Energy Harvesting for No-Power Embedded Systems

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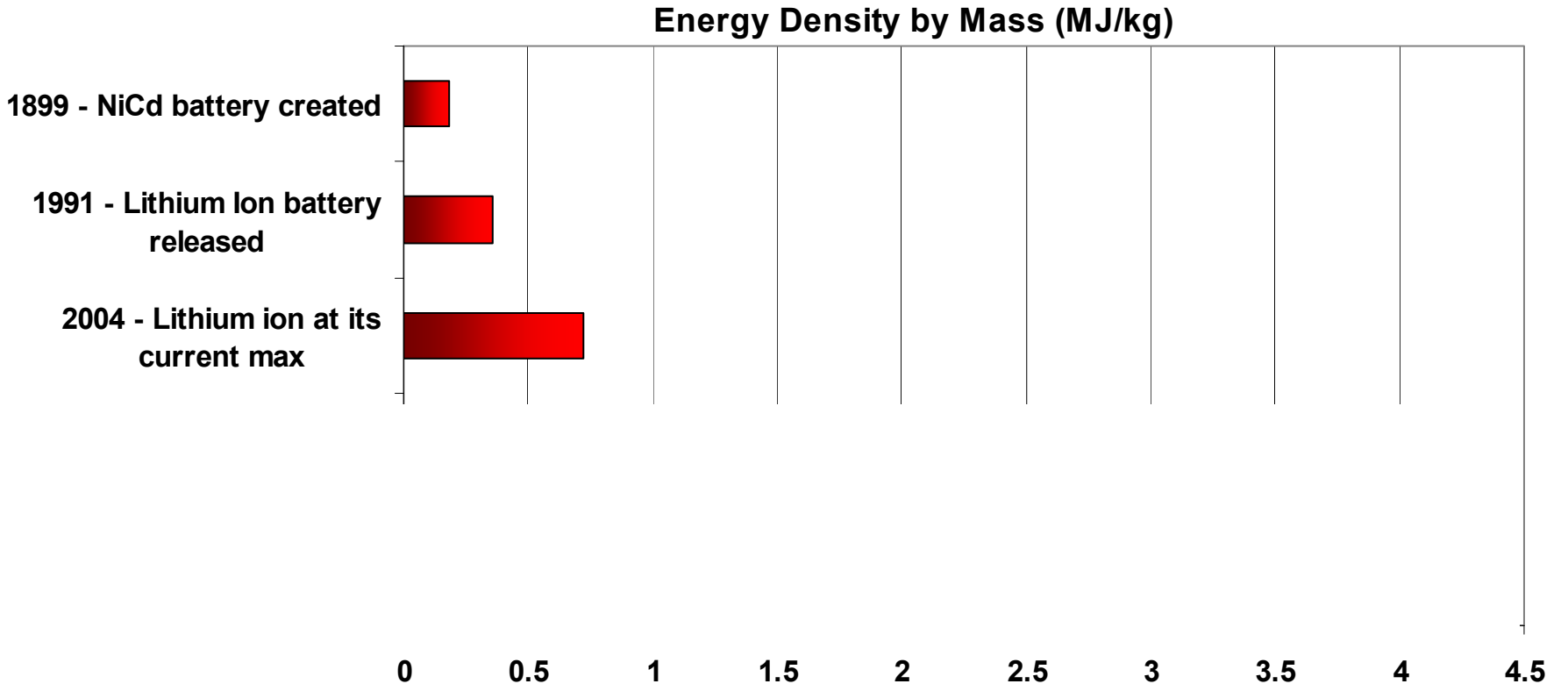
Limits to Battery Energy Density

- Processing power doubles every **2 years**, but…
- Battery capacity doubles every **10 years**
- *We need a more efficient way to enable longer life*



Available Energy is All Around

Light

Radio frequency

Motion and vibration

Heat

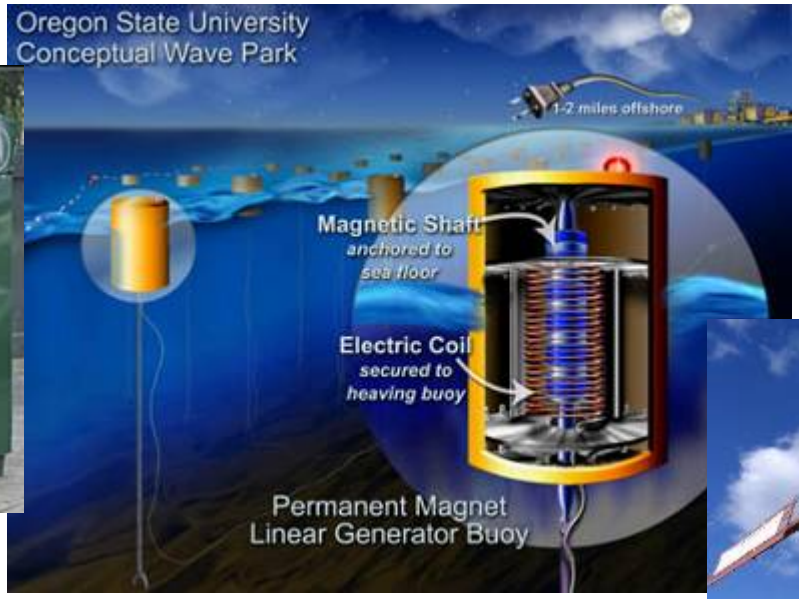
Energy Harvesting Basics

- ***Energy harvesting*** is the process by which energy is ***captured*** and ***stored***

- This term frequency refers to small autonomous devices – micro energy harvesting

- A variety of sources exist for harvesting energy
  - solar power
  - thermal energy
  - wind energy
  - salinity gradients
  - kinetic energy
  - radio frequency

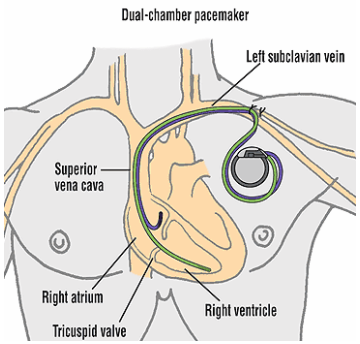
Energy Harvesting Isn't New



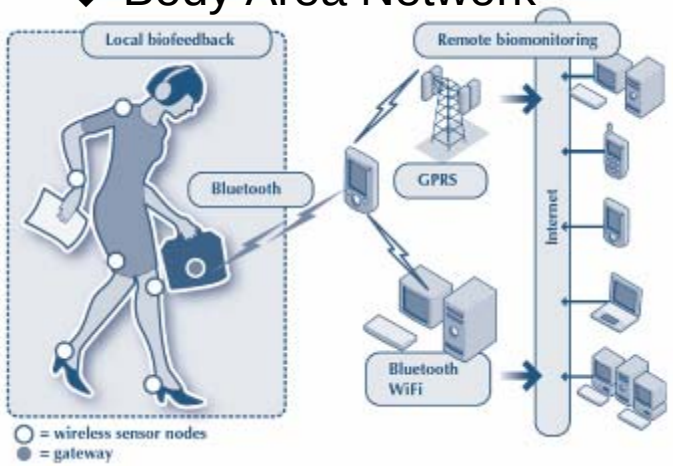
Energy Harvesting Applications

Low data rate, low duty cycle, ultra-low power

- Medical and Health monitoring



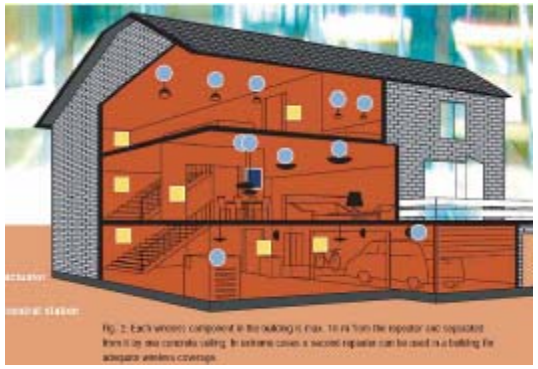
- Body Area Network



- Structure Health monitoring

- Wireless Sensor Networks

- Smart building



Energy Harvesting Tradeoffs

- **Advantages**
  - Mobile: no power wires
  - Easier installation
  - Lower maintenance
  - Environmentally friendly
  - Higher uptime
- **Disadvantages**
  - Dependent on availability of harvestable energy source
  - Strict power budget
  - Upfront cost may be higher
  - Less mature technology

When Does Harvesting Make Sense?

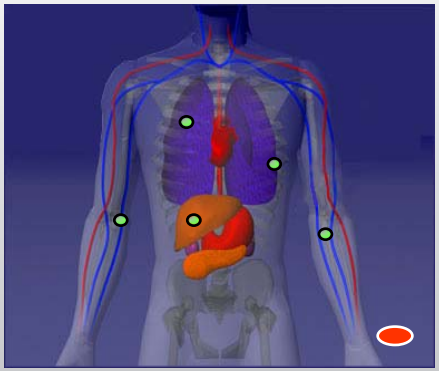
- Harvestable energy available
- Difficult to install or power devices
- Difficult to reach devices for maintenance
- Cords too costly
- Numerous devices
- Environmentally friendliness required
- High uptime demanded

One or more of these characteristics are required for energy harvesting to make sense compared to batteries

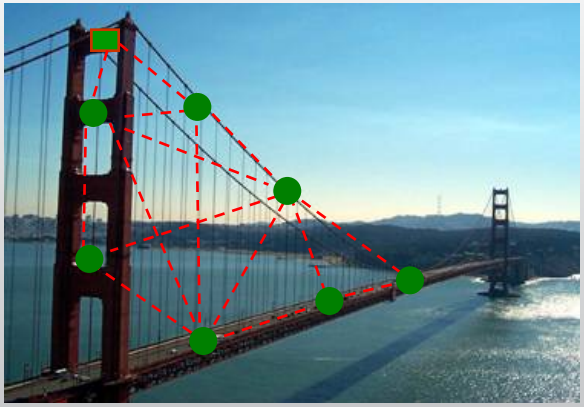
Permanently Powered Wireless Sensors

- Remote patient monitoring
- Harmful agents detection
- Efficient office energy control
- Surveillance and security
- Detecting and tracking enemy troop movement
- Vineyard or other agricultural management
- Home automation
- Implantable sensors
- Long range asset tracking
- Aircraft fatigue supervision

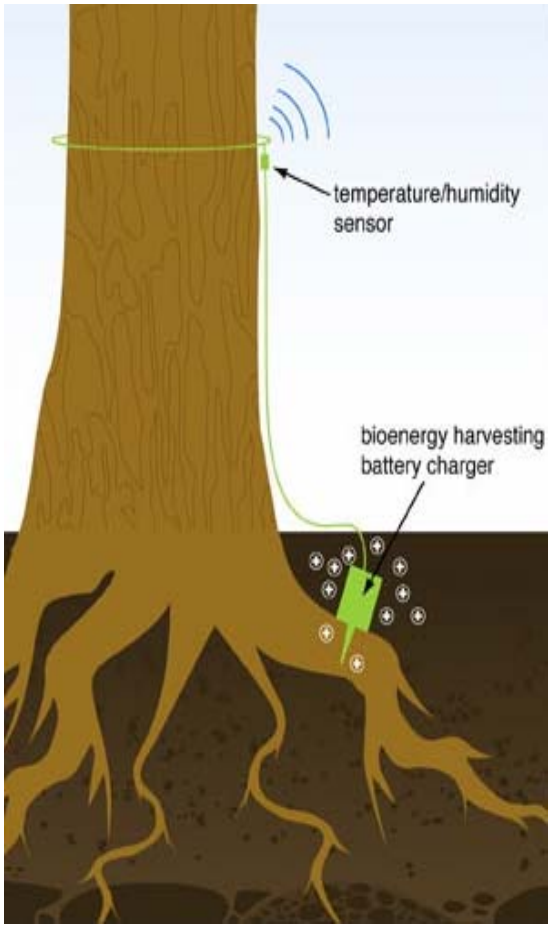
Remote patient monitoring (body heat)



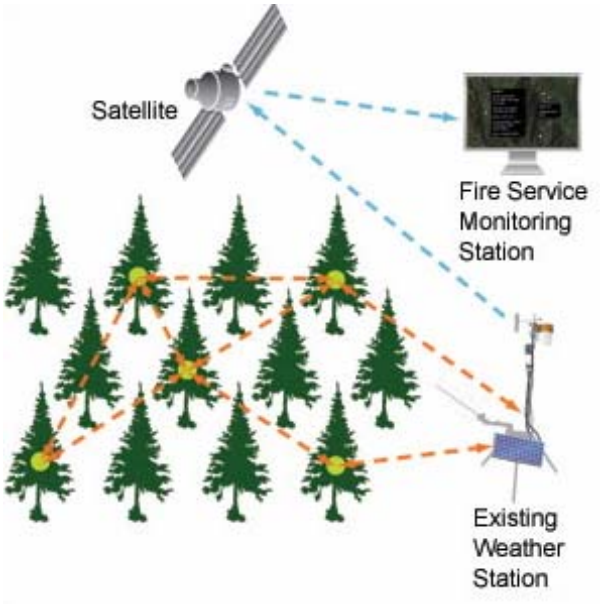
Structural monitoring (motion)



Tree Energy Harvesting

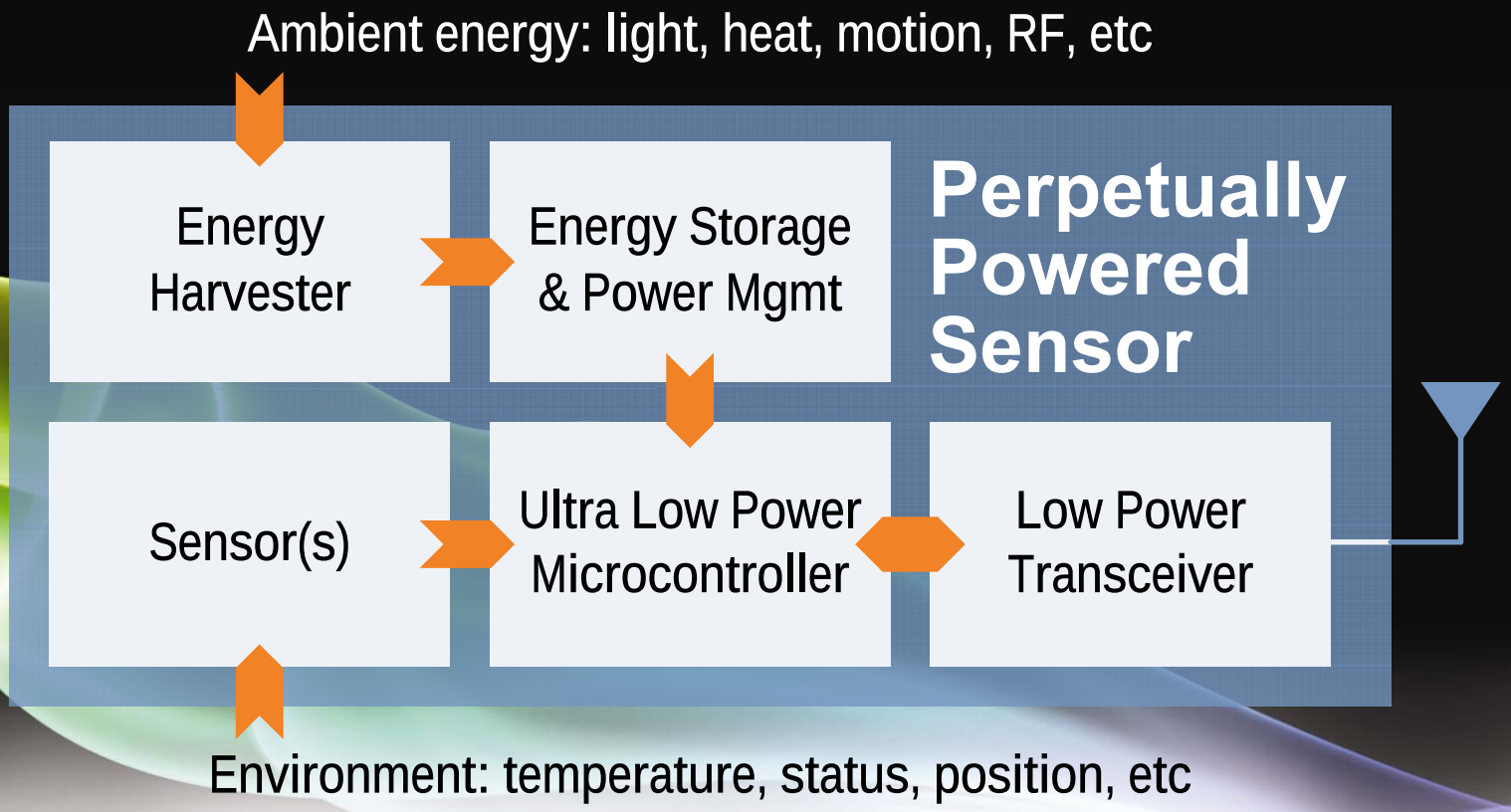


A new MIT tree sensor system taps into trees as a self-sustaining power supply. Each sensor is equipped with an off-the-shelf battery that can be slowly recharged using electricity generated by the tree.



The sensor system produces enough electricity to allow the trees' temperature and humidity sensors to regularly and wirelessly transmit signals. Each signal hops from one sensor to another, until it reaches an existing weather station that beams the data by satellite to a forestry command center.

Anatomy of an Energy Harvesting System



Energy Harvesting Design Guides

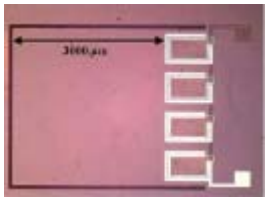
- Power budget – peak & standby
- Energy duty cycle
  - E_{in} vs. E_{out}
- Energy source
- Energy storage
- Operating condition
- Storage conditions
- Response time
- Cost of ownership

Energy Harvesting Sources

Energy Source	Characteristics	Efficiency	Harvested Power
Light	Outdoor Indoor	10~24%	100 mW/cm^2 100 µW/cm^2
Thermal	Human Industrial	~0.1% ~3%	60 µW/cm^2 ~1-10 mW/cm^2
Vibration	~Hz–human ~kHz–machines	25~50%	~4 µW/cm^3 ~800 µW/cm^3
RF	GSM 900 MHz WiFi	~50%	0.1 µW/cm^2 0.001 µW/cm^2

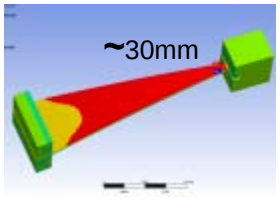
Seiko watch ~5uW

Holst Center ~40uW



2 channel EEG ~1mW

AdaptivEnergy ~10mW

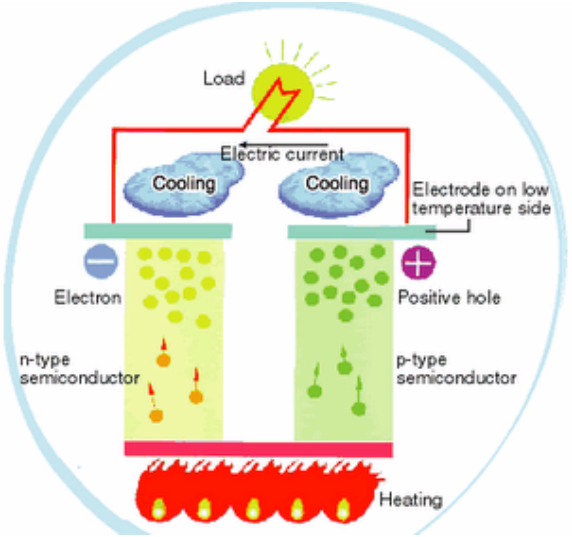


Elastometer ~800mW

BigBelly ~40W

1uW 10uW 100uW 1mW 10mW 100mW 1W+

Harvesting Thermal Energy



Thermocouple

Thermoelectric Seebeck Effect

Temp. gradient drives heat flow

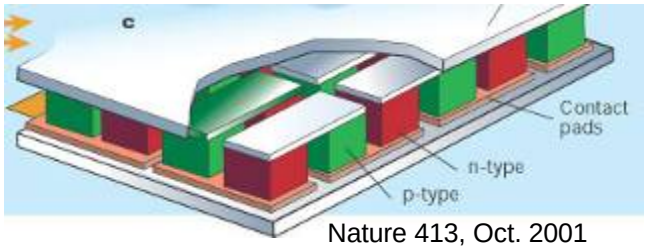
⇩

Electrons and holes flow in N-type and P-type lags made of semiconductor materials

⇩

Carnot Efficiency

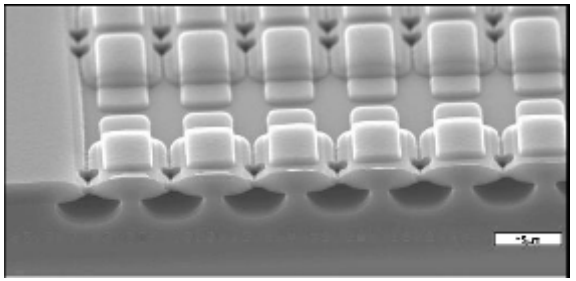
$\equiv \Delta T/T_H$



Nature 413, Oct. 2001

Thermopiles

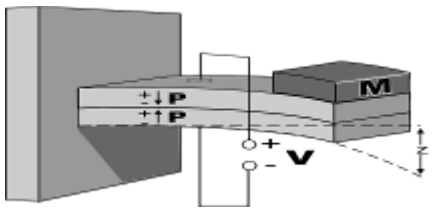
- thermally in parallel
- electrically in serial



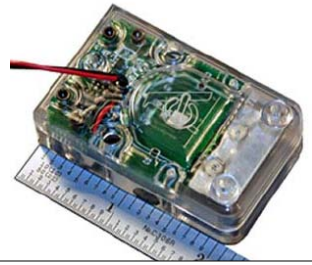
Si-thermocouples on chip

Harvesting Vibration Energy

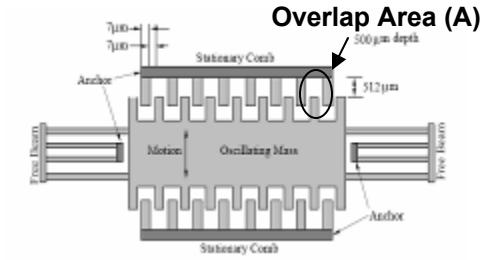
Piezoelectric



- Vibration → beam bending (strain)
- Piezoelectric material converts mechanical strain into electrical energy



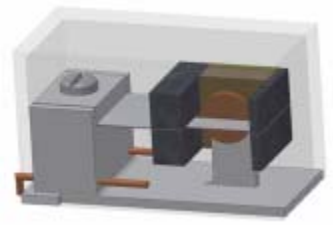
Electrostatic



- Vibration → motion of oscillating mass
- Comb overlap area (A) change
- Comb capacitance (C) change
- Voltage change at constant charge (Q)

$$C = \frac{\varepsilon_0 A}{d} \qquad Q = CV$$

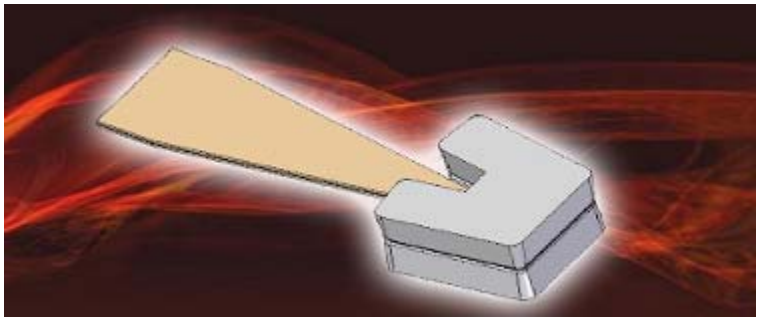
Electromagnetic



- Vibration → motion of magnetic field
- Current flows in the static copper coil

Vibration Solutions

- **AdaptivEnergy**
  - Highly efficient harvesting with periodic vibration
  - Higher energy output density with small form factor
  - Ability to customize to range of vibration frequencies



- **Perpetuum**
  - Vibration harvester
  - Sealed for rugged industrial environment application
  - Available today

Energy Harvesting Storage Required

- Scavenged energy is not constant
- Power not available on-demand
- High peak power not available
- An ideal energy storage device:
  - Infinite shelf life
  - Negligible leakage
  - Unlimited capacity
  - Negligible volume
  - No need for energy conversion
  - Efficient energy acceptance and delivery

…Ideal battery doesn't exist

Energy Storage Options

	Li-Ion	Thin Film Rechargeable	Super Cap
Recharge Cycles	100s	5k-10k	Millions
Self Discharge	Moderate	Negligible	High
Charge Time	Hours	Minutes	Sec-Minutes
SMT & Reflow	Poor-None	Good	Poor
Physical Size	Large	Small	Medium
Capacity	0.3-2500mAHr	12-700uAHr	10-100uAHr
Environmental Impact	High	Minimal	Minimal

What is a Thin-Film Battery?

- Small, electrochemical batteries fabricated to deposit thin layers of battery materials
- Main Features:
  - Solid State Cell Chemistry
  - Superior Cycle Life
  - High Energy Density
  - Flexible packaging options
  - Negligible leakage
  - Rapid recharge
  - Broad temperature performance

Thin Film Battery Solutions

- **Cymbet**
  - Surface-mount
  - Packaged in QFN package
  - No harmful gases, liquids or special handling procedures
  - EnerChip CBC050 example
    - Output Voltage: 3.8V
    - Capacity: 50 µAh
    - Package: 16-pin M8 QFN
    - Size: 8 x 8 x 0.9 mm

- **Infinite Power Solutions**
  - Flexible, electrolyte based rechargeable lithium battery
  - Very thin: 0.11mm
  - Flexible
  - >10,000 recharge cycles
  - MEC101-7P example:
    - Output Voltage: 4.2V
    - Capacity: 700 µAh
    - Size: 25.4 x 25.4 x 0.11mm

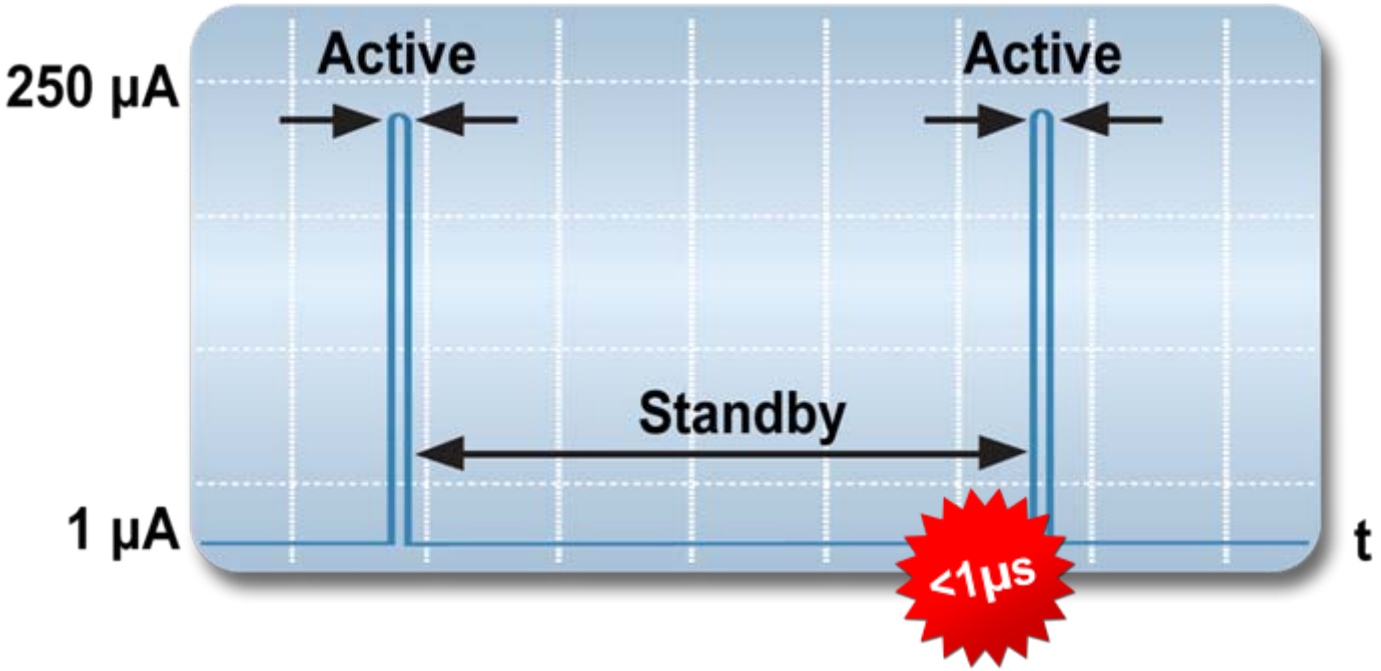
EH System MCU Design Challenges

- Ability to operate with lowest standby current to maximize storage of energy
- Consume lowest possible power when active
- Ability to turn on and turn off instantaneously
- Efficient operation with lowest duty cycle of active vs. standby modes
- Analog capability for sensor interfacing and measurements
- Ability to operate with a low voltage range
- Lowest leakage currents to maximize harvested energy

Ultra-Low-Power Processing Required

- MSP430 is ideal for energy harvesting
- Low standby current <1uA
- Low active current 160uA/MHz
- Instant off and quick wakeup time <1us
- Integrated low power ADC for precision measurements (great for sensors)
- Low operating voltage 1.8V to 3.6V
- Low pin leakage <50nA
- Lower power, highly integrated new products: 5xx-based RF SoC
- Efficient 16-bit architecture with high code density and processing power

Ultra-Low-Power Activity Profile



- Extended *Ultra-Low-Power* standby mode
- Minimum active duty cycle
- Interrupt driven performance on-demand

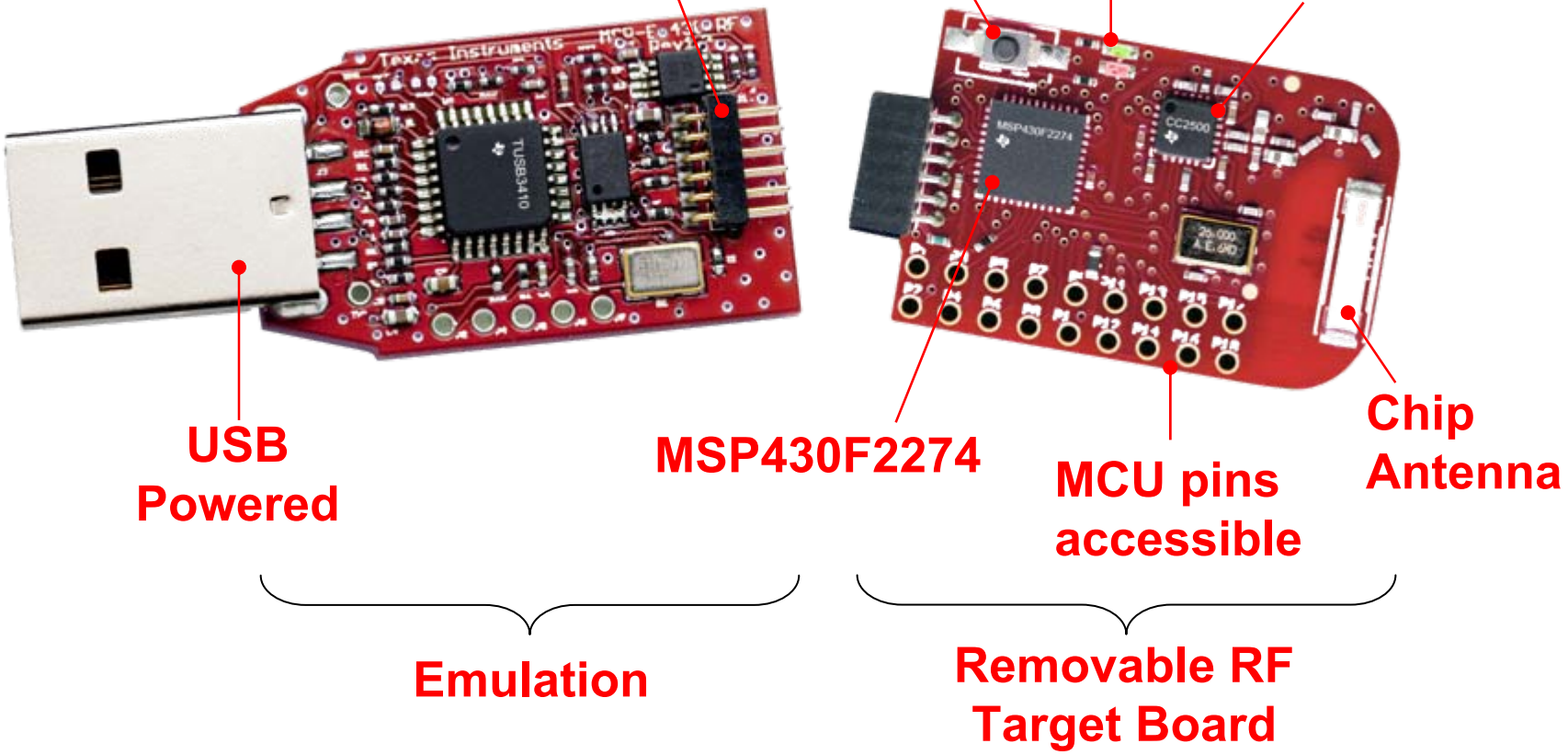
Ultra-Low-Power Wireless Connectivity

- TI offers a variety of low power wireless solutions
- Low Power RF devices (CCxxxx)
  - Highly configurable
  - Low power
  - ISM Band: 315/433/868/915 MHz and 2.4 GHz
  - ZigBee / 802.15.4
- Full stacks available:
  - Z-Stack
  - TI MAC (802.15.4)
  - SimpliciTI
- RFID also available

End Device:
CC2510EM

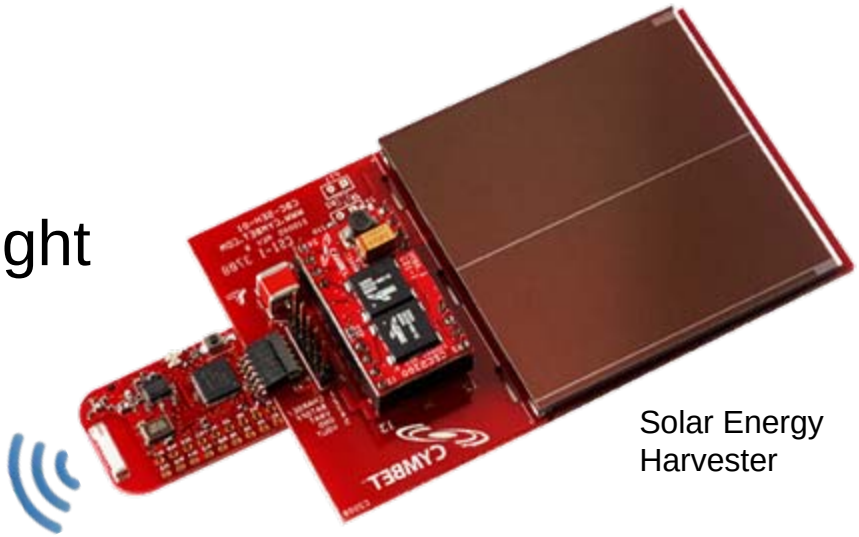
Getting Started

eZ430-RF2500 Development Tool



No-Power Solar Energy Harvester

- Solar Energy Harvesting module for eZ430-RF2500
- Works in low ambient light
- Negligible self-discharge
- 400+ transmission with no light
- Adaptable to any sensor and RF network

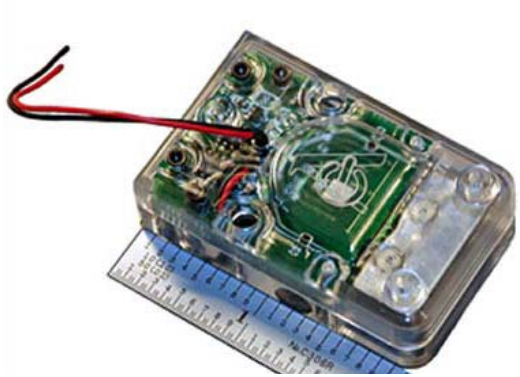


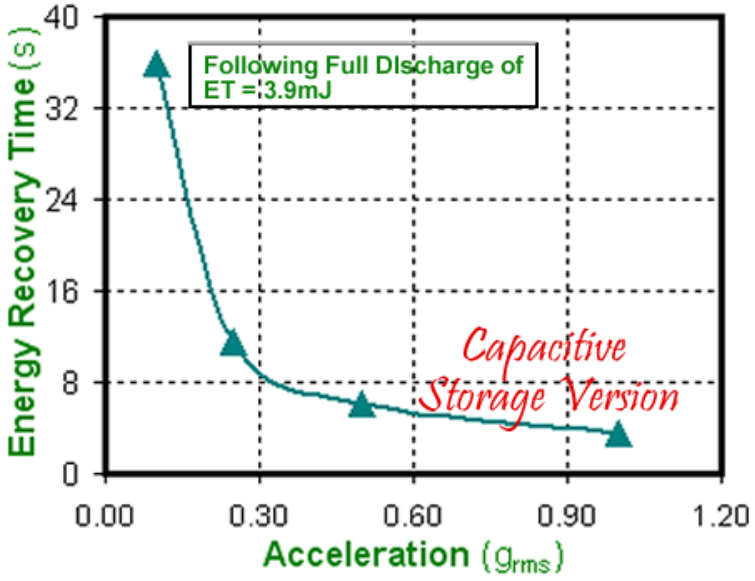
Solar Energy Harvester

eZ430-RF2500T
Wireless Target

Joule-Thief EVK from AdaptivEnergy

- Based on TI eZ430-RF2500 Wireless Dev Tool
- 60Hz Resonant Beam
- 440uF Capacitive Storage
- Perpetually Powered





Energy Recovery Time
vs.
Input Vibration Amplitude

Summary

- Ultra low power MCU enable perpetually powered operation through energy harvesting
- Various energy harvesters are available for many applications
- New energy storage technology enables new class of applications
- TI technology enables low power processing, sensing, wireless transmission, and power management

Thank you.