What is a Wireless Sensor Network?

A Wireless Sensor Network consists of a large number of node deployed in the environment being sensed and controlled through wireless communication

- WSN is not a novelty
  e.g. atmospheric sensor, weather balloon, space probes

- Old solutions:
  - Sensors use client-server paradigm (no p2p interaction)
  - Sensors are not capable of local processing and they are not flexible
  - Hardware is quite large (1dm³ or more)
Motivation and Objective

Wireless sensor and computing networks

“As people find more ways to incorporate these inexpensive, flexible and infinitely customizable devices into their lives, the computers themselves will gradually ‘disappear’ into the fabric of our lives.”

Small, low power, low cost, low data rate wireless platforms are being developed in many places.

A new breed of Sensor Network?

*Moore’s Law push towards smaller, cheaper, low-power and mobile units*

- Complete systems on a single chip
- Integrated low-power communication modules
- Integrated low-power transducers

*These trends work together to enable a new generation of Wireless Sensor Network*

With:
- Small physical size (cm³, mm³)
- Cooperative behavior
- Multifunctional, local intelligence
Watt nodes

μAMPS (MIT)

http://www-mtl.mit.edu/researchgroups/icsystems/uamps/

mWatt Nodes

http://www.btnode.ethz.ch/Projects/SensorNetworkMuseum
μWatt node

Smart Dust (Berkeley)

http://www-bsac.eecs.berkeley.edu/
http://robotics.eecs.berkeley.edu/~pister/SmartDust/
http://www-bsac.eecs.berkeley.edu/archive/users/warneke-brett/SmartDust/index.html

Moore’s Law of WSN
Anatomy of sensor nodes
Sensor node functional components:

- TinyOS
- BTnutOS
- ZigBee
- Wibree
- Bluetooth
- Data Fusion
- Pattern recognition
- Batteries
- Power Transmission
- Energy Harvesting

Power consumption is the primary metric to design a Sensor Node

And the Actuators?
Usually they need more power than a sensor unit

ROBOMOTE (U. of S. California)
http://asimov.usc.edu/resl/research/videos/sensornet.html

COTS BOTS (Berkeley)
http://www-bsac.eecs.berkeley.edu
Ambient Intelligence

Electronic environments that are sensitive and responsive to the presence of people

Ambient intelligence envisions a world where people are surrounded by smart infrastructures provided with intelligent devices and sensors embedded in the everyday objects. These environments recognize and respond to the presence and behavior of an individual in a personalized and relevant way.

The Dream

Ubiquitous computing’s dream of wireless sensors everywhere is accompanied by the nightmare of battery replacement and disposal.

Battery Technology is Stuck!

No Moore’s Law in batteries:
2-3%/year growth

Solution

Design systems that harvest limited energy from ambient (heat, light, radio, or vibrations…) or scavenge power from human activity.
Environmentally powered systems

Effective, long term, power supplies are lacking

Example: At an average power consumption of 100 mW, you need more than 1 cm³ of lithium battery volume for 1 year of operation.

**Goal**

To investigate power “scavenging” technologies that can provide an average of 100 mW/cm³ indefinitely.

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### Power supply and demand

<table>
<thead>
<tr>
<th>Source</th>
<th>Power (Energy) Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batteries (Zinc-Air)</td>
<td>1050 -1560 mWh/cm³ (1.4 V)</td>
</tr>
<tr>
<td>Batteries (Lithium ion)</td>
<td>300 mWh/cm³ (3 - 4 V)</td>
</tr>
<tr>
<td>Solar (Outdoors)</td>
<td>15 mW/cm² - direct sun 0.15 mW/cm² - cloudy day.</td>
</tr>
<tr>
<td>Solar (Indoor)</td>
<td>0.57 mW/cm²</td>
</tr>
<tr>
<td>Vibrations</td>
<td>0.001 - 0.1 mW/cm³</td>
</tr>
<tr>
<td>Acoustic Noise</td>
<td>3E-6 mW/cm² at 75 Db sound level 9.6E-4 mW/cm² at 100 Db sound level</td>
</tr>
<tr>
<td>Passive Human Powered</td>
<td>1.8 mW (Shoe inserts &gt;&gt; 1 cm²)</td>
</tr>
<tr>
<td>Thermal Conversion</td>
<td>0.0018 mW - 10 deg. C gradient</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>0.33 mW</td>
</tr>
<tr>
<td>Ambient radio frequency</td>
<td>&lt; 1 µW/cm²</td>
</tr>
<tr>
<td>Ambient airflow</td>
<td>1 mW/cm²</td>
</tr>
<tr>
<td>Fuel Cells</td>
<td>300 - 500 mW/cm³</td>
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</table>

<table>
<thead>
<tr>
<th>Sink</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Node Power Consumption</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>CPU</td>
</tr>
<tr>
<td>Radio</td>
</tr>
<tr>
<td>Sensors</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
</tr>
</tbody>
</table>

Energy from the environment + Aggressive energy management = Perpetual Powered Node
Energy Harvesting and WSN

Energy harvesting is the process by which energy is captured, stored and managed.

Hardware Design
- Conversion efficiency
- Impedance Matching
- Maximum power transferred
- ...

Software Design
- Scheduling algorithm
- Adaptive duty cycle
- Energy prediction algorithm
- ...

Energy Profile Examples

Devices are powered by unlimited and fluctuating energy source

Power waveform from human walk (piezo-scavengers)

Ex: solar power (PV-cells)
Environmental energy powered systems

Possible architecture

Key principles:

♦ Modular design
♦ Enable the interchange of energy harvesting technologies
♦ Host different Energy Storage Devices (ESD)

Environmental energy powered systems

Design philosophy

Analog approach

Digital approach
Solar energy has the highest energy density among energy harvesting methods.

If outdoor sunlight, or relatively intense indoor light is available, solar cells appear to be the best alternative.

Solar cells are a mature technology and a mature research area.

Commercially available.

---

Solar Harvesting

Solar harvesters are probably the most common today.
Solar Harvesting at UNIBO

[Solar-BTnode: ETH-UNIBO 06]  [Solar-Tmotesky: UNIBO 07]

[µsolar scavenger 10mm² PV surface: UNIBO 07]

Solar harvesting

Problems:
- Maximum Power point (MPP)
- Tracking MPP (MPPT)
- Low Power Budget (mW)

Goal:
- reduce PV-cell size
- reduce storage device size
- increase the autonomy

I-V chart

P-V chart
Direct Connection Efficiency

- Efficiency increases approaching maximum power point
- Charge characteristic very inefficient
- Control circuit required to maximize the output power

![Graph showing Vc (mV) vs. T (s)]

Improving Energy Transfer

- AMBIMAX project exploits sensors on the power sources to maximize impedance match
  - Achieves Maximum Power Point Tracking (MPPT)
- [UNIBO07] proposes modeling and estimation of scavenger to optimize MPPT

![Graph showing power vs. voltage with Maxima Power Point (MPP), Lower Bound, and Upper Bound]
MPP Regulator

Controlled variable

$V_{\text{low}}$, $V_{\text{high}} \rightarrow \text{duty cycle}$

Online control for tracking PV curve variations with incident light, temperature

MPP tracking with a pilot PV cell

Fractional Open Circuit Voltage technique

$V_{\text{MPP}}(T, L) \approx K_{\text{FOCV}} V_{\text{OC}}(T, L) \approx K_{\text{FOCV}} K_{T} V_{T}(T, L)$

Use $V_{T}$ from a micro PV cell to generate $V_{\text{low}}$, $V_{\text{high}}$
Is Tracking of the MPP important?

**Outdoor**
The power from a solar cell can vary significantly during the day (ever orders of magnitude)

Device with large storage devices and relevant power consumption

Small sensor node and ULP devices with small energy buffers

**Indoor**
Light intensity assumes approximately the same set of values (light pattern).

Approach

- WSN architecture support a wide voltage supply range (usually between 1V and 4V)
  - Tmote Sky 2,1 – 3,6 V
  - TinyNode 584 2,4 – 3,6 V
  - TI Node 1,8 – 3,6V

- Powering sensor nodes with unregulated and variable voltage supply from the solar cell

GOAL

Minimization of the energy used for ineffective operations (e.g. DC/DC or linear regulator)
**Approach**

- Select the desired light intensity and find the solar cell MPP.
- A window \((V_{th1}, V_{th2})\) is defined around the MPP forcing the sensor node to operate in this range of values.

**GOAL**

Maximization of the energy harvesting efficiency under the desired light intensity

**How it works**

Inductor-less solar harvester

Design of the energy storage and conversion circuitry together with the target platform

\[
E_{av}(t, t + T_{active}) = \frac{C}{2} (V_{th2}^2 - V_{th1}^2) + E_H(t, t + T_{active})
\]

Energy available for the whole Activity time

C, Vth1, Vth2 are evaluated in order to guarantee the complete execution of the worst-case task or activity.

Research supported by a grant of Telecom Italia
Implementation

Example

[C\text{\textmu}solar cell for ZigBee Sensor node]

\[ C_{\text{min}} \] is evaluated by characterizing the most power-consuming operations, in order to guarantee the completion of the worst-case task.

\[
C_{\text{min}} = 0.1 \text{F}
\]

Harvesting-Aware Policies

Temporal power profile

Spatial power profile

Rechargeable battery or super capacitor

Energy buffer

Task reconfiguration [Acquaviva06], scheduling [Brunelli06]

adaptation

scattered sensor nodes (ex fire detection)

Routing, distributed scheduling
Energy harvesting Electronic System Design

What is different in Software and Firmware development?

- Conventional energy management: **How do we save energy?**
- Energy harvesting management: **When do we use energy?**

- Determine an **optimal on-line scheduling** of activities:
  If the set of activities is schedulable, it determines a feasible schedule.

- Determine decisions on the **application level** that **optimize the long term system behavior**

System Reconfiguration

- Environmental energy is variable (solar power, vibrational microgenerators, thermal scavengers)
- Types of reconfigurations
  - SW:
    - Lazy scheduling [Brunelli06], adaptive power management [Kansal06,Moser07],
    - Game theoretic approach to determine sleep/wake-up schedules [Nihato07]
  - HW: Reconfiguration through FPGA [Nahapetian07,Susu07]

**Concept**
- Exploit period of “light” to reconfigure system to execute next tasks with less power
- Statistical energy availability estimation to decide about reconfiguration
- maximize the work done adapting to the available energy profile
**System Model**

- **Energy Source** $S$
- **Energy Storage** $E_C(t) \leq C$
- **Computing Device** $D$
- **Tasks** $J_1, J_2$

**Task $J_i$**
- Can be preempted
- Arrives at time $a_i$
- Has deadline $d_i$
- Needs total energy $e_i$ to complete
- Can consume power $0 \leq P_D(t) \leq P_{max}$
- Therefore, needs time $w_i \geq \frac{e_i}{P_{max}}$

---

**When do we use energy?**

- **Greedy scheduling is not suited.**
- **ALAP does not work either.**
- And what happens if the energy storage is full?
Lazy Scheduling Algorithm

Rule 1: All tasks with $s_i \leq t$ are processed with EDF scheduling using $P_{max}$.

$$s_i = d_i - \frac{\min(C, E_C(t) + \varepsilon(d_i - t))}{p_d}$$

Lazy Scheduling Algorithm

Rule 2: If there is no task with $s_i \leq t$ and the energy storage is full, all incoming power $P_S(t)$ is assigned to the task with the currently earliest deadline.
Features

- Start time $S_i$ can be computed once when the task is scheduled
- Energy is not wasted on task that can’t be finished

Admittance Test

A given set of event streams $J_i$, $i \in I$ is schedulable with initially stored energy $C'$, iff

$$\forall \Delta : \sum_{i \in I} c_i \alpha_i (\Delta - d_i) \leq \min \{c^l(\Delta) + C', P_{max} \Delta\}$$

The proof uses concepts of network calculus and real-time calculus.
Performance

X axis = max Capacity
Y axis = time of the first overflows

Capacity savings of ~40% measured for random task sets for LSA with ε(Δ) compared to EDF

Practical Task Processing
Energy harvesting Software Design
What is different?

- Conventional energy management: How do we **safe** energy?
- Energy harvesting: When do we **use** energy?

If sensor node **is not** OS equipped:

**Determine decisions on the application level that optimize the long term system behavior**

- Sensing rate
- Receive messages
- Data transmission
- Forward messages

Minimal sensing rate
Average throughput
Reactivity
Freshness of data

Work in conjunction with ETH Swiss Federal Institute of Technology
Principles: Model predictive control

Model predictive control is the class of advanced control techniques most widely applied in the process industries.

The main idea of MPC is to choose the control action by repeatedly solving on line an optimal control problem. MPC is based on iterative, finite horizon optimization of the system under control → Receding Horizon Control

MPC:

Model: A model of the process (system) under control is required.
Predictive: Optimization is based on the predicted evolution of the model
Control: It is usually adopted for complex systems (MIMO Multi-Input Multi-Output)

Principles: Receding Horizon Control

Two Step

- At time $k$, solve an open loop optimal control problem over a predefined horizon and apply only the first input (i.e. control law for time $k+1$)
- At time $k+1$ repeat the same procedure. (The previous optimal solution is discarded!)

MPC is like playing chess!!

- Prediction of opponents moves
- Optimization of outcome a few moves ahead
- An unexpected move from the opponent = change of strategy!
- Good players thinks several moves ahead = long prediction horizon!
System Model

Models for application, quality/utility, system behavior?
Optimization problem?
Efficient run-time implementation?

Principles

- Optimization problem: finite horizon control
- Example: Linear program for sensing/transmitting optimization

\[
\begin{align*}
\text{maximize} \quad & (\lambda - \mu) \quad \text{subject to:} \quad \quad \quad \quad \quad \quad \quad \quad (14) \\
\text{Rate of acquisition} \quad & s_1(t + k \cdot L) \geq \lambda \quad \quad \forall 0 \leq k < N \\
\text{Memory usage} \quad & M(t + N) \leq \mu \\
\text{Stored energy} \quad & E_C(t + k \cdot L) = E_C(t) + \sum_{j=0}^{k-1} \tilde{E}(t, j) - \\
& - \sum_{j=0}^{k-1} (L \cdot [0.1 \quad 0.9] \cdot S(t + j \cdot L)) \geq 0 \quad \forall 1 \leq k \leq N \\
\text{Used memory} \quad & M(t + k \cdot L) = M(t) + \\
& + L \sum_{j=0}^{k-1} [1 \quad -1] \cdot S(t + j \cdot L) \geq 0 \quad \forall 1 \leq k \leq N \\
\text{Final stored energy} \quad & E_C(t + N \cdot L) \geq E_C(t) - 150 
\end{align*}
\]
Principles

Solving a linear program in a resource-constraint sensor node at each time step?

- Efficient run-time implementation
  - **Approach** Solve the LP as a parameterized LP and implement the explicit solution [Morari, Bemporad et al.]:

\[
U_{opt,i}(t) = B_i X(t) + C_i \quad \text{if } H_i X(t) \leq K_i, i = 1, \ldots, N_{CR}
\]

Different control laws in different regions of the state space!

- The optimal controller is a set of controllers with an affine “controller selection” rule
  - Design issue: limiting the number of different controllers
  - Preliminary results on highly constrained CPU are promising

Simulation and Experiments

**Example 1**
- Sensing rate control
- Minimize interval between samples

**Example 2**
- Rate control with memory buffer
  - Minimize interval between samples
  - Minimize amount of stored data

Gain: 56.8%
Simulation and Experiments

- Overhead

Other Potential Energy sources....

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Performance</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient radio frequency</td>
<td>&lt; 1 µW/cm²</td>
<td>Unless near a transmitter³</td>
</tr>
<tr>
<td>Ambient light</td>
<td>100 mW/cm² (directed toward bright sun) 100 µW/cm² (illuminated office)</td>
<td>Common polycrystalline solar cells are 16%–17% efficient, while standard monocrystalline cells approach 20%. Although the numbers at left could vary widely with a given environment’s light level, they’re typical for the garden-variety solar cell Radio Shack sells (part 276-124).</td>
</tr>
<tr>
<td>Theroelectric</td>
<td>60 µW/cm²</td>
<td>Quoted for a Thermo Life generator at ΔT = 5°C⁰; typical thermoelectric generators ≤ 1% efficient for ΔT &lt; 40°C.⁶</td>
</tr>
<tr>
<td>Vibrational microgenerators</td>
<td>4 pW/cm² (human motion—Hz) 800 µW/cm³ (machines—kHz)</td>
<td>Predictions for 1 cm³ generators.² High volatility dependent on excitation (power tends to be proportional to ω² and y₀², where ω is the driving frequency and y₀ is the input displacement), and larger structures can achieve higher power densities. The shake-driven flashlight of Figure 3, for example, delivers 2 mW/cm³ at 3 Hz.</td>
</tr>
<tr>
<td>Ambient airflow</td>
<td>1 mW/cm²</td>
<td>Demonstrated in microelectromechanical turbine at 30 liters/min.²⁶</td>
</tr>
<tr>
<td>Push buttons</td>
<td>50 µJ/N</td>
<td>Quoted at 3 V DC for the MIT Media Lab Device.²⁰</td>
</tr>
<tr>
<td>Hand generators</td>
<td>30 W/kg</td>
<td>Quoted for Nisso Engineering’s Tug Power (vs. 1.3 W/kg for a shake-driven flashlight).²</td>
</tr>
<tr>
<td>Heel strike</td>
<td>7 W potentially available (1 cm deflection at 70 kg per 1 Hz walk)</td>
<td>Demonstrated systems: 800 mW with dielectric elastomer heel.²⁶ 250–700 mW with hydraulic piezoelectric actuator shoes,²⁴ 10 mW with piezoelectric insole.²⁵</td>
</tr>
</tbody>
</table>
Other Energy sources….

- RF
- Thermo
- Vibrational
- Human (impulse)

Wireless Power for Miniature Sensors

Eliminate wires and battery replacement for sensor applications by efficiently harvesting energy from RF sources through design of antenna elements and energy scavenging circuits optimized for ultra-low power levels

So far:
- Inductive coupling: not really waves
- RFID: near field, low power
- High-power beaming: use of solid-state power amplifier
Energy from Ambient EM fields

**Principle of RFIDs**

![Principle of RFIDs](image)

- Remotely power CMOS chip
- Smart badges, cards, animals, anti-theft detection
- Cheap
- ID response (e.g., 32-1K)
- Read all at once with swept reader

Energy from Environmental EM fields

- Radiative

![Energy from Environmental EM fields](image)
Cockcroft-Walton voltage multipliers

- With the Cockcroft-Walton circuit it is possible multiply the voltage of the input wave WITHOUT any battery. This allows to have a significative output voltage to supply a low power batteryless end devices.

- A Cockcroft-Walton prototype using Schottky diode has been designed, realized and successfully tested.

Multiplier design

- Printed Circuit Board
  - Miniaturized: 4 stage
  - Schottky diode: HBAT5402
  - Capacitor: 100 pF
  - One bottom ground plane

Network analyzer characterization

- Impedance 866 MHz
- Frequency sweep
- Power sweep
- Function generator
Multiplier parameter design

- \[ N_{\text{opt}} = \frac{3V_{\text{OUT}}}{4E_{\text{PK}}} = 3.9 \] Optimum stage number
- \[ C = \frac{fC(N_{\text{opt}})}{f} = \frac{I_{\text{load}}}{f} - \frac{N_{\text{opt}} + 3N_{\text{opt}}^2 + 4N_{\text{opt}}^3}{12E_{\text{PK}}N_{\text{opt}} - 6V_{\text{OUT}}} = 99.5 \text{ pF} \] Capacitor

Matching network design

- Advanced Design System: Smith tool
  - Smith chart with load and source impedance settable
  - All distribute and concentrate component usable for \( N \)
  - Network response
Power Delivery to Bio-Implantable wireless circuits

Output voltage to the implanted device 2.2V

Energy from Environmental EM fields

- Inductively powerered WSN Node

Energy harvesting exploiting the EM field from AC electric current

Research supported by a grant of Telecom Italia
Environmental Data Gathering Application

- Sensors: Temperature, Humidity, Light intensity…
- Adjustable duty cycle (13sec.)
- Low power consumption (19mA)

Energy from Human daily activity

Motion and Vibrations

Electrostatic

- More easily implemented in standard micro-machining processes
- Requires a separate voltage source (such as a battery) to begin the conversion cycle.

Electromagnetic

- Typically output AC voltages is below 1 volt in magnitude
- Not easy to implement with MEMS technologies

Piezoelectric

- The output voltage is irregular and depends on the constructions
- An overvoltage protection circuits is required

Electromagnetic generator

Uses the motion of a moving coil through a static magnetic field to induce a voltage across the coil.

Farady’s Law

\[ V = -N \frac{d\Phi_B}{dt} \]

Power provided: \( \sim 120 \text{nW} \)
Frequency: 1.3 to 9.5 kHz
Volume: 100 mm\(^3\)

Vibration Energy Scavenging (VIBES project)
www.vibes.ecs.soton.ac.uk/index.html
Energy from Feet and Hands movement…

*state of the art*

Vibrational Harvesters at UNIBO

**Piezoelectric**

- Size: 9.8 x 5.7 x 3 cm
- Weight: ~120 g
- Energy buffer: 4.7 μF
- Mean power (benchmark 2 Hz): 18 μW
- Energy (1 min.): 1.1 mJ

**Electromechanical**

- Size: 6.5 x 2.5 x 2.5 cm
- Weight: ~80 g
- Energy buffer: 4700 μF
- Mean power (benchmark 2 Hz): 206 μW
- Energy (1 min.): 12.4 mJ
Energy from hand movement

Usually they exploit the magnetic induction on a coil.

Requires several cycles/min to get and keep approx. 3-4W

Energy for Multimedia

$100 Laptop (OLPC Foundation)
1W power consuming

Regen,
1 hour MP3 listening with only 12 loops
Commercial products

- more than 20 mW in the presence of a significant vibration
- very weak vibration (e.g. microwave oven 0.24 g’s, 120 Hz) it is able to harvest 43µW.

Volture
www.perpetuum.co.uk

The Sustainable Dance Floor
www.enviu.org

Thermoelectric conversion

V = \int_{T_1}^{T_2} (S_B(T) - S_A(T)) dT

Thermoelectric conversion
Carnot efficiency : \( \frac{(TH - TL)}{TH} = \Delta T / TH \).

Seebeck-Peltier effect
- Applied Digital Solutions’ Thermo Life (10 µA at 3 V with only 5 degrees Celsius of temperature difference).
- Store extra energy produced during periods of higher \( \Delta T \) so they can continue to run during warmer, less efficient ambient temperatures.

Thermo pile (thermolife®)
Thermoelectric example

Seiko Thermic wristwatch, convert heat from the wrist (body heat) into electricity.

Energy from wrist movement

Proof mass oscillation directly cranks generator rotor
- Little intervening mechanics
- Charge accumulated on capacitor

Power Output:
- 5 μW average when the watch is worn
- 1 mW or more when the watch is forcibly shaken
Classic technologies
Windmills

- Sensor nodes with windmills of diameter 10 cm attached to a rotating cam that flexes a series of piezoelectric crystals as it rotates, causing them to generate a current
  - A 'gentle breeze' of 16km/h is enough to generate the 7.5mW

And the storage devices?

**Energy Storage Technologies**

- Options
  - Secondary (i.e. rechargeable) batteries
  - Capacitors
  - Flywheels
  - Fuel cell...

- Tradeoffs
  - Batteries
    - Mature technology, high energy density, less efficient, limited to few hundred full recharging cycles (significantly more shallow cycles)
  - Ultracapacitors (up to hundreds of Farads)
    - Virtually infinite recharge cycles, higher leakage current (goes up with size), higher power density, typically used for short duration power surges

- Configurations: Battery-only, Capacitor-only, Tiered Capacitor+Battery
Printing for Micro Power Storage

Battery printed on mote

Electrochemical capacitors in parallel with lithium ion batteries = High power, high energy micropower system

Battery or Supercapacitor?

Supercapacitor promises:
- Very high rates of charge and discharge.
- Little degradation over hundreds of thousands of cycles.
- Good reversibility
- Low toxicity of materials used.
- High cycle efficiency (95% or more)

<table>
<thead>
<tr>
<th>Fuel:</th>
<th>Energy Density</th>
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<tr>
<td>Diesel Fuel/Jet Fuel</td>
<td>12,000 Wh/kg</td>
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<tr>
<td>Methanol</td>
<td>5,000</td>
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<tr>
<td>High Explosive</td>
<td>1,000</td>
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<table>
<thead>
<tr>
<th>Battery:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Battery (est. max.)</td>
<td>500</td>
</tr>
<tr>
<td>Rechargeable (est. max.)</td>
<td>200</td>
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<tr>
<td>Li/SO₂ Battery (primary)</td>
<td>176</td>
</tr>
<tr>
<td>Alkaline Battery (primary)</td>
<td>80</td>
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<tr>
<td>Nickel-Cadmium (secondary)</td>
<td>40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power density (W/kg)</th>
<th>Fuel cells</th>
<th>Conventional batteries</th>
<th>1 hour</th>
<th>1 second</th>
<th>Ultracapacitors</th>
<th>Conventional Capacitors</th>
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<tbody>
<tr>
<td>0</td>
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<td>0.03</td>
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<td>1000</td>
<td></td>
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<tr>
<td>10,000</td>
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</tbody>
</table>
Fuel cell

Membrane splits electrons off hydrogen

Electrons recombine with proton on other side in catalyzed reaction w. oxygen to form water

Micro Fuel Cell examples

MTI Micro's Mobion®
- Methanol
- Up to a 95Wh
Application areas over next 10 years:
“smart” homes, fatigue monitoring, ubiquitous data access for people, building env. control, emergency response in commercial buildings, manufacturing monitoring and control, inventory tracking, etc.

Concluding: Fields of Application

Logistics and transportation e.g. tracking goods

Architecture and Conservation e.g. structural control

Military e.g. battlefield support

Environment science e.g. monitoring volcanoes

Agriculture e.g. monitoring crop growth

Medicine and biology e.g. health monitoring