Embedded Systems

Exercise 5: Low Power Design

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(based on slides by P. Kumar, G. Giannopoulou, J. Chen)
Motivation for Power Savings

• Rapid increase of power consumption
  • thermal side-effects
• Slow increase of the storage capacity
  • battery life of remote devices
• At both ends – embedded systems and servers
• Climate change!
What?
Types of power consumption

- Dynamic
  - charging and discharging capacitors
- Leakage
  - through leakage in transistors
  - thermal run-away
- Short circuit
  - short circuit current between supply rails while switching
How?
Dynamic Power Management

• Shut down devices if they are not to be used
• Wake them up when service is required
• Can reduce leakage and dynamic power
• Non-zero energy/time for switching

Questions
• When to shut down and when to wake up?
• Is there a minimum amount of time (break-even time) worth shutting down?
**Dynamic Voltage Scaling**

- Power consumption is a **convex** monotonically increasing function of frequency (or voltage)
  - Prefer running at lower frequencies
  - If possible, run at a constant frequency
- Can reduce dynamic power only

\[ z = a \cdot x + (1-a) \cdot y \]
Dynamic Voltage Scaling

• Questions
  • Is there a critical frequency of operation below which the watt per cycle increases?
  • How to assign frequencies such that a given set of jobs finish within their deadlines and energy consumption is minimized?
    • YDS algorithm
    • Online variant
The “Smart Dust”
Energy Harvesting

- Energy from various sources such as solar, wind can be used in remote devices
- Thus, energy available to the system increases with time
- Battery must never run out
- Questions
  - How to perform DVS given such a system?
  - Is YDS still optimal and when (battery dies or not)?
Exercises

You have 30 mins
Exercise 1 (1)

- Minimize $E \sim P(f)/f$

First derivative $E' = 20f - \frac{20}{f^2}$

Hence, $f_{\text{crit}} = 100 \text{ MHz}$
Exercise 1 (2)

• Energy saving should be greater than the switching-on overhead:

\[
\text{Energy}_{\text{idle\_min\_frequency}} - \text{Energy}_{\text{sleep}} \geq P(f_{\text{min}}) \times t_{\text{bev}} \geq 3 \times 10^{-5} \Rightarrow \\
\frac{3 \times 10^{-5}}{10^{-3} \times (10 \times 0.5^3 + 20)} = 1.412\text{ms.}
\]
Exercise 1 (3)

E1 = 0.1395 mJoule
Exercise 1 (4)

- **Idea**: avoid idle times, run at frequency $\leq f_{\text{crit}}$

$$E_2 = 0.12762 \text{ mJoule}$$
Exercise 1 (5)

- **Idea**: postpone task execution to increase sleep time

\[ E_3 = 0.11512 \text{ mJoule} \]
Exercise 2 (1)

- Critical intervals with highest intensity for each step

<table>
<thead>
<tr>
<th>Step #</th>
<th>Critical Interval (msec)</th>
<th>Intensity ($\times 10^6$)</th>
<th>Scheduled Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>[6,10]</td>
<td>2.0</td>
<td>{3}</td>
</tr>
<tr>
<td>2</td>
<td>[2,11]</td>
<td>1.0</td>
<td>{2,6}</td>
</tr>
<tr>
<td>3</td>
<td>[2,12]</td>
<td>0.7</td>
<td>{4,5}</td>
</tr>
<tr>
<td>4</td>
<td>[0,2]</td>
<td>0.5</td>
<td>{1}</td>
</tr>
</tbody>
</table>
Exercise 2 (1)

![Diagram showing frequency vs. time for different jobs with their corresponding speeds.]

<table>
<thead>
<tr>
<th>Job ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>speed</td>
<td>0.5</td>
<td>1.0</td>
<td>2.0</td>
<td>0.7</td>
<td>0.7</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Exercise 2 (2)

<table>
<thead>
<tr>
<th>Job ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>speed ($\times 10^6$ Hz)</td>
<td>0.125</td>
<td>0.675</td>
<td>0.675</td>
<td>2.0083</td>
<td>2.0083</td>
<td>0.7</td>
</tr>
</tbody>
</table>
Exercise 3 (1)

Required energy for calculations:

\[ E_{active} = 5 \cdot 10^6 \cdot P_{active} \cdot t_{task} = 12000J \]

Remaining energy from battery:

\[ E_{bat} - E_{active} = 13000J \]

Maximum interval (sleep) between 2 interrupts:

\[ t_{sleep} = \frac{13000J}{5 \cdot 10^6 \cdot 0.00009W} = 28.9 \text{ sec} \]

Therefore:

\[ T_{max} = t_{sleep} + t_{task} = 30.9 \text{ sec} \]

Lifetime restriction:

\[ Lifetime_{max} = 5 \cdot 10^6 \cdot T_{max} \approx 4.899 \text{ years} \]
Exercise 3 (2)

Schedule S1

Schedule S2

P

P

P_{active}

P_{sleep}

P_{active}

P_{sleep}

\text{t / ms}

\text{t / ms}
Exercise 3 (3)

Average energy difference over 2 periods

• Period 1:

\[
\Delta E_1 = t_1 \cdot \frac{P_{\text{active}} + P_{\text{sleep}}}{2} - t_1 \cdot P_{\text{active}}
\]

• Period 2:

\[
\Delta E_2 = t_2 \cdot \frac{P_{\text{active}} + P_{\text{sleep}}}{2} - t_2 \cdot P_{\text{sleep}}
\]

• Average:

\[
\Delta E = \frac{\Delta E_1 + \Delta E_2}{2} = \frac{(t_2 - t_1)(P_{\text{active}} - P_{\text{sleep}})}{4} \approx 13.875 \mu J
\]
Average energy difference over 2 periods results in:

\[ \Delta E' = \frac{(t_2 + t_1)(P_{\text{active}} - P_{\text{sleep}})}{4} \approx 27.75 \mu J \]