A Batteryless 19µW MICS/ISM-Band Energy Harvesting Body Area Sensor Node SoC

Fan Zhang, Yanqing Zhang, Jason Silver, Yousef Shakhsheer, Manohar Nagaraju, Alicia Klinefelter, Jagdish Pandey, James Boley, Eric Carlson, Aatmesh Shrivastava, Brian Otis, Benton Calhoun

University of Washington, Seattle, WA
University of Virginia, Charlottesville, VA
• Wireless body area sensor nodes (BASN) enable inexpensive continuous monitoring of patients
• Battery replacement for body-worn devices may not be feasible or desirable
Commercial-off-the-shelf (COTS) wireless BASN

Other Components: Amplifiers, ADC, Power, Interface

- $P_{AVG} > 20$ mW (continuous transmission)
- $< 2$ hours of battery life (33mAh)
Custom low-power BASN IC

- Digitize & transmit ECG, EMG, neural data
- No signal processing
- Battery life: 3 days (100% duty cycle (DC))

Rai, ISSCC 2009. Morrison, DAC 2010
Opportunity: energy harvesting

On-body measurement of COTS thermoelectric generator (TEG) (4 x 4 cm²)

Room Temp

6°C

Output Voltage (V)

Load Resistance (Ω)

- Forearm
- Back of Neck
- Chest
- Shoulder
- Abdomen
- Lower Abdomen
- Lower Thigh
- Lower Back
- Upper Calf
Opportunity: energy harvesting

On-body measurement of COTS thermoelectric generator (TEG) (4 x 4 cm²)

Room Temp

~60µW

6°C

~200µW

Output Voltage (V)

Load Resistance (Ω)

5 10 50 100 1 k

5 10 50 100 1 k

Forearm
Back of Neck
Chest
Shoulder
Abdomen
Lower Thigh
Lower Back
Upper Calf
Our proposed solution

**CONVENTIONAL:**
- Battery
- No signal processing
- Transmission at 100% DC

**PROPOSED:**
- *NO* battery $\rightarrow$ harvest power
- Extract information
- Selective transmission
Functional diagram

**POWER MANAGEMENT**
- $V_{\text{BOOST}}$
- Monitor
- Stoplight
- Regulate

**DPM: Digital Power Management**
- DPM

**SIGNAL PATH**
- AFE
- Processing
- RF

**ENERGY HARVESTING**
- TEG
- Boost
- ROM Boot

**AFE: Analog Front-End**
Startup and energy harvesting

**ENERGY HARVESTING**
- TEG
- Boost
- ROM Boot

**POWER MANAGEMENT**
- $V_{\text{BOOST}}$ Monitor
- Stoppight
- Regulate

**DPM**

**SIGNAL PATH**
- AFE
- Processing
- RF

RF-kick
Startup and energy harvesting

Energy Harvesting:
- TEG
- Boost
- ROM Boot

RF-kick
POR

Power Management:
- $V_{\text{BOOST}}$ Monitor
- Stoplight
- Regulate
- DPM

Signal Path:
- AFE
- Processing
- RF
Signal processing path

ENERGY HARVESTING
- TEG
- Boost
- ROM Boot

POWER MANAGEMENT
- $V_{\text{BOOST Monitor}}$
- Stoplight
- Regulate

DPM

SIGNAL PATH
- AFE
- Processing
- RF
Signal processing path

**ENERGY HARVESTING**
- TEG
- Boost
- ROM
- Boot

**POWER MANAGEMENT**
- $V_{BOOST}$ Monitor
- Stoplight
- Regulate

**SIGNAL PATH**
- DPM
- Processing
- AFE
- RF

Flexible signal path
Power management

**POWER MANAGEMENT**

- $V_{\text{BOOST Monitor}}$
- Stoplight
- Regulate
- DPM

**ENERGY HARVESTING**

- TEG
- Boost
- ROM Boot

**SIGNAL PATH**

- AFE
- Processing
- RF
Power management

**POWER MANAGEMENT**

- $V_{\text{BOOST}}$ Monitor
- Stoplight
- Regulate
- DPM

**ENERGY HARVESTING**

- TEG
- Boost
- ROM Boot

**SIGNAL PATH**

- AFE
- Processing
- RF
Energy harvesting
Hybrid energy harvesting

Capable of thermal, photovoltaic, and/or RF energy harvesting
• Measured efficiency of 38% for $V_{in} = 30\text{mV}$, $V_{out} = 1.35\text{V}$
• Requires minimum voltage ($V_{KILL}$) to sustain conversion
Wireless RF pulse provides one-time kick-start
The node runs indefinitely thereafter
Boot-up sequence

- POR issues reset at 1.0V
- Upon boot-up, the chip fetches instructions from the ROM (default) or the RAM
- If $V_{\text{BOOST}} < V_{\text{KILL}}$, RF burst can ‘revive’ chip to default algorithm in ROM
Analog front-end (AFE)

1 of 4 channels

- Chopper-stabilized low-noise amp
- Variable-gain amp
- 6 programmable gain 40 – 78 dB
- 3 µW / channel
Flexible signal path

Data processing

- Generic Path
  - MCU: microcontroller

- Example Custom Path
  - FIR
  - RR + AFib

- Example of Mixed Path
  - FIR
  - ENV Detect
  - MCU

Data transmission

- Stream
  - Processed Data
  - 4kB DMem

- Store and Burst
  - Data for TX
  - 4kB DMem

- Event-Based Burst
  - If event

- Data transmission: supports modes from streaming (100% DC) to rare event detection (~0% DC)

- Data processing: max flexibility (generic path) or max efficiency (biosignal accelerators)
Energy efficient accelerators

**Accelerators:**
- Programmable FIR
- Heart rate (R-R) extraction
- Atrial Fibrillation (AFib) detection
- Band energy extraction
- Direct memory access (DMA)
- Packetizer

**Energy Efficiency / Sample**

<table>
<thead>
<tr>
<th></th>
<th>MCU</th>
<th>Accel</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 Tap FIR</td>
<td>6.3 nJ</td>
<td>57.6 pJ</td>
</tr>
<tr>
<td>Env. Detect</td>
<td>3.6 nJ</td>
<td>530 fJ</td>
</tr>
<tr>
<td>R-R Extract</td>
<td>12 pJ</td>
<td>3 fJ</td>
</tr>
</tbody>
</table>

- 110x
- 6800x
- 4000x
DPM: signal path control

- Chip program
- Power and Channel control
- IMEM
- SAMPLING RATE CONTROL
- Digitized V_{BOOST}
- Power/clock gate, clock rate, and bus control
- Duty cycle, data rate control
- LNA
- V_{BOOST}
- VGA
- ADC
- DMA/SRAM
- Bio-signal Accelerators
- Packetizer
MCU vs. DPM

- Execution of instructions toggles automatically between MCU and DPM.

<table>
<thead>
<tr>
<th>Operation</th>
<th>DPM Energy</th>
<th>MCU Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOP</td>
<td>0.7 pJ</td>
<td>1.46 pJ</td>
</tr>
<tr>
<td>Control Signals</td>
<td>2.8 pJ</td>
<td>2.92 pJ</td>
</tr>
<tr>
<td>Branch Commands</td>
<td>2.9 pJ</td>
<td>4.38 pJ</td>
</tr>
</tbody>
</table>
Frequency multiplying TX

- Frequency multiplication:
  synthesis at low frequency, transmission at high frequency
- Edge-combiner based frequency multiplier
  - ILRO-based edge generator
  - PA integrates the edge combiner

Pandey, Otis, JSSC’11
• Quartz reference clock is pulled using $\Delta C$ (~200ppm)
• $\Delta f$ is multiplied by 9x (~100kHz)
Power management
Voltage regulation

V\textsubscript{BOOST}: 1.35V

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2V</td>
<td>PADS, AFE</td>
</tr>
<tr>
<td>1.0V</td>
<td>TX LO</td>
</tr>
<tr>
<td>0.5V</td>
<td>TX PA</td>
</tr>
<tr>
<td>0.5V</td>
<td>DPM, MEM, ACCEL</td>
</tr>
<tr>
<td>Variable</td>
<td>0.25-1.0V in 50mV, enabling DVS.</td>
</tr>
</tbody>
</table>
- $V_{BOOST}$ is scaled and digitized
- DPM compares $V_{BOOST}$ vs. $V_{THR}$ (programmable)
- DPM chooses reconfigurable modes ("stoplight")
Closed-loop power management

- **V_{TEG} (V)**
- **Supply (V)**
- **VGA Out (V)**
- **TX Duty-Cycle**

Time (s)

**Stoplight**

<table>
<thead>
<tr>
<th>MODES</th>
<th>AFE</th>
<th>Process</th>
<th>Data Mem.</th>
<th>Inst. Mem.</th>
<th>Transmit</th>
<th>(V_{THR})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>1.35 V</td>
</tr>
<tr>
<td>Yellow</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>x/✓</td>
<td>1.3 V</td>
</tr>
<tr>
<td>Red</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>x</td>
<td>0.9 V</td>
</tr>
</tbody>
</table>

\(V_{DD, AFE} \rightarrow V_{Boost}\)
• ECG signal measured from a healthy human subject
• Wireless link demonstrated between the custom IC and a commercial receiver (TI CC1101)
• $397 \ \mu W$ from $V_{BOOST}$
R-R interval extraction of ECG

- Every 5s, $V_{\text{BOOST}}$ is sampled to check for sufficient energy
- DPM enables RF crystal oscillator (20ms) and TX (650µs)
- 19 µW from $V_{\text{BOOST}}$
- Powered from a 30mV input
AFib detection of ECG

- When a rare AFib occurs, TX is enabled to transmit the last 8 beats of ECG (in the data memory).
- 19 µW from $V_{\text{BOOST}}$
- Powered from a 30mV input
Selective transmission

- Battery-free with TEGs today

- Selective TX and ULP circuits enable energy harvesting

With next-generation TEGs

TX DC: 0.013%
SoC die photo

0.13 µm CMOS

2.5 mm

3.3 mm
## Comparison with prior work

<table>
<thead>
<tr>
<th></th>
<th>This Work</th>
<th>Kim VLSI'11</th>
<th>Rai ISSCC’09</th>
<th>Verma JSSC’10</th>
<th>Yan JSSC'11</th>
<th>Chen ISSCC’10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensors</strong></td>
<td>ECG, EMG, EEG</td>
<td>ECG</td>
<td>Neural, ECG, EMG, EEG</td>
<td>EEG</td>
<td>ECG, TIV</td>
<td>Temp, Pressure</td>
</tr>
<tr>
<td><strong>Supply Voltage</strong></td>
<td>30 mV, -10 dBm</td>
<td>1.2 V</td>
<td>1 V</td>
<td>1 V</td>
<td>1.2 V</td>
<td>0.4/0.5 V</td>
</tr>
<tr>
<td><strong>E Harvesting</strong></td>
<td>Thermal, RF</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>Solar</td>
</tr>
<tr>
<td><strong>Supply Reg.</strong></td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td><strong>AFE</strong></td>
<td>4-ch</td>
<td>3-ch</td>
<td>1-ch</td>
<td>18-ch</td>
<td>4-ch</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>TX datarate</strong></td>
<td>200 kb/s</td>
<td>✗</td>
<td>100 kb/s</td>
<td>✗</td>
<td>1 Mbps</td>
<td>(On-body link)</td>
</tr>
<tr>
<td><strong>TX P&lt;sub&gt;DC&lt;/sub&gt;</strong> (100% on)</td>
<td>160 μW</td>
<td>✗</td>
<td>400 μW</td>
<td>✗</td>
<td>2.8 mW</td>
<td>✗</td>
</tr>
<tr>
<td><strong>TX P&lt;sub&gt;OUT&lt;/sub&gt;</strong></td>
<td>-18.5 dBm</td>
<td>✗</td>
<td>-16 dBm</td>
<td>✗</td>
<td>-6 dBm</td>
<td>✗</td>
</tr>
<tr>
<td><strong>TX band</strong></td>
<td>402 / 433 MHz</td>
<td>✗</td>
<td>402 / 433 MHz</td>
<td>✗</td>
<td>20-40 MHz</td>
<td>✗</td>
</tr>
<tr>
<td><strong>Power Mgmt.</strong></td>
<td>Clock + Power gating, DPM</td>
<td>✓</td>
<td>Clock gating</td>
<td>✗</td>
<td>✗</td>
<td>Power gating</td>
</tr>
<tr>
<td><strong>DVS</strong></td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td></td>
<td>This Work</td>
<td>Kim VLSI’11</td>
<td>Rai ISSCC’09</td>
<td>Verma JSSC’10</td>
<td>Yan JSSC’11</td>
<td>Chen ISSCC’10</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-----------</td>
<td>-------------</td>
<td>-------------</td>
<td>---------------</td>
<td>-------------</td>
<td>--------------</td>
</tr>
<tr>
<td><strong>Micro-processor</strong></td>
<td>1.5 pJ/Inst 200kHz (8b RISC ISA)</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>28.9 pJ/Inst 73kHz (32b COR-M3)</td>
</tr>
<tr>
<td><strong>Accelerator</strong></td>
<td>Prog. FIR, AFIB, DMA, Env. Det., Packetizer</td>
<td>4x SIMD, FIR, DMA, Encryption</td>
<td>✗</td>
<td>ASIC DSP</td>
<td>FIR, Packetizer, Compression</td>
<td>✗</td>
</tr>
<tr>
<td><strong>Memory</strong></td>
<td>5.5kB (0.3-0.7V)</td>
<td>42kB (1.2V)</td>
<td>✗</td>
<td>✗</td>
<td>20kB (1.2V)</td>
<td>5kB (0.4V)</td>
</tr>
<tr>
<td><strong>Dig. Power</strong></td>
<td>2.1µW</td>
<td>~12µW</td>
<td>N/A</td>
<td>2.1µW</td>
<td>500µW</td>
<td>2.1µW (MCU)</td>
</tr>
<tr>
<td><strong>Total Power</strong></td>
<td>19µW</td>
<td>31.1µW</td>
<td>500µW</td>
<td>77.1µW</td>
<td>2.4mW</td>
<td>7.7µW</td>
</tr>
<tr>
<td><strong>Note on Total Power</strong></td>
<td>8b ADC, DSP (R-R extract), TX at 0.013% DC</td>
<td>12b ADC, DSP (heart beat detection)</td>
<td>8b ADC, TX at 100% DC</td>
<td>12b ADC, DSP (EEG feature extraction)</td>
<td>10b ADC, DSP (data comp, FIR), SRAM, TX at 5% DC</td>
<td>Data acquisition, DSP (DFT), SRAM</td>
</tr>
<tr>
<td><strong>Technology</strong></td>
<td>130nm</td>
<td>180nm</td>
<td>130nm</td>
<td>180nm</td>
<td>180nm</td>
<td>180nm</td>
</tr>
</tbody>
</table>
Conclusion

1. First wireless biosignal processing chip powered solely from a TEG with RF kickstart enabling battery-free operation

2. Our chip integrates state-of-the-art MICS/ISM transmitter, AFE, powertrain, and biosignal accelerators

3. These blocks are intelligently controlled to enable programmable datapath and closed-loop power management
Thank you!