

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

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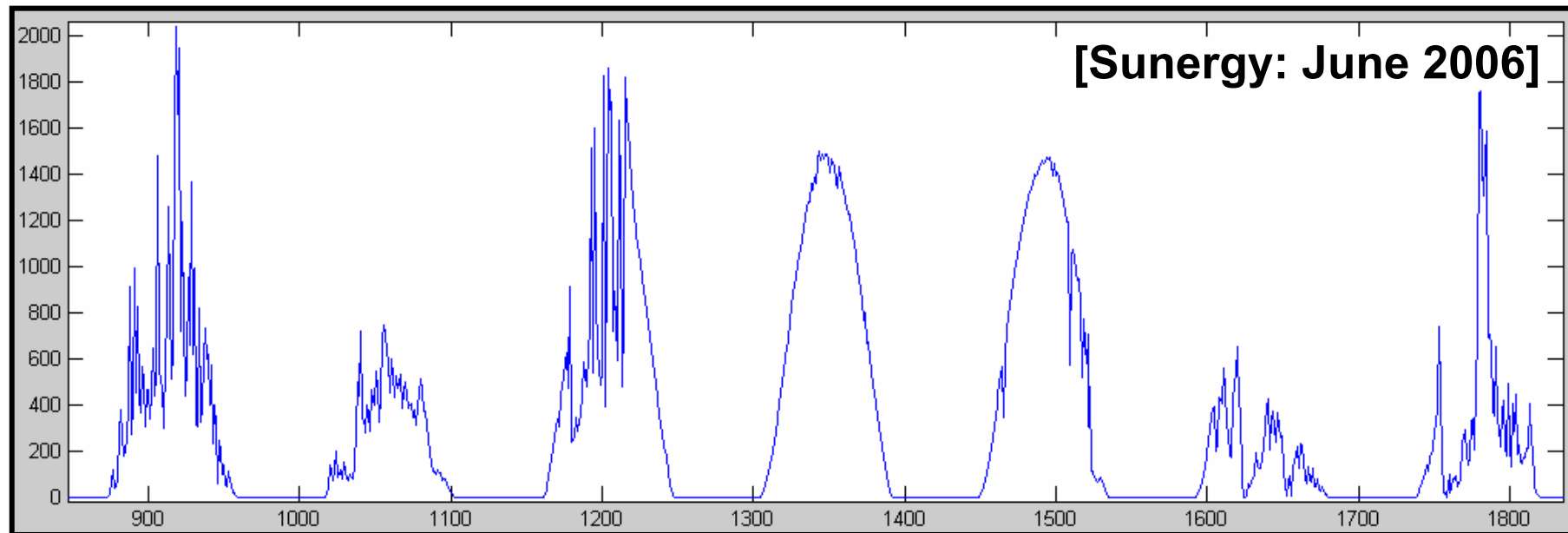


Promises and Potential



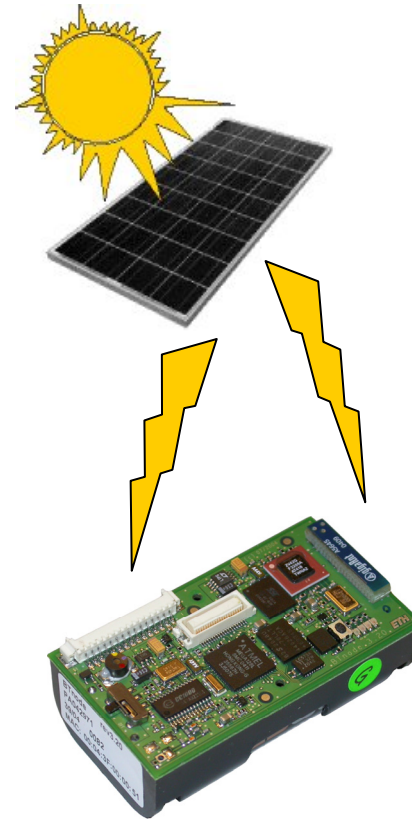
What is different?

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

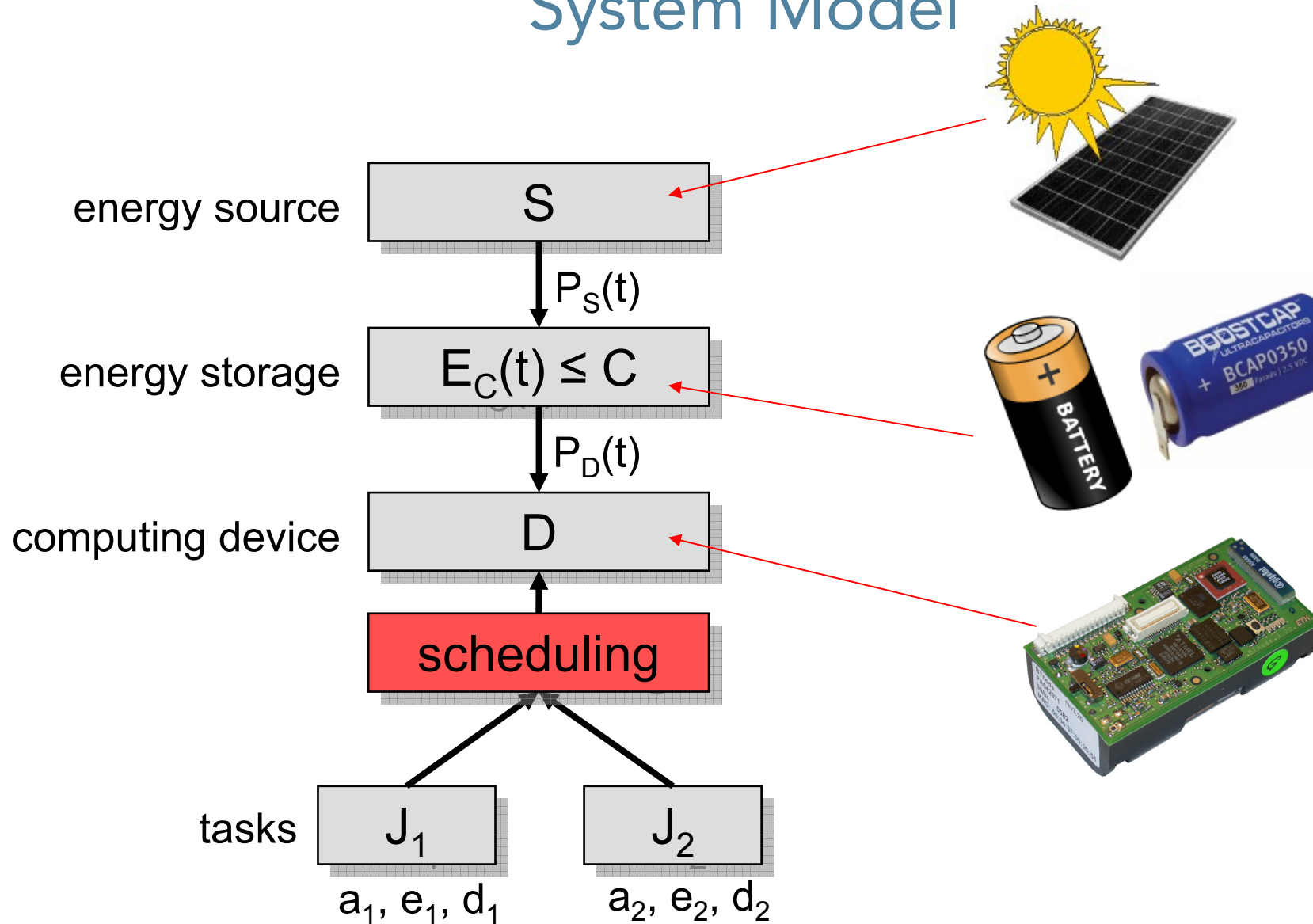


Outline

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

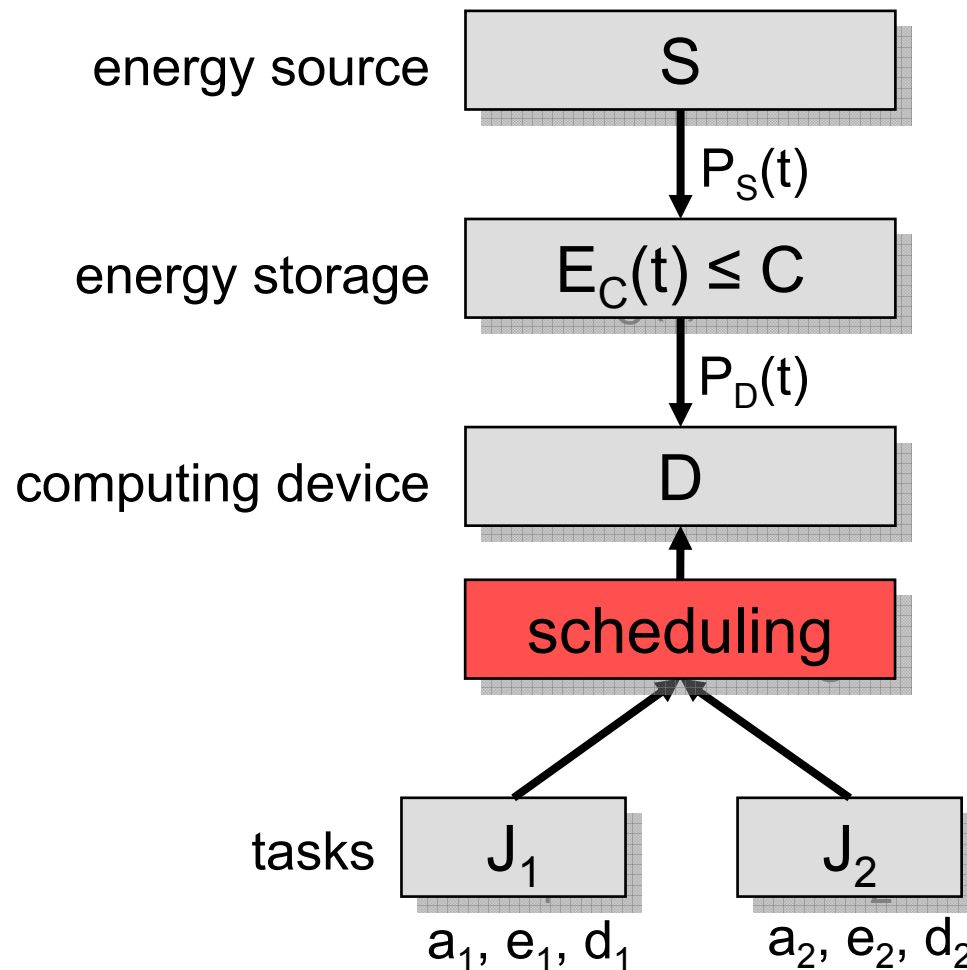


System Model



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

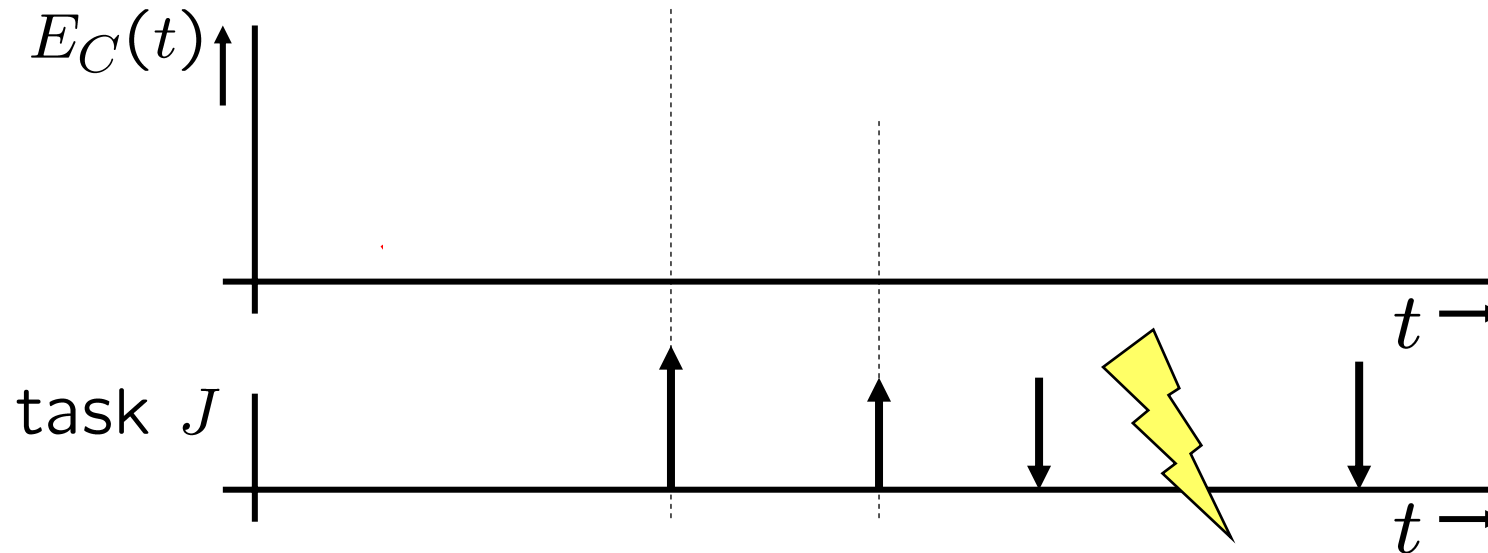
$$w_i \geq \frac{e_i}{P_{max}}$$

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.

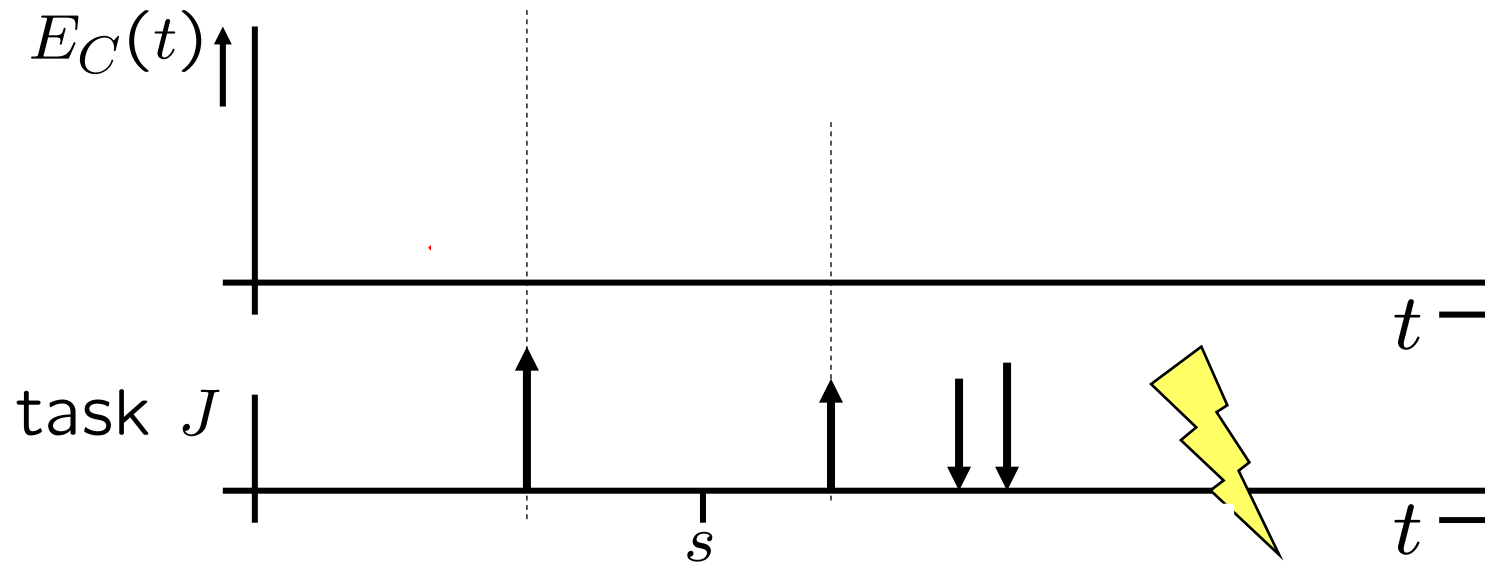
Nothing known so far ...

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

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

Energy storage is not full

Energy storage reaches the full state

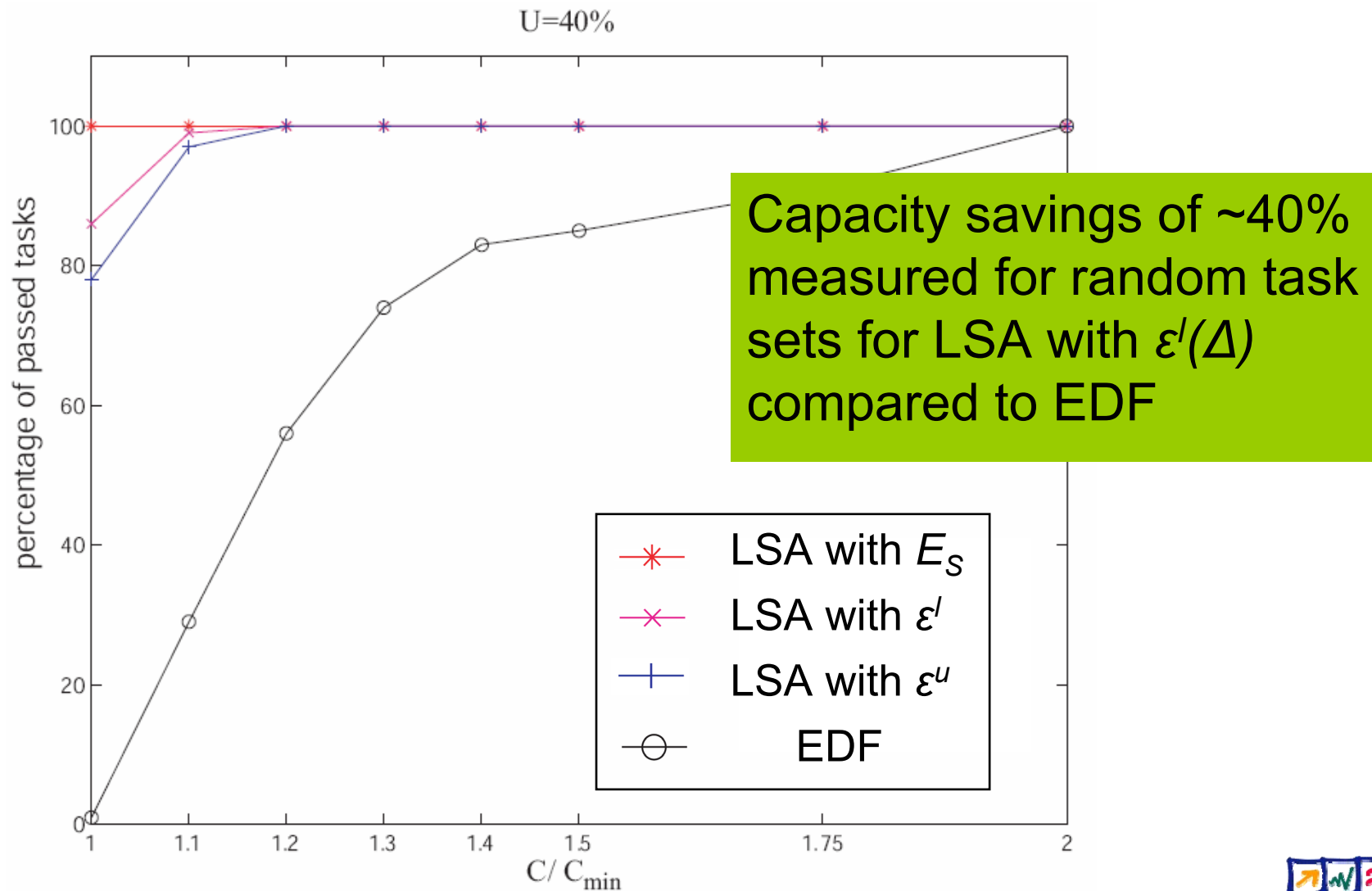
- Rule 1:** All tasks with $s_i \leq t$ are processed with EDF scheduling using P_{max} .
- Rule 2:** If there is no task with $s_i \leq t$ and the energy storage is full, all incoming power $P_S(t)$ is assigned to the task with the currently earliest deadline.

Optimality of Lazy Scheduling Algorithm

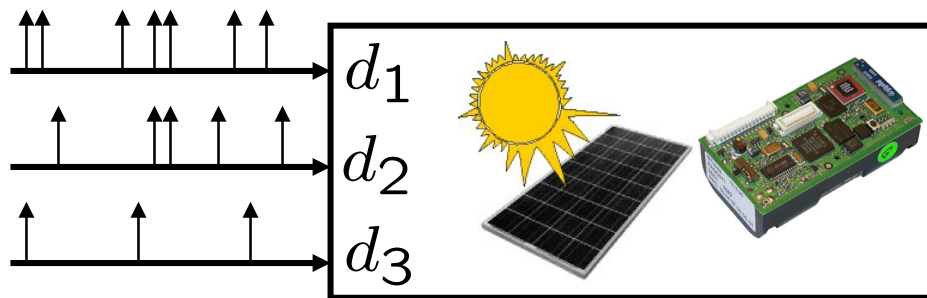
Theorem:

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

Simulation Results



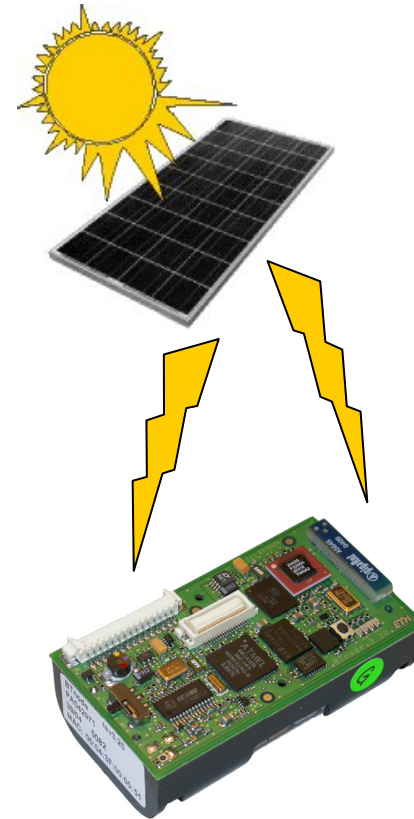
Future: Admittance Test



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

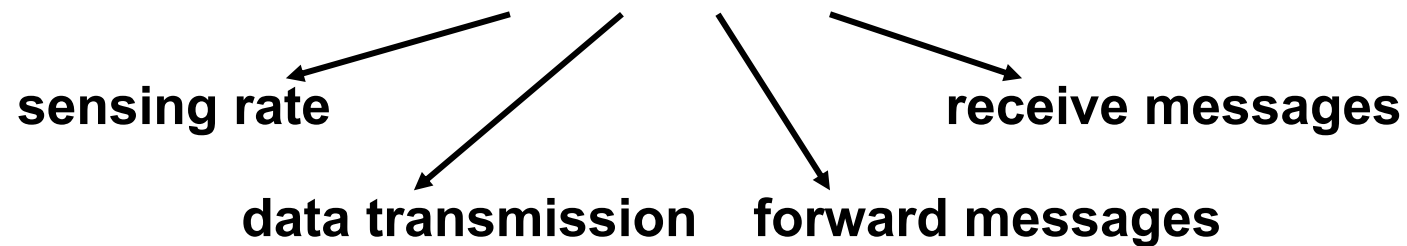
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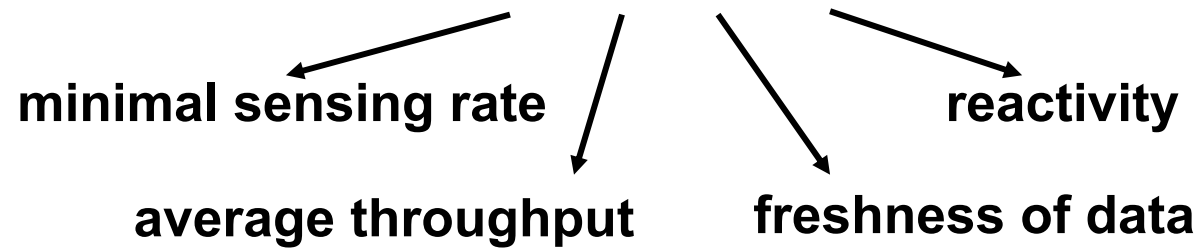
Problem Definition

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



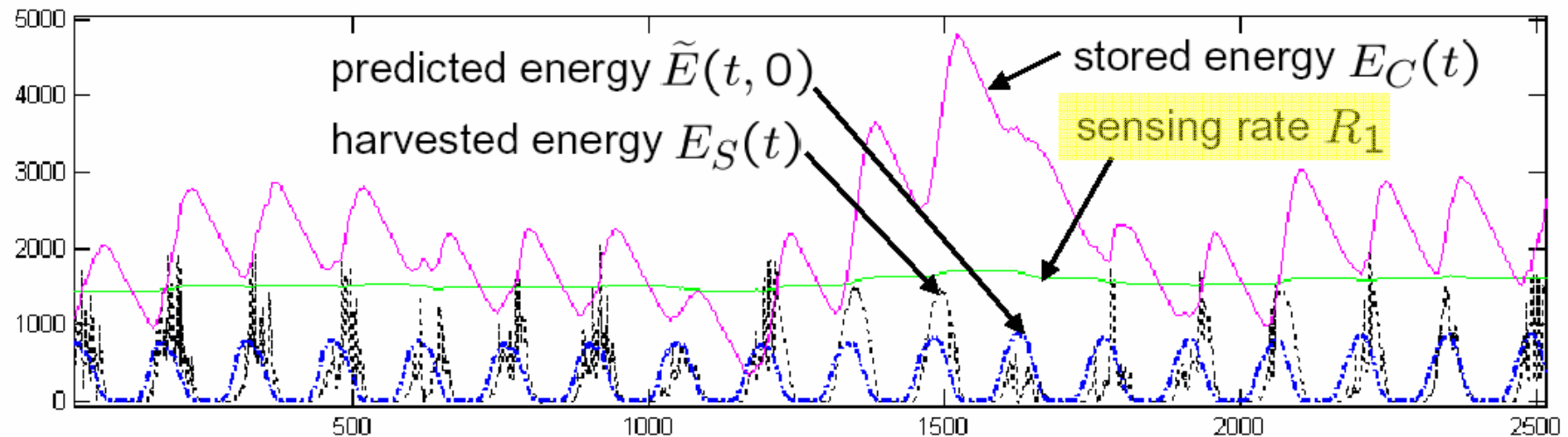
Problem Definition

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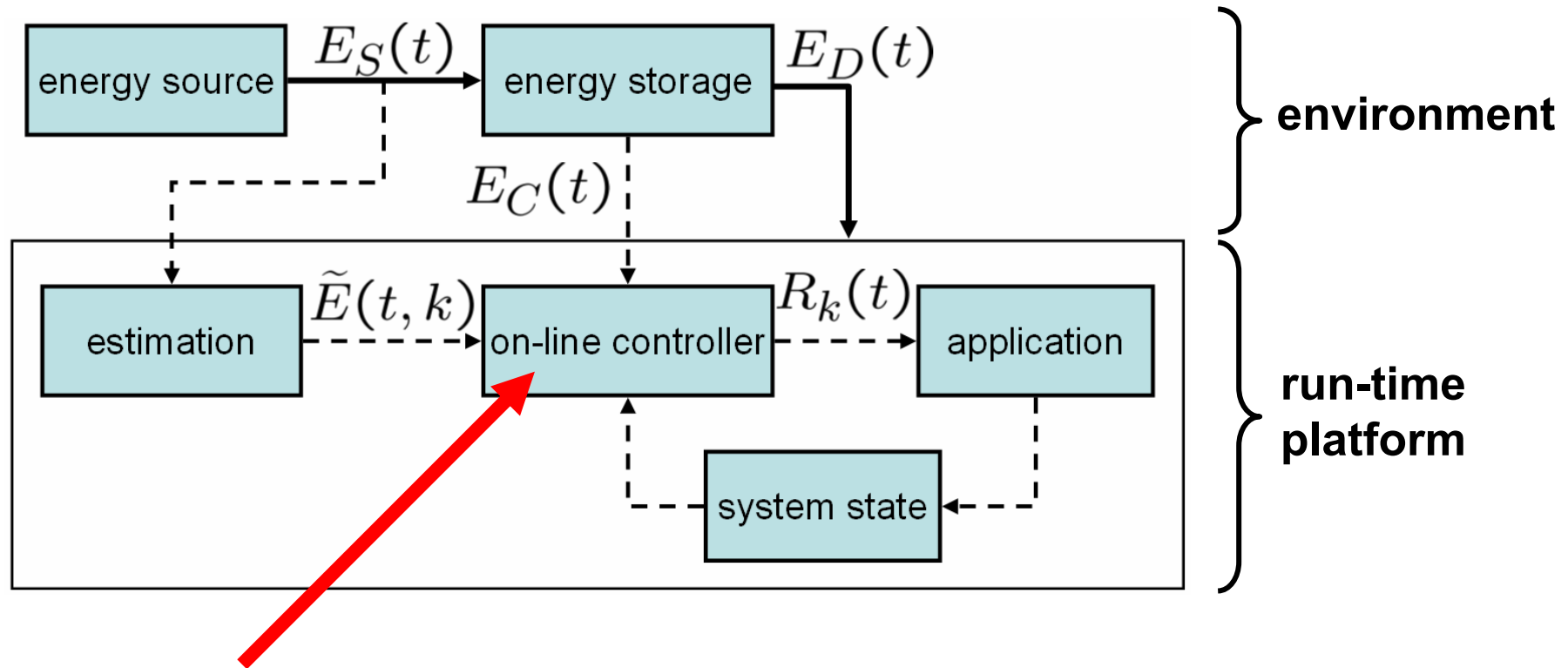


Problem Definition

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



System Model



Models for application, quality/utility, system behavior ?

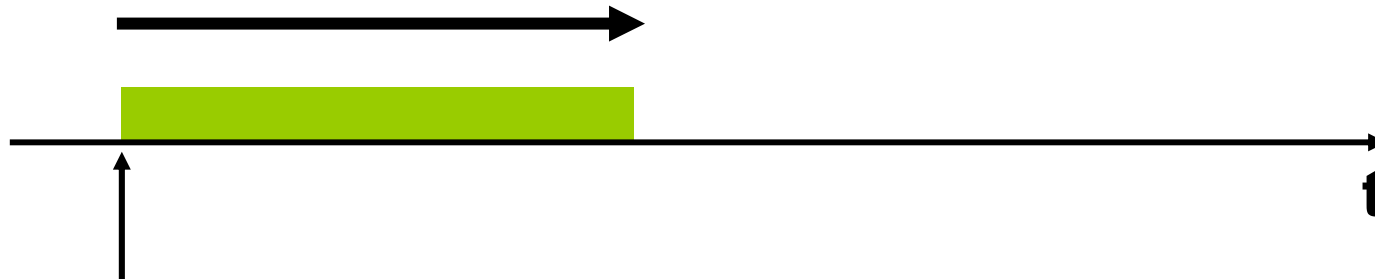
Optimization **problem** ?

Efficient run-time **implementation** ?

Principles

- Optimization problem: finite horizon control

**estimate environment (input energy)
determine optimal control**



current time

current state (memory, battery, ...)

current environment (input power)

Principles

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

maximize $(\lambda - \mu)$ subject to:

Rate of acquisition $s_1(t + k \cdot L) \geq \lambda \quad \forall 0 \leq k < N$

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

Stored energy $E_C(t + k \cdot L) = E_C(t) + \sum_{j=0}^{k-1} \tilde{E}(t, j) -$
 $-\sum_{j=0}^{k-1} (L \cdot [0.1 \ 0.9] \cdot \mathbf{S}(t + j \cdot L)) \geq 0 \quad \forall 1 \leq k \leq N$

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

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

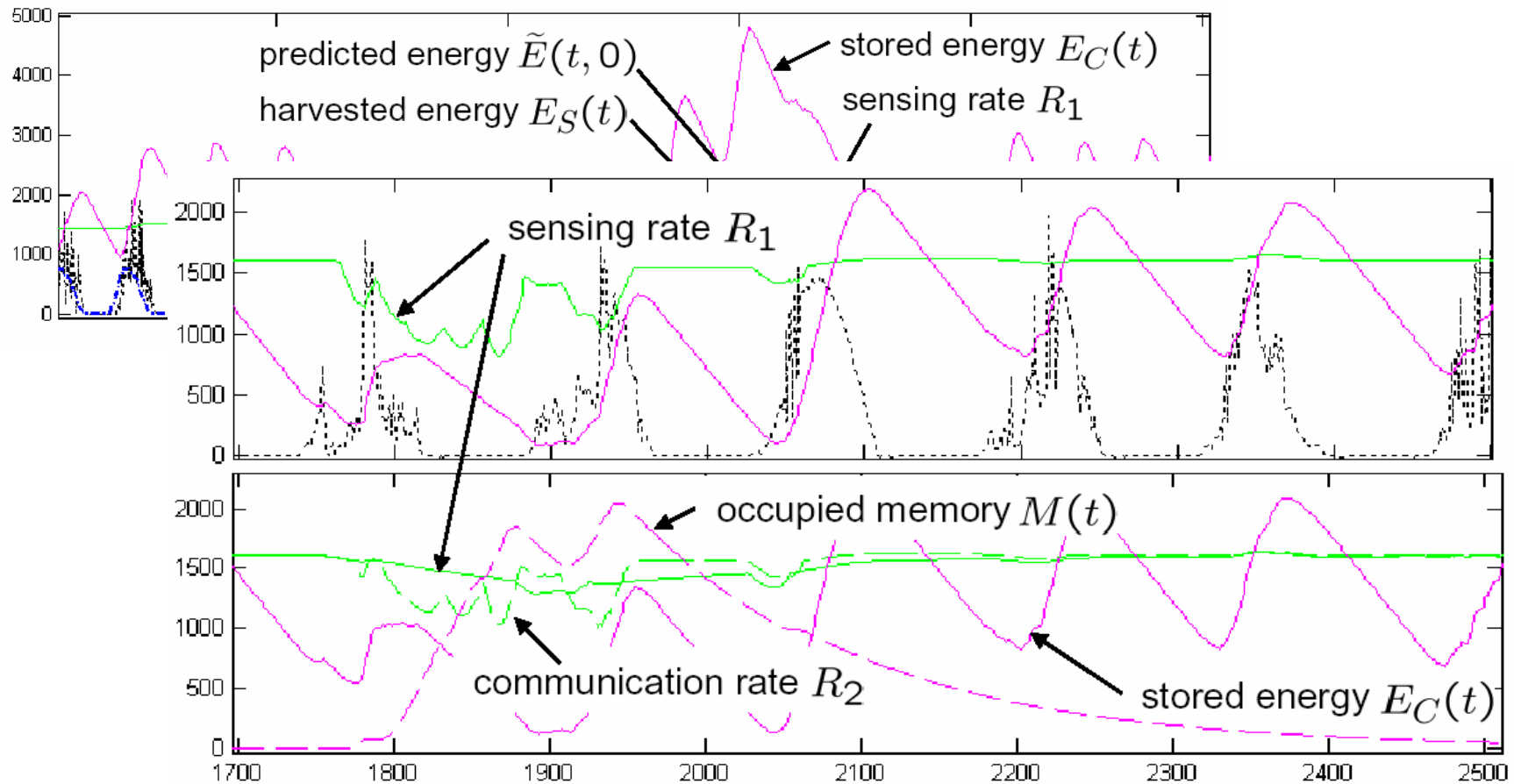
- Efficient run-time implementation
 - **Approach** Solve the LP as a parameterized LP and implement the explicit solution [Morari, Bemporad et al.]:

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

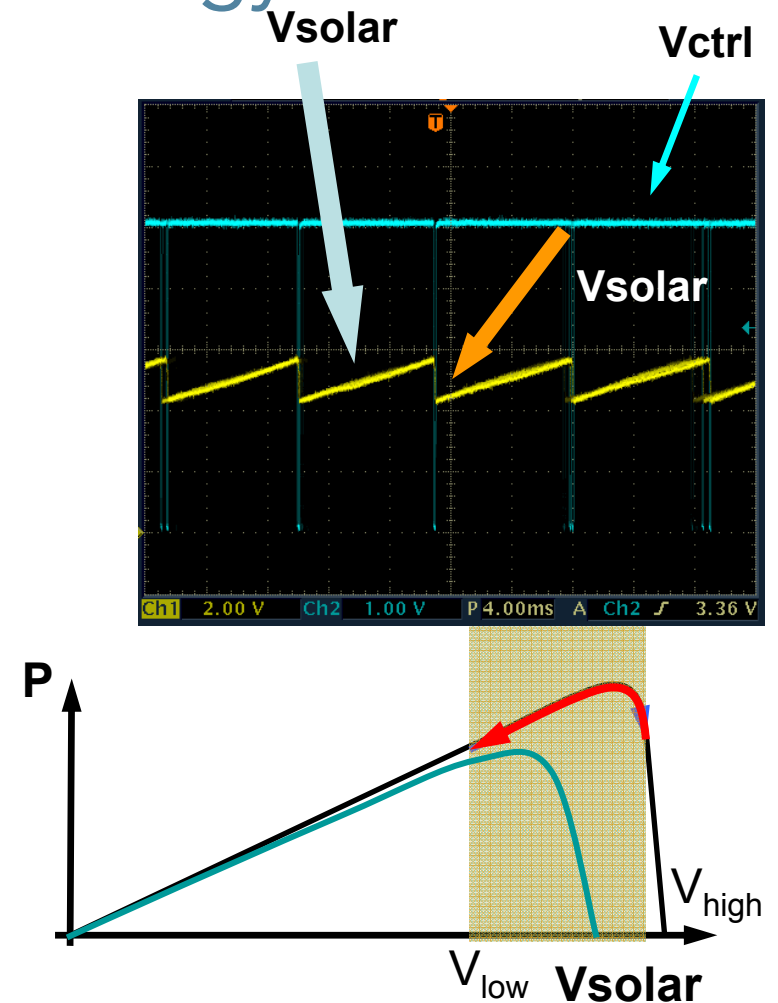
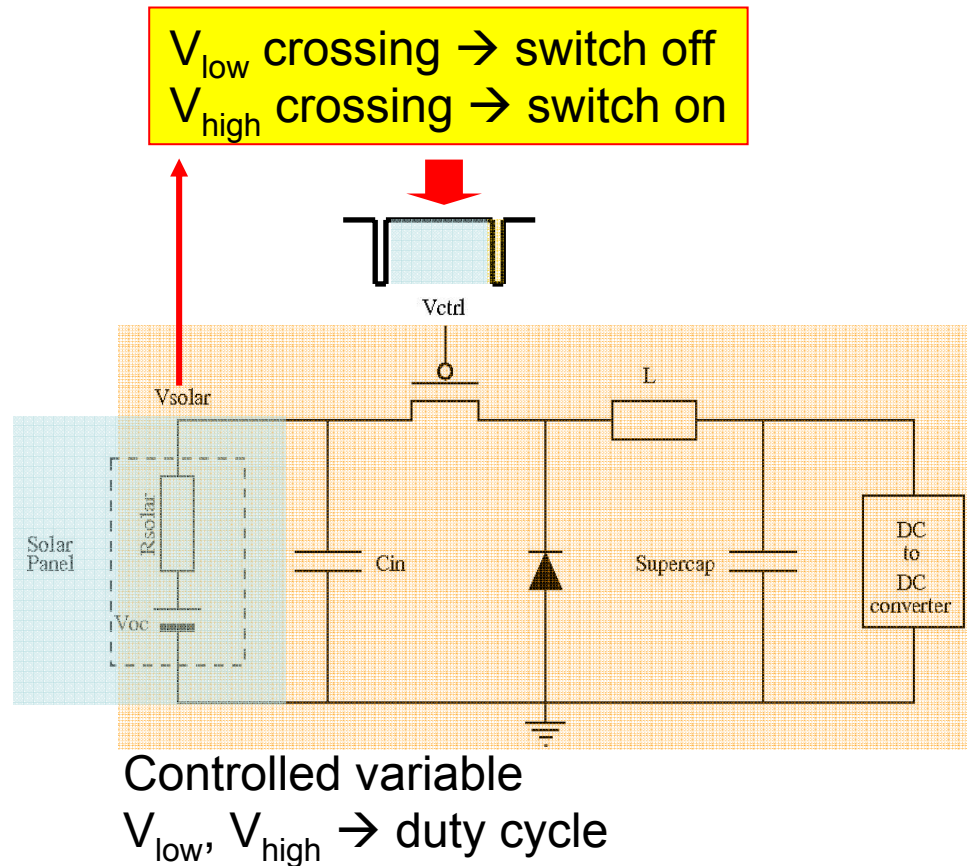
Different control laws in different regions of the state space!

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

Simulation and Experiments



Future: optimal control of energy conversion



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