SAPIENZA
UNIVERSITÀ DI ROMA

How can green wireless sensor networks extend the way we monitor and control the physical world

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Sistemi Wireless

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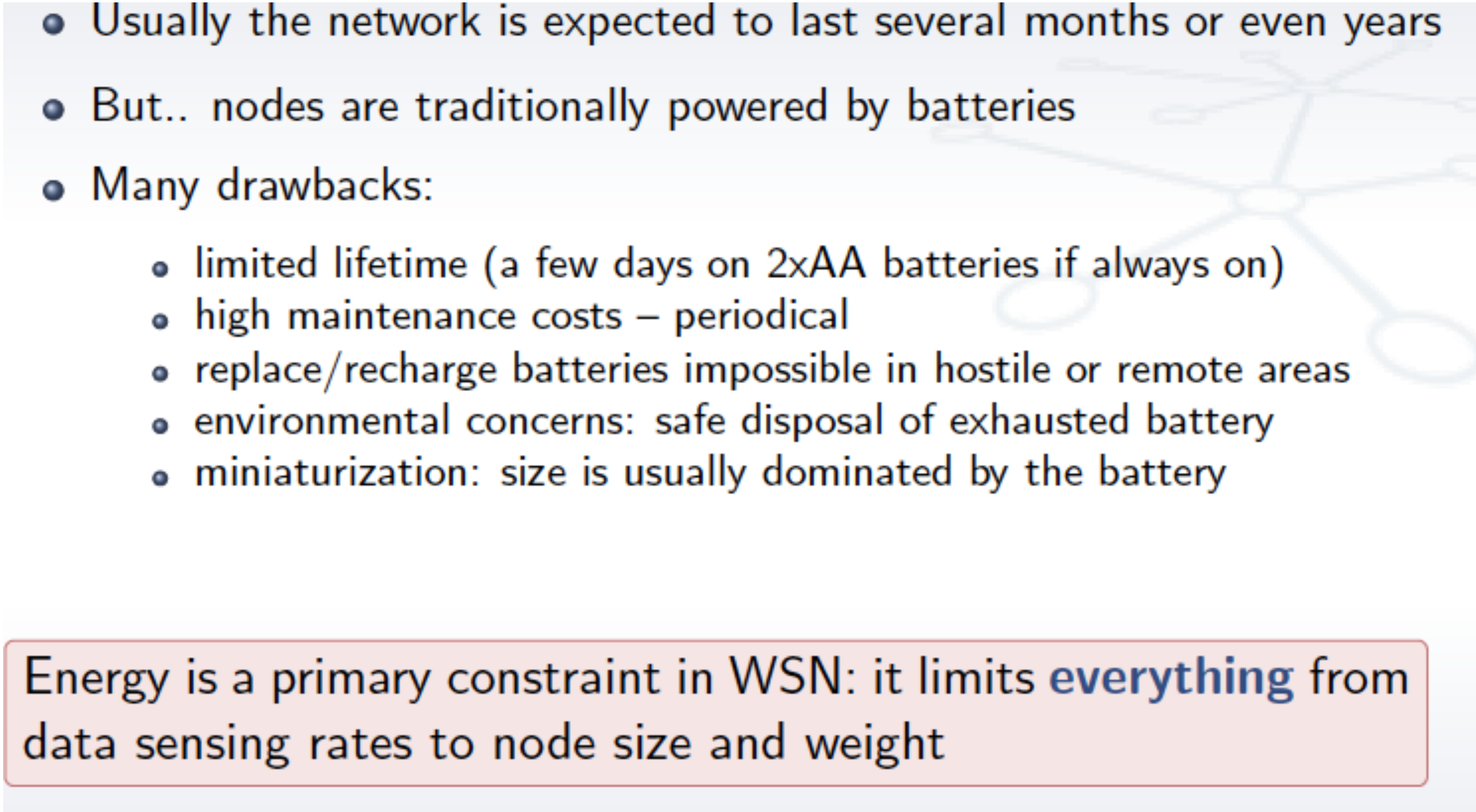
genesi.di.uniroma1.it
and to Dora Spenza

Power consumption in WSNs

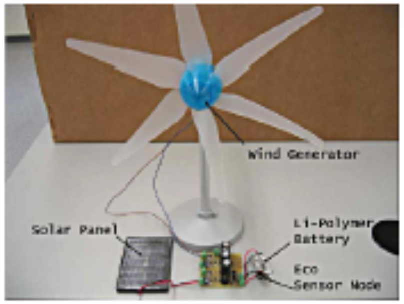


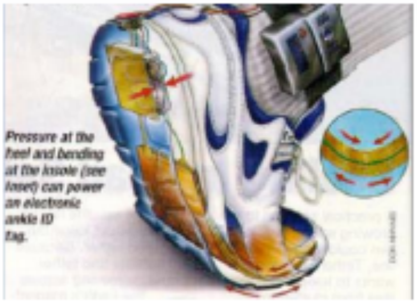
- Usually the network is expected to last several months or even years
- But.. nodes are traditionally powered by batteries
- Many drawbacks:
    - limited lifetime (a few days on 2xAA batteries if always on)
    - high maintenance costs – periodical
    - replace/recharge batteries impossible in hostile or remote areas
    - environmental concerns: safe disposal of exhausted battery
    - miniaturization: size is usually dominated by the battery

Energy is a primary constraint in WSN: it limits **everything** from data sensing rates to node size and weight

Green Wireless Sensor Networks

Energy Harvesting *The process by which energy readily available from the environment is captured and converted into usable electrical energy*





Pressure at the heel and bending at the insole (see inset) can power an electronic ankle ID tag.

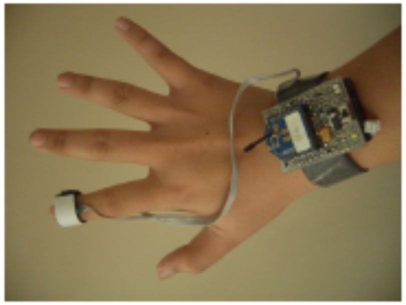
- ✔ Supplement or completely replace batteries
- ✔ Virtually unlimited lifetime (hardware longevity)

- ✗ Energy availability is uncertain in time and value
- ✗ Perpetual systems requires dedicated solutions

Application scenarios

Wildlife Tracking (ZebraNet, TurtleNet)

Monitoring in harsh environments



Health care

Surveillance

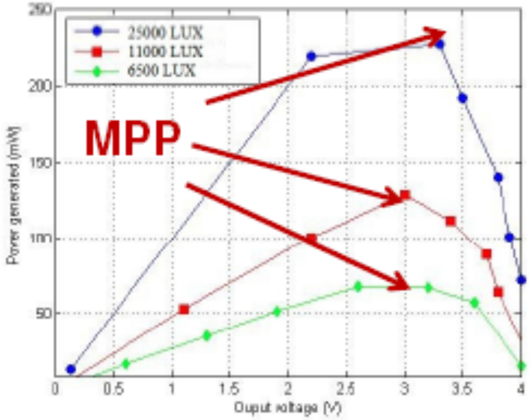
Structural healt monitoring

Which kinds of harvesting can be used ?

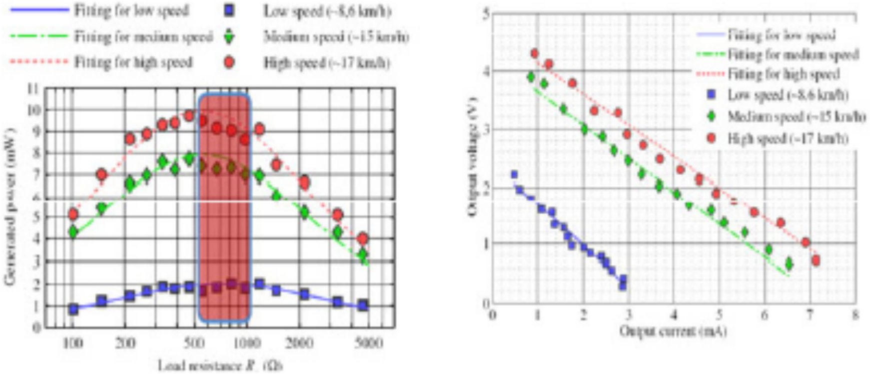
Harvesting opportunities

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**

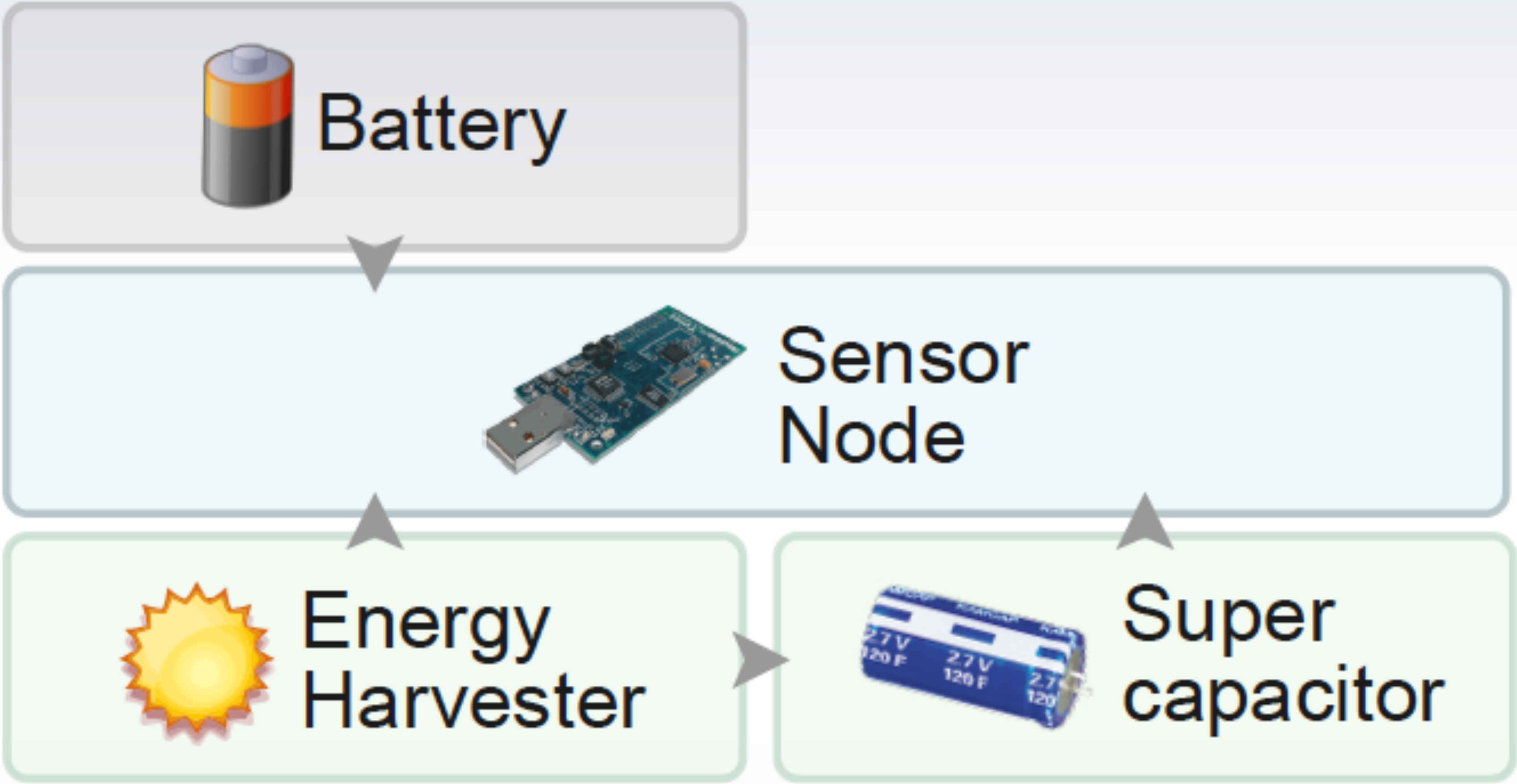
PV cell characteristic



Wind microturbine characteristic



Energy harvesting node architecture



Battery

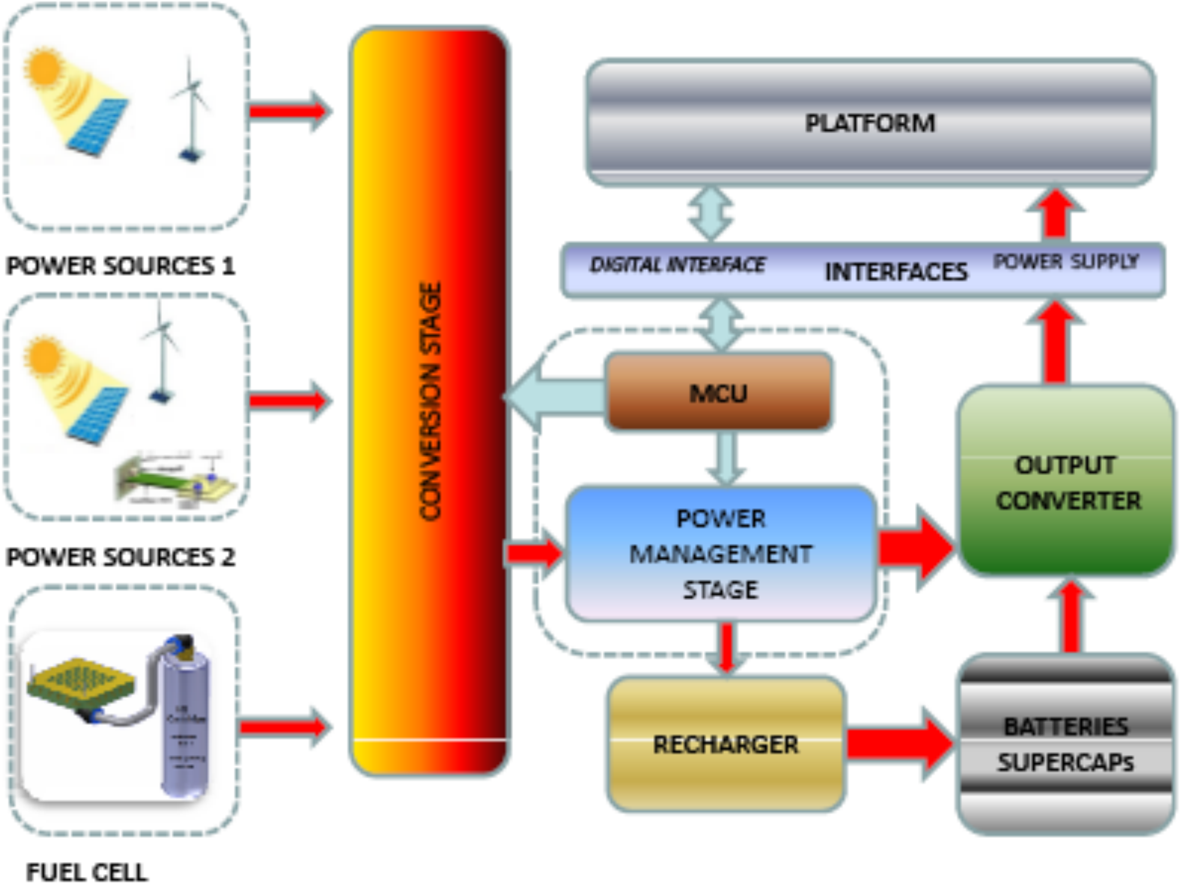
Sensor Node

Energy Harvester

Super capacitor

Many other architectures proposed in the literature: multi-source energy harvesting, no primary battery, two-stage harvesting storage, etc.

GENESI platform



POWER SOURCES 1

POWER SOURCES 2

FUEL CELL

CONVERSION STAGE

PLATFORM

DIGITAL INTERFACE

INTERFACES

POWER SUPPLY

MCU

POWER MANAGEMENT STAGE

OUTPUT CONVERTER

RECHARGER

BATTERIES SUPERCAPs

EH*-WSN operation

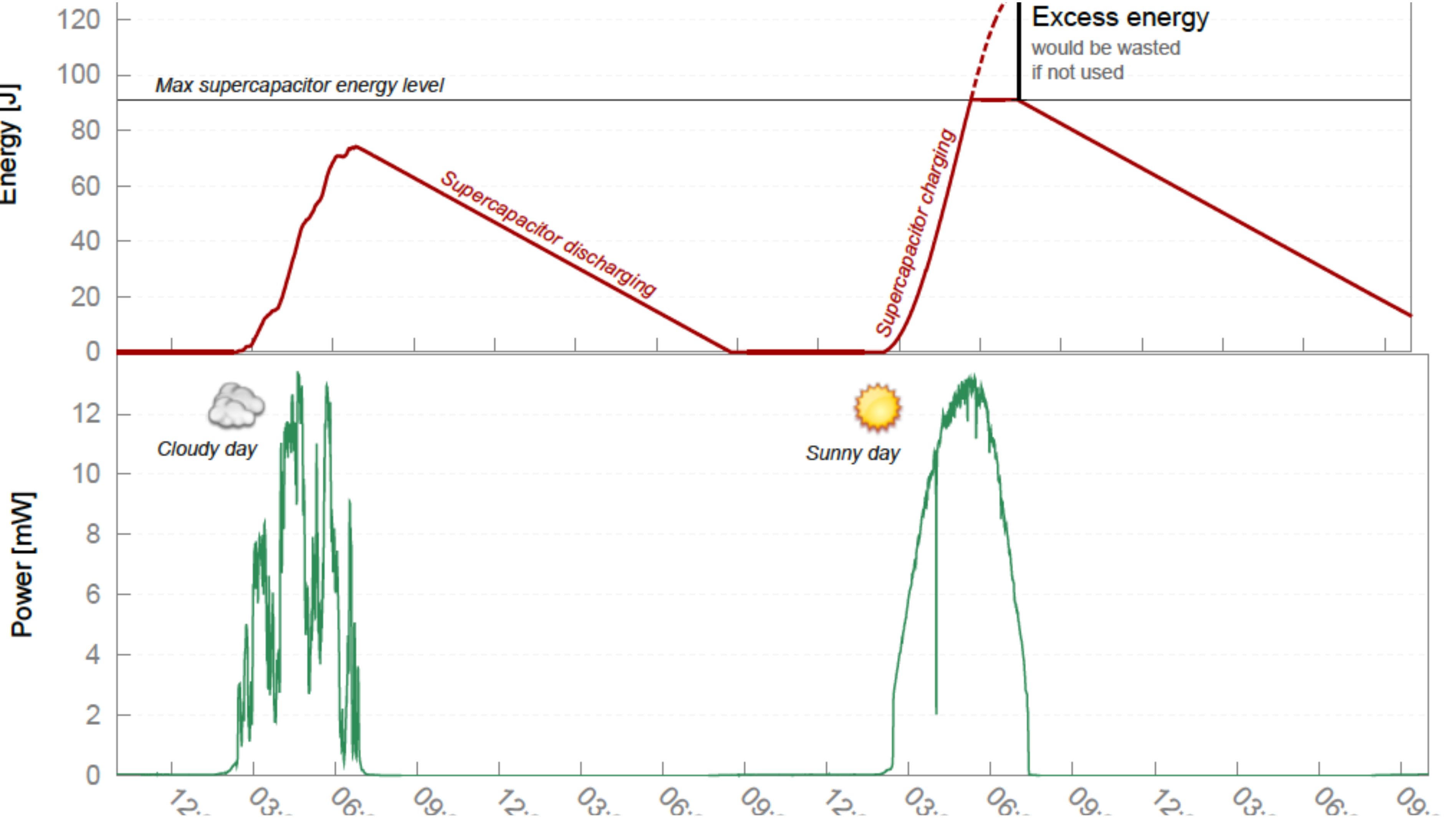
- A paradigm shift with respect to traditional WSNs
  - All activities on low power communication protocols and algorithms for WSNs are based on the following assumptions
    - Monotonically decreasing limited battery energy
    - Sensing cost is negligible
    - Comm. Cost high
      - We have to limit as much as possible when the transceiver is ON
      - Low energy consumption protocols and operations
      - Some solutions (security primitives, energy consuming operations, energy demanding sensing) are simply not feasible

* Energy Harvesting

EH-WSN operation

- These assumptions are not true in a EH- enabled system
  - Energy is non monothonic
  - There are some periods of time when an excess of energy maybe available which is wasted if not used
  - When to perform (energy intensive) tasks become an issue

EH: non monothonic behaviour

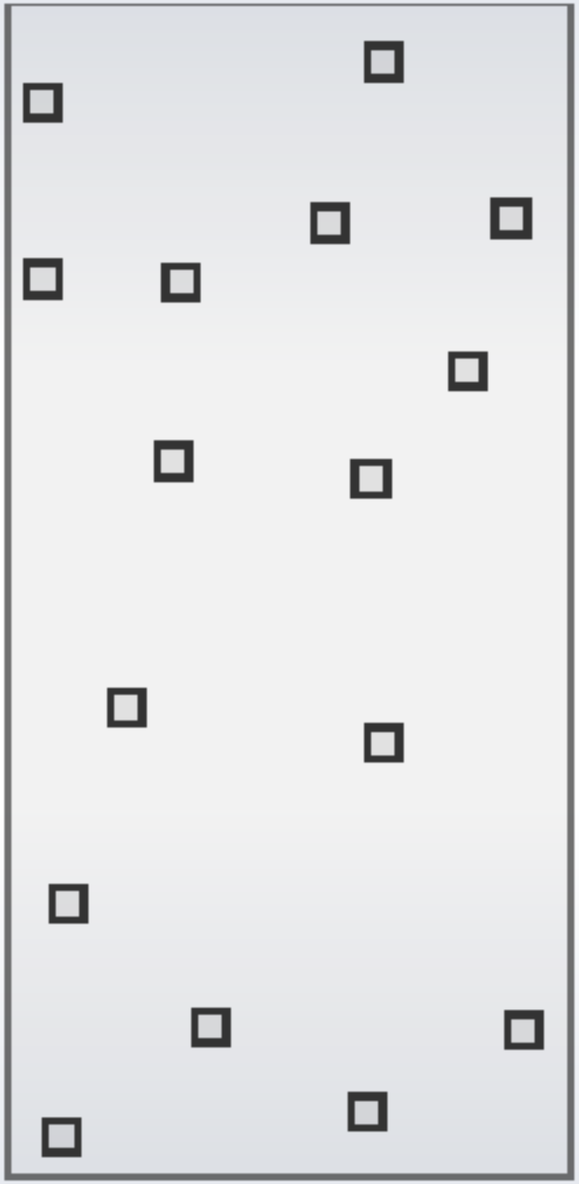


Introduction

- Static set of wireless sensor nodes deployed for monitoring applications
- **Missions** arrive in the network dynamically over time at different locations
- Multiple missions active at the same time ⇒ **competing** for the sensing resources

How to assign the sensing resources of the network?

Which nodes to assign to which mission?



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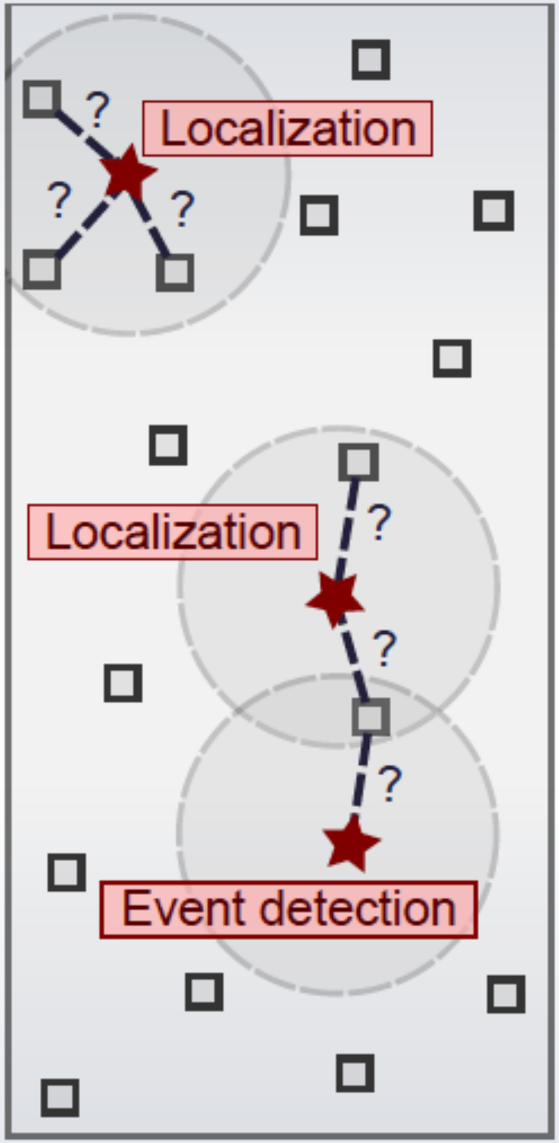
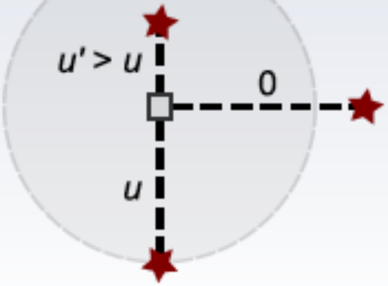
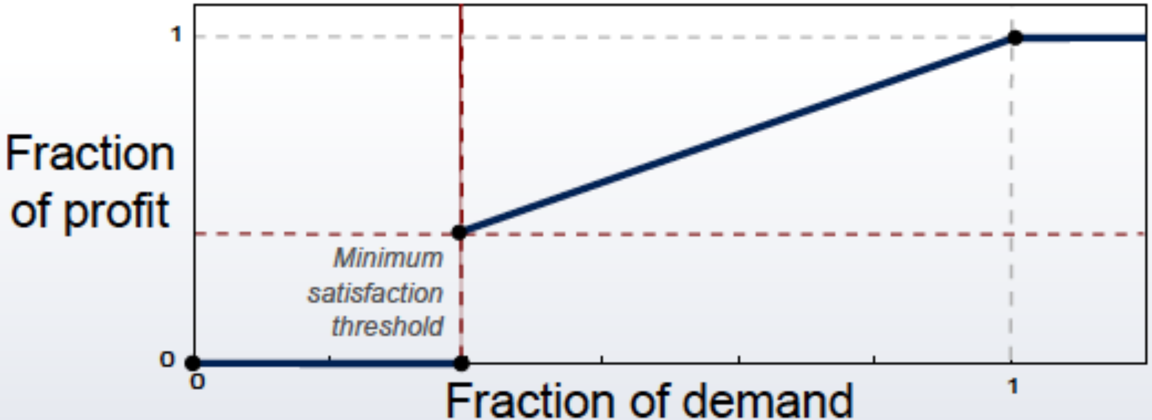


QoS aware operation

Assignments are not all equal..



- Nodes contribute to different missions with different **utility** (e.g., distance)
- Missions vary in amount of resources they require (**demand**) and importance (**profit**)
- **Goal:** Maximize the total profit achieved by the network for mission execution
- Profit achieved for mission execution depends on allocated demand



EN-MASSE

- Nodes make **independent** decisions about missions execution
- Decisions based on:

partial profit
1. profit of the mission
2. potential contribution to the mission

tune eagerness
3. target lifetime

classify missions
4. current energy level of the node
5. energetic cost of the mission
6. future energy availability (solar energy prediction model)

ENMASSE-Mission classification

A new mission arrives ⇒ check energy requirements and availability

more willing to accept

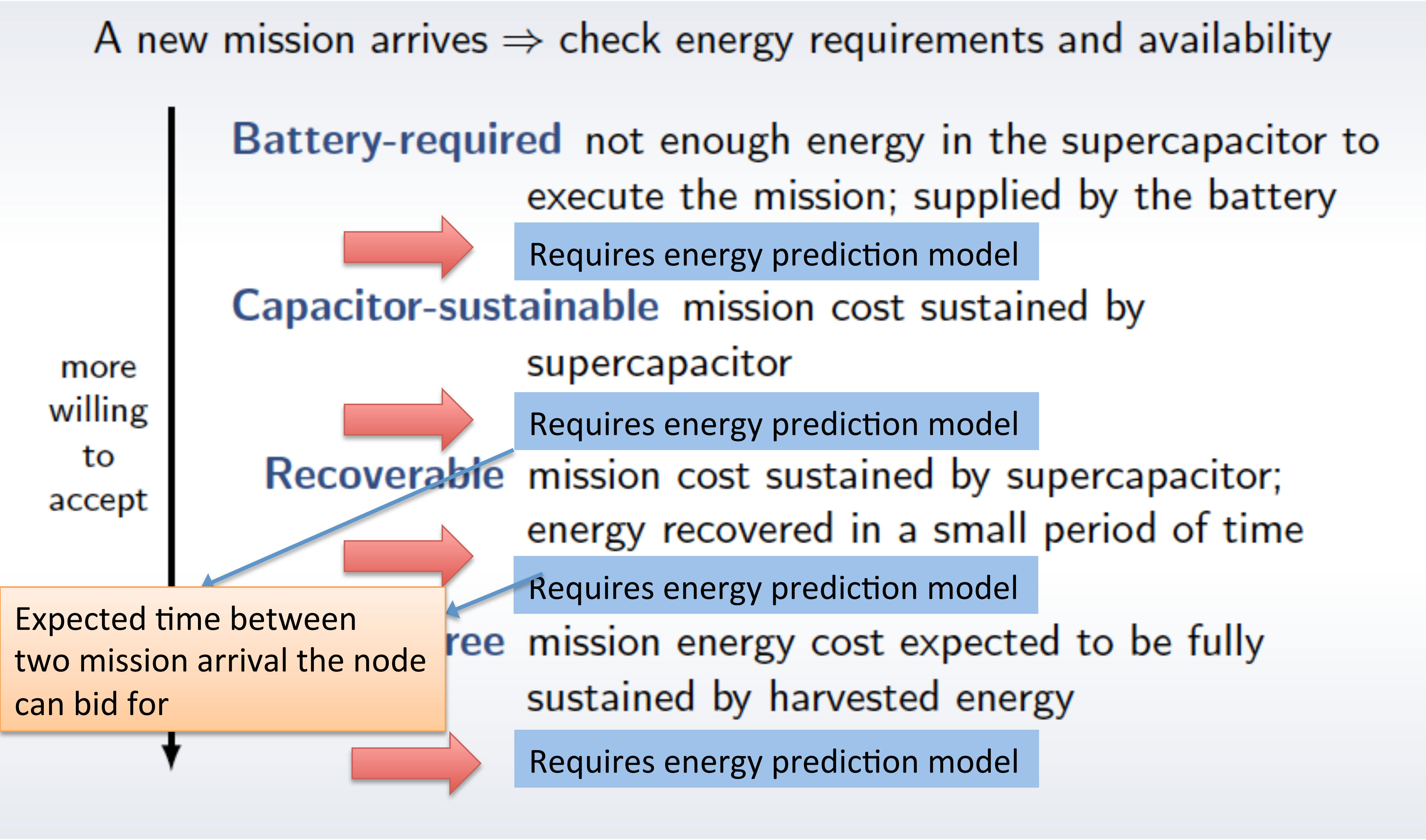
Battery-required not enough energy in the supercapacitor to execute the mission; supplied by the battery

Capacitor-sustainable mission cost sustained by supercapacitor

Recoverable mission cost sustained by supercapacitor; energy recovered in a small period of time

Free mission energy cost expected to be fully sustained by harvested energy

Mission classification



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Expected time between two mission arrival the node can bid for

EN-MASSE (details)

Always bid for free missions

$$\overline{p} = \frac{E[u]}{E[d]} \times \frac{E[p]}{P},$$

U=utility; d=demand; p=profit;P=max profit

$$p^* = \frac{u}{d} \times \frac{p}{P} \times w_m$$

partial profit achievable byparticipating to an Incoming mission

Weight associated to the mission classification (higher for recoverable)

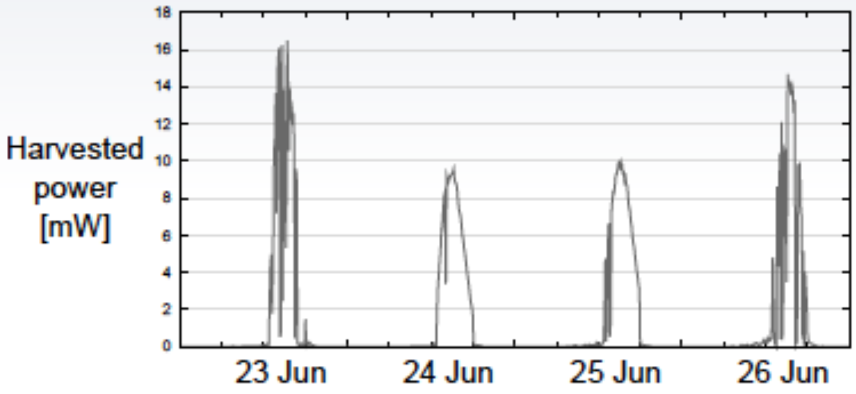
A node bids for a recoverable of capacitor sustainable mission only if p*> $\overline{p}$

Real harvesting systems

Modeling real harvesting systems

Real-life solar energy traces:

- Telos B motes interfaced with solar cells
- Deployed for 100 days: variable weather conditions, different locations

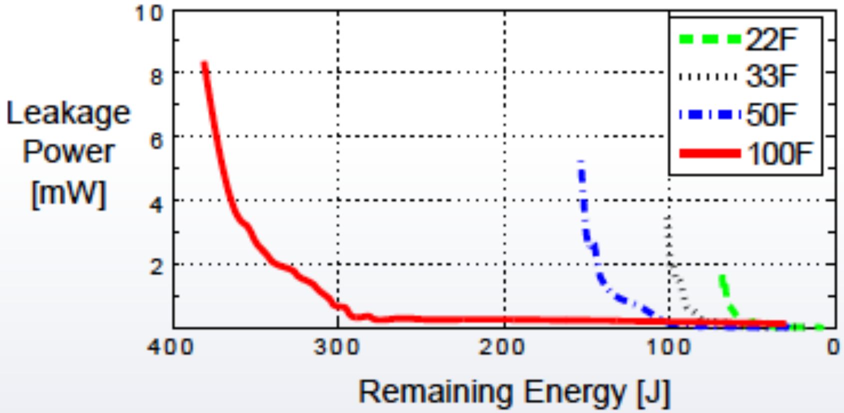


Non-ideal supercapacitor:

① finite size;

② charging/discharging efficiency < 1;

③ leakage



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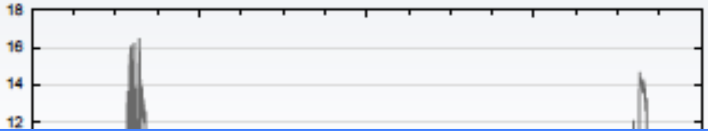

$$leak_i(t) = \begin{cases} a_1 \cdot B_i(t) + b_1, & B_{R_1} \leq B_i(t) < B_{R_2} \\ \vdots & \vdots \\ a_n \cdot B_i(t) + b_n, & B_{R_n} \leq B_i(t) < B_{R_{n+1}} \end{cases}$$

Non-ideal supercapacitor:

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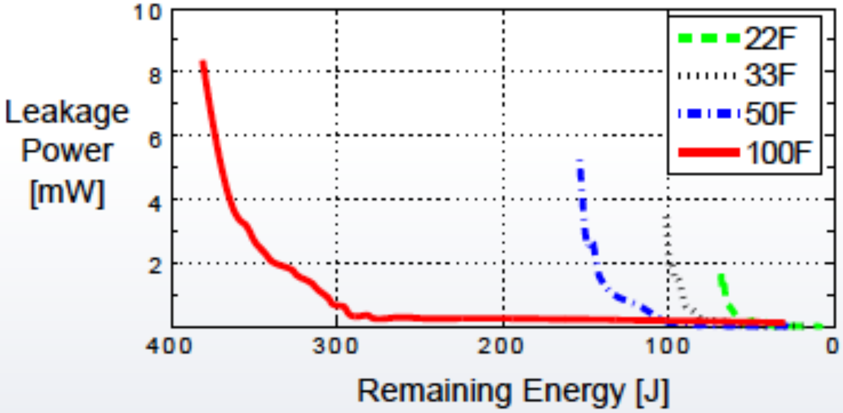
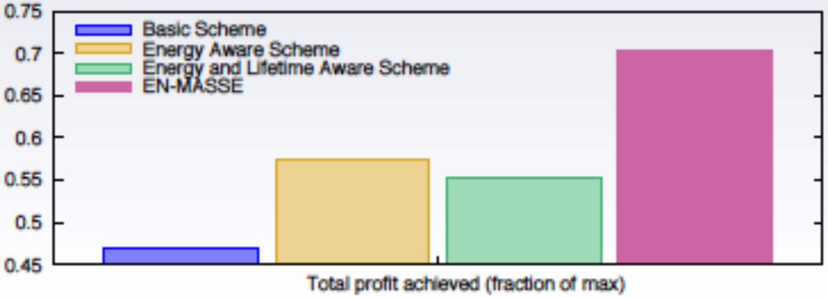
2. charging/discharging efficiency < 1;
3. leakage

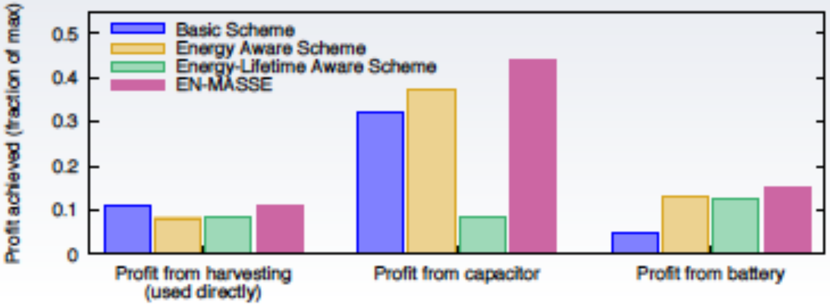


EN-MASSE performance

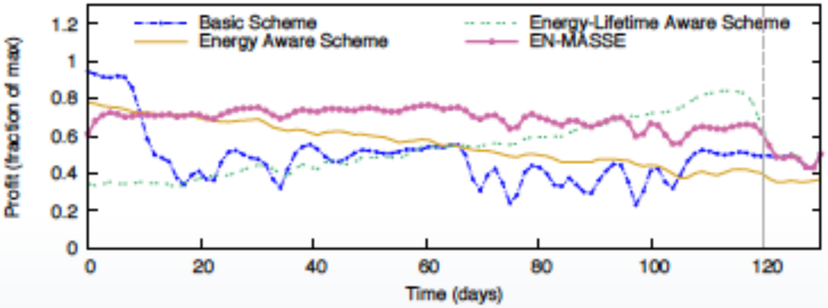
EN-MASSE vs other assignment schemes



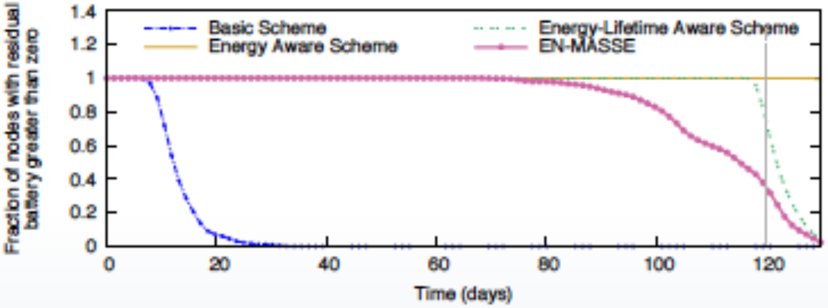
Greatest profit



Largest profit form harvesting



High stable profit over time



Graceful battery energy degradation

Parameters: 500 nodes, 400 × 400 m field, 22 missions/hour, target lifetime 120 days, 25F supercapacitor, average mission duration: 1 hour.

Energy prediction models

- EWMA: Exponentially Weighted Moving Average
  - the value of energy likely to be harvested at a particular time is computed as a weighted average of the energy received at the same time over a set of previous days
  - problem mix of days (cloudy/sunny)
- WCMA algorithm uses an E matrix of size D xN that stores N energy values for each D past days.
  - E**(**i, j**)** is the energy stored in the matrix for the jth sample on the ith day, and the predicted value is related to the previous sample in th same day and the mean value of the past samples (at the same hour of the day):

$$E(d,n+1) = \alpha \cdot E(d,n) + GAP_k \cdot (1-\alpha) \cdot M_D(d,n+1)$$

  - where MD**(**d, n**+1)** is the mean of D past days at n**+1** sample of the day:

$$M_D(d,n) = \frac{\sum_{i=d-1}^{d-D} E(i,n)}{D}$$

WCMA

Stima energia prox slot

$$E(d,n+1) = \alpha \cdot E(d,n) + GAP_k \cdot (1-\alpha) \cdot M_D(d,n+1)$$

$$M_D(d,n) = \frac{\sum_{i=d-1}^{d-D} E(i,n)}{D}$$

Media dell’energia dello slot
Negli ultimi D giorni

$$v_k = \frac{E(d,n-K+k-1)}{M_D(d,n-K+k-1)}$$

$$\mathbf{V} = [v_1, v_2, \cdots, v_K]$$

Per i K valori precedenti considera lo Spostamento tra l’energia generata nel giorno corrente e la media dei giorni precedenti

$$p_k = \frac{k}{K} \qquad \mathbf{P} = [p_1, p_2, \cdots, p_K]$$

$$GAP_k = \frac{\mathbf{V} \cdot \mathbf{P}}{\sum \mathbf{P}}$$

Da un peso maggiore per calcolare il fattore di correzione al recente passato

Pro-Energy

$$\hat{E}_{t+1} = \alpha \cdot C_t \; + \; (1-\alpha) \cdot E^d_{t+1} \tag{2}$$

where:

$\hat{E}_{t+1}$ is the predicted energy at timeslot $t+1$ on the current day;

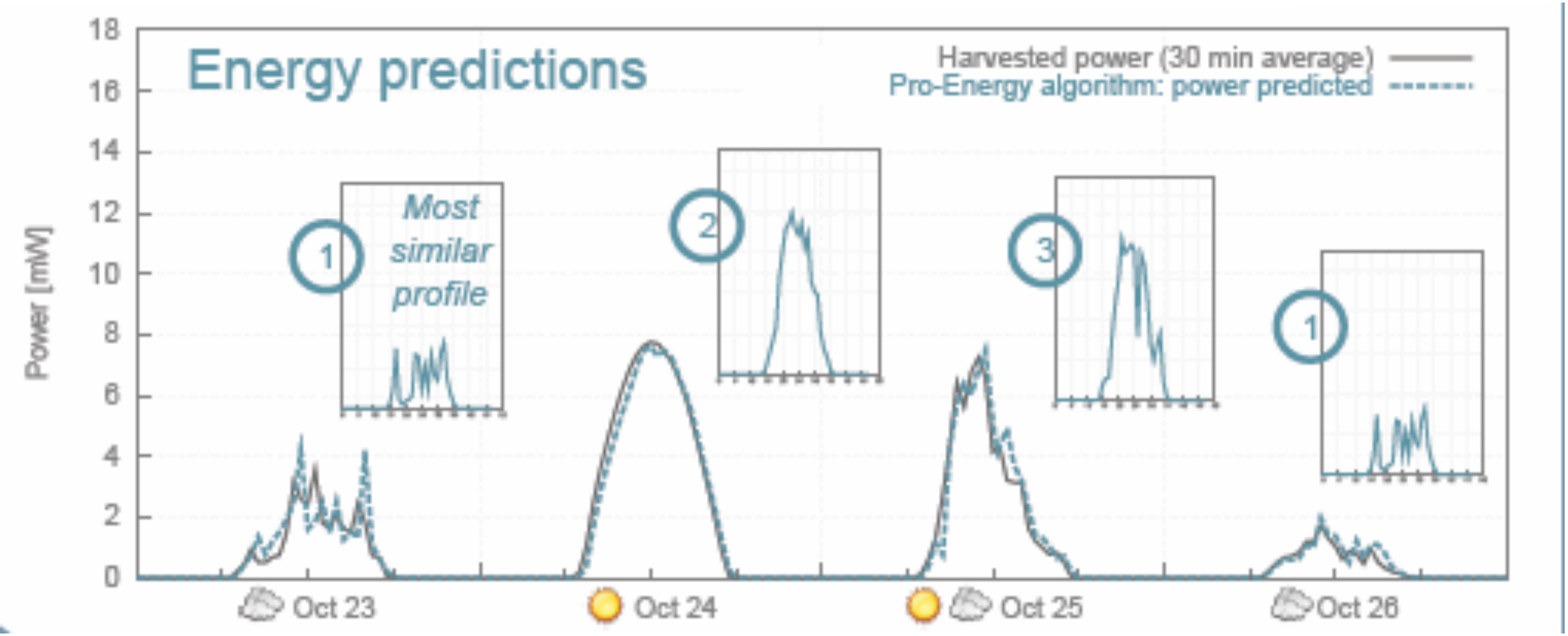
E^d_{t+1} is the energy harvested during timeslot $t+1$ on the stored day d;

C_t is the energy harvested during timeslot t on the current day C;

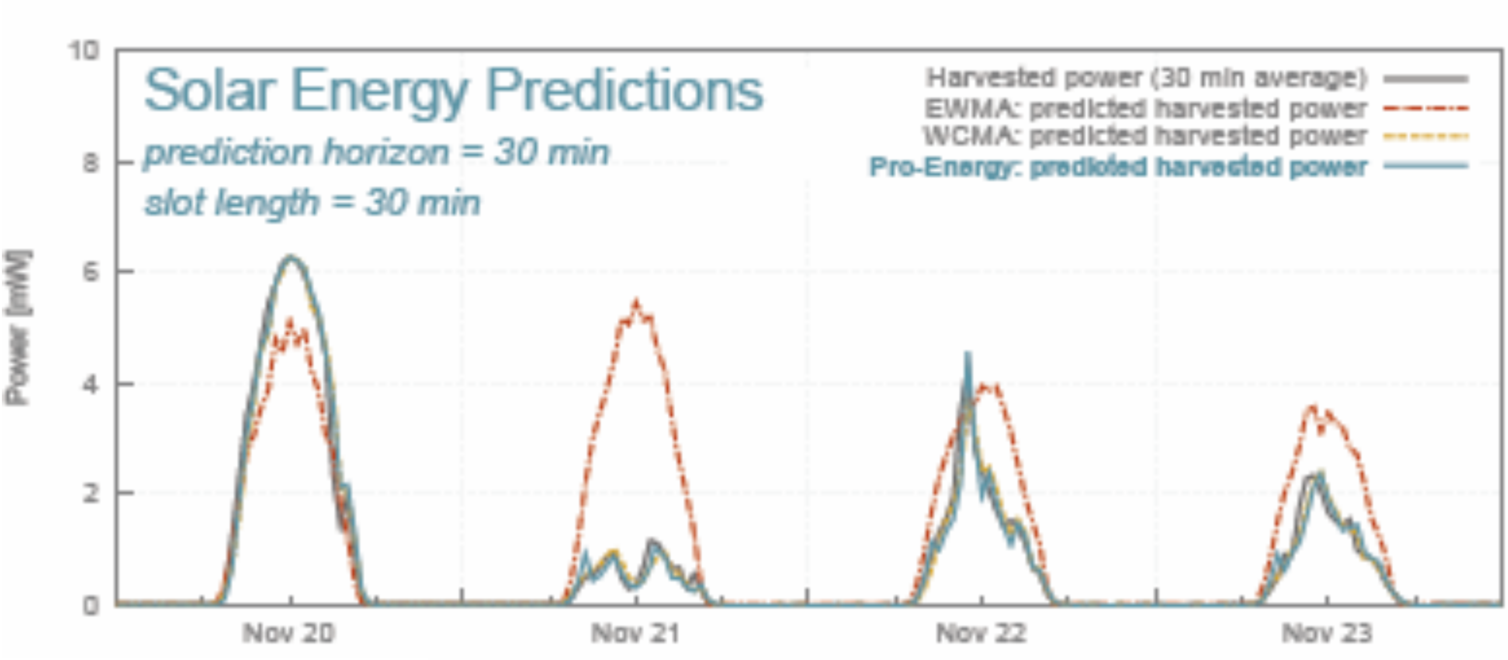
α is a weighting factor, $0 \leq \alpha \leq 1$.

Pro-Energy

$$\hat{E}_{t+1} = \alpha \cdot C_t + (1-\alpha) \cdot E^d_{t+1}$$



Solar energy prediction

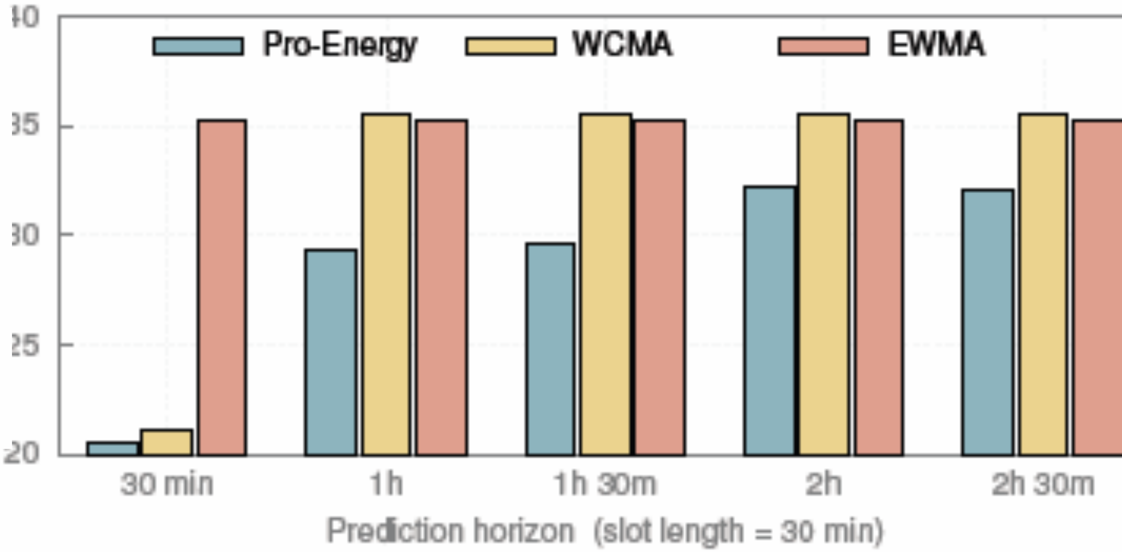


$$MAPE = \frac{1}{T}\sum_{t}\left|\frac{\overline{e}_t - \widehat{e}_t}{\overline{e}_t}\right|$$

$\overline{e}_t$ energy harvested during timeslot t

$\widehat{e}_t$ energy predicted for timeslots t

T number of samples



Wind energy prediction