Wireless Sensor Networks
9. Sensor Coverage & Lifetime

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Literature Energy Harvesting

- Kansal, Hsu, Zahedi, Srivastava
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
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,**...
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

![Solar Data Chart]

![Wind Speed Chart]

![Harvesting Source Diagram]
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 at 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

- **$P_s(t)$**: 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

\[
\text{Harvesting System with ideal energy buffer.}
\]

\[
\text{Harvesting System with non-ideal energy buffer.}
\]

\[
\text{from the system. In this case, the left hand side of (3) will be}
\]

\[
\text{where } B \text{ is the size of the energy buffer. Note that while (3) is}
\]

\[
\text{be satisfied:}
\]

\[
\text{energy buffer size. The buffer size limit requires the follo}
\]

\[
\text{B}
\]

\[
\text{below. First define a rectifier function}
\]

\[
\text{Let}
\]

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

\[
\text{Continuous operation if}
\]

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

\[
\text{B}_0 \text{ is the initial energy}
\]

\[
\eta \text{: efficiency of energy buffer}
\]

\[
P_{\text{leak}}(t) \text{: energy loss of the memory}
\]
Harvesting system with ideal energy buffer.

Below. First define a rectifier function which has a battery or an ultra-capacitor to store energy. Such spectrum and may not be typical. A more practical case is that powered flour-mill is another example: the mill operates when this energy is used to transmit a radio packet during the butt interval. For such harvesting devices, the device can operate at all times provided that a sufficient but not necessary - some functions not satisfying the condition (1) are possible. The stored energy may be used at any time later. The ideal energy buffer is real energy buffer is an energy storage mechanism 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

Non-ideal energy buffer with limited reception B

- Continuous operation if

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

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

- $P_c(t)$ satisfies the following

\[
\int_{\tau}^{\tau+T} P_c(t) dt \leq \rho T + \sigma _3
\]

\[
\int_{\tau}^{\tau+T} P_c(t) dt \geq \rho T - \sigma _4
\]
Substitution into the non-ideal energy source inequality:

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

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

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
Substituting in the second equation

\[ B_0 + \eta \cdot \max \left\{ \int_{T} P_s(t) dt \right\} - \min \left\{ \int_{T} P_c(t) dt \right\} - \int_{T} P_{\text{leak}}(t) dt \leq B \]

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

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

  - $\rho_2 \leq \eta \rho_1 - \rho_{\text{leak}}$
  - $B \geq \eta \sigma_1 + \eta \sigma_2 + \sigma_3$
  - $B_0 \geq \eta \sigma_2 + \sigma_3$
3.1 Buffer Size and Related Considerations

The first direct implication is on the design of the energy buffer required in the harvesting system. As an example consider a harvesting system that harvests solar energy. The power output from a solar cell [Kansal et al. 2004] is plotted in Figure 2 for nine days. Assuming this data is representative of the solar energy received on typical days of operation, this energy generation profile may be characterized by the \((\rho_1, \sigma_1, \sigma_2)\) model in Table I.

![Figure 2. Solar energy based charging power recorded for 9 days](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho_1)</td>
<td>23.6</td>
<td>mW</td>
</tr>
<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>
</tr>
</tbody>
</table>

Let us assume that the load can be designed to operate at \(\eta \rho_1 - \rho_{\text{leak}}\), where \(\rho_{\text{leak}}\) will depend on energy storage technology used. Then, the battery size required according to equation (19) is \(\eta (\sigma_1 + \sigma_2)\). Several technologies are available to implement this energy buffer, such as NiMH batteries, Li-ion batteries, ultracapacitors or NiCd batteries. For instance, for NiMH batteries, \(\eta = 0.7\) and the required size is \(3.32 \times 10^3\) Joules. This can be easily provided by an AA sized NiMH battery which has a capacity of 1800mAh, i.e., \(7.7 \times 10^3\) Joules. Note that using a larger battery than the above size does not help improve the supported energy neutral performance level. A larger battery than that calculated above may however be used to provide for practical considerations.
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
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