ADVANCED POWER SOLUTIONS FOR WEARABLE TECHNOLOGY AND INTERNET OF EVERYTHING SENSORS

WEBINAR
Webinar Agenda

1. Wearable Technology and Internet of Everything market dynamics
2. Examine WT and IoE system components and powering options
3. Techniques for harvesting ambient energy to recharge devices
4. New technologies and the cost trade-offs for advanced power solutions
5. Design tips for building ultra-low power systems with long battery life
6. Examples of real-world Energy Harvesting-powered WT and IoE devices
The Key Trends Driving Innovation for Internet of Everything and Wearable Tech

- New innovative products are smarter, smaller and wireless
- Smart devices that must communicate status/control
- There will be billions of new networked smart devices
- Health, Industrial, Buildings, Appliances, Transportation
- New Efficient and Cost-Effective Powering solutions needed
25 Years of Device Evolution to IoE

Fixed Computing to Internet of Everything

Rapid Growth of the Number of Things Connected to the Internet

“Fixed” computing (you go to the device) | Mobility / BYOD (the device goes with you) | Internet of Things (age of devices) | Internet of Everything (people, process, data, things)

1995 | 2000 | 2013 | 2020

200M | 10B | 50B

Source: Cisco
HP, IBM, Google, Cisco, et al...  
*Giving the Planet a Voice with Sensors*

**HP CeNSE Project**  
CeNSE

- Central Nervous System for the Earth
  - Awareness of planet
  - Measurement of impact
  - Tasteful/Tactile/Touch/Sound/Sight
  - Safety
  - Sustainability
  - Security

- 1 trillion sensor network  
  Quantity of data creates quality of data

**IBM Smarter Planet**

“Trillions of digital devices connected to the Internet, are producing a vast ocean of data…”

“The Internet of Everything builds on the Internet of Things by adding network intelligence and security that allows convergence, orchestration and visibility across disparate systems.

But.... Who’s going to change 1 Trillion Batteries????!
Use Energy Harvesting vs. Primary Batteries

- Energy can be harvested from almost any environment:
  - Light, vibration, flow, motion, pressure, magnetic fields, RF, etc.
- Energy Harvesting applications found in every industry segment
- EH-powered systems need reliable energy generation, storage and delivery:
  - Must have energy storage as EH Transducer energy source is not always available: (Solar @night, motor vibration at rest, air-flow, etc.)
  - Longer operating times – high-efficiency minimizes charge loss
  - Self-Powered allows remote locations & lower installation costs
  - High cycle life enables extended operation – fewer service calls
- Ideal solution is a highly-efficient, eco-friendly, power generation system that can be cycled continuously for the life of the product
EH Power Range for IoE and Wearables

Energy Harvesting Sweet Spot

- μP Standby
- Real Time Clock (RTC)
- Watch/Calculator
- RFID Tag
- Sensor/Remotes
- Hearing Aid/Wireless Sensor
- Bluetooth Transceiver
- GPS
- GSM Cell Phone
- Laptop Computer
- Power Tools

Peak Power

- 100W
- 10W
- 1W
- 100mW
- 10mW
- 1mW
- 100μW
- 10μW
- 1μW
- 100nW
- 10nW
- 1μV

Texas Instruments
MSP430 RF2500
Wireless Sensor Demo
(~60mW Peak)
Energy Harvesting Powered Wireless Sensor Diagram

“Energy Aware” Systems measure and report EH input power and Battery state of charge to optimize operation.
Key Design Issue for EH-Powered Systems

- High efficiency designs
  - Minimize losses (on-resistance, coil resistance, ESR, leakage, ...)
  - Minimize average standby/sleep power
  - Reduce wireless TX/RX power and/or lengthen radio pulse duty cycle
  - Maximize harvested power through the power chain
## Energy Harvesting Transducers

### What Ambient Energy is Available?

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Challenge</th>
<th>Typical Impedance</th>
<th>Typical Voltage</th>
<th>Typical Power Output</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Light</strong></td>
<td>Conform to small surface area; wide input voltage range</td>
<td>Varies with light input&lt;br&gt;Low $k\Omega$ to 10s of $k\Omega$</td>
<td>DC: 0.5V to 5V [Depends on number of cells in array]</td>
<td>10µW-15mW&lt;br&gt;(Outdoors: 0.15mW-15mW)&lt;br&gt;(Indoors: &lt;500µW)</td>
<td>$0.50 to $10.00</td>
</tr>
<tr>
<td><strong>Vibrational</strong></td>
<td>Variability of vibrational frequency</td>
<td>Constant impedance&lt;br&gt;10s of $k\Omega$ to 100$k\Omega$</td>
<td>AC: 10s of volts</td>
<td>1µW-20mW</td>
<td>$2.50 to $50.00</td>
</tr>
<tr>
<td><strong>Thermal</strong></td>
<td>Small thermal gradients; efficient heat sinking</td>
<td>Constant impedance&lt;br&gt;1$\Omega$ to 100s of $\Omega$</td>
<td>DC: 10s of mV to 10V</td>
<td>0.5mW-10mW&lt;br&gt;(20°C gradient)</td>
<td>$1.00 to $30.00</td>
</tr>
<tr>
<td><strong>RF &amp; Inductive</strong></td>
<td>Coupling &amp; rectification</td>
<td>Constant impedance&lt;br&gt;Low $k\Omega$s</td>
<td>AC: Varies with distance and power&lt;br&gt;0.5V to 5V</td>
<td>Wide range</td>
<td>$0.50 to $25.00</td>
</tr>
</tbody>
</table>

Designs must deal with different: Impedance, Voltages, Output power, etc.
Using Maximum Peak Power Tracking (MPPT)

- Match the Impedance of the Energy Harvesting Transducer Source to the Impedance of the Load using **Maximum Power Point Tracking circuitry** to provide the highest efficiency harvesting.
EH Power Conversion Techniques

- **MPPT algorithms**
  - Incremental conductance ($\Delta P/\Delta V$)
  - P&O
  - Fractional OCV

- **Fractional OCV (Open Circuit Voltage)**
  - MPP voltage has a **fixed ratio** to open circuit voltage (0.7 – 0.8)
  - But: Ratio **not constant** and **different** for every generator

- **Perturb & Observe**
  - **Generic** algorithm
  - **Oscillates** around MPP

**Hill climbing algorithms**
Variable Impedance EH Transducer - Solar

Normalized power from a photo voltaic cell

- $V_{oc}$: V Open-circuit
- $I_{sc}$: I Short-circuit

Power and Voltage as a percentage of open circuit voltage

Current as a percentage of short circuit current vs. $I_{sc}$
Constant Impedance – Thermal, Piezo, Electromagnetic
Solar Power Management Example

- Series / parallel combinations optimize panel voltages (1 to 4 volt range)
- Maximum power point tracking / control optimizes energy transfer
- Example: Cymbet CBC915 Energy Processor chip
MPPT with Thermoelectric Generator

- TEG has various Power outputs at different Temperature gradients and Peak Power Point occurs at different places.
- An example hill-climbing MPPT algorithm is shown to arrive at the Peak Power Point
EH vs. Primary Battery Costs Comparisons

- Small device designs that do not have a charging source – either AC/DC, Energy Harvesting or Wireless Power – use a primary battery
- Primary batteries have reached commodity status with billions/year shipped
- How to compare cost of Energy Harvesting to Primary Batteries?
- Model the Energy Harvester as a variable capacity battery and divide the cost of the EH components by the amount of energy created over the life of the EH-powered system.
Calculate the $/mAh for Batteries

• Example using 3Volt batteries 1K Quantity from Distributors:
  
  • CR2032 coin + holder: $.36/225mAh x 1 cycle = $0.0016/mAh
  • Tadiran coin: $4.82/1000mAh x 1 cycle = $0.0048/mAh
  • Alkaline 2 AAA + holder: $1.71/1000mAh x 1 cycle = $0.0017/mAh
  • Cymbet EnerChip: $2.70/50uAh x 10,000 cycles = $0.0054/mAh

• To charge rechargeable batteries, need to add the Cost for EH power system
• Supercapacitors can be used, but electrical characteristics are a concern
Calculating the $/mAh of the Energy Harvester

• Think of the Energy Harvester as a variable capacity battery
• The output energy will depend on the ambient energy conditions
• Energy Harvester designs will have a min/max energy output range
• Calculate the EH cost based on the energy output average
• Cost is Transducer + interface components+ storage + conversion electronics (IC)

Example: Simple Solar Energy Harvester at 400Lux with 24/7 operation
• Sanyo AM1815 4.9V solar cell $4.39 (1K pcs) output is 294uW
• Assume simple conversion electronic components for $1.25
• EnerChip Batteries – 200uAh total capacity $4.10
• 294uW/3.3V = 89microAmps output from Solar Harvester
• Total capacity over 10 year 24/7 life = 7796 mAh
• $/mAh for Solar EH = $0.0013/mAh. Lower than AAA and Coin cell costs

Energy Harvesters can be designed as cost effectively as Primary Batteries
Assigning $ Value to EH-Power Solution over Batteries

1. Primary Battery Change-out – device access and cost of replacement
2. What is the product power lifetime requirements – 200mAh, 1Ah, 10Ah?
3. Life of product duration expectations – 3, 5, 10, 20 years?
4. Battery Footprint and overall product size
5. Battery Height and overall product size
6. $cost/uAh/mm³ - how much energy for $ in how small a space?
7. Assembly Issues and Costs
8. Product Physical design – No doors or customer access
9. Electrical Characteristics - flat voltage, fast recharge, low discharge
10. Aging Characteristics – chemical leakage, seals drying out
11. Transportation Restrictions – UN and Country Air Safety shipping laws
12. Safety and End-of-Life Disposal - what are the procedures and costs
EH Power System Cost vs. Benefit

$ Cost vs. $ Benefit vs. Requirements
“Watt a waste.....”

Even if all 50 billion wireless devices could be powered by just a single coin cell

We would still need a line of batteries that wraps around the earth 4 times
IoE Needs a New Type of Battery

INDUSTRY TRENDS AND CURRENT SOLUTIONS ARE MISALIGNED

TREND: GROWTH OF ELECTRONIC DEVICES THAT ARE SMALLER, PORTABLE, CONNECTED

- Ultra-Low Power Processors
- Wireless Smart Devices & Sensors Everywhere
- Component Integration and Miniaturization
- Eco-Friendly and Renewable Energy

Key Trends Driving Billions of New Devices

CURRENT ENERGY STORAGE SOLUTIONS ARE INADEQUATE

- LARGER PROFILE / BULKY SIZE
- LOW ENERGY FOR SPACE USED
- INTEGRATION ISSUES
- HIGH WEAR-OUT AND FAILURE ISSUES
- TOXIC CHEMICALS – SAFETY AND DISPOSAL ISSUES
Cymbet Rechargeable Solid State Batteries

- Manufactured with standard silicon CMOS-type processes.
  - Small Chip-scale footprint - bare die or packaged parts - 150 microns thick
  - Thousands of Recharge cycles – “life of product” Fast recharge – 80% in 10 minutes
  - Ultra-low self-discharge + flat discharge profile - Uniquely suited to Energy Harvesting
  - Reflow tolerant for low cost automated assembly SMT - >360°C
  - Completely Eco-Friendly; No heavy metals, liquids, binders, etc
  - As a silicon-based device, can be co-packaged or embedded with MCUs, RTCs, etc.
Solid State Batteries Used in Several Applications

Meeting Customer Needs
- Never replace batteries
- Eco-friendly, no disposal issues
- Low cost automated assembly
- Thin profile - Small footprint
- Embed at board or chip level
- Flexible packaging options

With Superior Solutions
- Simple “drop in” power
- SMT/Reflow solder tolerant
- No special transportation or disposal
- Rechargeable – Lasts life of product
- 2 Fabs for high volume production
- Many applications, many industries

EnerChip™ Solid State Batteries on Wafer

Power Backup
- EnerChip SMT Package
- EnerChip CC Co-Package

Energy Harvesting
- EnerChip CC Energy Harvesting & Energy Storage
- EnerChip EP Energy Processor
- RF Induction Charging Data Loggers
- EH-Powered Internet of Things Wireless Sensors

Embedded Energy
- EnerChip Bare Die Batteries
- Co-Packaged with other ICs
- 3D Bare Die Stacking

Healthcare
- Wireless
- Networks
- Industrial

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Comparing Energy Storage Options

SSB = Best of Both Worlds

- High Drive Current
- High Energy Density
  - 50 X SuperCap
- Lowest Leakage
  - 4,000 X < SuperCap
- Rechargeable / Long Life
- Superior Lifetime Energy – never replace a battery
Solid State Batteries Provide Key EH Battery Requirements

Need:
- 1000’s charge cycles
- Flat Output voltage
- Fast Charge
- Low Self Discharge
Solid State Batteries Shrink Sensors

Reducing the IoE Sensor size 144,000x

Increasing Level of Integration

EnerChips + Solar replace AA Batteries
EnerChips + Solar with Energy Processor
EnerChip Stacked Die in 10x10x6 mm Sensor
EnerChip Bare Die in 1 mm$^3$ Sensor

144,000 mm$^2$
31,350 mm$^3$
600 mm$^3$
1 mm$^3$
4 Key Techniques for Successful EH Designs

1. Determine energy available from your environment
   - Type of Energy Source(s), Amount of Energy, Duty Cycle

2. Harvest energy as efficiently and cost effectively as possible
   - Use MPPT or optimized circuits

3. Calculate application power requirements in all operation modes and minimize design to fit available input EH power
   - System Start-up Power, Sleep, Radio TX/RX, Sensing, Leakage, etc.

4. Size storage for times when ambient energy is not available
   - Almost all systems need rechargeable storage device
Industry is Providing Ultra-Low Power Solutions for IoE

- Low Power Microprocessors with nanoAmp sleep currents
  - TI, Renesas, Microchip, NXP, Silicon Labs, etc.

- Low Power Radio Transceivers and Energy Efficient Protocols:
  - 802.15.4 Zigbee, 6LoWPAN using IP, Bluetooth Smart, ANT +, EnOcean

- Micro-power Sensors with low sleep currents
  - Sensiron, NXP, TI, others….

- Lower quiescent current peripheral circuits – PMICs, timers, A/D, etc.
Techniques for running IoT Sensors on 1uW Avg. Power

- Off-the-shelf MCUs are capable of 1uW computing
  - Acceptable Performance at 1-2KIPS (not 1-2MIPS!)
  - Utilize Sensor samples at 1-10 SPS
  - ULP standby clock
  - Instant-on and very accurate high-speed clock
  - I/O, interrupt capability, and all RAM retained

- Traps
  - Firmware – no loops, all interrupts
  - Temperature increases leakage significantly
  - Floating inputs
  - Multiple voltage domain saturation
  - Watch for un-deterministic clocking
  - Where to get a 2V supply in a real application?
There may be situations where the components used in the design have high power operation. In this case, a Power Switching technique called an “Enerrupt” can be implemented.

The power in the WT or IoE system is switched on/off by a timer device.

An ideal device for this implementation is the Cymbet EnerChip RTC CBC34803 (I2C-bus) or CBC34813 (SPI). In the lowest power timer mode, the EnerChip RTC uses only 14nA of current.
“Enerrupt” System Power Using an EnerChip RTC

Fig 1: Switched VSS (Ground) Configuration

Fig 2: Switched VCC Configuration
Example Power Savings from using Enerrupt Circuit

**Application Note AN-1059**

- Power savings calculations have several variables to balance – Active run times, sleep periods, active time/sleep time and number of instructions.

- Power Savings Ratio shows battery extension of up to 11 times

<table>
<thead>
<tr>
<th>Original Sleep current in</th>
<th>Active Runtime in ms</th>
<th>Sleep Period in ms</th>
<th>Active Current When Running (ua)</th>
<th>Active Time / Sleep Time</th>
<th>Number of Instructions</th>
<th>Power Savings Ratio</th>
</tr>
</thead>
<tbody>
<tr>
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<td>200</td>
<td>1</td>
<td>0.1</td>
<td>16</td>
<td>200.000</td>
<td>0.0063</td>
</tr>
<tr>
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<td>200</td>
<td>1</td>
<td>0.1</td>
<td>33</td>
<td>200.000</td>
<td>0.0030</td>
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<tr>
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<td>1</td>
<td>0.05</td>
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<td>200.000</td>
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<tr>
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<td>0.3</td>
<td>250</td>
<td>200.000</td>
<td>0.0012</td>
</tr>
</tbody>
</table>
Bluetooth Smart Wearables Will Scale Faster due to Simple Interoperability
Bluetooth Smart EH-Powered Beacon

- A Bluetooth Smart beacon with a miniature solar panel that runs on room light

- Works for 2-3 hrs in the dark
- 50 hours in standby
- > 3 connections/sec at 200-500 Lux
- Chip battery charges in less than 2 hours
- Dialog Bluetooth Smart (DA14580) uses < 20 uJ/Connection

Courtesy: Dialog Semiconductor
BLE Beacon Tear Down

- Dialog DA14580 BLE radio, Solar Cell to TI BQ25504 PMIC with Cymbet EnerChip CBC050 rechargeable solid state battery
EH-Powered Wearable Intra-Ocular Pressure Sensor

All the EH-powered sensor components are here: Sensor, Energy Storage, MCU with A/D, Solar Cell and Radio with Antenna
Example of Wireless EH-Powered Smart Contact Lens Concept

Cymbet EnerChip
Non-Cytotoxic
Rechargeable
Solid State Battery

Ultra Low Power Management IC Designs Integrated with MCU and Radio

Wireless Communication to Smartphone and Wireless Charging

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Summary

• Billions of smart devices deployed over the next 10 years need to:
  • Be powered autonomously and be “off-grid”
  • Have a power source that lasts the life of the device
  • Be small, integrated and cost effective
• Cost effective Energy Harvesting solutions can power products
• Success is based on the EH Ecosystem converging:
  • EH Transducers
  • High Efficiency power conversion
  • Life of Product Energy storage
  • Ultra low power Microcontrollers and Sensors
  • Low power wireless radios and protocols
  • Optimized system architecture, hardware and firmware
Q&A, Resources and Evaluation Kits:

- Free Executive Briefing that supports this presentation: “Powering Wearable Technology and Internet of Everything Devices” can be found here: [http://www.cymbet.com/design-center/white-papers.php](http://www.cymbet.com/design-center/white-papers.php)


- Steve Grady – [sgrady@cymbet.com](mailto:sgrady@cymbet.com)