Energy & Smart Systems

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Smart Dust

- **Smart Dust**: DARPA-funded research proposal of the University of California, Berkeley, in 1998.

- **Objective**: build wireless sensor nodes with a volume of one cubic millimeter.

- **Results**: working mote smaller than a grain of rice, and larger "COTS Dust" devices kicked off the TinyOS effort at Berkeley.
What does prevent a widespread adoption of wireless sensor networks?

• Reliability/robustness
• Cost
• Energy autonomy
Outline

• Context

• The energy autonomy roadblock

• Research challenges:
  – Smart energy management
  – Low-power communication
  – Increasing energy density
  – Efficient energy harvesting
  – Green storage

• Conclusion
The energy autonomy roadblock

• Energy generation and storage devices are generally bulky
• Batteries have a limited lifetime
  – Prohibitive maintenance cost
  – Environmental issue
• Batteries can have safety issues
• Application dependent

• MAIN CHALLENGES:
  – Smart energy management
  – Increasing energy density
  – Efficient energy harvesting
  – Green storage
Where does the energy go?

- Processing
  - excluding low-level processing for radio, sensors
- Radio
- Sensors
- Power supply
Smart energy management

• Energy-driven architecture: No “one-fit-all” solution
• Low-power design techniques (multi-VT, multi-voltage, VDD cut-off during sleep, sub-threshold logic, asynchronous logic, dark silicon, etc)
• Efficient conversion of supply voltages
• Duty cycle adapted to the available energy
• Low-power protocols
Advantages of IR-UWB* communication

- Low-energy impulse transmission
- Large frequency band
- Very short pulse
- Lower interference probability
- Small size antenna
- Geo-localization

Main challenges:
- Fast DAC/ADC
- Reception synchronization
- 1 pJ/bit

* Impulse Radio-Ultra Wide Band
Low power IR-UWB emitter/receiver

\[ P_{\text{consumption}} = 50 \text{ mW} \quad \text{Max data-rate : 500Mbps} \]

Energy/bit: 100pJ/bit (best case)
Clock synchronization precision \( \sim 10 \text{ ns} \)

Is there a way to avoid the energy issue?

Passive Sensors With EM Transduction

- **Principle:**
  - Electromagnetic resonator
  - Modification of resonance by input to be measured
  - FMCW RADAR interrogation

- **Advantages:**
  - Zero consumption
  - Compatible with harsh environment
  - No EM wave conversion losses: increased interrogation distance

**Future challenges:**
- Sensor optimization and integration
- Other sensors: temperature, radiation dosimetry, gas
- Localization/identification

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Input to be analyzed \((P, T^\circ, \ldots)\)

RF Transducer \(f_0 \rightarrow f_1\)

Antenna

RADAR

Passive Pressure Sensor

M.M. Jatlaoui, H. Aubert, P. Pons, 2008 IEEE MTT-S Int. Microwave Symposium
Effect of downscaling

- Reducing size also decreases the output power
Increasing Energy density

• Take advantage of micro & nano-technologies
• Integration: 3D, SoC, SiP, TSV, advanced assembly techniques...
• Take advantage of new materials: flexible substrate, macrofiber composite, nano-material & metamaterial synthesis, etc
• Take advantage of nanoscale, mesoscale effects
Microbatteries

- High energy density (>300Wh/l)
  - 3D architectures
  - Air cathodes
- Low-cost
  - Self-assembly, inkjet printing...
- High power density
  - Nanomaterials as electrodes
- Low toxicity (ex: Zn, graphene)
- No use of strategic materials
- Safe devices
  - Polymer or glass electrolytes
- Improved lifetime: ≥10 years, up to 10000 cycles
Energy harvesting

Mechanical

Thermal

Radiant

Chemical

Power density of sources available in the environment

• No universal source of ambient energy
• Choice of the best source is application dependent
• Multisources
• Use of multifunctional devices

PD. Berger, Mechanical Energy harvesting: How to enable WSN deployment in an Industrial context?, France-Japan Seminar, Tokyo, Nov. 8, 2011
Energy harvesting

• Thermogeneration
  – New materials for improved Z
  – Efficient power management (MPPT, self-starting...)

• Photovoltaic
  – Improve energy conversion efficiency >>10%
  – Indoor applications

• Vibrational
  – Increase bandwidth
  – Efficient AC-DC conversion

• RF
  – Efficient AC-DC conversion

*Graphene* properties are very promising ...
**Energy Harvesting Power Management**

- Generic power management circuit almost impossible: AC, DC, high voltage/low current or low voltage/high current...
- Availability of source over time: *multisource*
- High efficiency/low-power

Multisource (TEG/PZ) converter

Iddq=200nA

©CEA


©CEA
Multifunctional device

Application: SHM scenario

- Energy transducer
- DC power generator
- Storage
- Energy management
- Wireless communication
- Signal processing

Sensing

single flexible substrate

RF

DC power generator

Energy management

Wireless communication

Signal processing

SMARTER Project, FP7
Smart integrated storage

Battery-free system: storage on ultracapacitors

- **Advantages over batteries:**
  - Much longer lifetime ~ million cycles
  - Safer operation
  - Environment friendly

- **Main drawbacks:**
  - Lower energy density
  - Self-discharge

- **Integration on silicon**
  - lower self-discharge
  - co-integration with power management
  - smart adaptive storage

- **Single flexible substrate**

Multi functional device

Smart storage

DC power generator

Energy management

Wireless communication

Signal processing

RF

SMARTER Project, FP7
Smart adaptive storage

R. Monthéard et al, Patent pending
**Micro-storage on chip**

**Carbon-based micro-supercapacitor on silicon with liquid organic electrolyte**

- **ACTIVE MATERIAL DEPOSITION**
  - Inkjet printing -> high resolution
  - Electrophoretic deposition -> collective
  - Screen printing -> high thickness

- **ENCAPSULATION**
  - Wafer-level packaging
  - Low temperature process (< 150°C)
  - Hermetical (humidity free)

- **RESULTS (without encapsulation):**

  **Carbon Onions by electrophoresis**
  
  *Project Partner University Fund: Drexel University (USA), CIRIMAT, LAAS*

  **Activated carbon by screen printing**

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<th>$C$</th>
<th>$E$</th>
<th>$P$</th>
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<tbody>
<tr>
<td>1.7 mF.cm$^{-2}$</td>
<td>7.7 mJ.cm$^{-2}$</td>
<td>700 mW.cm$^{-2}$</td>
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  Very high specific power

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<tr>
<th>$C$</th>
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<tr>
<td>82 mF.cm$^{-2}$</td>
<td>257 mJ.cm$^{-2}$</td>
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  High specific energy

Future micro-storage challenges

– More Power, More Energy $\rightarrow 1 \text{F/cm}^2$
  
  • Enhanced materials:
    - Carbons: OLC, CDC, MWCNT...
    - Pseudo: RuO$_2$
  
  + Nanostructuration

  • New electrolytes:
    - Protonic Ionic Liquid, Ionogel, Hygrogel

  • Improved configurations:
    - down to nanoscale

  • Efficient encapsulation

  • Hybrid micro-devices
    - Capacitive / pseudo capacitive

Conclusion

Energy autonomy of smart systems is still a big challenge:

– Global *energy-driven* system design approach
  • Modeling/simulation
  • Low-power sub-systems

– Energy density increase
  • *Micro & nano-technologies* are key enablers
  • Metamaterials such as *graphene* are very promising

– Energy *harvesting* is essential
– *Green & low-cost* technologies
– *Reliability & robustness* need to be addressed
We have ADREAM*...

*Architectures for Dynamic Resilient Embedded Autonomous and Mobile Systems

ADREAM: open cooperative platform dedicated to the topic of Ambient Cyber Physical Systems