Ultra Low Power Electronics in the Next Decade

Ajith Amerasekera
Texas Instruments Inc.
Dallas, USA
February 2012
amerasekera@ti.com

SSCS Distinguished Lecture
OUTLINE

• Growth in Electronics
• What Do We Need?
• Next Steps in Low Power Electronics
• Key Challenges
• Conclusion
Growth in Electronics

Number of Units vs. Year

- Centralized
- MainFrame Computers/DataCenters
- Personal Computing/Telecomms
- Mobile Comms/Consumer Electronics
- Personal Technology/Health/Environment/Safety
- Immersion

Most of these will be portable/mobile systems.
10x to 100x Increase in Units
But Cost is Important

- Semiconductor Revenue grows at <10%/year on average.
- Low cost solutions are critical to growth.

Source: iSuppli
Reducing Chip Power Has Big Impact

- CO2 eliminated from the Atmosphere equivalent to taking the following number of cars off the road...
  - 12,500 Cars

- Each 1 Watt power reduction per IC can reduce MW of power on the grid...
  - +2,500 Cars
  - +3,000 Cars
  - +6,700 Cars
  - +2,700 Cars

- Average Power Savings
- Estimated Product Quantity: 1M Units/year
- For each 1W of power saved
- **Total Power Savings: 1 Mega-Watts**

**Initial Design**
- Initial Power
- Multi-Vt 25/75%
- Vectored Flops
- Strong-1Sigma
- 1.05V, 105°C
- Update RFQ

**Power Improved**
- Power Improved
- Clock Gating
- 65

**AVE**
- AVS
- 59

**Technology Migration**
- Technology Migration
- Single Rail
- Multi-Vt 25/75%
- Vectored Flops
- Strong-1Sigma
- 0.945V, 105°C

**w/CG**
- w/Clock Gating
- 47
- 39
- 34
Wireless?

Growth of Wireless to Continue Unabatedly!

- 5 Billion people to be connected by 2015 (Source: NSN)
- 7 trillion wireless devices serving 7 billion people in 2017 (Source: WWRF)
  - 1000 wireless devices per person?

[Courtesy: Niko Kiukkonen, Nokia]
THE IT PLATFORM OF THE NEXT DECADE(S)

Infrastructural core

Sensory swarm

Mobile access

TRILLIONS OF CONNECTED DEVICES

[J. Rabaey, ASPDAC'08]
WHAT DO WE NEED?
Life in the Future

From back in the 60’s!!

Techno-Optimism

• Man on the Moon
• Concorde and Jumbo Jets
• Electric Music, Video, Cassettes
• etc......

But......major limitations to the Jetson’s World

• Power, Cost, size

What does it take?
• Wireless Networks
• Low Power Circuits
• Sensors
• Human Machine Interfaces
• Energy Harvesting
• RF/Analog
• High speed Data Communication
• Data Analysis
Energy Generation and Management

• Major limitation for expansion of the application space for semiconductors
  – Intelligent environment requires wireless and autonomous systems that can operate for approximately 10 years.
  – Two types of portable electronics:
    • Performance “hub” devices such as computers, multi-media devices, wireless hubs and PDAs which have 1W to 5W needs today.
    • Distributed systems with micro and nano watt needs.

• Typical autonomous system would be:
  – 10 years life.
  – Battery size/cost point is ~1mAh.
  – Average power available from battery < 1nW.
Battery Technology Is Trailing Demand

- Battery technology scaling at about 2x every 10 years compared to semiconductor technology at 2x every 18 months.

## Power Management Techniques

<table>
<thead>
<tr>
<th>Method</th>
<th>Dynamic Power Reduction(^1)</th>
<th>Leakage Power Reduction(^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-VT and Multi-L</td>
<td>Varies</td>
<td>34%/~7x</td>
</tr>
<tr>
<td>Clock Gating</td>
<td>~12% - 30%</td>
<td>Varies</td>
</tr>
<tr>
<td>Memory PM Modes</td>
<td>~2x</td>
<td>3-30x</td>
</tr>
<tr>
<td>Voltage Islands</td>
<td>CV(^2)F</td>
<td>~1.5x</td>
</tr>
<tr>
<td>Adaptive Voltage Scaling Static (Open Loop)</td>
<td>~9-15%</td>
<td>~10% -27%</td>
</tr>
<tr>
<td>Adaptive Voltage Scaling Dynamic (Closed Loop)</td>
<td>~10-19%</td>
<td>~15%-50%</td>
</tr>
<tr>
<td>Optimized IP</td>
<td>Varies</td>
<td>Varies</td>
</tr>
<tr>
<td>Power Islands</td>
<td>NA</td>
<td>~20-100x</td>
</tr>
<tr>
<td>Dynamic Voltage and Frequency Scaling (DVFS)</td>
<td>Varies</td>
<td>Varies</td>
</tr>
</tbody>
</table>

\(^1\) Figure of Merit, Impact is design dependent
Energy gap of a mobile device

**New use cases:**
Web, email, video, 3D graphics

**New use models:**
Always on, always connected

Source: Öfversten [IWPC’08], Samms [IWPC’08]
Silicon performance advances require power management

- Performance: +20~30% node-to-node
- Leakage: a concern in 90nm, required fundamental change in 65nm

Source: Gammie [ISSCC’08]
Industry breakthrough examples (published)

- **Power & performance** management technology
- Reduces both leakage and active power, increases performance

**65nm leakage power reduction: 300X**
- SRAM retention
- Logic power gate
- Channel length
- Logic retention
- Process/temp AVS
- DVFS

**45nm active power reduction: 1000X**
- Adaptive Body Bias (ABB) for performance & power
- Retention 'Til Access (RTA)

*Delagi, ISSCC10*
Directions in ultra-low power

Ultra-low power video codec

- Video decoding for <2 mW at Vdd = 0.7V
- H.264 video codec
- 720p, 30 frames/sec
- Video decoding for <2 mW at Vdd = 0.7V

Ultra-low power medical processor

- MSP430 uC with SRAM at Vdd = 0.3V
- 128Kb SRAM array
- 75% efficiency down to 10 μA

Ultra-low power DC-DC converter

- 65nm CMOS
- DC-DC with 75% efficiency down to 10 μA

Energy scavenging

- Scavenging energy from the environment
- µW-mW energy scavenging devices
- Thermal, Electromagnetic, Electrostatic, Piezoelectric, Photovoltaic

Source: JSSC 2009

Source: ISSCC 2008
Next Steps in Low Power Electronics
Ultra Low Power Chip Design

Typical Design for Intelligent Ambient Applications

- 1mA-Hr Battery for 10 years
- 1μA average power budget
- <1μA average for digital system

- Use circuit design techniques for optimizing energy-performance

- Then apply system design and software management to reduce power by another order of magnitude

Sridhara, VLSI Symp. 2010
Battery Technology is Critical

• Li-ion was the game-changer for the 2000’s.

  – In 1990s nickel cadmium and nickel metalhydride rechargeable batteries were the preferred energy technology
  – In last 10 years, lithium batteries have taken over with a current market share of over 70%.
  – lithium cell is its high energy density, => small size, lightweight, longer lifespan than comparable battery technologies.
  – Also, high power, high-energy efficiency, low self-discharge, and good cycle life. Specific energy densities greater than 190 Wh/kg.
  – But now approaching its limit with small incremental gains

• We need the next breakthrough in energy delivery for the 2020s!!

  • Capacity, Cycles, Rate, are critical parameters.
Renewable Energy

• Renewable Energy Has Tremendous Potential

• Solar energy products
  – Photovoltaic systems
  – DC/AC power inverters

• Wind energy products
  – Wind turbines

• Hydro energy products

• Heating systems
Energy Harvesting

• Vibrational, thermal, photovoltaic, RF power have been proposed.
  – Harvest energy from motion, heat, light and RF.
  – Great for triggering imagination.

• But micro and nano ampere power levels are very inefficient.

• Laws of conservation usually apply
  – Inserting a harvester can increase the energy usage by the generating system.

Need a lot more understanding to appreciate trade-offs and practical solutions.
## Energy Scavenging Efficiencies

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Characteristics</th>
<th>Efficiency</th>
<th>Harvested Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>Outdoor</td>
<td>10~24%</td>
<td>100 mW/cm²</td>
</tr>
<tr>
<td></td>
<td>Indoor</td>
<td>10~24%</td>
<td>100 µW/cm²</td>
</tr>
<tr>
<td>Thermal</td>
<td>Human</td>
<td>~0.1%</td>
<td>60 µW/cm²</td>
</tr>
<tr>
<td></td>
<td>Industrial</td>
<td>~3%</td>
<td>~1-10 mW/cm²</td>
</tr>
<tr>
<td>Vibration</td>
<td>~Hz–human</td>
<td>25~50%</td>
<td>~4 µW/cm³</td>
</tr>
<tr>
<td></td>
<td>~kHz–machines</td>
<td>25~50%</td>
<td>~800 µW/cm³</td>
</tr>
<tr>
<td>Embedded Energy</td>
<td>Chemical</td>
<td>~90+%</td>
<td>~90+%</td>
</tr>
<tr>
<td></td>
<td>Radioactive</td>
<td>~30%</td>
<td>~1- 20 µW/cm³</td>
</tr>
<tr>
<td>RF</td>
<td>GSM 900 MHz</td>
<td>~50%</td>
<td>0.1 µW/cm²</td>
</tr>
<tr>
<td></td>
<td>WiFi</td>
<td>~50%</td>
<td>0.001 µW/cm²</td>
</tr>
</tbody>
</table>

⇒ Need to look at non-traditional areas for scavenging energy. What else do we have?
⇒ Energy generation using biological, micro-fuel cells, etc.
Mobile Internet System

- A distributed computer system
  - The internet of things – **THE SWARM**
- **Use multiple energy sources**
  - Battery for general functionality
    - energy management and control, wake-up functions, etc.
  - Storage caps for high current functions
    - storage, communications
  - Energy scavenging for extended battery life
  - Wireless power sources for connection to grid
    - Directional use of RF, light, etc. in localized area for “topping up”.
- **Intelligent energy management and control**
  - Highly efficient on-chip power processing
  - Control of energy sources and delivery
  - Management of power demand and access
  - Unreliable energy sources
KEY CHALLENGES
Challenges for Next Decade - 1

• **Low-Power Electronic Design**
  – Need another two to three orders of magnitude of power reduction.
  – Most known circuit design approaches have been utilized.
  – System-level power optimization is needed.
  – Can the process technology help? Not just digital any more.

• **System Design**
  – Managing interconnectivity: wireless and network connectivity; protocols are expensive in power and complexity.
  – Partitioning for power optimization.
  – Security.

• **Low-Power Sensor Technology**
  – The intelligent environment requires a wide range of high performance sensors.
  – Sensor interface and control needs to become sophisticated.
Challenges for Next Decade - 2

• **Battery and Storage Technology**
  – We need micropower and nanopower battery capability
  – Nanotechnology can provide some of the solutions
  – Smart Batteries, intelligent power management

• **Energy Scavenging**
  – Truly scavenged from waste
  – Efficiency in collection and storage.
  – We need more work in understanding availability, applicability, and harvest/storage.

• **Off-grid power distribution**
  – Local wireless power to storage elements
  – Sense and deliver on-demand
  – Connecting to the grid
CHANGING PARADIGM
Optimizing the system requires collaboration and co-design

- **System & Software:**
  - Essential to maximize circuit level advances

- **Architecture & Packaging:**
  - Duty-cycle of CPUs
  - 3D ICs

- **Silicon Technology:**
  - Low-power optimized

- **Circuit Technology:**
  - Power management

*Delagi ISSCC 2010*
Concluding Reflections

• We are on the threshold of a new wave of electronic technology as we move into the decade.

• Applications driven roadmaps will define what we do.
  – Process technology not driving the roadmap any more

• Ubiquitous intelligence is going to drive wireless connectivity.

• Energy generation and management are critical.

• Low power and cost are key drivers for market growth.

• Close collaboration across all disciplines of electronic engineering from transistors to systems to software.
THANK YOU!!