Wireless Sensor Networks

9. Energy Harvesting

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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
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,...
Differences Compared to Batteries

- **Time dependent**
  - form of operation has to be adapted over time
  - sometimes not predictable

- **Location dependent**
  - different nodes 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

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**Diagram Descriptions**

- Solar Data
- Wind Data
- Harvesting Source
- Harvesting System
- Load
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
  \[ \int_0^T P_c(t) \, dt \leq \int_0^T P_s(t) \, dt + B_0 \quad \forall \ T \in [0, \infty) \]
  - where $B_0$ is the initial energy
  - energy buffer is lossless, store any amount of energy
Harvesting Theory

- $P_s(t)$: Power output from energy source at 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

- Continuous operation if

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

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

$P_s(t) > P_c(t)$
Harvesting Theory

- $P_s(t)$: Power output from energy source at 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
    \[
    B_0 + \eta \int_0^T [P_s(t) - P_c(t)]^+ dt - \int_0^T [P_c(t) - P_s(t)]^+ dt - \int_0^T P_{\text{leak}}(t) dt \geq 0
    \]
  - $B_0$ is the initial energy of the buffer
  - $\eta$: efficiency of energy buffer
  - $P_{\text{leak}}(t)$: leakage power of the energy buffer

\[
B_0 + \eta \int_0^T [P_s(t) - P_c(t)]^+ dt - \int_0^T [P_c(t) - P_s(t)]^+ dt - \int_0^T P_{\text{leak}}(t) dt \leq B
\]
If the power source $P_s(t)$ occurs regularly, then it satisfies the following equations:

\[
\begin{align*}
\int_{\tau}^{\tau+T} P_s(t) \, dt & \leq \rho_1 T + \sigma_1 \\
\int_{\tau}^{\tau+T} P_s(t) \, dt & \geq \rho_1 T - \sigma_2
\end{align*}
\]

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

\[
\int_{\tau}^{\tau+T} P_c(t) \, dt \leq \frac{\rho_2 T}{2} + \sigma_3
\]

\[
\int_{\tau}^{\tau+T} P_c(t) \, dt \geq \frac{\rho_2 T}{2} - \sigma_4
\]

$S_2 \leq S_n$
Substitution into the non-ideal energy source inequality:

\[ B_0 + \eta \cdot \min \left\{ \int_T P_s(t) dt \right\} - \max \left\{ \int_T P_c(t) dt \right\} - \int_T P_{\text{leak}}(t) dt \geq 0 \]

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

This inequality must hold for \( T=0 \)

\[ B_0 \geq \eta \sigma_2 + \sigma_3 \]

This condition must hold for all \( T \)

\[ \eta \rho_1 - \rho_{\text{leak}} \geq \rho_2 \]

If these inequalities hold then continuous operation can be guaranteed.
Necessary Energy Buffer for Benign Energy Sources

- Substituting in the second equation

\[ B_0 + \eta \cdot \max\{ \int_T \! P_s(t) \, dt \} \! - \! \min\{ \int_T \! P_c(t) \, dt \} \! - \! \int_T \! P_{\text{leak}}(t) \, dt \leq B \]

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

- 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

\[ \eta \rho_1 - \rho_{\text{leak}} \leq \rho_2 \]

- 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:
  
  1. \[ \rho_2 \leq \eta \rho_1 - \rho_{\text{leak}} \]
  
  2. \[ B \geq \eta \sigma_1 + \eta \sigma_2 + \sigma_3 \]
  
  3. \[ B_0 \geq \eta \sigma_2 + \sigma_3 \]
Fig. 2. Solar energy-based charging power recorded for 9 days

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
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<tr>
<td>$\rho_1$</td>
<td>23.6</td>
<td>mW</td>
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<tr>
<td>$\sigma_1$</td>
<td>$1.4639 \times 10^3$</td>
<td>J</td>
</tr>
<tr>
<td>$\sigma_2$</td>
<td>$1.8566 \times 10^3$</td>
<td>J</td>
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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 seldom, but will never stop
Wireless Sensor Networks
9. Sensor Coverage & Lifetime

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