Ultra-low-Power Networked Systems

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Wireless Vision: 1990

Set-top box doubles as basestation and gateway from WAN

Allows family and personal use of set-top box access

1990 WINLAB workshop on Third Generation Wireless Information Networks

Prof. R. Brodersen, BWRC
Parallelism = Energy Efficiency

A. Chandrakasan, S. Sheng, R. Brodersen, “Low-power Digital CMOS Design” (April 1992)

“slower is better”

The InfoPad (Anantha Chandrakasan, Robert Brodersen, et al.) – ISSCC 1994

6 ICs < 2mW

Research ICs: mW (1990) ⇒ μW (current) ⇒ nW (future)
Energy Efficiency is Still a Key Consideration

Deep Brain Stimulator

Battery lasts about 5 years - surgery needed to replace it!

Energy Efficiency Impacts Time Between Surgery
Self-Powered Connected Personal Health

Enable a New Class of Bio-Medical Systems that Leverage the Power of Silicon and Nanotechnology
Key Enablers of Internet of Everything

- Tremendous advances in commercial low-power electronics – ultra-low-power sensors, radios, signal processing, energy harvesting
- Cost reduction of electronic components
- Simple interfaces – easy access through smartphone apps (medical, fitness, energy, etc.)
- Standards for internet-of-things
- Compelling applications that matter to the end users – e.g., fitbit and fitness monitors
Vibration-to-Electric Energy

Self-powered Wireless Corrosion Monitoring Sensors

Piezoelectric Micro-Power Generators

Power Converter

Sang-Gook Kim (MIT)

10μW - 100μW generated

Vibrations Power Distributed Sensor Devices (Battery-less Operation)
Body Heat Powered Electronics

System Concept

Thermo-Electric Devices

Thermal Energy Chip

Future ULP Electronics (e.g., body worn sensors) Can be Powered from Body Heat

[Y. Ramadass and A. Chandrakasan, ISSCC 2010]
Energy Combining: Solar, Thermal, Vibrations

- Shared inductor minimizes board components
## Multi-Input Energy Harvesting Design

### Summary

<table>
<thead>
<tr>
<th>Technology</th>
<th>0.35µm CMOS</th>
</tr>
</thead>
</table>
| **Input Voltages**  | 20 - 150mV Thermal  
                      | 0.2 - 0.75V Solar         
                      | 1.5 – 5V Piezoelectric   |
| **Output Voltages** | 1.8V Regulated            
                      | 1.8 - 3.3V Storage        |
| **Passives**        | 1 Inductor (22µH)  
                      | 5 capacitors              |
| **Thermal**         | Seebeck 50mV/K, ΔT=1.7K   |
| **Solar**           | 1500lux, 15cm²            |
| **Piezoelectric**   | PZT 3in², 1g              |
| **Thermal Boost**   | 96µW                      |
| **Solar Boost**     | 262µW                     |
| **Piezoelectric Buck-Boost** | 40µW                  |
| **Total Power**     | 398µW                     |

[Bandyopadhyay, JSSC 2012]
A (New) energy harvesting source: inside the inner-ear

Can we tap the energy reservoir in the **endocochlear potential** to power electronics?
Endocochlear Potential circuit model

Maximum energy extraction  
→ maximum power transfer  
→ Set $R_{in} = R_{elec}$

$$P_{EP,max} = \left(\frac{V_{EP}}{2}\right)^2 \frac{1}{R_{in}}$$

$$= \frac{(40\text{mV})^2}{1\text{M}\Omega} = 1.6\text{nW}$$
Endoelectronics chip: EP harvester architecture

The endocochlear potential (EP) was discovered 60 years ago by Georg von Békésy.

In 1961, he won a Nobel Prize for his work on the ear.

The EP has never before been used as an energy source for electronics.

With S. Bandyopadhyay, A. Lysaght, P. Mercier, Dr. K. Stankovic
Every Picowatt Counts!

Leakage Power from Input: 20pW
Leakage Power from Output: 223pW
Every Picowatt Counts!

40mV

V_{IN}

506pA

Leakage from Input

<1pA

Leakage from Output

V_{DD}

0.9V

1.6V

Leakage Power from Input: 20pW

Leakage Power from Output: <1pW

• Use “old” digital tricks – “reverse biasing”
**Pico-Powered Transmitter!**

*High-Vt PMOS gating:*  
Up to 4000X lower leakage than with no gating

**Fine Grained Power Gating**
System Measurements

- **Voltage Measurement**
  - $V_{PUMP}$
  - $V_{DD}$

- **Component Diagram**
  - Chip
  - Antenna
  - $C_{EP}$
  - $C_{DD}$
  - $L$ (bottom)

- **Voltage vs. Time**
  - Guinea pig #1
  - Guinea pig #2
  - Guinea pig #3

- **Power Distribution**
  - ESD: 17.1 pW
  - Drivers: 93.6 pW
  - Charge Pump: 91.8 pW
  - Timer: 352.8 pW

- **Graphs**
  - Voltage vs. Time
  - Power vs. Time
Directions in Ultra-low-Power Processing for IoT Systems

- Use of hardware accelerators
- Use of non-volatile processing for variable energy
- Ultra-low-voltage operations using parallelism
- Activity driven processing
- Light-weight machine learning for data reduction
100-1000x reduction in energy by using accelerators
Operation down to 0.5V – techniques can be combined
Accelerators reduce overall energy by >10x in complete applications compared to CPU-only approach
  - EEG feature extraction for seizure detection: 10.2x savings
  - EKG analysis: 11.5x savings
Non-Volatile Processor

Desired operation:

FIR filter test-case:

Replace all flip-flops with Non-volatile D Flip-Flop (NVDFF)

Embed non-volatile memory elements into registers

[M. Qazi, ISSCC 2013]
Computing Architecture with Energy Harvesting

- Rapid transition from sleep to active
Ultra-Low-Power Using Parallelism

Parallel H.264

2mW H.264 decoder 720p in 65nm
(14x lower power)

Parallel H.265 (HEVC)

[C. Huang, ISSCC 2013]
Computational Photography

**HDR Imaging**

-1 EV

0 EV

+1 EV

**Tonemapped HDR output**

**Glare Reduction**

Before Filtering

After Filtering

**Low-light Enhancement**

Flash

No-Flash

**LLE output**
- Bilateral filtering using a 3D data structure called the Bilateral Grid
- Parallel processing for high throughput at low frequencies
Computational Photography

<table>
<thead>
<tr>
<th>Processor</th>
<th>Technology (nm)</th>
<th>Frequency (MHz)</th>
<th>Power (mW)</th>
<th>Runtime* (s)</th>
<th>Energy* (mJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intel Atom [24]</td>
<td>32</td>
<td>1800</td>
<td>870</td>
<td>4.96</td>
<td>4315</td>
</tr>
<tr>
<td>Qualcomm Snapdragon [25]</td>
<td>28</td>
<td>1500</td>
<td>760</td>
<td>5.19</td>
<td>3944</td>
</tr>
<tr>
<td>Samsung Exynos [26]</td>
<td>32</td>
<td>1700</td>
<td>1180</td>
<td>4.05</td>
<td>4779</td>
</tr>
<tr>
<td>TI OMAP [27]</td>
<td>45</td>
<td>1000</td>
<td>770</td>
<td>6.47</td>
<td>4981</td>
</tr>
<tr>
<td>This Work</td>
<td>40</td>
<td>98</td>
<td>17.8</td>
<td>0.771</td>
<td>13.7</td>
</tr>
</tbody>
</table>

1. **Correlation of Pixel Data**

2. **# of Read Accesses > # of Write Accesses**
   - Write once and read multiple times
     - Data reuse between consecutive blocks

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**Reduce energy/access in read accesses by utilizing correlation of pixel data**

[Mahmut Sinangil, ISSCC 2013]
Energy Monitoring Circuit Operation:

- An off-chip storage capacitor ($C_{sto}$) is used to power up the circuit during energy monitoring.
- If the voltage over $C_{sto}$ drops by $\Delta V$ from $V_1$ to $V_2$ in $N$ cycles, energy per operation (EOP) can be approximated as: $c_{sto} \times V_1 \times \Delta V / N$.

Measurement result:
$2x$ change in energy per operation is observed due to transient effects.
Energy Monitoring Circuit (1/3)

- implemented and demonstrated with integrated power management circuits

- STEP 1 – Normal Operation: Buck Converter powers up the system
STEP 2 - Discharge: $C_f$ is discharged from $V_1$ to $(V_1 - \Delta V)$ by $I_{LOAD}$ in $N$ cycles
STEP 3 – Recovery: Voltage is restored to initial VDD.

Energy per operation is measured as $CF \times V1 \times \Delta V / N$
Sensor with Power Management Demonstrated

The operation of the system when performing energy monitoring and voltage changes
Light-weight Machine Learning in Hardware

On-scalp Field Potentials (EEG):

- Electrical onset: ~7.5 sec
- Clinical onset:

### Epileptic Seizure Onset Detection

- Process: TSMC 0.18 nm 1P6M CMOS
- Area: 5.0 x 5.0 mm
- Supply Voltage: 1.8V (AFE) 1.0V (DBE, ADC)
- Channel: 1 to 8 Scalable
- Input Dyn. Range: 30-59 dB (4 step)
- AFE Power: 66nW
- Bandwidth: 30Hz / 100Hz
- ADC: Fully Differential SAR ADC 10b, 4-32KS/s
- Classifier Type: Support Vector Machine
- Latency: < 2s
- Accuracy: 84.4%
- Efficiency: 2.03mJ/Classification

[Jerald Yoo, ISSCC 2012]
Security for IoT

IoT introduces many unique security challenges:

- Widely deployed sensors collecting private and sensitive data
- All interconnected and potentially accessible to attackers

Example attack scenarios:

- Pacemakers can be hacked to cause unwanted stimulation
- Activity tracker logs can help an attacker profile users
- Home automation devices can be compromised to give attackers access

Opportunities:

- Implement new crypto primitives like FHE to enable secure systems
- System solutions to provide complete security for IoT applications
A Voltage and Resolution Scalable SAR ADC

- Energy-efficient 5b to 10b resolution scalable DAC
- Voltage scalable from 0.4V (5kS/s) to 1V (2MS/s)
- Leakage power-gating important at low voltage/sample rates

![Diagram of SAR ADC with energy-efficient DAC and voltage scalable from 0.4V to 1V](image)

**Figure:**

- Fixed DAC, Constant $V_{DD}=1V$
- Resolution Scaling, Constant $V_{DD}$
- Resolution and Voltage Scaling

**Graph:**

- $1.7X$ from DAC scaling
- $5X$ from DAC + voltage scaling

Resolution scaled by truncating 10b data

$0.55V$, $0.6V$, $0.6V$, $0.65V$, $0.7V$

[Reference: M. Yip, ISSCC 2011]
Data Dependent SAR

\[ \alpha = \text{<code>}/\text{range} \]

\[ \alpha_{\text{ECG}} = 0.6\% \]

\[ \alpha_{\text{Accel}} = 6.7\% \]

ECG Signal, 1 kS/s

Vibration Signal, 5 kS/s
Data Dependent SAR

- Conventional SA always uses the same initial guess
- Alter the algorithm to exploit low signal activity
  - Start search at previous sample.
  - Use fewer bitcycles when initial guess is close to final output code.
Measurement Results

ADC response to ECG test input signal at VDD=0.5V and f_s=1 kHz

Multi-Channel FBAR Transmitter

- Oscillator consumes 150μW from 0.7V supply
- Fast startup-time minimizes energy overhead

[A. Paidimarri, VLSI Symp. ‘12]
## Transmitter Testchip

<table>
<thead>
<tr>
<th>Technology</th>
<th>65nm CMOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply</td>
<td>0.7V (RF), 1V (Switch)</td>
</tr>
<tr>
<td>Num. Chan.</td>
<td>3</td>
</tr>
<tr>
<td>Startup Time</td>
<td>4μs</td>
</tr>
<tr>
<td>Data Rate</td>
<td>1Mb/s</td>
</tr>
<tr>
<td>Phase Noise</td>
<td>$-132$dBc/Hz (at 1MHz)</td>
</tr>
<tr>
<td>$P_{OUT}$</td>
<td>$-17.0$dBm to $-2.5$dBm</td>
</tr>
<tr>
<td>Energy per bit and Average $P_{OUT}$</td>
<td></td>
</tr>
<tr>
<td>OOK (Gauss)</td>
<td>440pJ/b at $-12.5$dBm</td>
</tr>
<tr>
<td>BPSK (SRRC)</td>
<td>530pJ/b at $-11.0$dBm</td>
</tr>
<tr>
<td>GMSK</td>
<td>550pJ/b at $-10.0$dBm</td>
</tr>
</tbody>
</table>

![Diagram of Transmitter Testchip](image_url)

- **Published TXs**
- **This Work**

**Output Power (dBm)** vs **Energy per bit (nJ/bit)**

- Diamond: Published TXs
- Triangle: This Work
e-Textiles with Wireless Power/ Data Transfer

Network of diverse, remotely-powered sensors wirelessly linked to eTextiles

Nachiket Desai, ISSCC 2013
Putting it Together: Fully-Implantable Cochlear Implant

Conventional CI

External microphone, processor, coil

Fully-Implantable Solution

Limitations

- Usage in shower/water sports
- Aesthetics and social stigma

M. Yip, R. Jin, H. Nakajima, K. Stankovic, and A. P. Chandrakasan,
“A Fully-Implantable Cochlear Implant SoC with Piezoelectric Middle-Ear Sensor and Energy-Efficient Stimulation in 0.18µm HVCMOS”, ISSCC 2014
Prototype Implementation

Fully-implantable CI SoC

1.5 V Piezoelectric sensor front-end (PZFE)

Charge amplifier
Programmable-gain amplifier
ADC driver (S2D)

Piezoelectric sensor

3-stage decimation filter
0.6 V Reconfigurable sound processor

Arbitrary waveform current stimulator

Channel select
Waveform select
0.6 V Digital arbitrary waveform control

HV electrode switch matrix
Config. registers

0.6 V, 9-bit, 16 kS/s SAR ADC

3.6mm x 3.6mm
Efficient Portable-to-Portable Wireless Charging

Wirelessly charge low-power portables by high-power portables

• Charge in 2 minutes for typical day use
Summary

- Energy efficiency achieved through:
  - Ultra-low-voltage operation
  - Hardwired architectures
  - Exploiting application attributes (e.g., data-driven processing)
  - Digital control of energy processing
  - Optimizing for short duty cycles

- Next generation sub-Hz optimized electronics will enable new energy harvesting applications

*Exciting Opportunities Beyond Moore’s Law Scaling*