Sub-threshold Operation and Cross-Hierarchy Design for Ultra Low Power Wearable Sensors

Benton H. Calhoun¹, Jonathan Bolus¹, Sudhanshu Khanna¹, Andrew D. Jurik², Alfred C. Weaver², Travis N. Blalock¹

¹Electrical and Computer Engineering, ²Computer Science, University of Virginia
Charlottesville, VA, USA
Thesis Statement for this Talk

• Observation:
  Sub-threshold digital circuits tend to be designed as standalone blocks

• Limitation:
  This approach limits savings to digital portion only

• THESIS STATEMENT:
  To get full benefits from sub-threshold digital circuits, we must CO-DESIGN them with the system in which they are deployed
Outline

• Body Area Sensor Networks (BASNs)
• Sub-threshold Circuits for BASNs
• Body Area Sensor Design
• Conclusions
## Generic Wireless Micro-sensor Nodes

### System Specifications

<table>
<thead>
<tr>
<th>Application Characteristics</th>
<th>Typical Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extended Lifetime</td>
<td>5 years+</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>100’s – 1000’s</td>
</tr>
<tr>
<td>Node Size</td>
<td>&lt;1 cm³</td>
</tr>
<tr>
<td>Energy</td>
<td>1000’s Joules</td>
</tr>
<tr>
<td>Clock Speed</td>
<td>1kHz – 1MHz</td>
</tr>
<tr>
<td>Avg. Power Requirement</td>
<td>~100 μW</td>
</tr>
</tbody>
</table>

Sub-$V_T$ perfect for long lifetimes on small energy!
Body Area Sensor Networks (BASNs)

- Sensors worn / implanted: Need long life, small
- Important factors for adoption (on top of technical barriers):
  - Perceived value
  - Safety / Fidelity
  - Ease of use
  - Privacy
  - Security

- Well-suited for Sub-$V_T$ operation

[IEEE Computer, Jan 2009]
BASN Node examples

- Special purpose nodes
- COTS
- Few IC deployments
### BASNs – NOT just another WSN

<table>
<thead>
<tr>
<th>Multipurpose Wireless Sensor Networks (WSNs)</th>
<th>Wearable Body Area Sensor Networks (BASNs)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Network Scale</strong></td>
<td>10s to 1000s of nodes over wide area; multi-hop communication; ad hoc placement</td>
</tr>
<tr>
<td></td>
<td>&lt;10 nodes; 1 hop communication; fixed placement; each node critical</td>
</tr>
<tr>
<td><strong>Lifetime</strong></td>
<td>Very long; rely on many nodes to bypass dead nodes</td>
</tr>
<tr>
<td></td>
<td>Mid to long; more conducive to periodic recharging</td>
</tr>
<tr>
<td><strong>Form factor</strong></td>
<td>Less crucial constraint</td>
</tr>
<tr>
<td></td>
<td>Must be unobtrusive; small, light, “invisible”</td>
</tr>
<tr>
<td><strong>Security</strong></td>
<td>Physical access to nodes defeats many security protocols</td>
</tr>
<tr>
<td></td>
<td>Nodes carry health info, so secure transmission is critical</td>
</tr>
</tbody>
</table>

[IEEE Computer, Jan 2009]
Gap and Opportunity

• Existing COTS BASNs energy inefficient
  – Lifetimes of <24 hours
• Need custom solutions
• Sub-threshold circuits are ideal technology, but what about other factors?

• How can we best leverage sub-threshold?
Outline

• Body Area Sensor Networks (BASNs)
• Sub-threshold Circuits for BASNs
• Body Area Sensor Design
• Conclusions
Sub-threshold Operation

- Sub-threshold logic operates with $V_{DD} < V_T$
- Both *on* and *off* current are sub-threshold “leakage”
Sub-Threshold Digital Circuits Overview

• 1972: Sub-threshold theorized for minimum $V_{DD}$ operation
  \cite{Swanson1972}

• Major challenges:
  – Reduced Ion/Ioff
  – Variation (local $V_T$ variation, especially)

• Last 5 years: sub-threshold demos
  – Logic
  – Memory (SRAM)
  – Micro-processors
Benefits of Sub-threshold

- Sub-threshold benefits: $V_{DD}$ from $[1.8,1.0]V$ to $[0.4,0.2]V$

Leakage Power Decreases: $\text{Power} = V_{DD} I_{\text{off}}$

$V_{DD}$ goes down: 2.5X to 9X

DIBL reduces $I_{\text{sub-threshold}}$: 2X to 10X

$I_{\text{gate}}$ and $I_{\text{GIDL}}$ become negligible

$P_{\text{leak}}$: 5X to 90X

Energy Consumption Decreases

$E_{\text{active}} = CV_{DD}^2$

$E_{\text{total/operation}}$ minimized in sub-$V_T$

Reliability Effects Improve

$E_{\text{total/operation}}$ minimized in sub-$V_T$

Main Limitation: Slow Speed, but OK for BASN

NBTI, EM, TDDB
Sub-$V_T$ Minimum Energy Operation

\[
E_{\text{Total}} = C_{\text{eff}} V_{DD}^2 + W_{\text{eff}} L_{DP} K C_g V_{DD}^2 e^{-\frac{V_{DD}}{nV_{th}}} = V_{DD}^2 \left( C_{\text{eff}} + W_{\text{eff}} K C_g L_{DP} e^{-\frac{V_{DD}}{nV_{th}}} \right)
\]

Assumes the circuit is always active
Technology Selection for BASNs

- Sleep periods are likely in BASNs
- Even with power gating (e.g. assume 10X reduction here), sleep energy contributes substantially to overall energy

<table>
<thead>
<tr>
<th>PTM (nm)</th>
<th>$T_{\text{sleep}=0}$</th>
<th>$T_{\text{on}} + T_{\text{sleep}=0.1\text{ms}}$</th>
<th>$T_{\text{on}} + T_{\text{sleep}=1\text{ms}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>107</td>
<td>107</td>
<td>129</td>
</tr>
<tr>
<td>65</td>
<td>77.7</td>
<td>85.5</td>
<td>147</td>
</tr>
<tr>
<td>45</td>
<td>58.4</td>
<td>69.8</td>
<td>193</td>
</tr>
<tr>
<td>32</td>
<td>47.2</td>
<td>84.0</td>
<td>428</td>
</tr>
<tr>
<td>22</td>
<td>41.2</td>
<td>222</td>
<td>1860</td>
</tr>
</tbody>
</table>
Technology Selection for BASNs

• Assuming 1000X reduction in sleep power, older technologies better for any substantial

• Use older nodes for BASNs
Outline

• Body Area Sensor Networks (BASNs)
• Sub-threshold Circuits for BASNs
• Body Area Sensor Design
• Conclusions
Example Wireless Electrocardiogram (ECG) System

• Medical goals – ambulatory ECG; identify cardiac arrhythmias, etc.
  – Doctor look at ECG waveform

• Technical Goal – build a BASN node to see system level issues; how to leverage sub-threshold circuits most effectively
ECG Monitoring System

- Patch has technical challenges
  - Long lifetime requirement
  - Small form factor, unobtrusive, comfortable
- Sub-threshold design!
  - Use sub-$V_T$ for digital parts, right?

ECG sensing “patch”

- Analog Front end
- ADC
- Digital Processing
- RF TX/RX

Existing networks
WLAN, web, etc.

Local Base Station
(e.g. PDA, body area aggregator)
Discrete Prototype: Wireless ECG

- Wireless ECG patch with COTS parts
- Base station client
- Secure web service
- Multiple user support
Discrete Prototype

- Streaming ECG data:
  - ~94mW
  - 93% in RF (Bluetooth)
  - 6% in analog (Frontend amp & ADC)
  - 1% in digital computation (MSP430)

- Data transmission is the problem
- Sub-$V_T$ processor would affect only 1% of system power
- We can make the digital consume ~0 of the system power – can “free” digital help?
  - Local goals (e.g. Patch lifetime)
  - System goals (e.g. Information collection / fidelity)
Revisit the ECG system: What are the goals?

• Goals of ECG Monitoring for the wearer:
  – Goal 1) Heart rate analysis

• Goals of ECG Monitoring for the wearer’s physician(s):
  – Goal 1) Heart rate analysis
  – Goal 2) Identify / Monitor cardio arrhythmias
  – Goal 3) View full ECG of arrhythmia events

• How to achieve Goal 1?
  – Need to extract heart rate from ECG signal
  – Could use digital processing

• How to achieve Goals 2 and 3?
  – Talk to some M.D.s ➔ It turns out that we can detect most arrhythmias of interest by processing heart rate
  – So, meet Goal 1 always and only send ECG when needed
System Partitioning: How to meet the goals?

Existing networks: WLAN, web, etc.

Local Base Station (e.g. PDA, body area aggregator)

ECG Sensor (Patch)

“Dumb sensor” approach

Data collection

Data aggregation

Information extraction

Information targeting

“Smart sensor” approach

Data collection

Information extraction

Information targeting

Flexibility to migrate tasks
System Partitioning: How to meet the goals?

“Smart sensor” approach

<table>
<thead>
<tr>
<th>Data collection</th>
<th>Data aggregation</th>
<th>Information extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Information extraction</td>
<td>Flexibility to migrate tasks</td>
<td>Information targeting</td>
</tr>
</tbody>
</table>

Beefier Processing
On-chip

- Heart rate detection on chip (e.g. modified Pan-Tompkins algorithm)
  - ~430X reduction in wireless data rate
- Compression
  - Additional 2X to 10X+ reduction
- On-board arrhythmia detection
  - Data rate approaches 0; bursts of high activity during events
- (Need a radio / protocol that scales energy with data rate)
Conclusions

• Wireless transmission is a power hog
• Need energy-scalable radio
• Processing on board can help
  – Smart node, not dumb
• Opportunity for sub-threshold
  – Cross hierarchy / system aware design

• What comes next?
Mixed Signal ECG System on Chip

ECG sensing “patch”

- Analog Front end
- ADC
- Digital Processing
- RF TX/RX

Analog frontend

2.3mm

1.5pJ/instr

[to appear at Symp. VLSI Circuits]

Leverage Sub-Vₚ processing by re-partitioning tasks at system level

Heart rate computation cuts wireless data rate by 500X
Thank you

• Any questions?