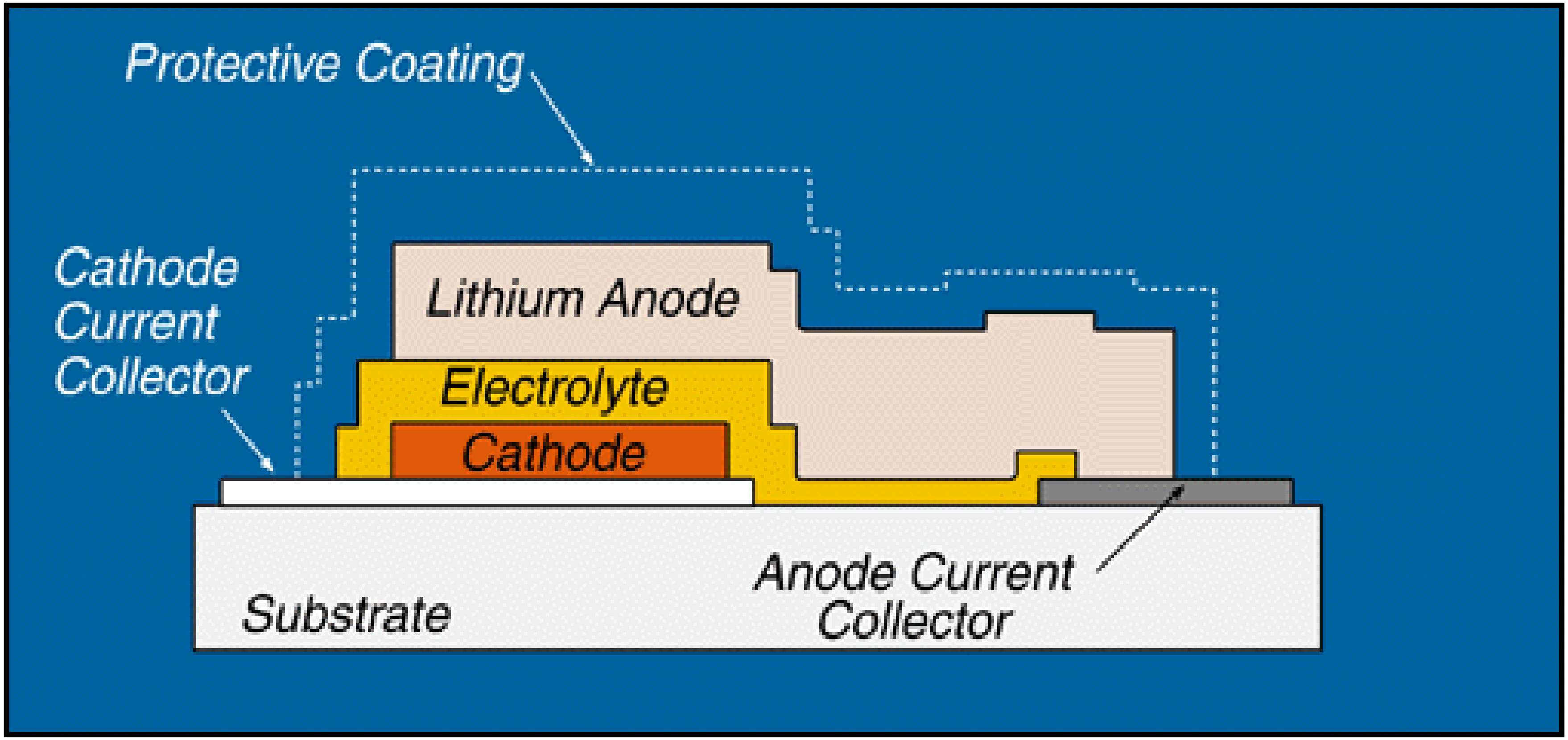
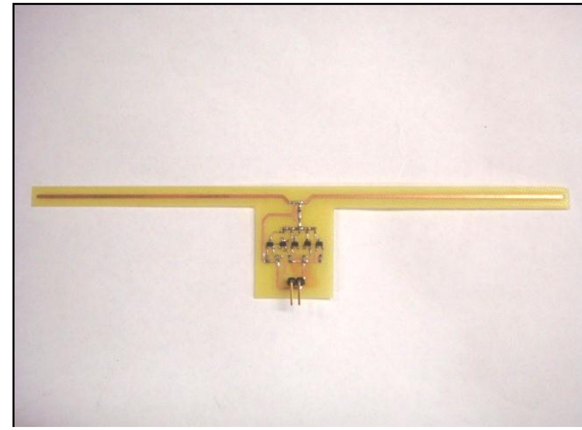
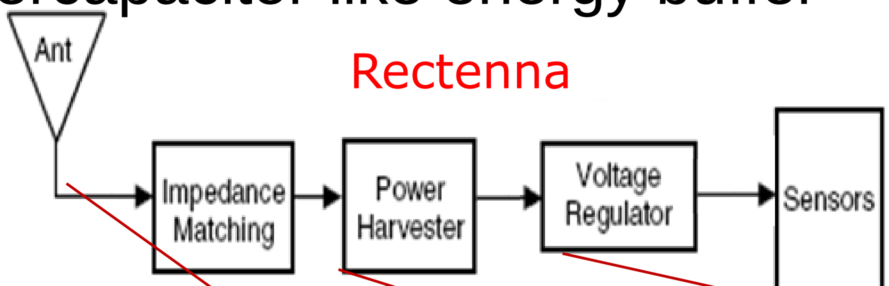


Image Courtesy DOE-ORNL

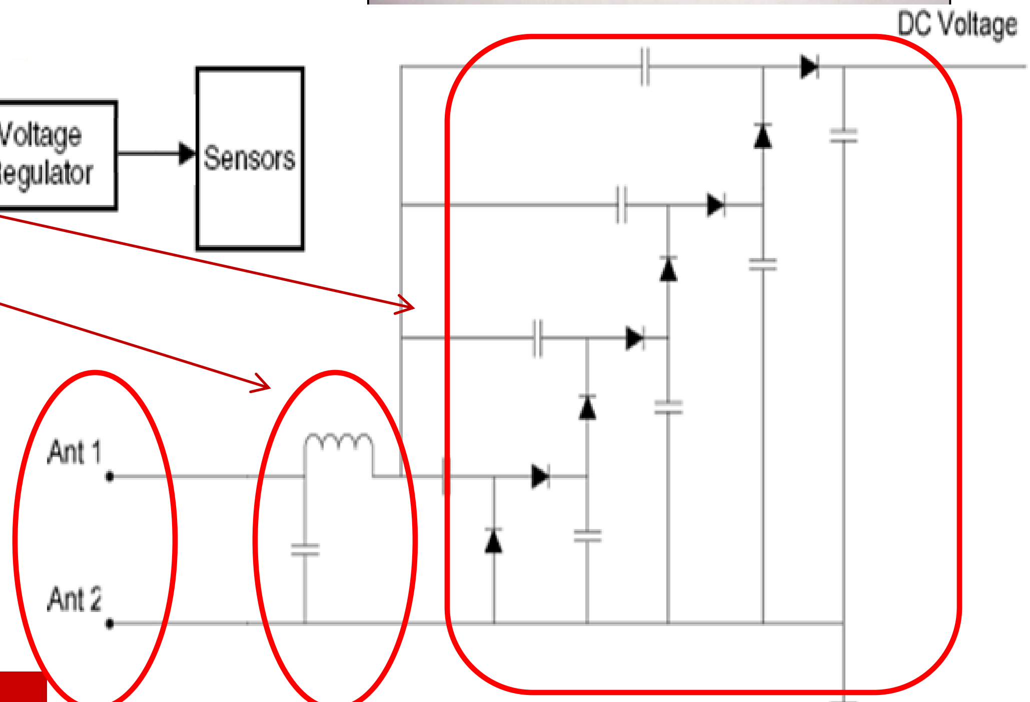
Micro Power Transmission

- Energy harvested from RF waves, generated by a transmitter (wireless power transmission)
- Store the energy with supercapacitor like energy buffer





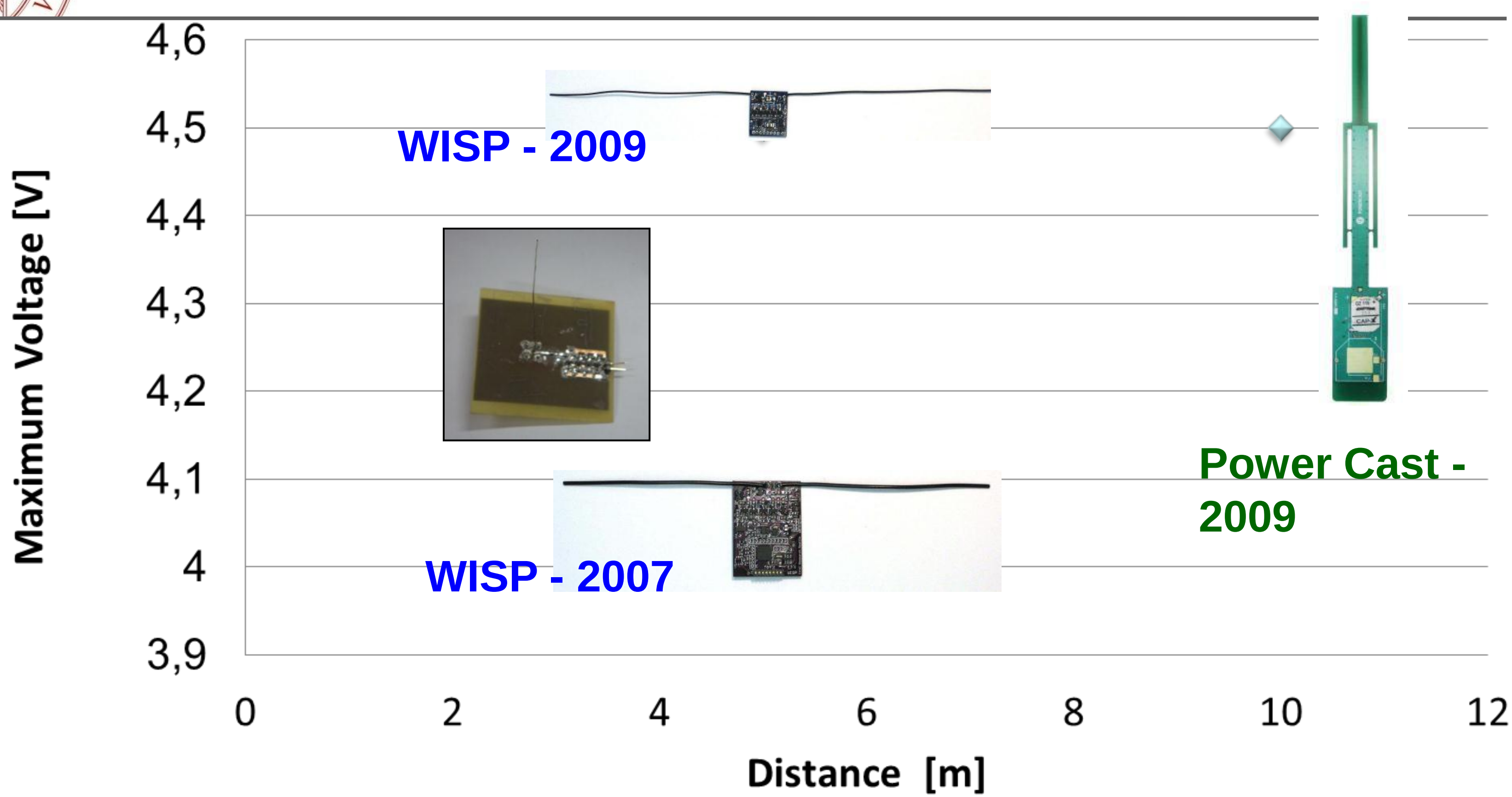
Rectenna



RFID transmitter

868 MHz

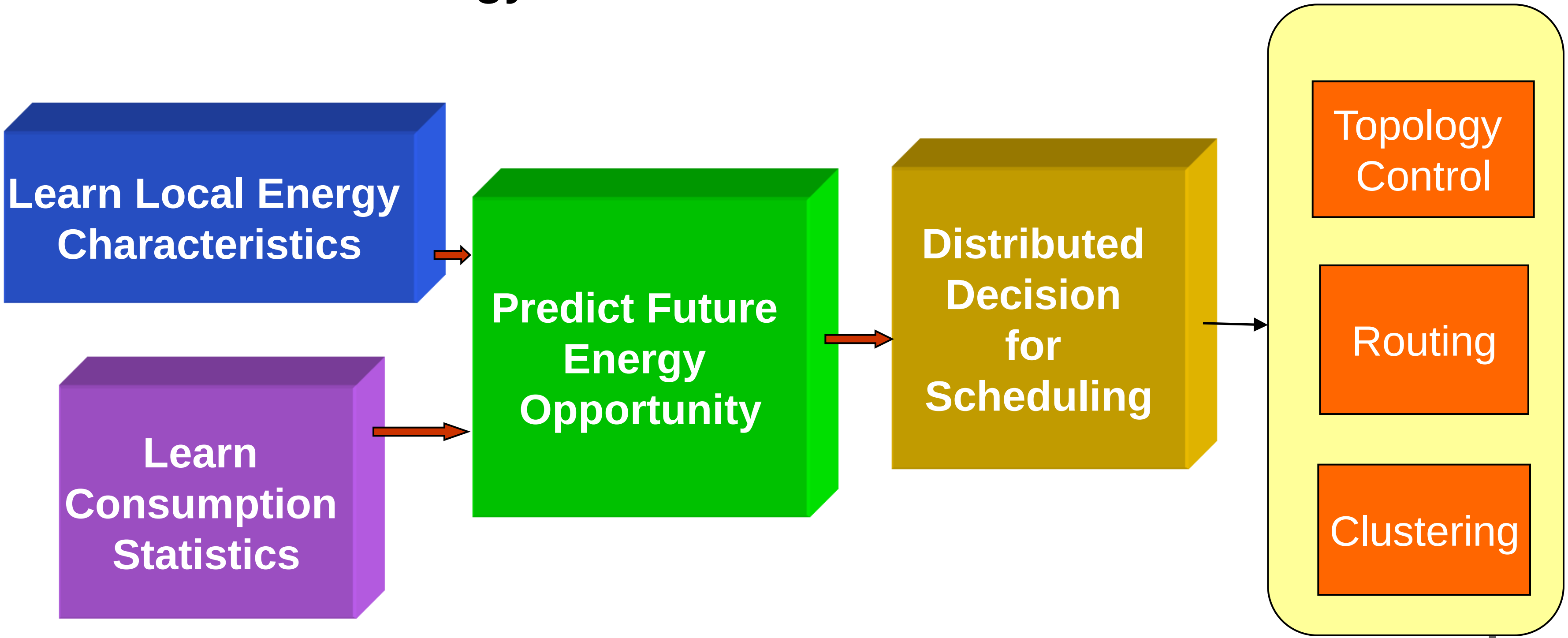
Power Transfer Efficiency



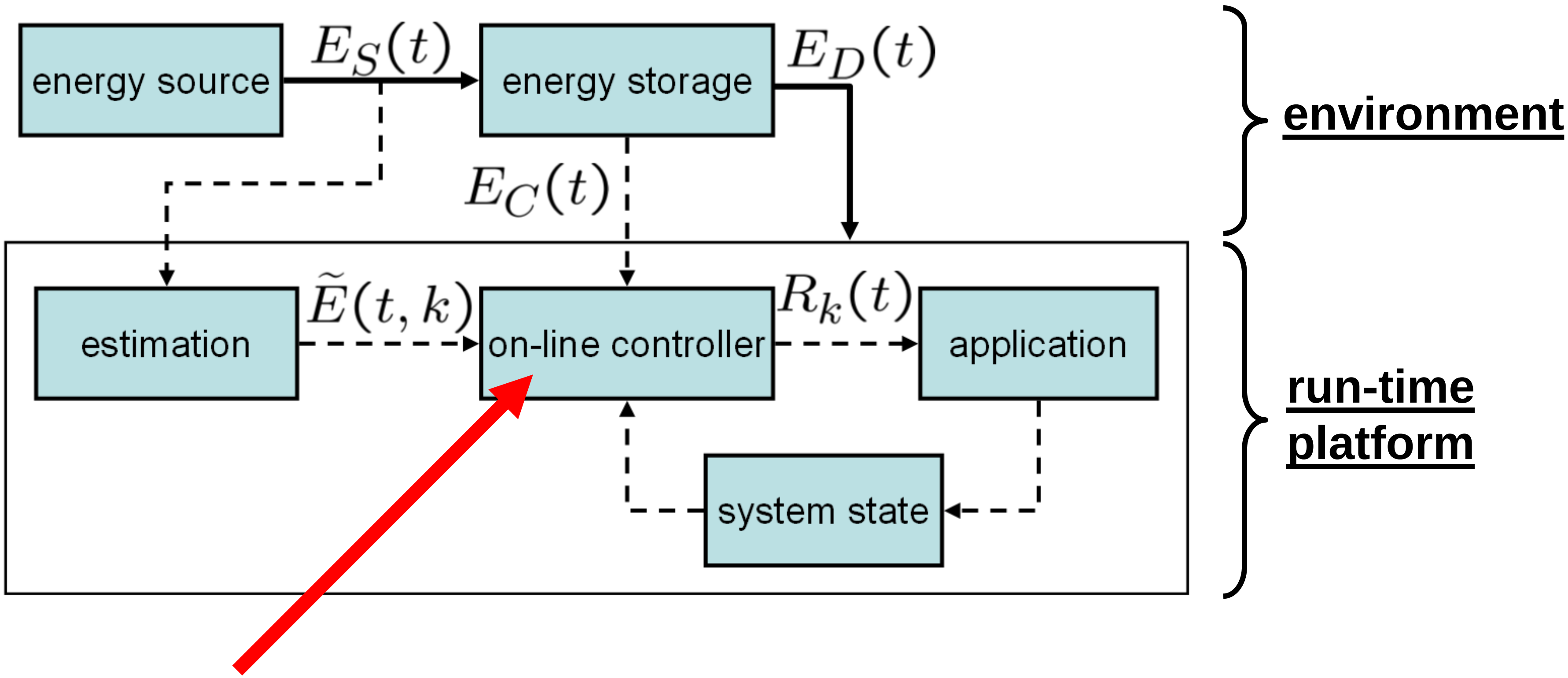
Power levels are low (tens of µW)
Advanced RF & Antenna design is needed

Harvesting-aware Management

- Tasking aware of battery status & harvesting opportunities
  - Richer nodes take more load
  - Looking at the battery status is not enough
- Learn the energy environment



System Model



Models for application, quality/utility, system behavior

Optimization problem

Efficient run-time implementation

Example: MPC for harvesting

- Optimization problem: finite horizon control
  - Example: Linear program for sensing/transmitting optimization

$$\text{maximize } (\lambda - \mu) \text{ subject to:} \qquad (14)$$

Rate of acquisition

$$s_1(t + k \cdot L) \geq \lambda \qquad \forall 0 \leq k < N$$

Memory usage

$$M(t + N) \leq \mu$$

Stored energy

$$E_C(t + k \cdot L) = E_C(t) + \sum_{j=0}^{k-1} \widetilde{E}(t, j) -$$

$$- \sum_{j=0}^{k-1} (L \cdot [0.1 \;\; 0.9] \cdot \mathbf{S}(t + j \cdot L)) \geq 0 \qquad \forall 1 \leq k \leq N$$

Used memory

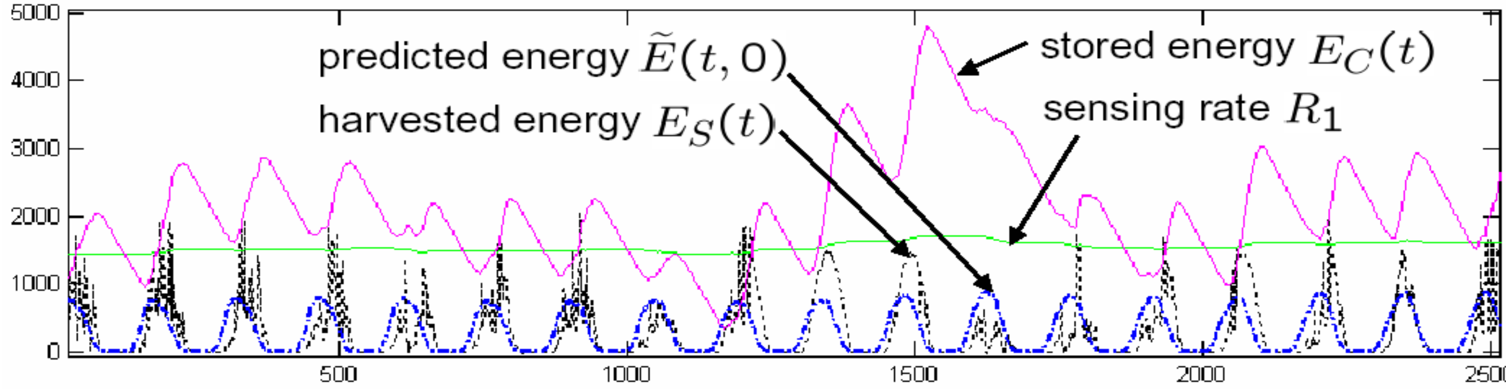
$$M(t + k \cdot L) = M(t) +$$

$$+ L \sum_{j=0}^{k-1} [1 \;\; -1] \cdot \mathbf{S}(t + j \cdot L) \geq 0 \qquad \forall 1 \leq k \leq N$$

Final stored energy

$$E_C(t + N \cdot L) \geq E_C(t) - 150$$

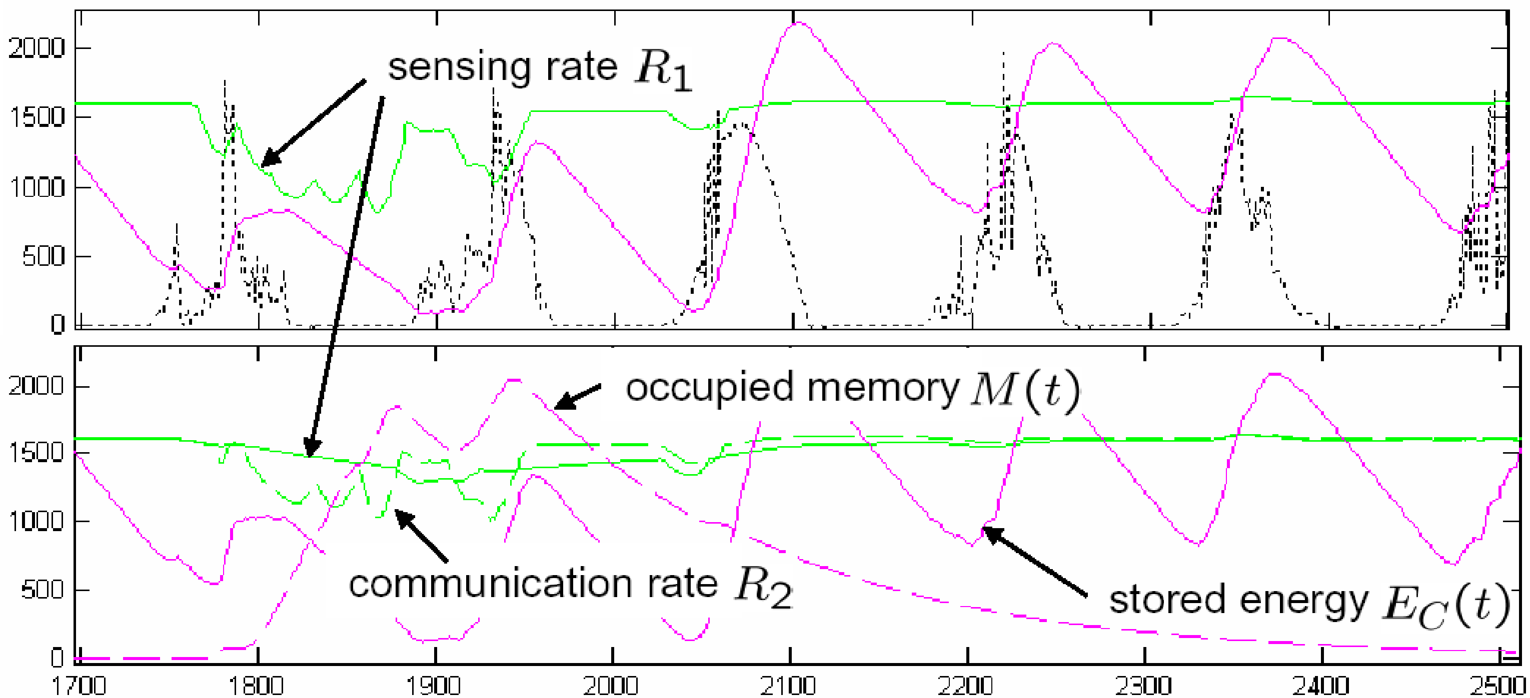
MPC at Work



Example 1

sensing rate control

minimize interval between samples

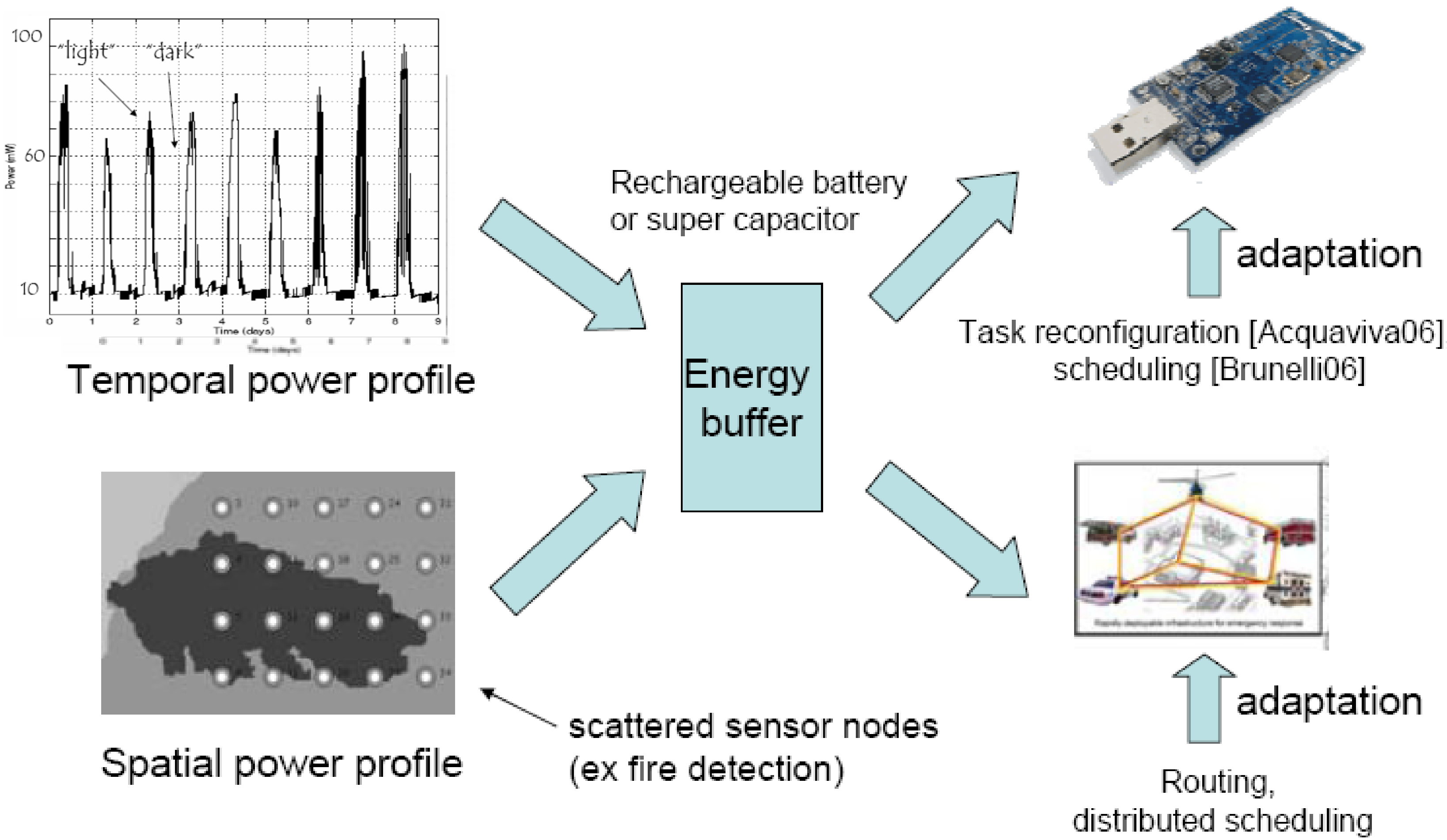


Example 2

rate control with memory buffer

- *minimize interval between samples*
- *minimize amount of stored data*

Toward the *Micro Smart Grid*



Heterogeneous, Collaborative EH + Power transmission

An exciting future…