Wireless Sensor Networks
9. Energy Harvesting

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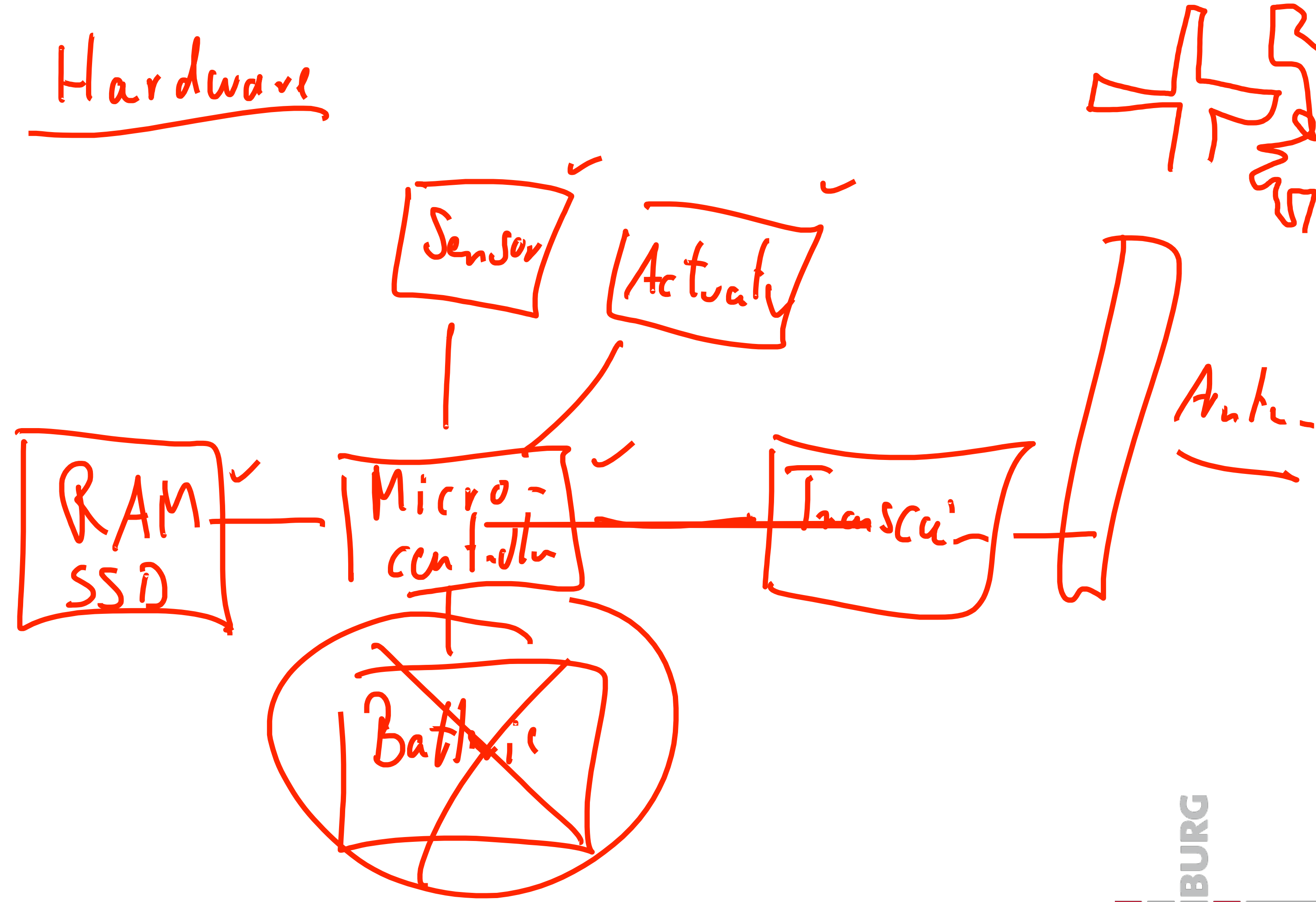
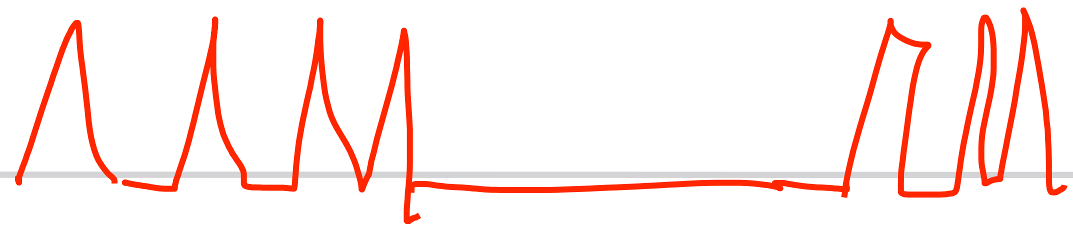
Literature Energy Harvesting

- Kansal, Hsu, Zahedi, Srivastava
  - *Power management in energy harvesting sensor networks*. ACM Trans. Embed. Comput. Syst. 6, 4, Sep. 2007



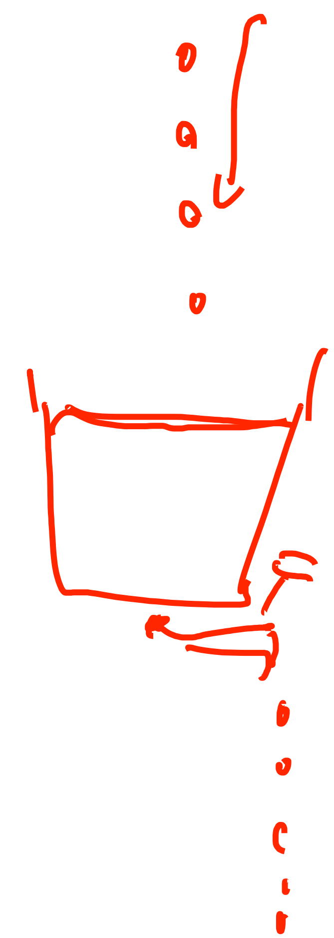
Motivation



- Energy harvesting
  - can remove batteries from WSNs
  - potentially infinite lifetime
  - active time can be increased (or reduced)
- Example
  - solar energy only available at daylight
- Energy concept
  - necessary for the entire period
  - regulates interplay of sleep phase, data rate and short term energy source

Harvesting Paradigma

- Typical task in battery operated WSN
  - minimize energy consumption
  - maximize lifetime
- Task in harvesting-WSN
  - continuous operation
    - i.e. infinite lifetime
  - term: energy-neutral operation



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Possible Sources

- Piezoelectric effect
  - mechanical pressures produces voltage
- Thermoelectric effect
  - temperature difference of conductors with different thermal coefficient
- Kinetic energy
  - e.g. self-rewinding watches
- Micro wind turbines
- Antennas
- Chemical sources,...

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Differences Compared to Batteries

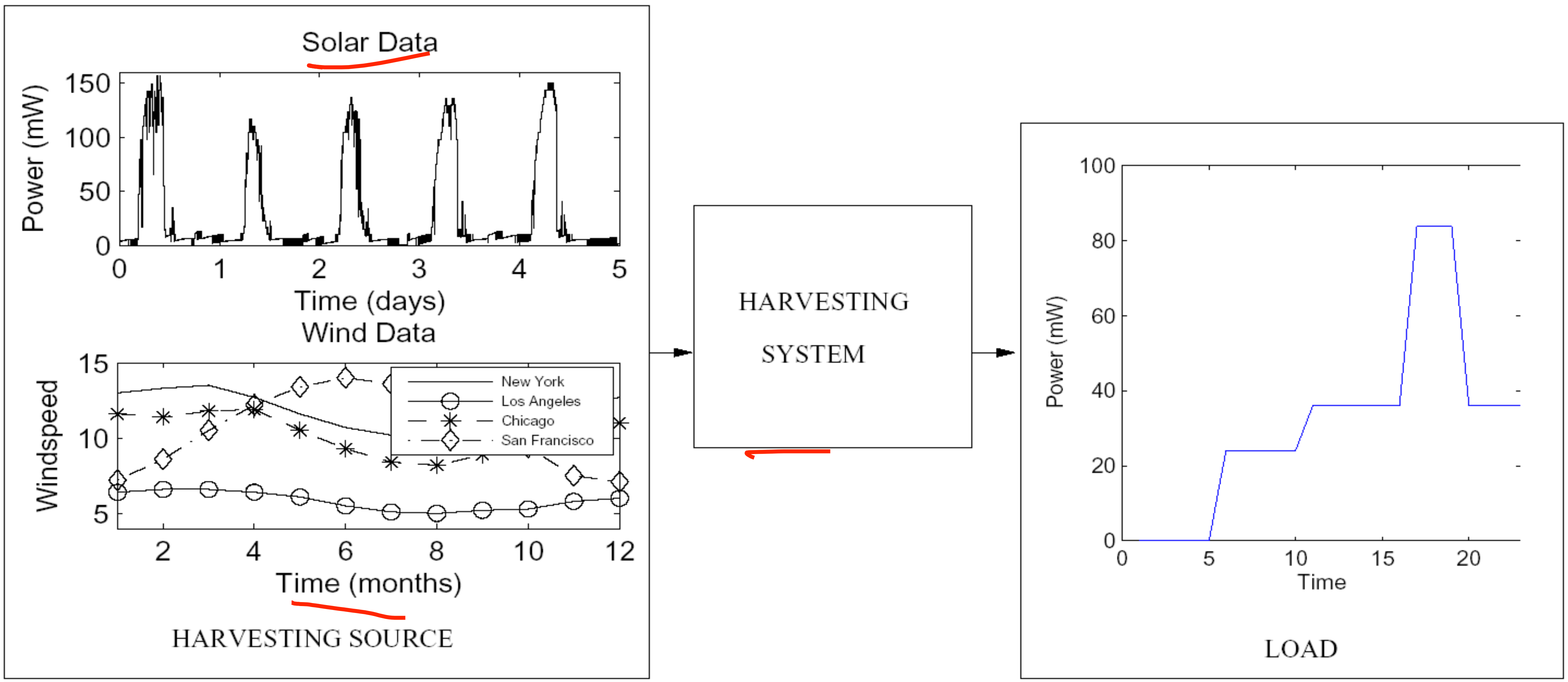
- Time dependent
  - form of operation has to be adapted over time
  - sometimes not predictable
- Location dependent
  - different nodes have have different energy
    - load balancing necessary
- Never ending supply
- New efficiency paradigm
  - utilization of energy for maximum performance
  - energy saving may result in unnecessary opportunity costs

Solutions without Power Management

- Without energy buffer
  - harvesting hardware has to supply maximal necessary energy level at minimum energy input
  - only in special situation possible
    - e.g. light switch
- With energy buffer
  - power management system necessary

Power Management System

- Target
  - Providing the necessary energy from external energy source and energy buffer



Energy Sources

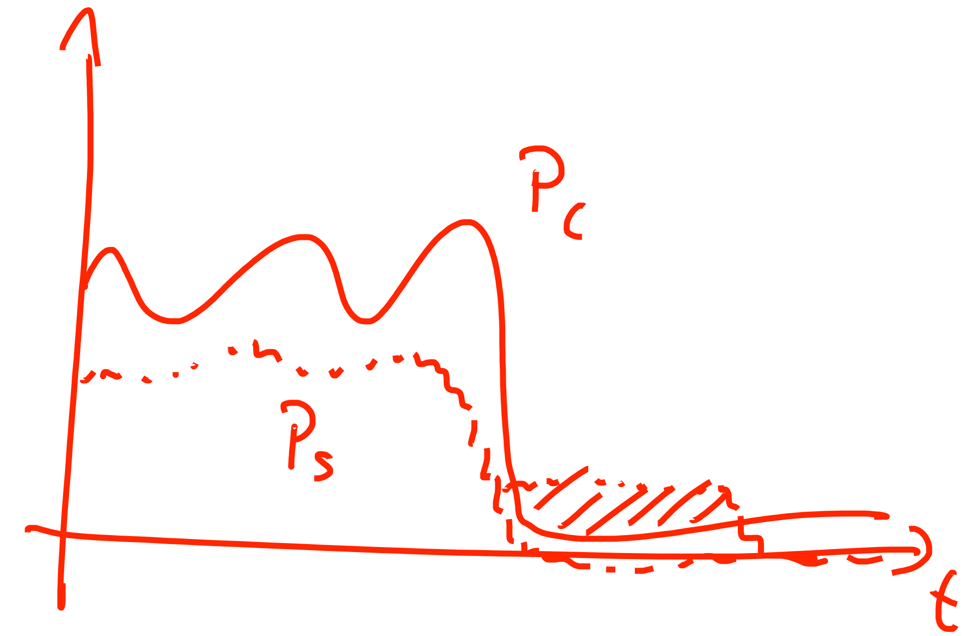
- Uncontrolled but predictable
  - e.g. daylight
- Uncontrolled and unpredictable
  - e.g. wind
- Controllable
  - energy is produced if necessary
  - e.g. light switch, dynamo on bike
- Partially controllable
  - energy is not always available
  - e.g. radio source in the room with changing reception

Harvesting Theory

- $P_s(t)$: Power output from energy source a time t
- $P_c(t)$: Energy demand at time t
- Without energy buffer
  - $P_s(t) \geq P_c(t)$: node is active
- Ideal energy buffer
  - Continuous operation if

$$\int_0^T P_c(t)dt \leq \int_0^T P_s(t)dt + B_0 \quad \forall \quad T \in [0, \infty)$$

  - where B_0 is the initial energy
  - energy buffer is lossless, store any amount of energy



Harvesting Theory

[x - 1000]+

- $P_s(t)$: Power output from energy source a time t
- $P_c(t)$: Energy consumed at time t

$P_s(t) > P_c(t)$

- Let

$$[x]^+ = \begin{cases} x & x \geq 0 \\ 0 & x < 0 \end{cases}$$

- Non-ideal energy buffer
  - Continuous operation if

$$B_0 + \eta \int_0^T [P_s(t) - P_c(t)]^+ dt - \int_0^T [P_c(t) - P_s(t)]^+ dt - \int_0^T P_{leak}(t) dt \geq 0$$

storing $P_s < P_c$

  - B_0 is the initial energy
  - η: efficiency of energy buffer
  - $P_{leak}(t)$: energy loss of the memory

Harvesting Theory

- $P_s(t)$: Power output from energy source a time t
- $P_c(t)$: Energy consumed at time t
- Let $$[x]^+ = \begin{cases} x & x \geq 0 \\ 0 & x < 0 \end{cases}$$
- Non-ideal energy buffer with limited reception B
  - Continuous operation if

$$B_0 + \eta \int_0^T [P_s(t) - P_c(t)]^+ dt - \int_0^T [P_c(t) - P_s(t)]^+ dt - \int_0^T P_{leak}(t) dt \geq 0$$

  - B_0 is the initial energy of the buffer
  - η: efficiency of energy buffer
  - $P_{leak}(t)$: leakage power of the energy buffer

$$B_0 + \eta \int_0^T [P_s(t) - P_c(t)]^+ dt - \int_0^T [P_c(t) - P_s(t)]^+ dt - \int_0^T P_{leak}(t) dt \leq B$$

Model of Benign Energy Behavior

- If the power source $P_s(t)$ occurs regularly, then it satisfies the following equations

$$\int_{\tau}^{\tau+T} P_s(t)\,dt \;\leq\; \rho_1 T + \sigma_1$$

$$\int_{\tau}^{\tau+T} P_s(t)\,dt \;\geq\; \rho_1 T - \sigma_2$$

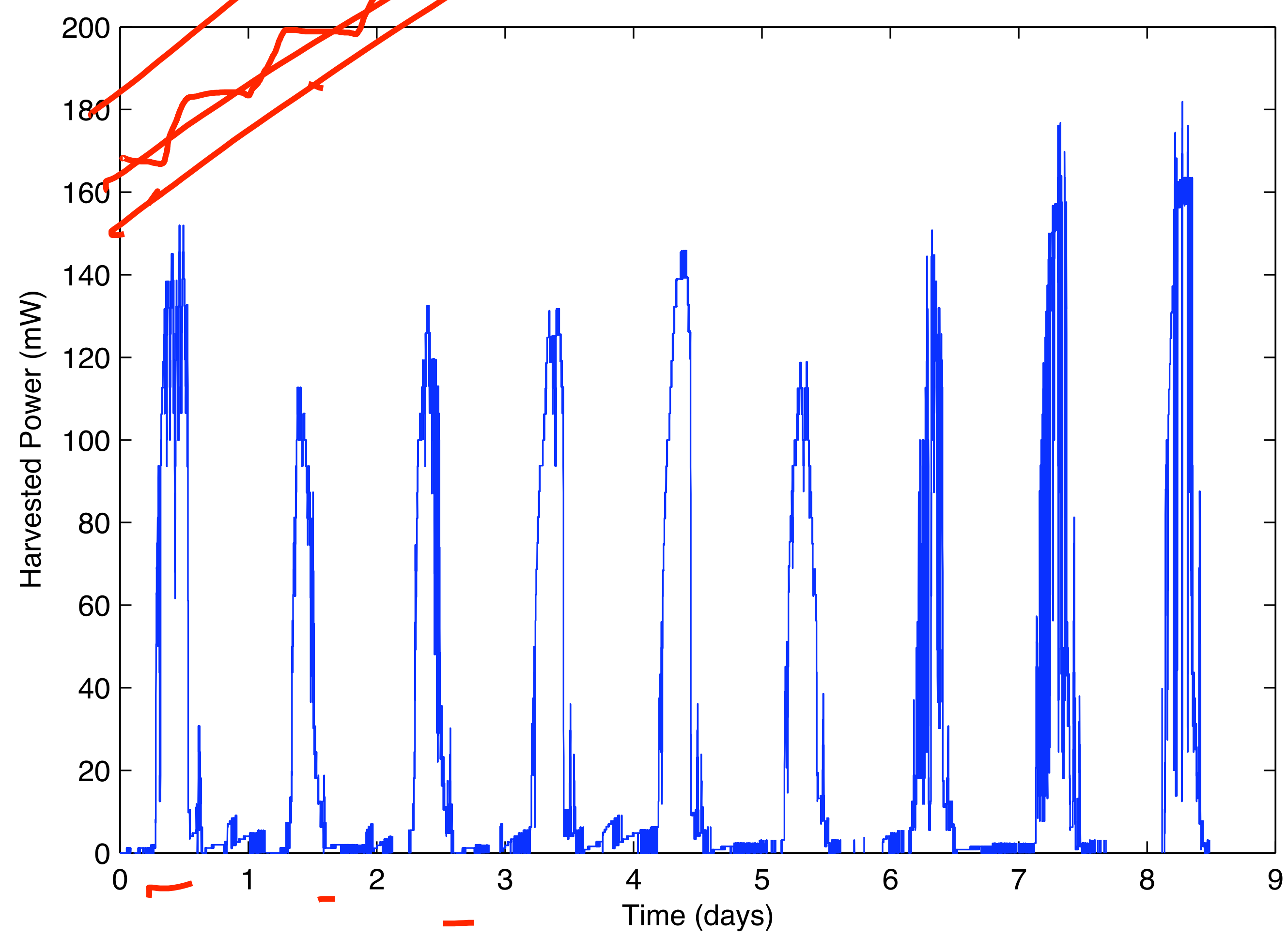


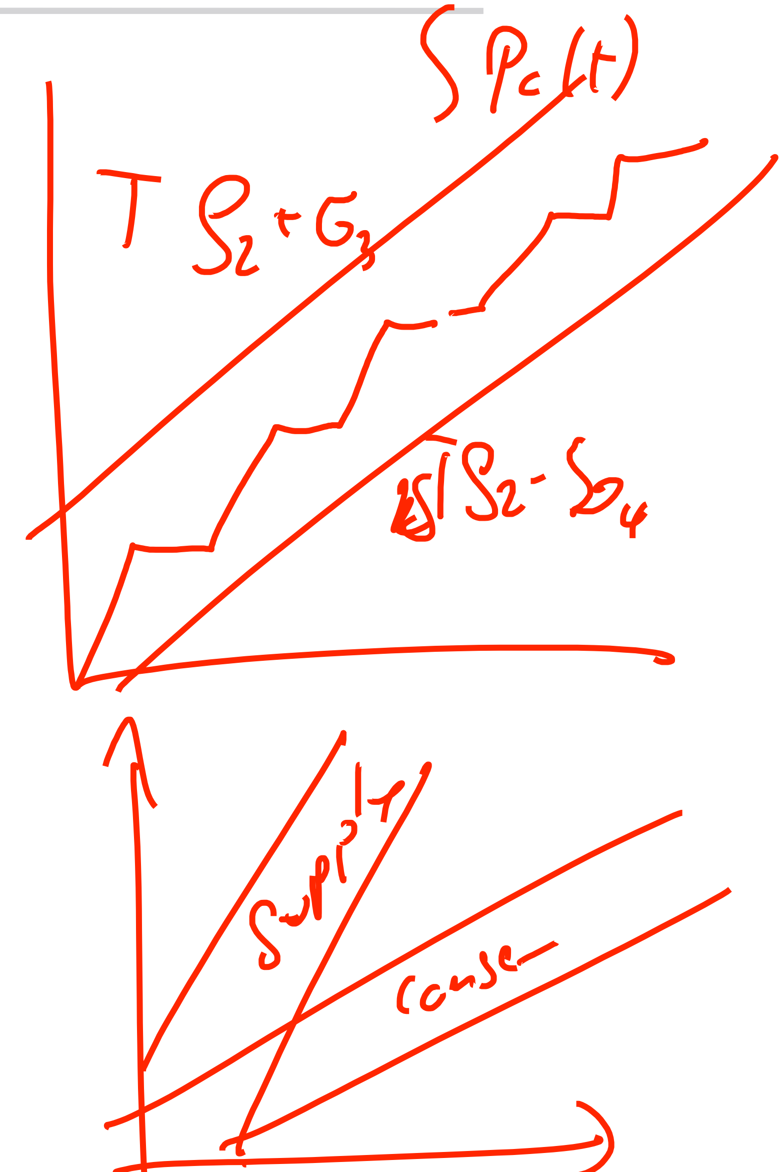
Fig. 2. Solar energy based charging power recorded for 9 days

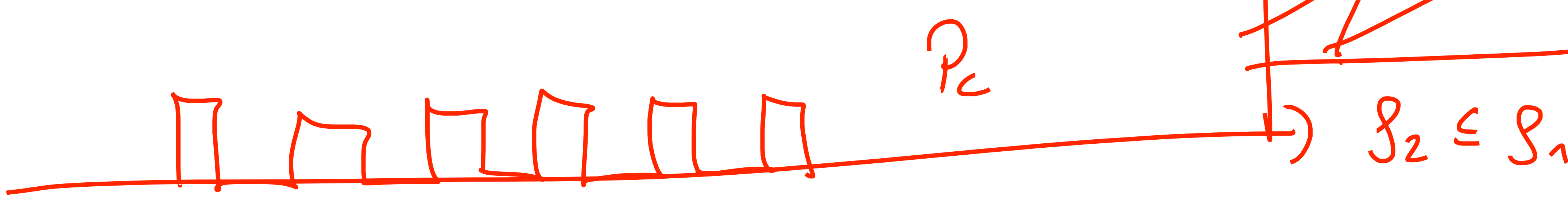
Model of Benign Energy Behavior

- Benign energy consumption:
  - $P_c(t)$ satisfies the following

$$\int_{\tau}^{\tau+T} P_c(t)dt \le \rho_2 T + \sigma_3$$

$$\int_{\tau}^{\tau+T} P_c(t)dt \ge \rho_2 T - \sigma_4$$





Energy Neutrality for Benign Sources

- Substitution into the non-ideal energy source inequality:

$$B_0 + \eta \cdot \min\{\int_T P_s(t)dt\} - \max\{\int_T P_c(t)dt\} - \int_T P_{leak}(t)dt \ \geq \ 0$$

$$\Rightarrow B_0 + \eta(\rho_1 T - \sigma_2) - (\rho_2 T + \sigma_3) - \rho_{leak} T \ \geq \ 0$$

- This inequality must hold for T=0

  $B_0 \geq \eta\sigma_2 + \sigma_3$

- This condition must hold for all T

  $\eta\rho_1 - \rho_{leak} \geq \rho_2$

- If these inequalities hold then continuous operation can be guaranteed

Necessary Energy Buffer for Benign Energy Sources

- Substituting in the second equation

$$B_0 + \eta \cdot \max\{\int_T P_s(t)dt\} - \min\{\int_T P_c(t)dt\} - \int_T P_{leak}(t)dt \leq B$$

$$\Rightarrow B_0 + \eta(\rho_1 T + \sigma_1) - (\rho_2 T - \sigma_4) - \rho_{leak} T \leq B$$

- For T=0 we need

$$B_0 + \eta(\sigma_1 - \sigma_4) \leq B$$

- Substitution of $B_0 \geq \eta\sigma_2 + \sigma_3$ yields

$$B \geq \eta(\sigma_1 + \sigma_2) + \sigma_3 - \sigma_4$$

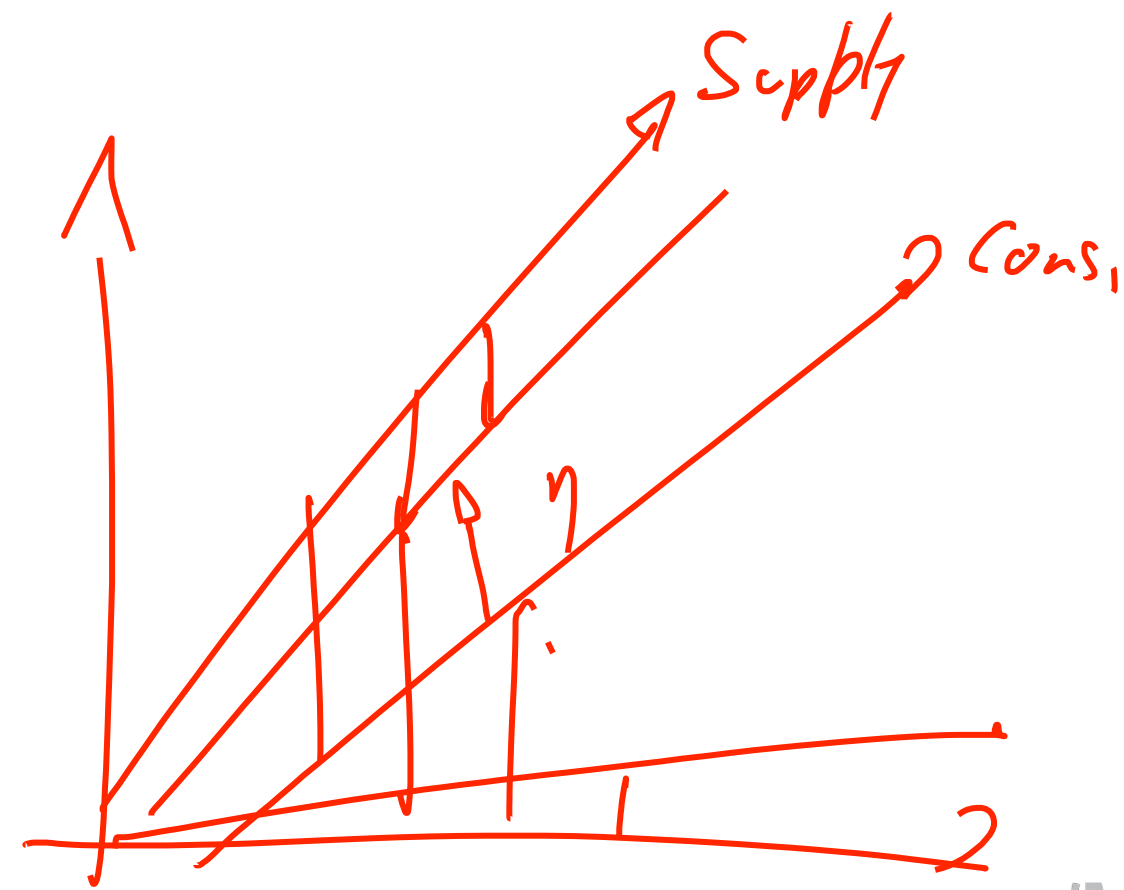
- For $T \to \infty$ we have

$$\eta\rho_1 - \rho_{leak} \leq \rho_2$$

  - This condition may be violated without problems

Energy Neutral Operation

- Theorem
  - For benign energy sources the energy neutrality can be satisfied if the following conditions apply
    - $\rho_2 \leq \eta\rho_1 - \rho_{leak}$
    - $B \geq \eta\sigma_1 + \eta\sigma_2 + \sigma_3$
    - $B_0 \geq \eta\sigma_2 + \sigma_3$



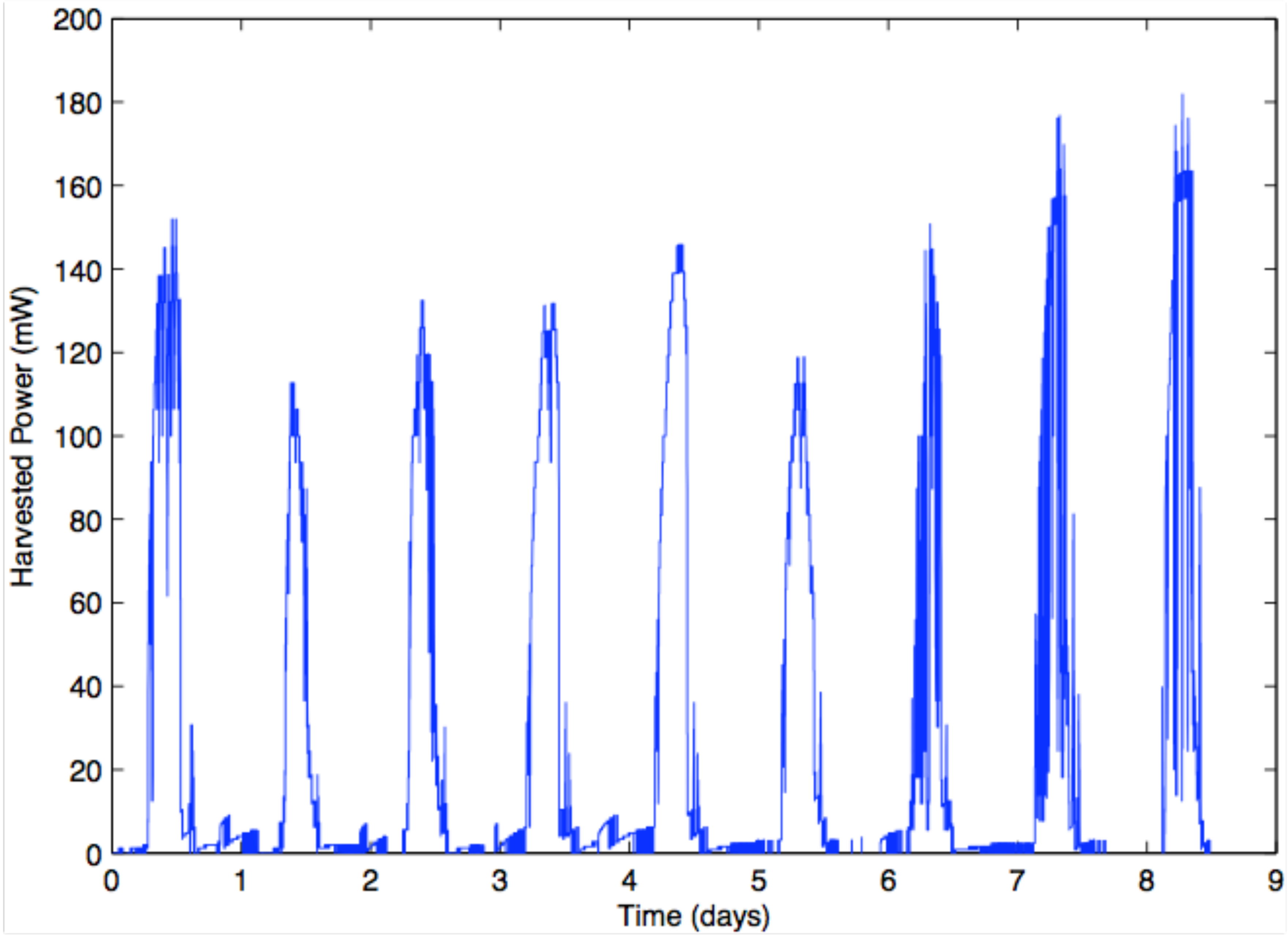


Fig. 2. Solar energy based charging power recorded for 9 days

Parameter	Value	Units
ρ_1	23.6	mW
σ_1	1.4639×10^3	J
σ_2	1.8566×10^3	J

Further Considerations

- The behavior of energy sources can be learned
  - As a result, the available energy can be calculated
  - The task can be adapted to the energy supply
- Thereby
  - Nodes with better energy situation can take over routing
  - Measurements can occur seldomer, but will never stop

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9. Sensor Coverage & Lifetime

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