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Outlines

- Research Background
- Charge Redistribution of Supercapacitor
- Impact of Charge Redistribution on PW in WSN
- New PM algorithms to Reduce Charge Redistribution Loss
- Conclusions & Future work
Background

Energy Harvester
More than 500,000 life cycles
High Power Density
High charging/discharging efficiency

Energy Storage Device
Low Energy Density
Self discharge
Charge Redistribution
Motivation

• How to better use SC in harvesting aware WSN?

Previous Literatures:
- Empirical SC Model
- Leakage Power

Our Research:
- Variant Leakage Resistance (VLR) Model
- Charge Redistribution Loss
- Propose new PM algorithm to reduce Charge Redistribution Loss
Charge Redistribution of SC

- VLR---a simplified SC equivalent circuit model

\[ C_1 = C_0 + K_v \cdot V_{C1} \]

Self discharge

Voltage dependent capacitance

VLR model

Constant capacitance
### VLR parameters for different size of SC

<table>
<thead>
<tr>
<th>Capacitance (F)</th>
<th>Manufacturer</th>
<th>V$_{\text{nom}}$(V)</th>
<th>VLR Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>R$_1$(Ω)</td>
</tr>
<tr>
<td>10</td>
<td>Maxwell</td>
<td>2.7</td>
<td>0.067</td>
</tr>
<tr>
<td>50</td>
<td>Maxwell</td>
<td>2.7</td>
<td>0.014</td>
</tr>
</tbody>
</table>

For 10 F SC:

\[
R_3 = \begin{cases} 
  (-2.969V_{sc} + 8.043) \times 10^6 & 2.68 \leq V_{sc} \leq 2.7 \\
  (-5.515V_{sc} + 14.87) \times 10^6 & 2.662 \leq V_{sc} < 2.68 \\
  (-5.821V_{sc} + 15.66) \times 10^6 & 0 \leq V_{sc} < 2.662 
\end{cases}
\]

For 50 F SC:

\[
R_3 = \begin{cases} 
  (-1.942V_{sc} + 5.291) \times 10^6 & 2.666 \leq V_{sc} \leq 2.7 \\
  (-2.340V_{sc} + 6.354) \times 10^6 & 2.625 \leq V_{sc} < 2.666 \\
  (-3.656V_{sc} + 9.566) \times 10^6 & 0 \leq V_{sc} < 2.625 
\end{cases}
\]
• When $V_{C_1}$ and $V_{C_2}$ unbalances with each other, the charges stored in the SC begin to migrate from the high voltage branch to the lower one.

$P_{\text{chd}} = \frac{(V_{C_1} - V_{C_2})^2}{R_2}$

Larger SC tends to have smaller $R_2$, which causes higher charge redistribution loss with the same voltage difference.

Charge redistribution power of different sizes of SC
Long Term SC charge redistribution

- Algorithm 1: VLR based SC Simulation

Initialization: \( V_{sc}(t_0) \)
\( V_{c1}(t_0) \)
\( V_{c2}(t_0) \)

Start Simulation

Get Input:
- Harvesting Power \( P_{har} \)
- Sensor Node Power \( P_{node} \)

Update \( I_{R1}, I_{R2} \)

Update \( V_{c1}, V_{c2} \)

Update \( V_{sc} \)
Get \( P_{chd} \)

If reach simulation end condition

Simulation End

Increment time: \( t \leftarrow t + \Delta t \)
Simulation Configuration

- EH-WSN with Supercapacitor

\[ \overline{P_{\text{har}}} \cdot T = \sum_{i=1}^{K} P_i \cdot t_{di} \]

- Pulse-wised harvester profile

- Boost DC-DC converter

- Active mode: \( P_{\text{active}} \)
- Sleep mode: \( P_{\text{sleep}} \)
- Duty cycle: \( D \)
- Assigned with periodic tasks

\[ \overline{P_{\text{node}}} = D \cdot P_{\text{active}} + (1 - D) \cdot P_{\text{sleep}} \]
Harvesting Energy Trace:
- **phase**: the time that the charging pulse starts
- **$t_d$**: Duration of the pulse

Sensor Node Task Trace:
- **$t_{sch}$**: the time that the node start to execute

---

**Harvesting Energy Trace**

- **phase**: 8 s
- **$t_d$**: 10 s

**Task Trace**

- **$t_{sch}$**: 90 s
- **$D$**: 10%
- **$T$**: 100 s
Charge Redistribution Simulation--10F

- Harvesting Profile: fixed phase VS random phase
- Sensor Node: Lazy Scheduling

Charge Redistribution Loss Analysis for 10 F SC
Charge Redistribution Simulation—50F

Charge Redistribution Loss Analysis for 50 F SC

Conclusion: Random phase leads to more charge redistribution loss.
Alg. 1 Validation

Validation of the VLR based simulation model:

Using MACCOR Test System to validate the proposed algorithm 1.

MACCOR Test Platform

Algorithm 1 validation for 10 F Supercap in one hour

<table>
<thead>
<tr>
<th></th>
<th>Charge Redistribution Loss(J)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MACCOR Test</td>
</tr>
<tr>
<td>Fixed Phase</td>
<td>1.064</td>
</tr>
<tr>
<td>Random Phase</td>
<td>3.663</td>
</tr>
</tbody>
</table>
A snapshot into the simulation—Fixed Phase

(a) Harvesting profile

(b) Load Power

(c) V1 and V2 difference

(d) Charge redistribution power

Snapshot for the fixed phase harvesting profile
A snapshot into the simulation—Random Phase

(a) Harvesting profile

(b) Load Power

(c) V1 and V2 difference

(d) Charge redistribution power

Snapshot for the random phase harvesting profile
How to reduce charge redistribution loss?

• If task can be executed right after the charging pulse, charge redistribution loss will be reduced.

• We propose a pulse tracking algorithm to minimize charge redistribution loss.

• Objective: Low computational overhead; effective in tracking harvesting pulses;
Algorithm 2

- HW & SW combined method
- Guaranteed Eager Scheduling
- Put Sensor Node back to sleep as much as it can
Simulations:

Four Power Management strategies are tested under ENO condition:

No Power Management (PM)

Proposed Algorithm 2

Adaptive duty cycling

Hybrid (duty cycling and Alg. 2)

Simulation results of no PM and adaptive DC

Simulation results of Alg2 and Hybrid
One week test case

Power Consumption of Mobile Device

<table>
<thead>
<tr>
<th>Device</th>
<th>Power Consumption(mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mica2 Sensor Board</td>
<td>2.5</td>
</tr>
<tr>
<td>Atmega 128L(active)</td>
<td>24</td>
</tr>
<tr>
<td>CC2420(RX at 0 dbm mode)</td>
<td>63</td>
</tr>
<tr>
<td>MICA2 EEPROM(write)</td>
<td>61</td>
</tr>
<tr>
<td>Proximity(TDA0161)</td>
<td>420</td>
</tr>
<tr>
<td>Flow control(FCS-GL1)</td>
<td>1250</td>
</tr>
</tbody>
</table>

Power Management Algorithms

- No PM: 632.636
- Adaptive duty cycling: 60.699
- Algorithm 2: 38.142
- Hybrid(Alg. 2 and Adaptive duty cycling): 30.899

The hybrid Alg can save a lot!
Conclusion

• We propose VLR-based SC simulator to analyze charge redistribution loss.

• We demonstrate that charge redistribution loss can be accumulated to be considerably high.

• We propose a low overhead, wide applicable phase tracking algorithm to mitigate charge redistribution.
Future work

- What is Charge Redistribution Loss with real harvesting profile
• How Charge Redistribution Loss affect network performance?
What about energy dissipation of SC module?
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