EXPLORING THE BOUNDARIES OF ULTRA-LOW POWER DESIGN - MICROSCOPIC WIRELESS

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The Sensory Swarm

“Adding senses to the Internet”

Trillions of connected devices

Infrastructural core

Sensory swarm

Mobile access

The driver for Ultra-Low Energy design over past years

UCB PicoCube

Philips Sand module

UCB mm³ radio
Yet ... True Immersion Still Out of Reach

Microscopic Wireless: $< \text{mm}^3$, $< 1 \mu\text{W}$

Artificial Skin

Interactive Surfaces

Smart Objects

“Microscopic” Health Monitoring

Another leap in size, cost and energy reduction
Example: Microscopic Wireless to Power Brain-Machine Interfaces (BMI)

The Age of Neuroscience

BMI – The Instrumentation of Neuroscience
- Learning about operation of the brain
- Enabling advanced prosthetics
- Enabling innovative human-machine interfaces

mm$^3$ nodes remotely powered uWs to 1 mW power budget
Why Is This SO Interesting?

Microscopic wireless technologies to have profound impact on information processing and communication for decades to come.

- Traditional scaling rules to have minor impact
- Scaling is in the number of components, not in the transistor sizes
- A path to “More Than Moore” or “Beyond Moore”

[H. De Man, Keynote Address, ISSCC 2005]
The Holy Grail: Reducing the Energy/Operation

- Communication
- Digital Processing
- Data Acquisition
The Holy Grail: Reducing the Energy/Operation Communications Power harvesting, storage and distribution

Communications
Digital Processing
Data Acquisition

Wireless communication dominant factor

Primary Challenge: Improving TX Efficiency & Combatting Overhead
Short Distance Wireless Communication

The Achievable Bounds are well Known

Ideal link: Modulation achieves Shannon capacity, noiseless zero power RX, ideal TX (100% efficiency).

Minimum energy/bit (infinite bandwidth) = \( kT \ln 2 \times \text{Link Budget} \)

Works well for long distance links, somewhat irrelevant for short distances
Short Distance Wireless Communication

The Reality – State of the Art

Example 1: [Chee06 TX, Pletcher 08 RX] Low sensitivity ULP receiver

\[ \frac{\text{Link margin} \times kT \ln 2}{(P_{Tx} + P_{Rx}) / R} \]

\[ = \frac{72 \text{db} \times 2.9e-21}{1.05 \text{mW}/100e3} \]

\[ = -53.6 \text{ dB} \]

Example 2: [Chee06 TX, Otis 05 RX] High sensitivity Low-rate receiver

\[ \frac{\text{Link margin} \times kT \ln 2}{(P_{Tx} + P_{Rx}) / R} \]

\[ = \frac{100 \text{db} \times 2.9e-21}{1.55 \text{mW}/5e3} \]

\[ = -40.3 \text{ dB} \]

Transmitter inefficiency and receiver overhead dominate

Observe: This assumes perfect synchronization between TX and RX

This is far from the case in typical sensor applications

[After analysis by B. Cook, PhD, UCB]
Creativity: Combining passive components with technology scaling

Example:
50 µW 100 kbit/sec receiver

BAW resonator (FBAR) provides frequency selectivity

Enables usage of inaccurate ring oscillator as mixer (scales with technology)

0.5V VDD
-72 dBm sensitivity

[N. Pletcher, ISSCC’08]
The Opportunity

- Sensing applications are largely asymmetrical
  - Tx is what matters!

The Lure of Pulse-Based Communications:
Higher TX efficiency + Duty Cycling

[Courtesy: S. Gambini, UCB]
Pulse-Based Communication

- Highly efficient transmitter – reduced overhead
- Energy efficiency set by timing accuracy
  - improved by technology scaling
- Make receiver chain as simple as possible – augment using digital tuning

1 Mbit/sec
1-5 cm distance
6 GHz carrier
25pJ/100pJ TX/RX
Revisiting the Opportunity

- Most sensing applications are asymmetrical
  - Tx is what matters!

Pulse-Based TX
- Scales with technology
- Ideal duty cycling
- Needs power source

Reflective (RFID)
- Zero-power
- Very low sensitivity
- Low data rates

Reflective Impulse
- Best of both worlds
The Holy Grail: Reducing the Energy/Operation

Primary Challenge: Improving TX Efficiency & Combating Overhead
Energy Limits in Digital

Shannon-Von Neumann-Landauer Bound:

Minimum energy/operation = $kT \ln(2)$

= $4 \times 10^{-21}$ J/bit at room temperature

More than 4 orders of magnitude below current practice (65 nm at 1V)
Technology Scaling Not the Solution

[Based on actual and predictive models]
Lowering Supply Voltage Only Option

(recoup performance through parallelism)

BUT: CMOS Has Minimum Energy Point Set by Leakage

![Graph showing energy vs. VDD (V)].

- Energy (norm.)
- V_DD (V)

Legend:
- **Total**
- **Switching**
- **Leakage**

0.3V, 12x
Sub-Threshold Operation Leads to Minimum Energy/Operation

Energy-Aware FFT Processor
[Chang, Chandrakasan, 2004]

But at a huge cost in performance and variability

Subliminal µprocessor for retinal implants
3 pJ/inst @ 350 mV
[Blaauw, VLSI’07]
Back off a Little: Design in the VTH + $\Delta V$ Space

[H. Kaul et al, ISSCC08]

Challenges: Modeling, Variability
Leakage-Insensitive Logic?

Low VT Pass Transistors

SAPTL
[Alarcon, 07]

Logic: Moderate Inversion
Driver and SA: Subthreshold

High VT Transistors

Minimal impact on leakage when reducing VTH
How About Mechanical Computing?

NEMS Relay

Energy/op vs. Delay/op across $V_{dd}$

[Courtesy: TJ King, E. Alon, UCB]
The Holy Grail: Reducing the Energy/Operation

Microscopic Systems need more than digital

Challenge: Even harder to scale voltage
The Limits of Low-Voltage Signal Conversion

Voltage reduction limited by noise (high accuracy) or matching considerations (low accuracy)

Innovative architectures explore minimization of “active analog”

14 µW 0.5 V 1.5 MS/s 6 bit SAR 120 fJ / Conversion Step

[S. Gambini, ‘07]
Mostly Digital ADC’s

Example: Pipelined converter
On track to 20 fJ/conversion step

Charged-based bucket brigade pipeline \textit{without} usual gain-boost amp, \textit{with} new digital correction

[Courtesy: B. Murmann, Stanford]
Avoiding Transistors Altogether?

Revisiting the NEMS Relay

Flash Analog-Digital Converter

- $V_{core} = 0.3V$
- $C = 500fF$
- $R = 4k\Omega$
- $V_{REF} = 1V$
- $f_{samp} = 10\ MS/s$

6-bit res: 5.5fJ/conv

[Courtesy: E. Alon ‘09]
How about a NEMS Spectrum Analyzer?

60 MHz  
Q = 48,000

1.2 GHz  
Q = 14,600

1.5 GHz  
Q = 11,555

1mm² = roughly 2000 resonators  
Assume 100 μW / analog channel

Mechanical-Analog wins for low resolutions

[Spectrum analysis @ 1 GHz with N bins]
An Extreme Perspective – Combining Passive Sensing and Communication

Immersed neural activity sensor: Potassium-modulated resonator

 Powered and interrogated by array of Ultra low-power wireless transceivers

[Courtesy: M. Maharbiz, UCB]
Some Reflections ...

- For information-technology revolution to go forward, further scaling of energy per operation essential
- Plenty of room for innovative architectures and computational paradigms
- But ... Potential of CMOS ultimately limited
- Exploration of innovative materials, active and passive devices, and architectures exploiting them is a must

Microscopic wireless as ground-breaker and game-changer