A Power Manager with Balanced Quality of Service for Energy-Harvesting Wireless Sensor Nodes

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Toward Connected Objects...

Connected objects are expected to 50 billions by 2020 *(Cisco Systems 2014)*

**Energy consumption** for a huge number of connected objects?

**Autonomous designs** with battery independency?
Wireless Sensor Networks (WSNs)

- WSN node
- Wireless link
- Wire link

- Environment Monitoring
- Health Monitoring
- Structure Monitoring
Energy Harvesting (EH): a new paradigm for Power Manager (PM):
- The objective is no more to minimize the consumed energy as battery-powered WSN
- But rather to satisfy Energy Neutral Operation (ENO) condition [KAN2007]
  \[ \text{consumed energy} = \text{harvested energy} \]

Power Manager Challenges

• How to control energy consumption?
  – Adapt the wake-up interval ($T_{WI}$)
  – Adapt transmit power
  – Dynamic Voltage and Frequency Scaling (DVFS)

• Consumed energy model:
  – Depend on scenarios or functional modes

• Harvested energy model:
  – Different energy sources: solar, wind, thermal...
  – Real-time monitoring

• Which kind of energy storage?

  ![Diagram of energy storage options]

  **500 recharge cycles**
  - Difficult to estimate the state of charge
  - Low leakage current

  ![CapXX logo]  
  ![Cymbet logo]  
  - **500 000 recharge cycles**
  - Easy to estimate the state of charge
  - High leakage current

http://www.cymbet.com  
http://cap-xx.com
Related Work: KAN-PM \cite{KAN2007}

- Designed for \textbf{solar-powered} WSN with \textbf{rechargeable batteries}
- Adaptations are based on \textbf{prediction of harvested energy}:
  - Energy consumption is a constant
  - \textbf{State of Charge (SoC)} is not considered
- Time domain is divided in fixed slots (30 minutes)

- \textbf{Low response} to the change of harvested energy
- \textbf{Battery failure can occur} (WSN is shutdown!!!)
- \textbf{High performance} when harvested energy is available
- \textbf{Low performance} when there is no harvested energy

Related Work: CL-PM [CAS2012]

- Adaptations are based on **current harvested energy** and **State of Charge (SoC)** of the battery:
  - Harvested energy model is based on a luminance sensor
  - Consumed energy model is based on a Look Up Table (LUT)
- Dynamic adaptation periods
- **Fast response** to the change of harvested energy
- **Battery failure** is avoided in CL-PM
- **High performance** when harvested energy is available
- **Low performance** when there is no harvested energy

Contributions

• Global power manager for supercapacitor-based energy harvesting WSN node:
  – Balance performance while satisfying ENO
  – Energy sources independence: solar, wind, thermal...
  – Precise energy model: consumed, harvested and SoC models
  – Low complexity, memory footprint

• Periodic energy sources:
  – Light energy in an office
  – Energy Interval ($T_{EI}$)
  – Non-Energy Interval ($T_{NEI}$)
1. Multiple Energy Sources Converter (MESC)
   1. Hardware Architecture
   2. Energy Monitor
   3. Energy Predictor

2. Power Manager with Balanced Quality of Service (BQS-PM)
   1. Positive Energy Power Manager (PE-PM)
   2. Negative Energy Power Manager (NE-PM)

3. Simulations and Comparisons

4. Conclusions
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Multiple Energy Sources Converter (MESC)

- Support different sources: solar, thermal, wind
- Supercapacitor-based energy storage
- Optimized energy flow
- DC/DC converter efficiency: $\eta = 0.85$
- Optimized sizing **OutCap** and **StoreCap**
Multiple Energy Sources Converter (MESC)

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Software-based Energy Monitor

- Provide energy profiles
  - Current energy in the StoreCap ($\tilde{e}_S$)
  - Leakage energy of the whole system ($\tilde{e}_{\text{Leak}}$)
  - Consumed energy of the WSN node ($\tilde{e}_C$)
  - Harvested energy from harvesters ($\tilde{e}_H$)

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**Look Up Table**

<table>
<thead>
<tr>
<th>Activity</th>
<th>Energy ($E_x$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculation Before Transmission</td>
<td>$E_{\text{CBT}}$ 9.7µJ</td>
</tr>
<tr>
<td>Transmit/Receive wake-up beacon</td>
<td>$E_{\text{WUB}}$ 51µJ</td>
</tr>
<tr>
<td>Data Transmission</td>
<td>$E_{\text{DT}}$ 80µJ</td>
</tr>
<tr>
<td>Data Reception</td>
<td>$E_{\text{DR}}$ 100µJ</td>
</tr>
<tr>
<td>Clear Channel Assessment</td>
<td>$E_{\text{CCA}}$ 18µJ</td>
</tr>
</tbody>
</table>

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Adaptive Filter-based Energy Predictor

- Low complexity and memory footprint
- Acceptable average error (less than 15%)
- Independent of energy sources: outdoor solar, indoor light, wind

\[ \hat{e}_H(n+1) \]: Predicted harvested energy in slot \( n+1 \)
\[ err(n+1) \]: Prediction error
\[ w(n) \]: Filter coefficients

Low-complexity filter order \( p = 1 \)

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Power Manager with Balanced Quality of Service (BQS-PM)

**Energy Monitor**

- \( V_S(n) \)

**Positive Energy Power Manager**

\[
\tilde{P}_H(n) > \varepsilon \\
\tilde{e}_S(n+1)
\]

**Negative Energy Power Manager**

\[
\tilde{P}_H(n) \leq \varepsilon \\
\tilde{e}_S(n+1)
\]

**Adaptive Filter**

- \( \tilde{P}_H(n) \)
- \( \tilde{P}_H(n+1) \)
- \( \tilde{e}_S(n+1) \)
- \( \tilde{e}_{Active}(n+1) \)

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</tr>
<tr>
<td>Clear Channel Assessment</td>
<td>( E_{CCA} ) 18µJ</td>
</tr>
<tr>
<td>Sensing</td>
<td>( E_{SEN} ) 27µJ</td>
</tr>
<tr>
<td>Transmit/Receive Acknowledgment</td>
<td>( E_{ACK} ) 51µJ</td>
</tr>
</tbody>
</table>

**EWMA(*)**

- \( EWMA(*) \): Exponentially Weighted Moving Average

**ZEI (#)**

- \( ZEI \): Zero Energy Interval [CAS2012]

**Time**

- \( T_{WI}(n+1) \)
- \( T_{EI} \)
- \( T_{NEI} \)

\[
TS(n-1) = kTWI(n-1) \\
TS(n) = kTWI(n)
\]
Positive Energy Power Manager (PE-PM)

• Energy constraint to respect ENO:

\[
\frac{\hat{e}_H(n+1)}{1 + \varphi} = \frac{1}{\eta} \hat{e}_C(n+1) + P_{\text{Leak}} T_S(n+1)
\]

\[
\varphi = \frac{T_{\text{NEI}}}{T_{\text{EI}}}
\]

\[
\frac{\hat{e}_H(n+1)}{1 + \varphi} = \frac{1}{\eta} [\hat{e}_{\text{Active}}(n+1) + P_{\text{Sleep}} T_S(n+1)] + P_{\text{Leak}} T_S(n+1)
\]

• Next wake-up interval:

\[
T_{\text{WI}}(n+1) = \frac{(1 + \varphi) \hat{e}_{\text{Active}}(n+1)/k}{\eta \hat{P}_H(n+1) - (1 + \varphi)(\eta P_{\text{Leak}} + P_{\text{Sleep}})}
\]
Negative Energy Power Manager (NE-PM)

• Remaining time of non-energy interval:

\[ R(n+1) = R(n) - T_S(n) = R(n) - kT_{WI}(n) \]

• Available energy for waking-up:

\[ E_R(n+1) = \frac{1}{2} C_S \left[ V_S^2(n) - V_0^2 \right] - (P_{Sleep} + \eta P_{Leak})R(n+1) \]

• Next wake-up interval:

\[ T_{WI}(n+1) = \frac{R(n+1)\hat{e}_{Active}(n+1)}{kE_R(n+1)} \]
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Evaluation metrics

- $W_{EI}(s)$: Average wake-up interval during $T_{EI}$
- $W_{NEI}(s)$: Average wake-up interval during $T_{NEI}$
- $W_C(s)$: Average wake-up interval during $T_C$
- Mem(words): Memory footprint
- Mul: Number of multiplications
- $B_f$(minute): Battery failure duration
- Gap: the difference of $W_{EI}$ and $W_{NEI}$

\[
\text{Gap} = \left| \frac{W_{EI} - W_C}{W_C} \right| + \left| \frac{W_{NEI} - W_C}{W_C} \right|
\]

Single-hop EH-WSN

- $C_S = 1.8F$, $V_{Min} = 1.8V$, $V_{Max} = 5.2V$
Receiver Initiated Protocol (RICER) [EYL2004]

\[ T_b = 50\text{ms} \]

Wake-up beacon (WUB)

Receiver

Idle listening

Clear Channel Assessment (CCA)

Transmitter

\[ T_{idle} = 52\text{ms} \]

– After receiving a beacon packet (WUB), the transmitter forwards data package (DT) after Clear Channel Assessment (CCA)

BQS-PM Simulation Results

- Wake-up interval presents an inverse shape according to the harvested power
- ENO condition is satisfied after a day (24 hours)
- There is no battery failure or overflow
KAN-PM Simulation Results

- Low response to the change of harvested energy
- Does not well satisfy ENO condition
- Low $T_{WI}$ during $T_{EI}$ but very high $T_{WI}$ during $T_{NEI}$
CL-PM Simulation Results

- Fast response to the change of harvested energy
- Satisfies ENO condition, without battery failure
- Low $T_{WI}$ during $T_{EI}$ but very high $T_{WI}$ during $T_{NEI}$
### PEO-PM, KAN-PM and CL-PM Comparisons

<table>
<thead>
<tr>
<th></th>
<th>BQS-PM (s)</th>
<th>KAN-PM (s)</th>
<th>Gain (%)</th>
<th>CL-PM (s)</th>
<th>Gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_{EI}$</td>
<td>21.1</td>
<td>11.1</td>
<td>-47.4</td>
<td>10.4</td>
<td>-50.7</td>
</tr>
<tr>
<td>$W_{NEI}$</td>
<td>18.9</td>
<td>125.2</td>
<td>84.9</td>
<td>111.6</td>
<td>83.1</td>
</tr>
<tr>
<td>$W_{C}$</td>
<td>19.9</td>
<td>111.6</td>
<td>3.13</td>
<td>19.6</td>
<td>-0.26</td>
</tr>
<tr>
<td>Gap</td>
<td>0.2</td>
<td>5.6</td>
<td>98.0</td>
<td>5.13</td>
<td>97.9</td>
</tr>
<tr>
<td>Mem (words)</td>
<td>11</td>
<td>48</td>
<td>77.08</td>
<td>10</td>
<td>-10.00</td>
</tr>
<tr>
<td>$Mul$</td>
<td>16</td>
<td>28</td>
<td>42.86</td>
<td>9</td>
<td>-77.78</td>
</tr>
<tr>
<td>$B_f$ (min)</td>
<td>0</td>
<td>18</td>
<td>-</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>

- While balancing wake-up interval, $W_{NEI}$ is significantly improved.
- Difference of wake-up interval between $T_{EI}$ and $T_{NEI}$ is removed.
- Low complexity, low memory footprint and no battery failure.
Conclusions

• Power manager with Balanced Quality of Service (BQS-PM):
  – Adapt the node to **ENO, without battery failure**
  – **Improve 85%** the QoS when there is no more harvested energy

• Independence of periodic energy sources

• Low memory footprint, low complexity
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