Ultra-low-power electronic components for the IoT

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& our groups of researchers (20+)
A sustainable Internet-of-Things?

Connecting trillions of things to the Internet

→ Technical challenges

From sensors...

→ Sustainability challenges

... to the cloud
A sustainable Internet-of-Things?

Connecting trillions of things to the Internet

→ Technical challenges

→ Five IoT sustainability challenges

1. Avoiding battery replacement for sustainable maintenance
2. Limiting carbon footprint of production and end-of-life for sustainable deployment
3. Avoiding spectrum congestion for sustainable networking
4. Limiting M2M wireless traffic and embedding security for sustainable operation

From sensors...

... to the cloud
Smart electronics for a sustainable IoT

1. Energy harvesting & ultra low-power design

2. All the system - in-a-package (SiP) or on-a-single-chip (SoC)

3. Agile RF communications

4. On-chip data / signal processing

5. Computationally- and physically-secure operation
1. Energy harvesting and power management

- **Miniaturized harvesters:**
  - Photovoltaic cells (Si, CIGS, CZTS) for outdoor and indoor conditions
  - RF (inductive coils at 13.56 MHz for implanted biomedical, next → GHz)

- **Energy-harvesting & power management units (EH-PMU)** controlling and interfacing:
  - harvesters (20 – 1000 mV)
  - rechargeable battery or supercap (3 – 4 V)
  - and loads (sensors, circuits... at 0.4 – 3 V)

...At very high efficiencies in a wide power range
Case study 1: EH-PMU transferred to e-peas

Best in-class integrated energy management subsystem able to:
- Extract DC power from PV cells or TEGs with lowest input power
- Recharge battery or supercap with fastest speed
- Supply the system with highest efficiency
- And overall lowest number of external components.

<table>
<thead>
<tr>
<th></th>
<th>Vmin (cold start)</th>
<th>Input Power @ Vmin</th>
<th>MPPT</th>
<th>Input voltage operation</th>
<th>External components</th>
</tr>
</thead>
<tbody>
<tr>
<td>e-peas</td>
<td>380mV</td>
<td>8µW</td>
<td>On-chip</td>
<td>0.1-2.5V</td>
<td>7</td>
</tr>
<tr>
<td>cots1</td>
<td>330mV</td>
<td>15µW</td>
<td>On-chip</td>
<td>0.1-5.1V</td>
<td>17</td>
</tr>
<tr>
<td>cots2</td>
<td>380mV</td>
<td>15µW</td>
<td>external</td>
<td>0.08-3.3V</td>
<td>14</td>
</tr>
</tbody>
</table>
2. Fully integrated on-chip microsystems

**Universal SOI-CMOS on-membrane platform for**
- Sensors: T, RH, P, Flow, Gas
- Read-out analog interface circuits
- Resistance to harsh environments (high temperature, radiations)
- Micro-heater for stability, calibration...
  (collaborations with Univ. Cambridge, CISSOID, X-FAB...)

**Bacteria detection on CMOS chips post-processed with thin ALD Al₂O₃**
- 200 MHz in high-ionic buffer solutions
- 64 pixels of 200 μm² for 5 bacteria resolution

0.25 μm CMOS, 29 μW, Sensitivity of 55 mV / fF, Limit of detection = 450 aF

*can be extended to other impedimetric sensors*
Case study 2: A solar-powered video analysis SoC

SunPixer 65nm SoC

- Micro solar cells
- Supercapacitor
- External radio
- Power
- Energy

**50MHz / 0.37V SIMD microcontroller**

**Inductor-less harvesting power management unit**

**0.5V CMOS image sensor**

- Pictures, video, features, events
3. On-chip DSP to limit wireless data traffic

Example: Home camera, H.264 compression

Carbon footprint [% household] vs Home cameras per household

- 0.2 Mbps
- 1.2 Mbps

Sustainable operation

Target: compress, classify, extract the meaningful information from sensed data, at extremely-low power, without killing computation speed!

65nm LP CMOS

$E_{cycle} \div 9 @0.4V$

Speed $\div 2000 @0.4V$

Frequency [Hz] vs $V_{dd}$ [V]
Case study 3: μ-controller SoC for sensor nodes

- Low system CO₂ footprint
  - low die area
  - few off-chip components
- Energy-harvesting operation
  - low active energy
  - adaptive voltage scaling 0.32-0.48V
- Compatibility with commercial components
  - MSP430 instruction set, same memory capacity and peripherals
  - 25MHz speed robust under industrial conditions

<table>
<thead>
<tr>
<th>MSP430</th>
<th>This work [Bol, ISSCC, 2012]</th>
<th>MIT (best research) [Kwong, ISSCC, 2008]</th>
<th>TI (best commercial) [Zwerg, ISSCC, 2011]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed [MHz]</td>
<td>25 @ 0.4V</td>
<td>0.3 @ 0.5V</td>
<td>24 @ 1.5V</td>
</tr>
<tr>
<td>Energy [μW/MHz]</td>
<td>7</td>
<td>27.3</td>
<td>164</td>
</tr>
<tr>
<td>CO₂ footprint [kg/1000 units]</td>
<td>14</td>
<td>47</td>
<td>83</td>
</tr>
</tbody>
</table>
4. RF components and technologies

UWB (2-8 GHz) data transfer and localization (< cm):

- Low-power pulse generators, wideband LNA / PA, energy detectors...
- 700-μW IEEE 802.15.4a IR-UWB RF transmitter SoC in 28 nm FD-SOI CMOS

27 Mbps @ 10m with 100x less power than commercial solutions (i.e. enabling energy-harvesting operation)
Case study 4: SOI substrates for RF switches

Major requirement: improve linearity by 20-30 dB when going from 2G to 4G LTE!

Trap-rich technology introduced in 2005
→ mass-market now for >90% RF switches in smartphones

Next: Full Front End module integration (antenna switches, tuner, diplexer, PA, filters)
5. Security pitfalls of IoT nodes

• Critical functionality: nodes controlling transportation infrastructure, the utility grids, communication systems
• Huge replication
• Wrong security assumptions
• Not easily patched
• Long life cycle up to 20 years
• Proprietary/industry specific protocols
• Deployed outside of enterprise security

www.iconlabs.com
Case study 5: Embedded cryptographic algorithms

Towards Green Cryptography: a Comparison of Lightweight Ciphers from the Energy Viewpoint

Frequency / voltage scaling:
- supply voltages from 1.2V to 0.4V
- frequencies from GHz to 100 MHz

Figures of merit for efficiency comparison:
Energy per bit (pJ) vs Throughput per Die area
UCL expertise & experimental platforms for IoT

- **Micro - chips & - system design :**
  - Cutting-edge research : innovative concepts, Simulation, Fabrication (internal or external), Programmation, Test, Applications
  - Strong added value @ system / application levels when off-the-shelf components limit the specs / performances

- **Winfab for micro-nano-fabrication**
  - 1000 m² of fully-equipped clean rooms
  - Processes : Lithography, 2D/3D patterning, deposition, etching…
  - Materials : Semiconductor, dielectric, metallic, organic

- **Welcome for electromagnetic characterization :**
  - 350 m² of measurement set-ups : DC to 110 GHz, low to high T°, …
  - Antennas, MMIC, analog / digital / RF components, devices, circuits, sensors, optoelectronics…
Thanks for your attention

Questions?