Towards Self-Powered Wireless Biomedical Devices

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Outlines

• An introduction to Wireless Body Sensor networks
• Self-powered wireless sensor devices: a dream or reality?
• Challenges in the design of self-powered sensors and possible solutions
• Some design examples of low power wireless biomedical sensors
• Conclusions

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Wireless Body Sensor Networks

- A latest evolution of healthcare system.
- Seamless integration with home, working, and hospital environments.


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Wireless Biomedical Sensors (WBS)

- Sensor types: wearable/injectable/ingestible/implantable
- Function: context-sensitive measurement of parameters leading to faster acquisition of accurate and actionable information

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Wireless Health

• The use of body sensor networks to facilitate personalized and prevention-oriented healthcare
• Reducing healthcare cost in ageing society
• Improving productivities for healthcare providers, patients, and payers.
• Huge market size and potential new market segment in wireless health

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Estimated Market Size for Wireless Health

• Current wireless home health market: around $304 million
• Expected to grow to: $4.4 billion in 2013 with estimated growth rates of 96% in 2010, 126% in 2011, 95% in 2012 according to CTIA(The Wireless Association)
• Expected wireless wearable sensors: more than 400 million devices by 2014 and revenue around $5 billion according ABI Research.

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Self-Powered Wireless Biomedical Sensor: a Dream or Reality?

• Available commercial wireless sensors

<table>
<thead>
<tr>
<th>Platform</th>
<th>Power(Rx/Tx)</th>
<th>Sleep power</th>
</tr>
</thead>
<tbody>
<tr>
<td>TelosB</td>
<td>18.8/17.4 mA</td>
<td>0.02-426 µA</td>
</tr>
<tr>
<td>MicaZ</td>
<td>18.8/17.4 mA</td>
<td>0.02-426 µA</td>
</tr>
<tr>
<td>SHIMMER</td>
<td>40/60 mA</td>
<td>50-1400 µA</td>
</tr>
<tr>
<td>IRIS</td>
<td>15.5/16.5 mA</td>
<td>20 nA</td>
</tr>
<tr>
<td>Sun SPOT</td>
<td>18.8/17.4 mA</td>
<td>0.02-426 µA</td>
</tr>
</tbody>
</table>

Two key limitations:
• Size and capacity
• Lifetime

Energy Harvesting

• Energy harvesting options

<table>
<thead>
<tr>
<th>Type</th>
<th>Energy sources</th>
<th>Power density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiant</td>
<td>Photovoltaic</td>
<td>12000µW/cm²</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Electrostatic, piezoelectric</td>
<td>3.89µ-830µW/cm³</td>
</tr>
<tr>
<td>Thermal</td>
<td>Thermoelectric</td>
<td>2000µW/cm² @12°C gradient</td>
</tr>
<tr>
<td>Magnetic</td>
<td>Electromagnetic</td>
<td>0.01µ-0.3µW/cm²</td>
</tr>
<tr>
<td>Chemical</td>
<td>Glucose</td>
<td>2-4mW/cm²</td>
</tr>
</tbody>
</table>

ThermoLife®
(5 °C gradient: 30 µW).

IMEC Wrist
TEG(300µW at 22°C).

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Human Energy Scavenging

- Wearable devices can generate 0.3mW – 8 W from breathing, finger motion, blood pressure, body heat, walking.
- Implantable nanowire devices:
  - Current density: ~8.9nA/cm²
  - Output voltage: ~96mV
  - Power density: 2.7mW/cm³


Challenges in Designing of Self-Powered WBS
Challenges in Designing of Self-Powered WBS

- Complicated system contains analog, mixed-signal, digital, RF, and power blocks.
- Energy scavenging from body and ambient are unstable.
- Limited power budget
  - Less than few mW for wearable devices.
  - Less than 1 mW for implants

Possible Solutions

- Asynchronous architecture.
- Sub-threshold circuits.
- Wireless communication using human body – intra body communication.
  - Event driven ADC with continuous-time digital signal processing achieves upto 80% dynamic power saving in terms of number digital outputs for audio signals.


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Design Examples

- 1-V 450nW programmable ECG sensor interface
- 1-V 2.3µW ECG-on-Chip
- 1-V 22µW 32-channel ECoG chip
- 0.5V 18µW 16-channel neural recording chip
- 250mV digital filter for QRS detection

NanoWatt ECG Recording Chip

- Fully integrated, configurable chip for ECG recording
- 450 to 900nW
- Low voltage on-chip tunable band-pass filter (4.5mHz-290Hz)
- Programmable
- 12-bit ADC
- On-chip oscillator

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Measured Performance of ECG Chip

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Voltage</td>
<td>1 V</td>
</tr>
<tr>
<td>Core Current</td>
<td>450 nA (QRS mode)</td>
</tr>
<tr>
<td>3 dB Bandwidth</td>
<td>4.5 mHz ~ 292 Hz (Tunable)</td>
</tr>
<tr>
<td>Mid-band Gain</td>
<td>45.6 / 49 / 53.5 / 60 dB</td>
</tr>
<tr>
<td>Input Referred Noise</td>
<td>&lt; 0.6% (@ full output swing)</td>
</tr>
<tr>
<td>Amplifier THD</td>
<td>&gt; 71.2 dB</td>
</tr>
<tr>
<td>CMRR</td>
<td>&gt; 84 dB</td>
</tr>
<tr>
<td>PSRR</td>
<td>12 bits</td>
</tr>
<tr>
<td>ADC Resolution</td>
<td>&lt; ±0.8 LSB</td>
</tr>
<tr>
<td>ADC Sampling Rate</td>
<td>&lt; ±1.4 LSB</td>
</tr>
<tr>
<td>ADC SFDR</td>
<td>74 dB</td>
</tr>
<tr>
<td>ADC SNDR</td>
<td>63 dB</td>
</tr>
</tbody>
</table>

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Performance Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Yin'07</th>
<th>Wattanapanitch'07</th>
<th>Wu'06</th>
<th>NUS ECG Chip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage</td>
<td>±1.7 V</td>
<td>2.8 V</td>
<td>1 V</td>
<td>1 V</td>
</tr>
<tr>
<td>Process Technology</td>
<td>1.5 µm CMOS</td>
<td>0.5 µm CMOS</td>
<td>0.35 µm CMOS</td>
<td>0.35 µm CMOS</td>
</tr>
<tr>
<td>Current (TB-FEA)</td>
<td>8 µA</td>
<td>743 nA</td>
<td>330 nA</td>
<td>337 nA</td>
</tr>
<tr>
<td>Mid-band Gain</td>
<td>39.3 / 45.6 dB</td>
<td>40.9 dB</td>
<td>40.2 dB</td>
<td>45.6 / 49 / 53.5 / 60 dB</td>
</tr>
<tr>
<td>-3 dB BPF Bandwidth</td>
<td>0.015 Hz ~ 4 kHz (Tunable)</td>
<td>0.392 Hz ~ 295 Hz (Fixed)</td>
<td>0.003 Hz ~ 245 Hz (Fixed)</td>
<td>0.0045 Hz ~ 292 Hz (Tunable)</td>
</tr>
<tr>
<td>Input Referred Noise</td>
<td>3.6 µVrms</td>
<td>1.66 µVrms</td>
<td>2.7 µVrms</td>
<td>2.04 µVrms</td>
</tr>
<tr>
<td>Noise Efficiency Factor</td>
<td>4.9</td>
<td>3.21</td>
<td>3.8</td>
<td>2.66</td>
</tr>
<tr>
<td>Output @ 1% THD</td>
<td>~48% Full Swing</td>
<td>~29% Full Swing</td>
<td>~85% Full Swing</td>
<td>100% Full Swing</td>
</tr>
<tr>
<td>CMRR</td>
<td>N/A</td>
<td>66 dB</td>
<td>64 dB</td>
<td>≥71.2 dB</td>
</tr>
<tr>
<td>PSRR</td>
<td>N/A</td>
<td>75 dB</td>
<td>62 ~ 63 dB</td>
<td>≥84 dB</td>
</tr>
<tr>
<td>ADC Resolution</td>
<td>N/A</td>
<td>N/A</td>
<td>11-bit</td>
<td>12-bit</td>
</tr>
<tr>
<td>ADC Sampling Rate</td>
<td>N/A</td>
<td>N/A</td>
<td>1 KS/s</td>
<td>1 KS/s</td>
</tr>
<tr>
<td>ADC DNL</td>
<td>N/A</td>
<td>N/A</td>
<td>&lt;±1.5 LSB</td>
<td>&lt;±0.8 LSB</td>
</tr>
<tr>
<td>ADC INL</td>
<td>N/A</td>
<td>N/A</td>
<td>&lt;±2 LSB</td>
<td>&lt;±1.4 LSB</td>
</tr>
<tr>
<td>Total Power</td>
<td>27.2 µW (Amplifier)</td>
<td>2.08 µW (Amplifier)</td>
<td>2.3 µW</td>
<td>445 nW ~ 895 nW</td>
</tr>
</tbody>
</table>

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**ECG-on-Chip**

- 2.3 μW fully integrated programmable ECG chip for signal conditioning, ADC, QRS detection, memory, and MCU interface

<table>
<thead>
<tr>
<th>Analog Frontend</th>
<th>Supply Voltage</th>
<th>1.0 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pass-band</td>
<td>0.05 ~ 100 Hz</td>
<td></td>
</tr>
<tr>
<td>Gain</td>
<td>46 ~ 60 dB</td>
<td></td>
</tr>
<tr>
<td>Input-referred</td>
<td>2.5 μV rms (0.05 ~ 460 Hz)</td>
<td></td>
</tr>
<tr>
<td>Noise</td>
<td>&lt; 0.6%</td>
<td></td>
</tr>
<tr>
<td>THD @ FS Output</td>
<td>&lt; 0.6%</td>
<td></td>
</tr>
<tr>
<td>Sampling Freq</td>
<td>256 Hz</td>
<td></td>
</tr>
<tr>
<td>ADC ENOB</td>
<td>&gt; 10.2</td>
<td></td>
</tr>
<tr>
<td>Power @ 1.0 V</td>
<td>0.75 μW</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>QRS + FIFO + SPI + PO</th>
<th>Supply Voltage</th>
<th>1.5 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal SRAM</td>
<td>2 Kb</td>
<td></td>
</tr>
<tr>
<td>Interface</td>
<td>SPI slave &amp; master</td>
<td></td>
</tr>
<tr>
<td>Power @ 1.5 V</td>
<td>1.5 μW</td>
<td></td>
</tr>
</tbody>
</table>

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**Application (1): Wireless ECG Plaster**

![Diagram of Wireless ECG Plaster system](image)

1. ECG Plaster
2. Wireless Adapter
3. Smart Phone Software

- Electrode
- Smart Medical Chip
- Telemmedicine
- Remote Monitoring Center
- Medical Server
- 3G/WiFi
- Internet

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Prototype of NUS ECG Sensor

- ECG data received by PDA
- Wearable ECG Device
- Detected QRS and heart rate

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Detection of QRS for Exercise ECG under Running by NUS Algorithm (NanoWatt)

- Original ECG
- Detected QRS

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32-Channel EEG Chip

- 32-channel EEG recording chip (lowest power consumption < 20µW)
- Reconfigurable with amplifiers, filters, 10-bit ADC
- Intracranial EEG recording (ECoG)

Applications: Wearable EEG Sensor

- Wearable wireless EEG for seizure detection, brain-computer-interface, gaming, education, cognitive enhancement.

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Multi-Channel Neural Recording Chip

- 0.5V 18-μW 16-Channel chip for implantable neural recording
- 10kHz bandwidth with on-chip filter, programmable gain, and 10-bit ADC
- Power consumption: 30 times less than current state of the art.

A Design Example: Sub-1 mW Wireless ECoG Sensor

- Applications
  - Prediction of seizure and monitoring of epilepsy patients, deep brain stimulation, and Brain-Computer-Interface
- Implantable ECoG requirements:
  - Low noise(<1.5μV_{rms}) and low power
  - Multiple channels: at least 32-channel
  - Small chip area and long battery life
Wireless ECoG Sensor

Sensor Front-End

Programmable Multi-channel amplifier

Tunable filter

ADC

Transceiver

Electrodes

Microprocessor

Memory

Power management unit

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Front-End Architecture

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Low Power Low Noise Preamplifier

- Fully balanced tunable pseudo-resistors
- Low signal distortion

Challenges on SAR ADC

- Low supply voltage → rail-to-rail range to boost SNDR.
- To support multiple channels → sufficient input BW.
- Power limited application → energy efficient.
Dual-Capacitive-Array SAR ADC

- A hybrid between the two conventional designs.
- Additional S/H array for quantization.
  - First 5 bits (MSB) are obtained from 5-bit S/H array
  - Remaining 5 bits from 10-bit DAC array

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Performance Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dension’07</th>
<th>Yazicioglu’08</th>
<th>Zou’08</th>
<th>This work*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply voltage</td>
<td>1.8 V</td>
<td>3 V</td>
<td>1 V</td>
<td>1 V</td>
</tr>
<tr>
<td>Process</td>
<td>0.8 µm CMOS</td>
<td>0.5 µm CMOS</td>
<td>0.35 µm CMOS</td>
<td>0.35 µm CMOS</td>
</tr>
<tr>
<td>Current (front-end amplifier)</td>
<td>1.2 µA</td>
<td>2.3 µA</td>
<td>337 nA</td>
<td>385 nA</td>
</tr>
<tr>
<td>Input referred noise</td>
<td>0.93 µV (0.5~100 Hz)</td>
<td>0.57 µV (0.5~100 Hz)</td>
<td>2.04 µV (0.05~300 Hz)</td>
<td>1.15 µV (0.5~150 Hz)</td>
</tr>
<tr>
<td>NEF</td>
<td>4.9</td>
<td>4.1</td>
<td>2.66</td>
<td>2.24</td>
</tr>
<tr>
<td>ADC resolution/ Sampling rate</td>
<td>--</td>
<td>11-bit / 8 kS/s</td>
<td>12-bit / 1 kS/s</td>
<td>10-bit / 10 kS/s</td>
</tr>
<tr>
<td>Total power</td>
<td>2.2 µW</td>
<td>198 µW</td>
<td>0.9 µW</td>
<td>22 µW</td>
</tr>
<tr>
<td>No. of channel</td>
<td>1</td>
<td>8</td>
<td>1</td>
<td>32</td>
</tr>
<tr>
<td>Average power per channel</td>
<td>2.2 µW (amplifier)</td>
<td>24.75 µW</td>
<td>0.9 µW</td>
<td>0.69 µW</td>
</tr>
<tr>
<td>Area per channel (analog part only)</td>
<td>1.4 mm²</td>
<td>0.45 mm²</td>
<td>0.64 mm²</td>
<td>0.08 mm²</td>
</tr>
</tbody>
</table>

*ISSCC2010

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Sub-mW Wireless Transceiver

- ECoG front-end consumes only 22µW (NanoWatt per channel)
- Most power goes to wireless transceiver, e.g. 20mW++ for commercially available wireless transceiver (ZigBee).
- Sub-mW wireless transceiver is necessary for implantable solution → reduced battery size or extended battery life.

Proposed Pulse-Based Ultra-Wideband Transceiver

To turn LNA “ON” or “OFF”

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Conclusions

- It is possible to design self-powered wireless biomedical sensors for both wearable and implantable applications.
- Many challenges in system architecture, low voltage circuit techniques.
- Call for revolutionary signal processing flow that improves energy efficiency.
- Be aware of challenges beyond CMOS: system integration, packaging, etc.
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Thank You.

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