Year 2 Review
Paris, November 8th and 9th, 2006

Scientific Highlight:

Scheduling and resource management for Energy Harvesting systems

Execution Platforms – Design For Low Power

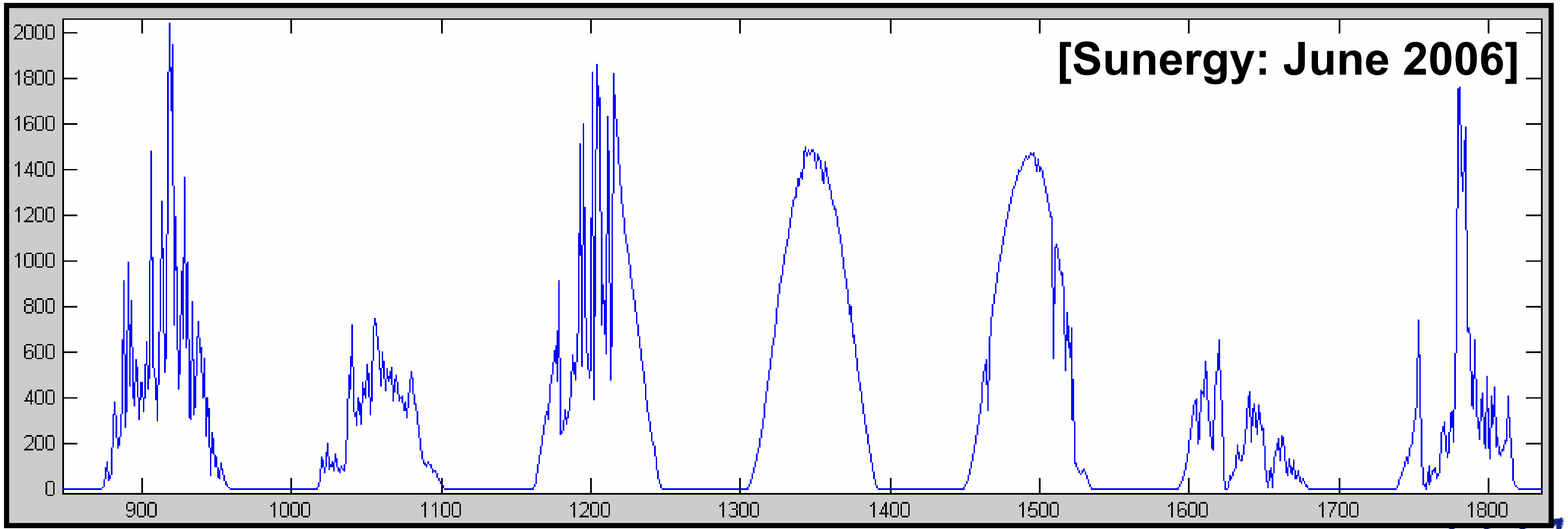
Luca Benini

DEIS Università di Bologna

Promises and Potential

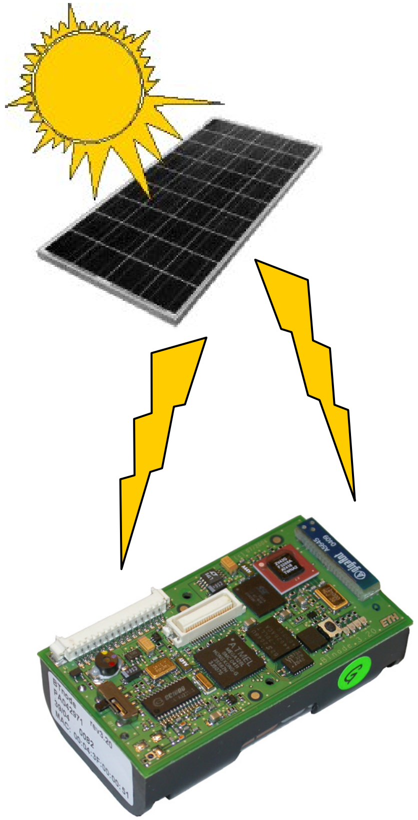
What is different?

- Conventional energy management:
  - How do we **save** energy ?
- Energy harvesting:
  - When do we **use** energy ?

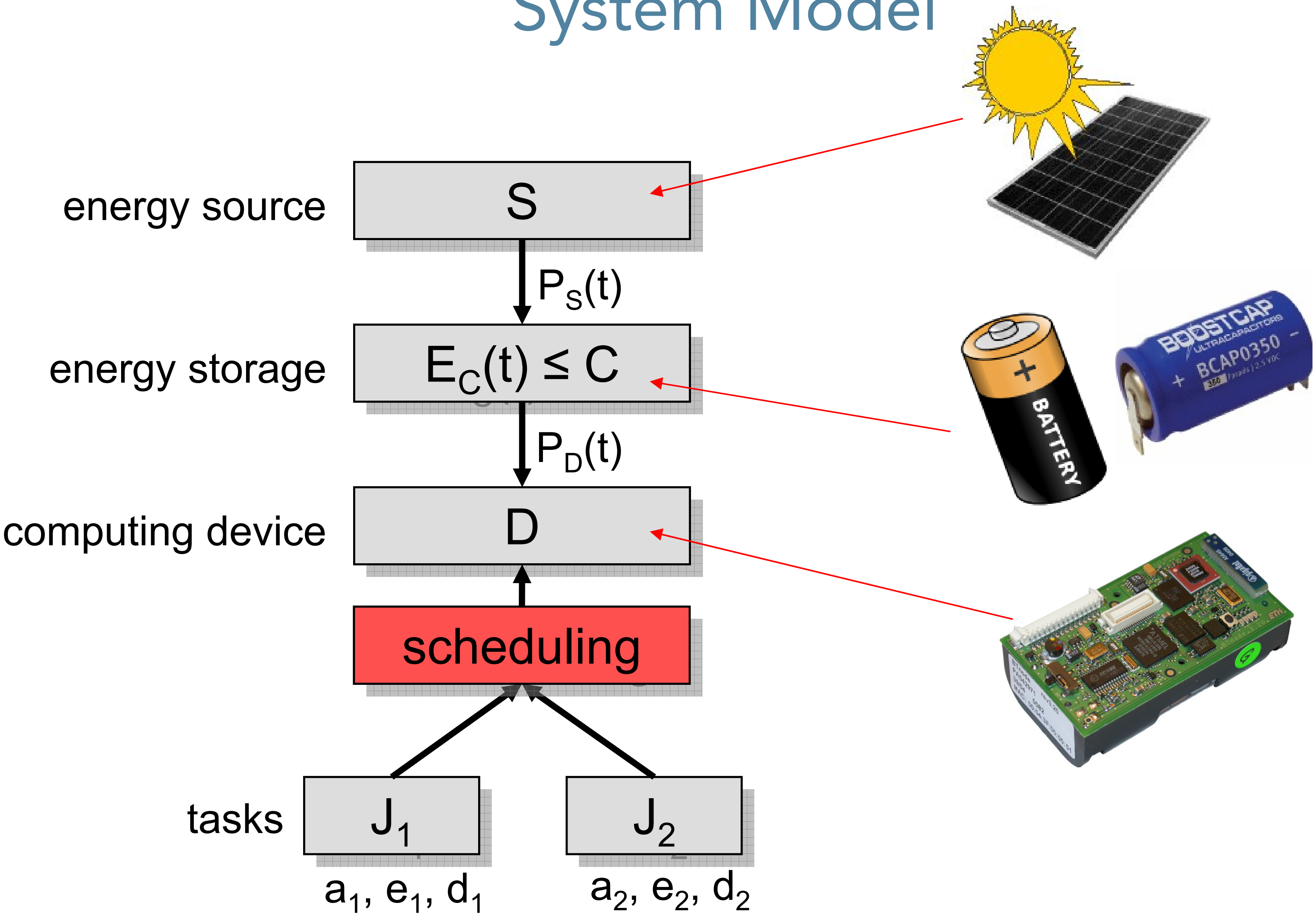


Outline

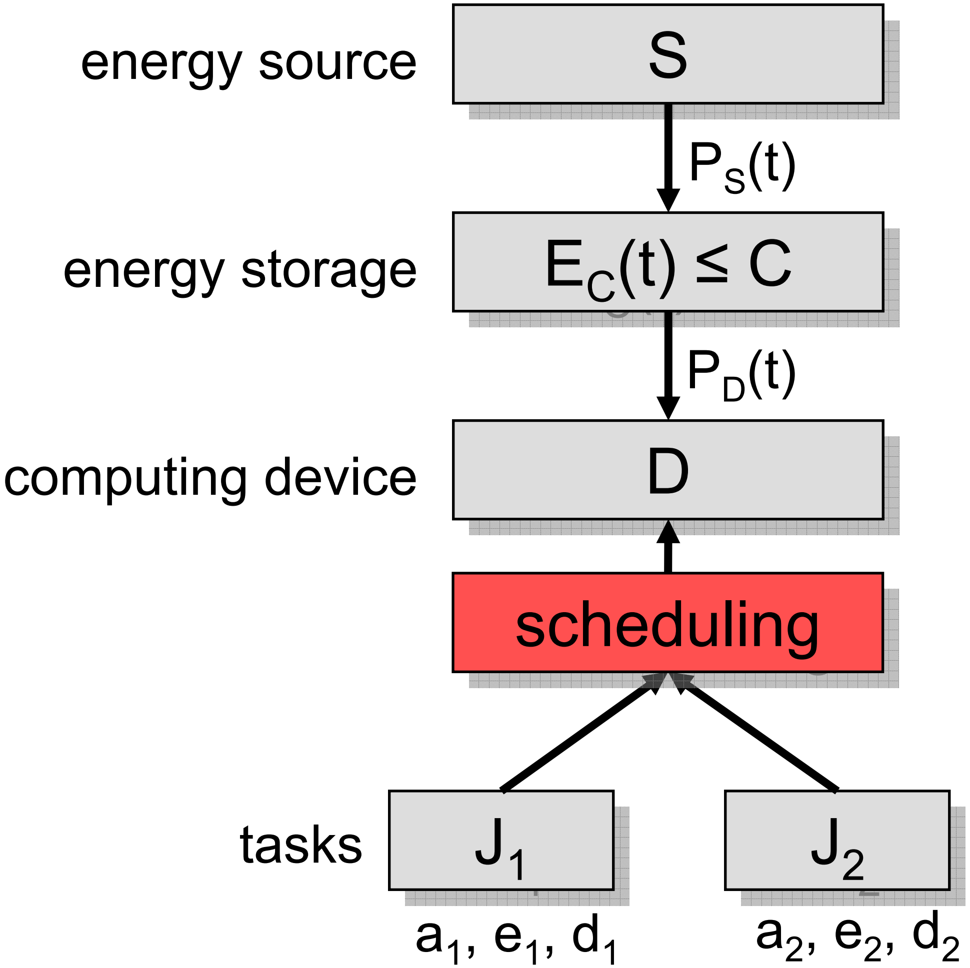
- Task Level Scheduling
  - Problem Definition
  - Lazy Scheduling Algorithm
- Resource management
- Outlook



System Model



System Model



- Task J_i
  - can be preempted
  - arrives at time a_i
  - has deadline d_i
  - needs total energy e_i to complete
  - can consume power

    $$0 \leq P_D(t) \leq P_{max}$$

  - therefore, needs time

    $$w_i \geq \frac{e_i}{P_{max}}$$

Problem Statement

- Determine an *optimal on-line scheduling* algorithm:

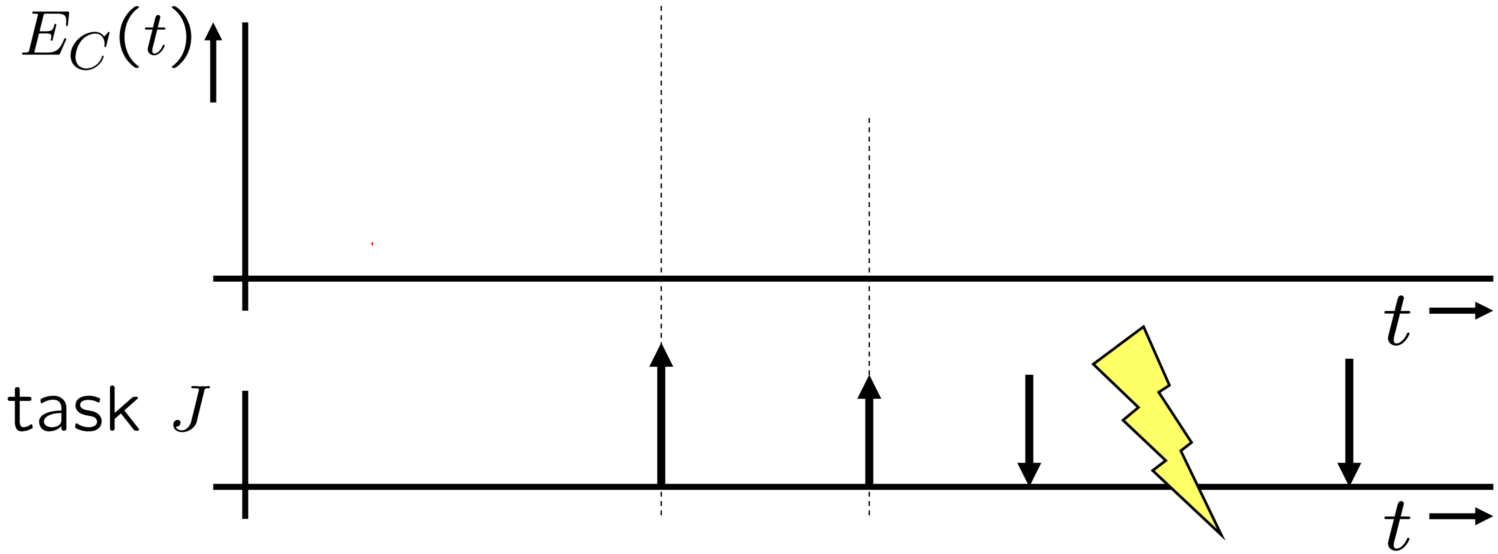
  If the task set is schedulable, it determines a feasible schedule.

- Construct an *admittance test*:

  Determine, whether a set of event streams with a given characteristic is schedulable.

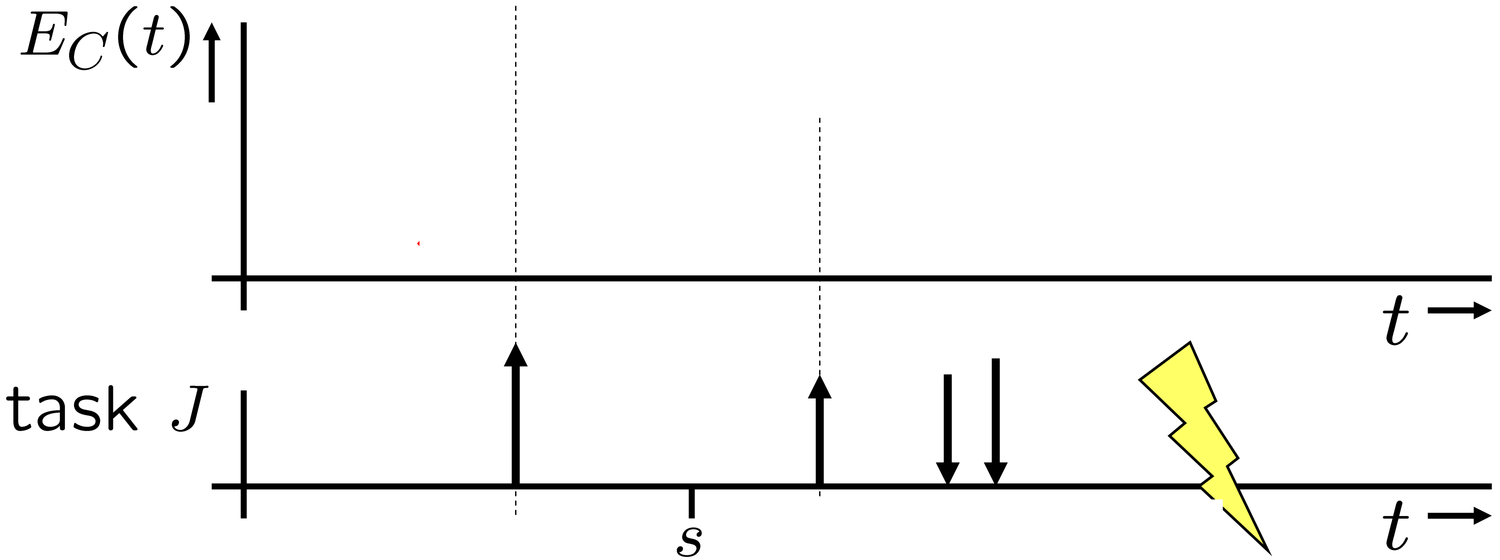
Nothing known so far …

Problem Statement - EDF



Greedy scheduling is not suited.

Problem Statement - ALAP



ALAP does not work either.
And what happens if the energy storage is full?

Lazy Scheduling Algorithm

Upon task arrival, perform start time computation

$$s_i = d_i - \frac{\min\left(E_C(a_i) + E_S(a_i, d_i), C + E_S(s_i, d_i)\right)}{P_{max}}$$

Energy storage is not full

Energy storage reaches the full state

Rule 1: All tasks with $s_i \leq t$ are processed with EDF scheduling using P_{max}.

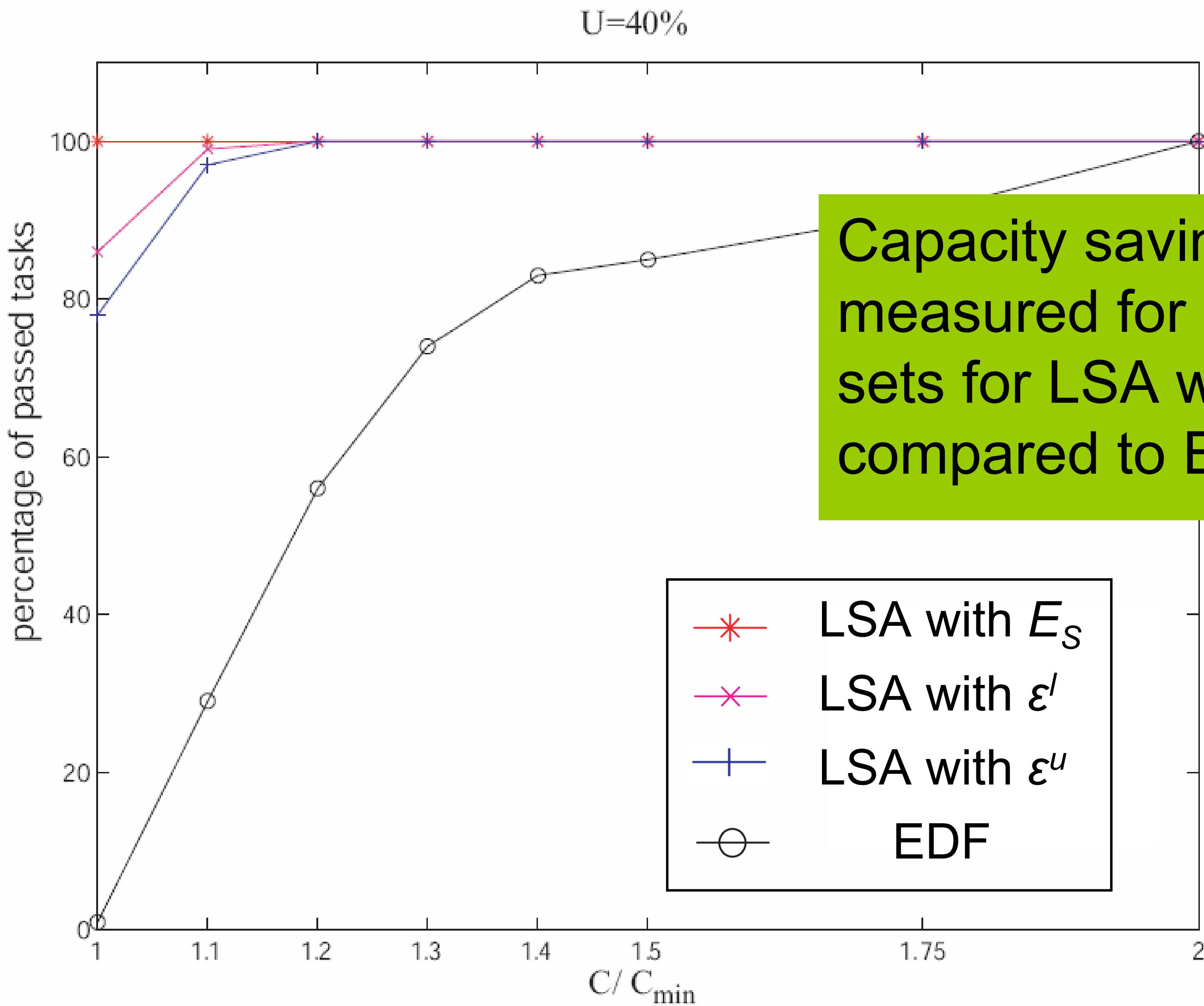
Rule 2: If there is no task with $s_i \leq t$ and the energy storage is full, all incoming power $P_S(t)$ is assigned to the task with the currently earliest deadline.

Optimality of Lazy Scheduling Algorithm

Theorem:

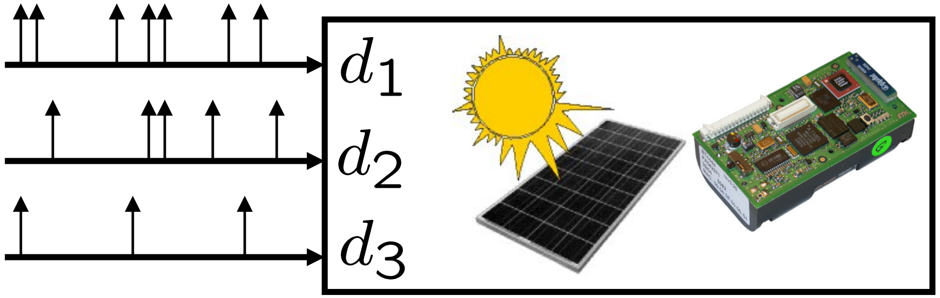
If the Lazy Scheduling Algorithm LSA cannot schedule a given set of tasks, then no other scheduling algorithm can schedule it.

Simulation Results



Capacity savings of ~40% measured for random task sets for LSA with $\varepsilon^l(\Delta)$ compared to EDF

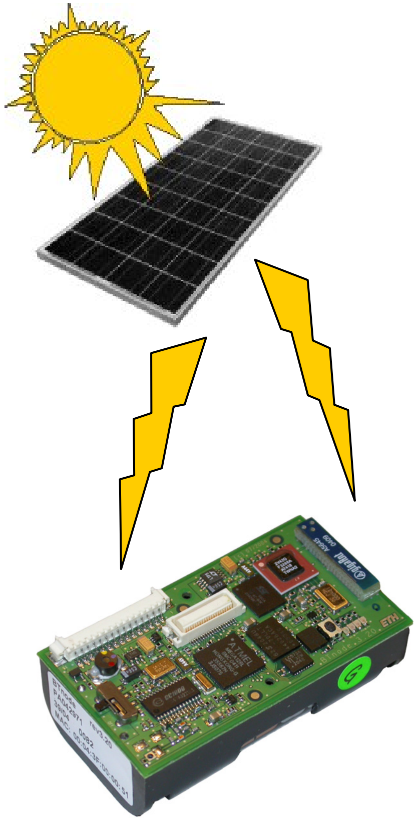
Future: Admittance Test



Is the scheduling of the event streams feasible with Lazy Scheduling ?

Outline

- Task Level Scheduling
  - Problem Definition
  - Lazy Scheduling Algorithm
- Resource management
- Outlook



Problem Definition

Determine decisions on the application level that optimize the long term system behavior

- **sensing rate**
- **data transmission**
- **forward messages**
- **receive messages**

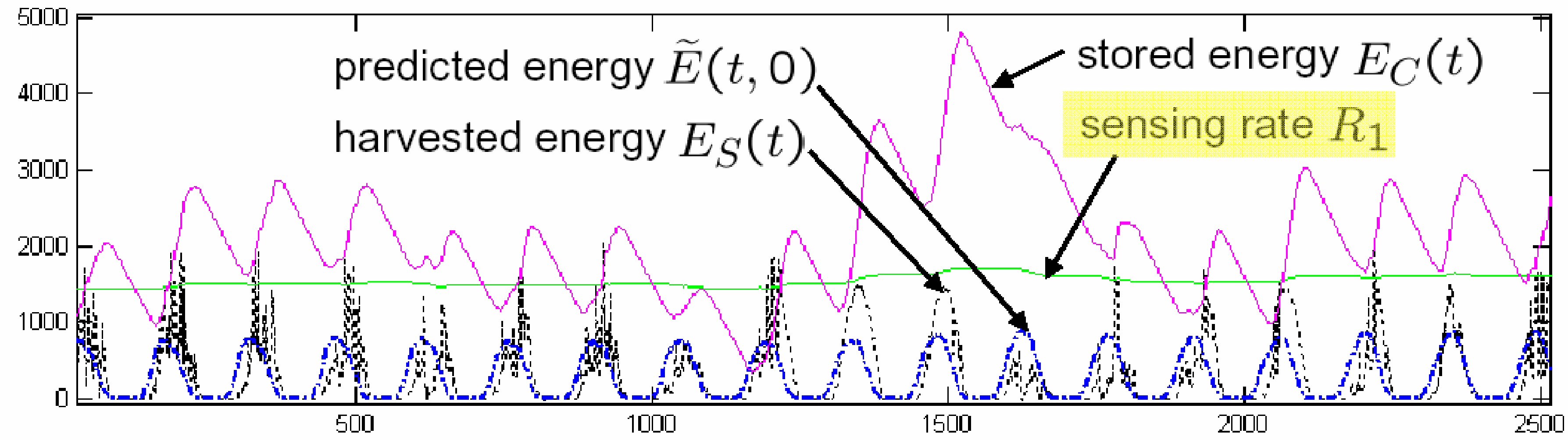
Problem Definition

Determine decisions on the application level that optimize the long term system behavior

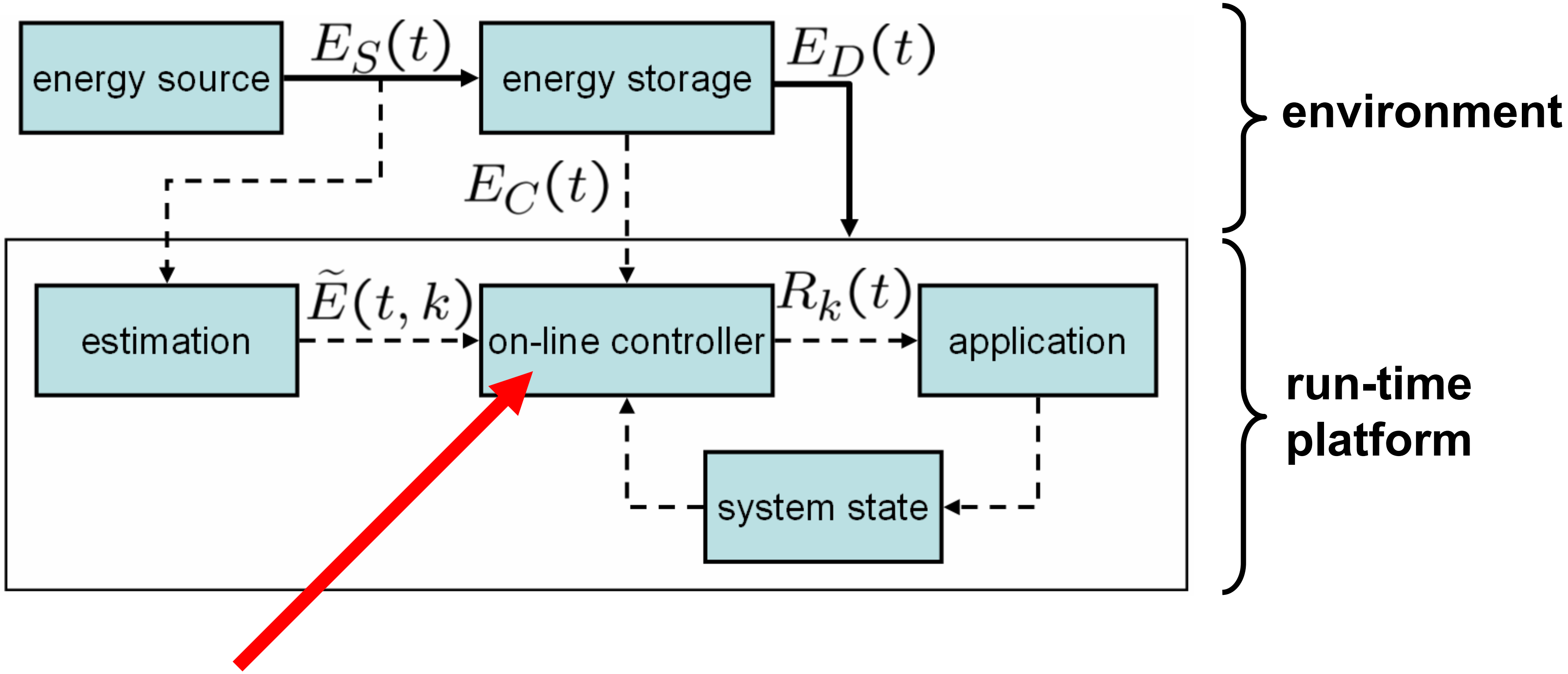
- **minimal sensing rate**
- **average throughput**
- **freshness of data**
- **reactivity**

Problem Definition

Determine decisions on the application level that optimize the long term system behavior



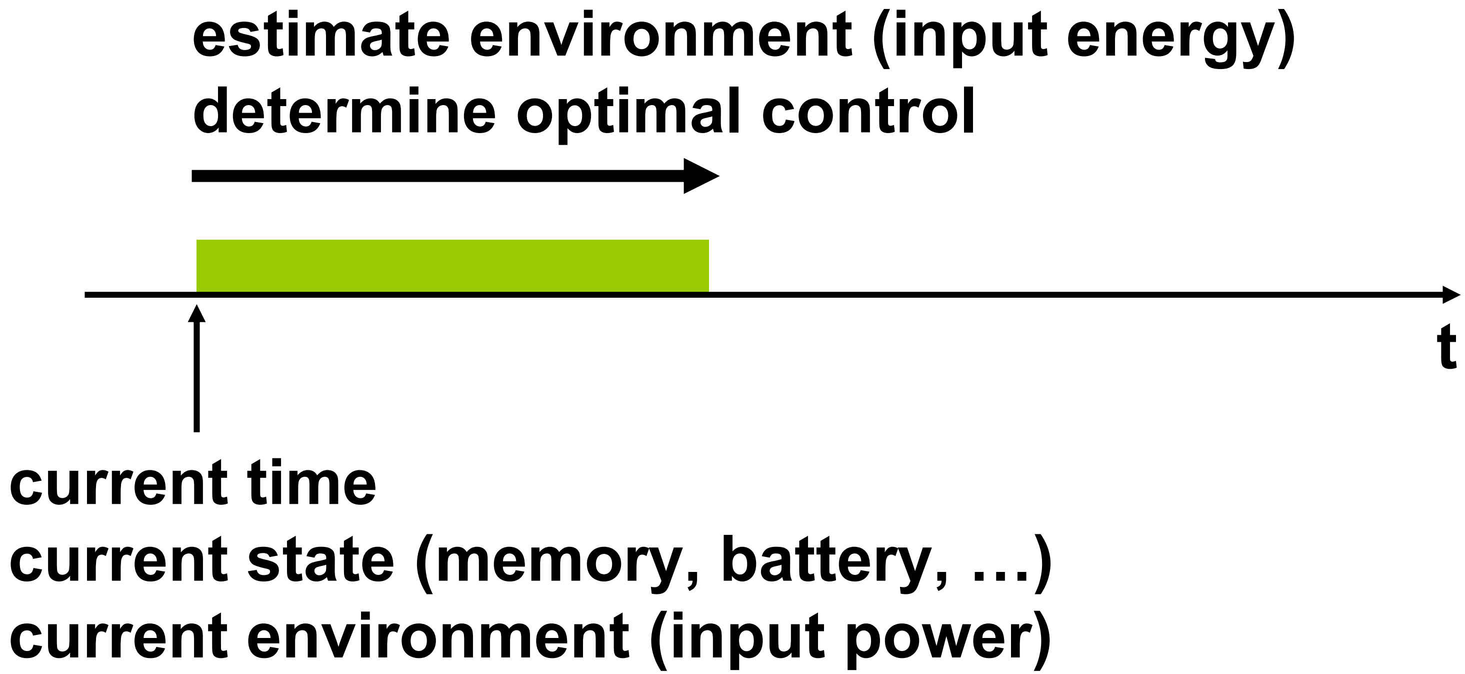
System Model



Models for application, quality/utility, system behavior ?
Optimization problem ?
Efficient run-time implementation ?

Principles

- Optimization problem: finite horizon control



Principles

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

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

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

Principles

- Efficient run-time implementation

Solving a linear program in a resource-constraint sensor node at each time step ?

Principles

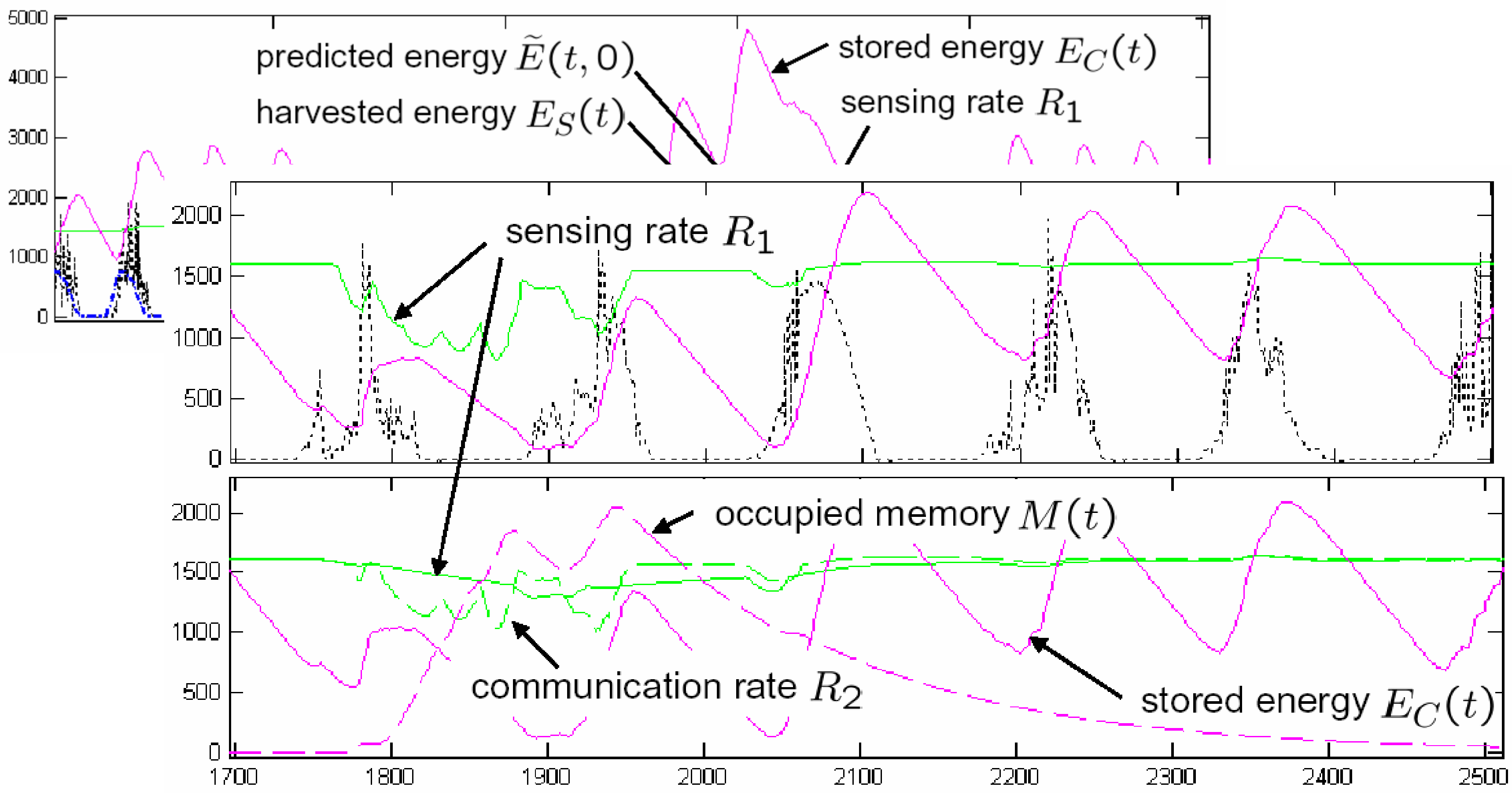
- Efficient run-time implementation
  - Approach Solve the LP as a parameterized LP and implement the explicit solution [Morari, Bemporad et al.]:

$$\mathbf{U}_{opt,i}(t) = \mathbf{B}_i \mathbf{X}(t) + \mathbf{C}_i \quad \text{if } \mathbf{H}_i \mathbf{X}(t) \leq \mathbf{K}_i, i = 1, \ldots, N_{CR}$$

Different control laws in different regions of the state space!

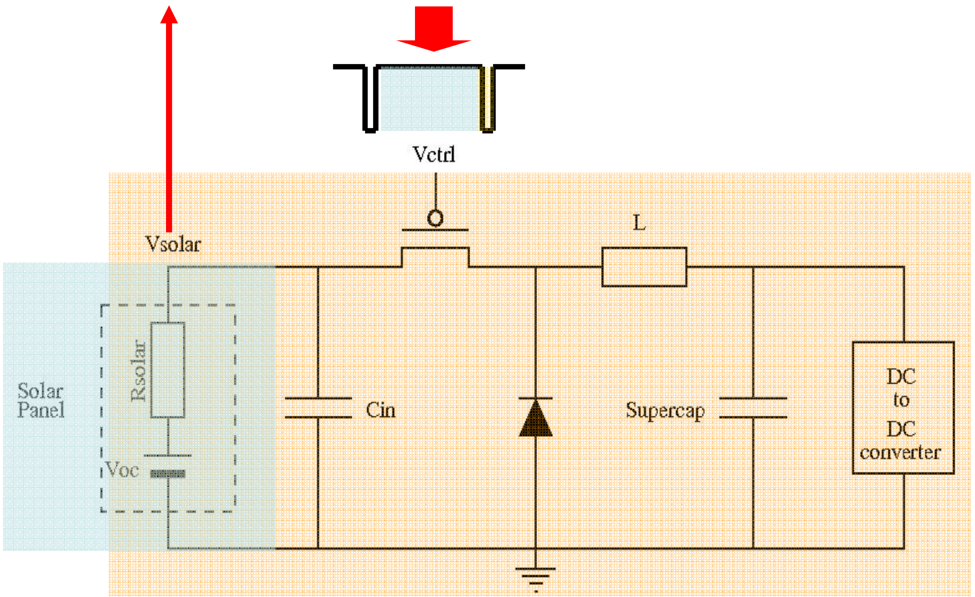
  - The optimal controller is a set of controllers with an affine "controller selection" rule
    - Desgin issue: limiting the number of different controllers
    - Preliminary results on highly constrained CPU are promising

Simulation and Experiments

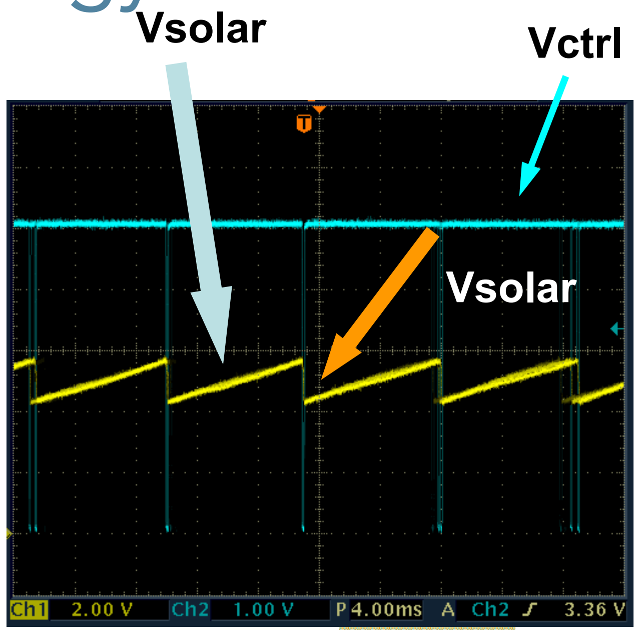


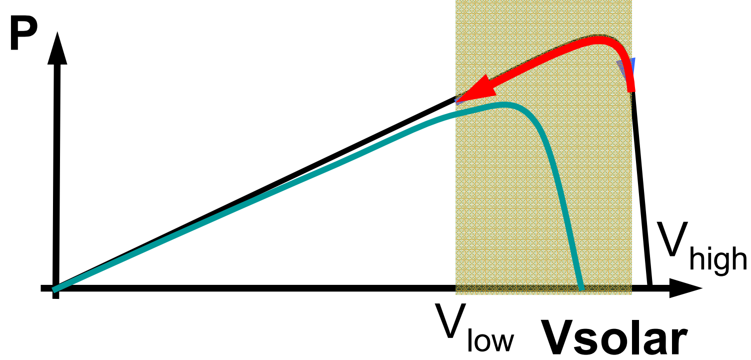
Future: optimal control of energy conversion

V_{low} crossing → switch off
V_{high} crossing → switch on



Controlled variable
V_{low}, V_{high} → duty cycle





Online control for tracking PV curve variations with incident light, temperature

Joint Publications

- "Real-Time Scheduling for Energy Harvesting Sensor Nodes.", C.Moser, D.Brunelli, L.Thiele, L.Benini. Int. Journal Real-Time Systems, January 2007.
- "Adaptive Power Management in Energy Harvesting Systems.", C.Moser, D.Brunelli, L.Thiele, L.Benini. DATE 2007
- "Real-time scheduling with regenerative energy", C. Moser, D. Brunelli, L. Thiele and L. Benini, Euromicro Conference on Real-Time Systems (ECRTS 06)
- "Lazy Scheduling for Energy Harvesting Sensor Nodes", C. Moser, D. Brunelli, L. Thiele and L. Benini, 5th IFIP Conference on Distributed and Parallel Embedded Systems DIPES 2006