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Energy Harvesting Research Group
University of Exeter
EH Research Group at Exeter

Critical mass:
- 1 RF and 3 ARF
- 3 PhD students+1 recruited
- 1 Lecturer recruited

Research Areas:
- Energy harvesting
- Power management
- Wireless sensing
- Modelling and simulation
- Integration & characterisation
Research Challenges on Integration for Wireless Sensing

- Limited energy harvested (mW range)
- Mismatches between:
  - Energy harvested and energy demanded
  - Harvester electric load and WSN electric load connected
- High power consumption of WSN
- High power consumption of PM unit
Initial Integration

Using off-the-shelf commercially available products and “plug and play” method do not work for the EH integration

For 600με at 10Hz, 3.44mW generated

V for 10mF
- 1.76V after 158s and then stable
- unable to reach 3.16V

Current for 10mF
- WSN is unable to start
- WSN unable to work
- No single transmission

Rectification + storage

Energy Harvester
Power Management Module
Transceiver
Microcontroller
Sensor 1
... Sensor n

Environmental vibrations

Capacitor
WSCN

0 50 100 150
0 0.1 0.2 0.3 0.4
Time (s)
Current (mA)
New System Architecture for Integration

Our strategies:

To **maximise** power extracted from harvesters:
Adaptive maximum power point (MPP) finding analogue circuit

To **manage** energy flow:
Autonomous energy-aware circuit and software

To **reduce** power consumptions
Introducing two interfaces and reducing complexity of circuits
Our Approach to MPP Finding

- Normal way is using sensing circuitry & μC
- Track the voltage charging profile of capacitor, $V_{HP}$
- Implemented by analogue control circuit (ACC) through $d/dt$ without sensing circuitry & μC

MPP in $V_{OC}/2$
MPP Performance of our Approach

Performance:
- Able to transfer MPP for variable vibrations and for any connected loads
- Tracking capability of up to 98.66%
- Consumes as little as 5.16 µW of power during operations
- Without start-up problem.
Our approach to energy flow management

Simple philosophy:
- There is vibration, we will harvest energy and store it without waste.
- Once enough energy is stored, we will use the energy to power WSNs.

How to implement: **smart switching** through energy-aware interface (EAI).

Pre-scheduled approach - time-based

Move to **energy-aware based**
How we developed the EAI

EAI benefits:

- Reduce the power consumption of WSNs during the sleep time down to about 1 μw.
- Allow harvested energy to be accumulated in the energy storage
- Allow to deal with mismatch of energy harvested and energy demanded
WSNs for Vibration Measurement

Wireless sensor nodes

Power hungry

A long active time
A number of data samplings within the active time for vibration measurement
Need a low power consumption

Reduction of power consumption

Active time
Sleeping time
Software to Reduce the power consumption

Start

WSN keeps non-active

N

V_{cc} \geq V_{threshold}

Y

Hardware EAI turns on the WSN

WSN starts to active

Take 1 reading from the humidity sensor

Take 1 reading from the temperature sensor

Take 48 readings from the accelerometer

Y

ECS is enough?

N

Transmit all the data to the base station

Reset the Hardware EAI

Hardware EAI turns off the WSN

Software EAI

Time(s)

Current(mA)

Initialization and calibration

Sample

Transmission

Software EAI

Hardware EAI
Strain Energy Harvester for Aircraft Wing

Piezoelectric transducer onto composite materials

Macro-Fibre Composite (MFC) [patented by NASA]

Advantages
- Flexible and durable
- Multifunction: energy generation, actuation/sensing
- Crack tolerant
- Conforms to curved surfaces
For structural health monitoring
Energy Harvested Powered WSNs in Lab

Receiver board with wireless microcontroller

Base station

Vibration powered WSN

Data transmitted
Multichannel and On-line Characterisation

Characterised performance:
- Energy generation from harvesters
- Energy consumption in the system
- Powering the WSN capability
Energy Generation and Consumption

For peak-to-peak strain loading of 600με at 10Hz
• An average power generated: 3.38 mW
• An average power delivered to WSN: 2.54 mW
• Sleep current → 1.26μA
• $\eta_{overall} = 75\%$
Powering WSN Capability

For 10mF, peak-to-peak strain loading of 600με at 10 Hz

After 26.69s, V reaches 3.16V, able to power the WSN for 1.16s after every 8.53s, i.e., 13.6% of duty cycle.

- 20.06mJ/active time
- $48 \times 6 + 2 = 290$ samplings @ 580 bytes (96*6+4)
- 34μJ/byte, including wake up, sampling and transmission
- Sensor current consumptions: 7.83μA (T), 7.42μA (H) and 12.45μA (A)
Comparisons of power with different Conf.

<table>
<thead>
<tr>
<th>Configurations</th>
<th>$\bar{P}_g$ (mW)</th>
<th>$\bar{P}_{rec}$ (mW)</th>
<th>$\bar{P}_c$ (mW)</th>
<th>$\eta_{rect}$ (%)</th>
<th>$\eta_{all}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFC+68.96kΩ</td>
<td>5.03</td>
<td>4.92</td>
<td></td>
<td>97.76</td>
<td>97.76</td>
</tr>
<tr>
<td>MFC+98 kΩ+22µF</td>
<td>3.44</td>
<td>3.34</td>
<td></td>
<td>97.15</td>
<td>97.15</td>
</tr>
<tr>
<td>10mF+MFC+EAI+WSN</td>
<td>0.50</td>
<td>0.35</td>
<td>0.35</td>
<td>70.00</td>
<td>70.00</td>
</tr>
<tr>
<td>10mF+MFC+PMM+EAI+WSN</td>
<td>3.38</td>
<td>3.34</td>
<td>2.53</td>
<td>99.00</td>
<td>75.00</td>
</tr>
</tbody>
</table>
## Comparisons of currents with and without EAI

<table>
<thead>
<tr>
<th>Conf.</th>
<th>WSS software</th>
<th>Performance</th>
<th>Average sleep current (µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MFC+PMM+EAI</td>
<td>Microcontroller in any sleep mode</td>
<td>WSS able to work</td>
<td>0.95</td>
</tr>
<tr>
<td>2 MFC without EAI</td>
<td>Microcontroller in sleep mode</td>
<td>$V_{CS}$ reaches ~1.2V, WSS unable to work</td>
<td></td>
</tr>
<tr>
<td>3 MFC+PMM without EAI</td>
<td>Microcontroller in sleep mode</td>
<td>$V_{CS}$ reach ~2V, WSS unable to work</td>
<td></td>
</tr>
<tr>
<td>4 DC Power Source + PMM+EAI</td>
<td>Microcontroller in sleep mode</td>
<td>WSS able to work</td>
<td>28.3</td>
</tr>
<tr>
<td>5 DC Power Source + PMM+EAI</td>
<td>Microcontroller in deep sleep mode</td>
<td>WSS able to work</td>
<td>17.3</td>
</tr>
</tbody>
</table>
Welcome to Energy Harvesting Demonstration Event at Exeter

Monday, 13\textsuperscript{th} Jun 2016
Acknowledgments

Engineering and Physical Sciences Research Council

Technology Strategy Board

SEVENTH FRAMEWORK PROGRAMME