Dynamic Energy Burst Scaling for Transiently Powered Systems

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Design Trends

Battery-based → Batteryless

What are Transiently Powered Systems?

Energy-harvesting based systems with limited energy storage capacity

Why harvesting based?

- Low-cost
- Long-term
- Environmentally friendly

Why limit energy storage?

- Batteries (and supercaps) self-discharge, limited cycles
- Storage is expensive in terms of cost, form factor
- Storage requires energy surplus
**Transient System Design Goals**

Energy-driven embedded systems that:

- Have low cost
- Operate efficiently
- Guarantee program progress

**Challenging Scenario:**

- Low power harvesting conditions
Directly Coupled Systems

“Checkpointing” for MCU’s:

Federating Energy:

**Advantage:**
- Simplicity, no additional sources of leakage/losses

**Disadvantage:**
- Source must have the same operating power point as the load
Boost-Buck Converter Topology

- Decoupled voltages:

Source | Storage | Load

Source: $P_{\text{in}}, V_{\text{in}}$
Boost Converter
Buck Converter: $P_{\text{load}}, V_{\text{load}}$
Load

**Advantages:**
- Source at Maximum Power Transfer Point
- Load has regulated voltage

**Disadvantage:**
- Introduces new sources of losses (converter inefficiencies, leakage, etc)
- No tracking of load’s optimal operating point

WispCam: [Naderiparizi2015]
Our Proposed System

Energy Management Unit (EMU):

- Based on the Boost-Buck topology
- Optimized storage element
  - Minimized wake-up time, cold-start energy
- Tracks load’s optimal operating point
  - Feedback-based Dynamic Energy Burst Scaling
How can we design transient applications?

Basic Sense (S) and Process (P) Application

• Consists of two atomic tasks: S and P
  • Known energies ($E_S$, $E_P$) and operating voltage ($V_{load}$)
  • Two burst-based ways of executing this application: together, individually

Single Burst @ $V_{load}$

- Higher buffer sizes
- Longer timing constants
- Application-level optimization

Multiple Bursts @ $V_{load}$

- Minimized buffer sizes
- Minimum start-up time
- Task-level optimization
Minimizing the Storage Element

- For a single-capacitor system, $C_{\text{min}}$ ensures functionality

\[
C_{\text{min}} = \frac{2 \max(E_{\text{task},i})}{\eta_{\text{buck}} \cdot (V_{\text{max}}^2 - V_{\text{load}}^2)}
\]

- $C_{\text{min}}$ also minimizes cold-start energy and start-up time

\[
t_{\text{start-up}} = \left\{ t \mid V_{\text{cap}}(t) = \sqrt{\frac{2 \int_0^t E_{\text{cap}}' \, d\tau}{C_{\text{cap}}}} = V_{\text{load}} \right\}
\]
Dynamic Energy Burst Scaling:

+ Minimizes task energy

- Requires control mechanism!
Dynamic Energy Burst Scaling

Feedback Loop:

• Minimizes task energy required to execute application

• Load configures EMU to provide $E_{\text{burst}} @ V_{\text{load}}$

• Task execution is triggered by EMU interrupt
Energy Burst-Based Flow

After a long period of energy unavailability, the system triggers an energy management unit. Following this, the system transitions from off to power up. If the power-on reset (POR) is confirmed, the system enters the deep sleep mode. Otherwise, the system reads the configuration and performs tasks like initialization (Task\_init), execution (Task\_exec), and deinitialization (Task\_deinit). After a task is completed, the system updates the configuration.

The figure shows the relationship between the voltage across the capacitor ($V_{cap}$) and the load power ($P_{load}$) over time ($t$). The voltage across the capacitor ($V_{cap}$) is shown to increase as the load power ($P_{load}$) is active. At certain points, the system enters deep sleep mode, and the load power decreases to a low level. When the system wakes up, the load power increases to a higher level, and the system performs tasks and updates configurations.

Key equations:
- $E_{stored}(t) = E_S$ for deep sleep mode.
- $E_{stored}(t) = E_P$ for active mode.

Load power levels:
- $P_{load} = 60$ nW
- $P_{load} = \sim 4$ mW
- $P_{load} = 60$ nW
- $P_{load} = \sim 3$ mW
Modeling Transient Applications

**Discrete-Time Simulation:**

- Calculate voltage changes in capacitor (with non-ideal converters, leakage, etc)
- Verify understanding of EMU behavior

**Inputs:**
- Source’s power trace
- $E_{task}$, $V_{task}$, $P_{task}$

**Output:**
- Energy Efficiency
- Total Executions

\[ P_{in}(t) \rightarrow \text{EMU Model} \rightarrow V_{cap}(t) \rightarrow E_{load} / E_{harvested} \rightarrow P_{load}(t) \]

\[ \text{task set} \rightarrow \text{capacitance} \rightarrow \text{power consumption} \]
Experimental Set-Up

**Energy Management Unit**

- **Optimal Cap**: 80 μF
- **Control Circuit**
- **Buck**: TPS62740

**Control Interface**

- **Load**: $P_{EMU} \approx 10\ \mu W$

**Load:**
- Sensor: Centeye Stonyman (3V)
- Processor: MSP430 (2V)

**Metrics:**
- Energy harvested
- Energy consumed by the load
- Application execution rate
## Constant Bursts - Characterization

### Energy Stored

\[ E_{\text{stored}} = V_{\text{load}} \cdot \frac{1}{2} \cdot \text{Time} \cdot \text{Voltage} \]

\[ E_{S+P} = 401.2 \mu J \]

\[ P_{\text{avg}} = 3.98 \text{ mW} \]

### Table: Energy Burst Characterization

<table>
<thead>
<tr>
<th>Stage</th>
<th>Voltage [V]</th>
<th>Time [ms]</th>
<th>Energy [μJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boot</td>
<td>3.0</td>
<td>3.20</td>
<td>6.4</td>
</tr>
<tr>
<td>Sense</td>
<td>3.0</td>
<td>47.0</td>
<td>174.0</td>
</tr>
<tr>
<td>Process</td>
<td>3.0</td>
<td>50.6</td>
<td>220.8</td>
</tr>
<tr>
<td>Total</td>
<td>100.8</td>
<td></td>
<td>401.2</td>
</tr>
</tbody>
</table>
Dynamic Bursts - Characterization

\[ E_{\text{stored}} \]

\[ E_{\text{S+P}} = (190 + 146.8) \, \mu J = 336.8 \, \mu J \]

\[ P_{\text{avg,S+P}} = \sim 3.34 \, \text{mW} \]

### 1st Burst = Sense

<table>
<thead>
<tr>
<th>Phase</th>
<th>Voltage [V]</th>
<th>Energy [\mu J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boot</td>
<td>3.0</td>
<td>6.1</td>
</tr>
<tr>
<td>Sense</td>
<td>3.0</td>
<td>183.9</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>190.0</td>
</tr>
</tbody>
</table>

### 2nd Burst = Process

<table>
<thead>
<tr>
<th>Phase</th>
<th>Voltage [V]</th>
<th>Energy [\mu J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boot</td>
<td>2.0</td>
<td>3.1</td>
</tr>
<tr>
<td>Process</td>
<td>2.0</td>
<td>143.7</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>146.8</td>
</tr>
</tbody>
</table>

**Constant Bursts:** 401.2 \( \mu J \) required per execution

**Dynamic Bursts:** 336.8 \( \mu J \) required per execution
Experimental Evaluation

Harvesting Scenarios:

- Constant/variable input power
- Low power ranges: $0 - 400 \, \mu W$

EMU Testing Methodology:

- Constant Bursts Experiment
- Dynamic Bursts Experiment
- Run simulations with recorded input power traces
- Compare measured/simulated outputs
Dynamic Bursts

Constant Bursts

Efficiency is bounded by converter efficiencies (~78%)
Application Execution Rate

**Dynamic Bursts**

- Model: ~50 exec/min @ 400 uW
- Experimental: ~50 exec/min @ 400 uW

**Constant Bursts**

- Model: ~40 exec/min @ 400 uW
- Experimental: ~40 exec/min @ 400 uW
## Variable Input Power Experiment

Camera worn around the lab for 15 mins. in various lighting conditions

### Experiment 1:

<table>
<thead>
<tr>
<th>Avg. $P_{\text{in}}$</th>
<th>Metric</th>
<th>Simulation</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>111.9 $\mu$W</td>
<td>Exec. Rate</td>
<td>9.87 min$^{-1}$</td>
<td>9.93 min$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$\eta_{\text{system}}$</td>
<td>67.76 %</td>
<td>68.01 %</td>
</tr>
</tbody>
</table>

### Experiment 2:

<table>
<thead>
<tr>
<th>Avg. $P_{\text{in}}$</th>
<th>Metric</th>
<th>Simulation</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>92.3 $\mu$W</td>
<td>Exec. Rate</td>
<td>9.93 min$^{-1}$</td>
<td>10.33 min$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$\eta_{\text{system}}$</td>
<td>66.11 %</td>
<td>68.82 %</td>
</tr>
</tbody>
</table>
Summary

Proposed Energy Management Unit (EMU):

- *Large* operating ranges (source/load decoupling)
- *Minimized* storage element, wake-up time, cold-start losses
- *Optimized* Power Point Tracking for source and load
- Feedback-based technique (Dynamic Energy Burst Scaling)