# *Energy Harvesting*

an Enabling Technology for Autonomous Sensors in Automatic Machinery

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# Energy Harvesting (EH)

**What is it?**


Energy harvesting (also known as energy scavenging) is the process by which ***energy is captured and stored***.

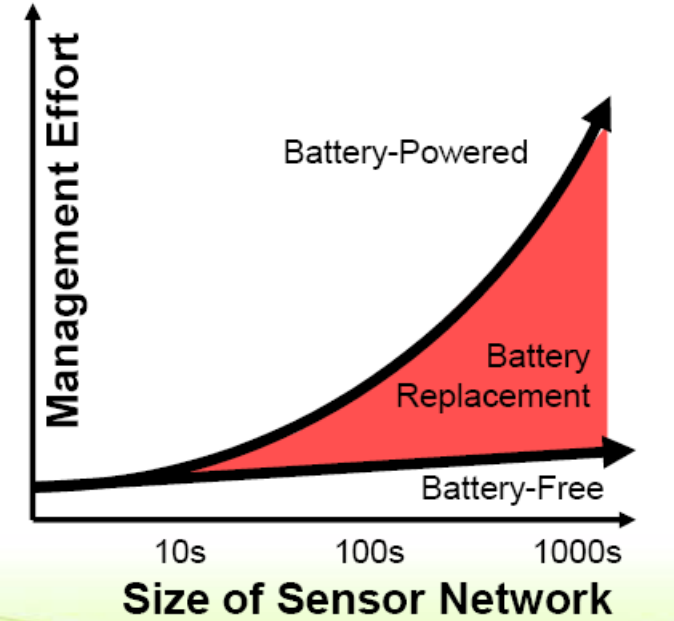
**Why for Autonomous Sensors?**

It is a solution to ***extend battery lifetime*** and possibly to ***replace battery*** in a wide range of Ultra Low Power (ULP) applications

- Wireless Sensor Network (WSN) ,
- Consumer and Portable Electronics,
- Automatic Machineries, etc…

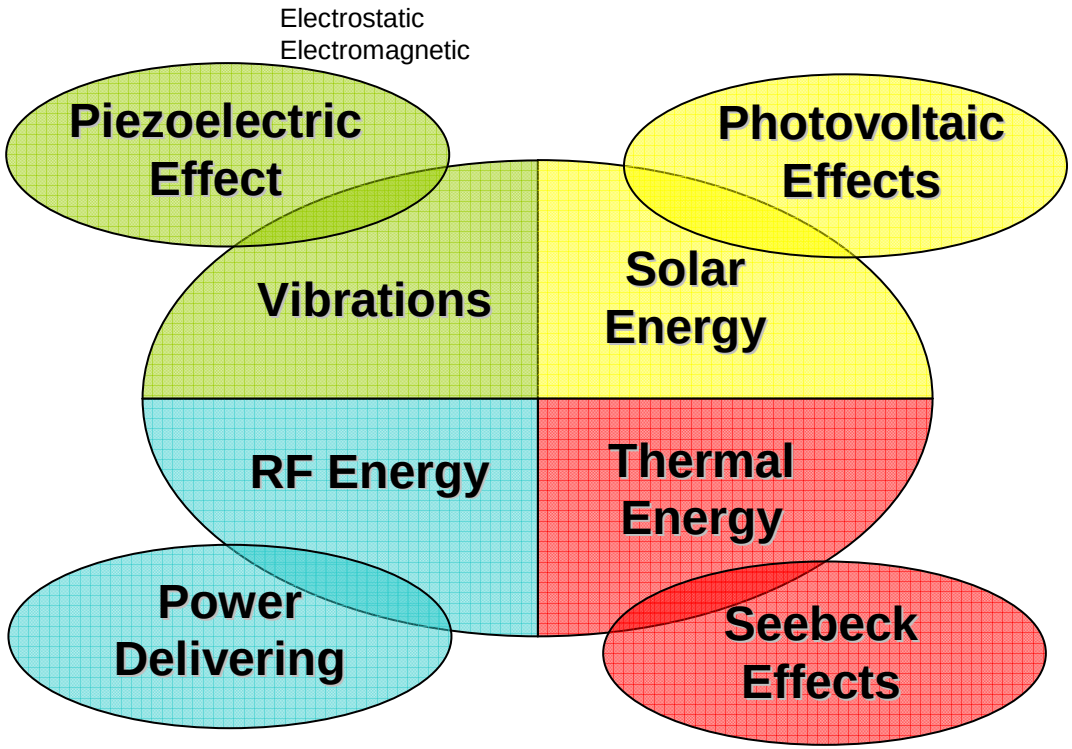
# Nowadays solutions exploit batteries

- Processing power doubles every **2 years**
- Batteries capacity doubles every **10 years**
  - High Environmental Impact
  - High Replacement Costs




***We need of a more efficient way to enable longer life***

# Energy Harvesting from **renewable sources**



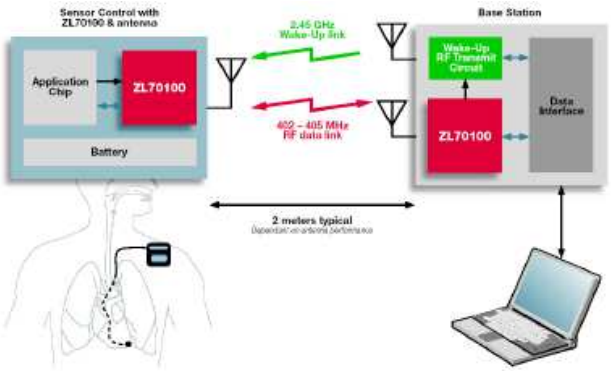

| Energy Source | Harvested Power |
|---|---|
| **Vibration/Motion** | |
| Human | 4 μW/cm² |
| Industry | 100 μW/cm² |
| **Temperature Difference** | |
| Human | 25 μW/cm² |
| Industry | 1–10 mW/cm² |
| **Light** | |
| Indoor | 10 μW/cm² |
| Outdoor | 10 mW/cm² |
| **RF** | |
| GSM | 0.1 μW/cm² |
| WiFi | 0.001 mW/cm² |

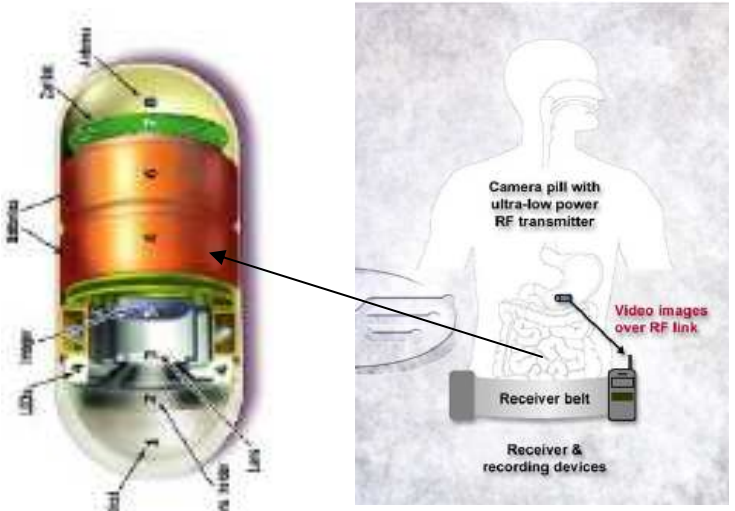
***Source: Texas Instruments***

# Energy Harvesting is not New !!


***Source: Texas Instruments***

# New EH Applications Fields – *Biomedical*



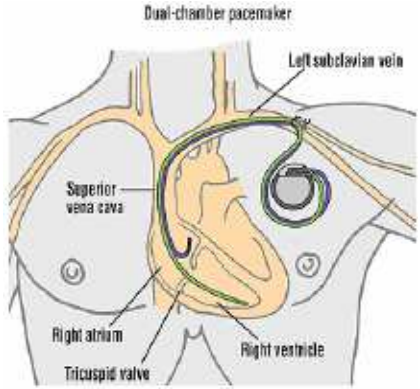




## Problems

- Autonomy of the Battery
- Batteries are toxic

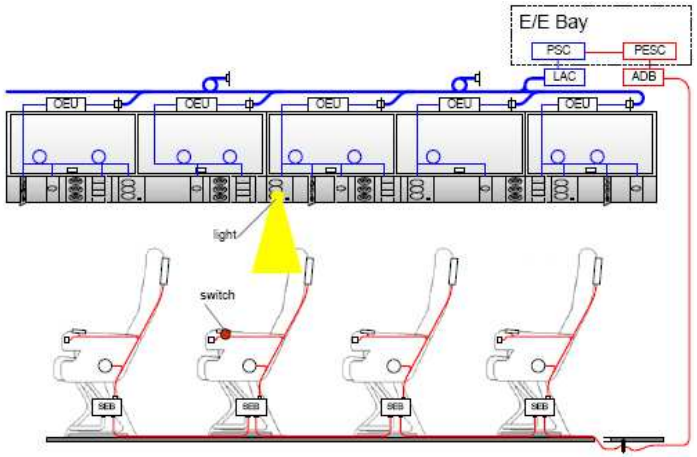
## Solution

- Energy harvested by the human body
- RF power delivery



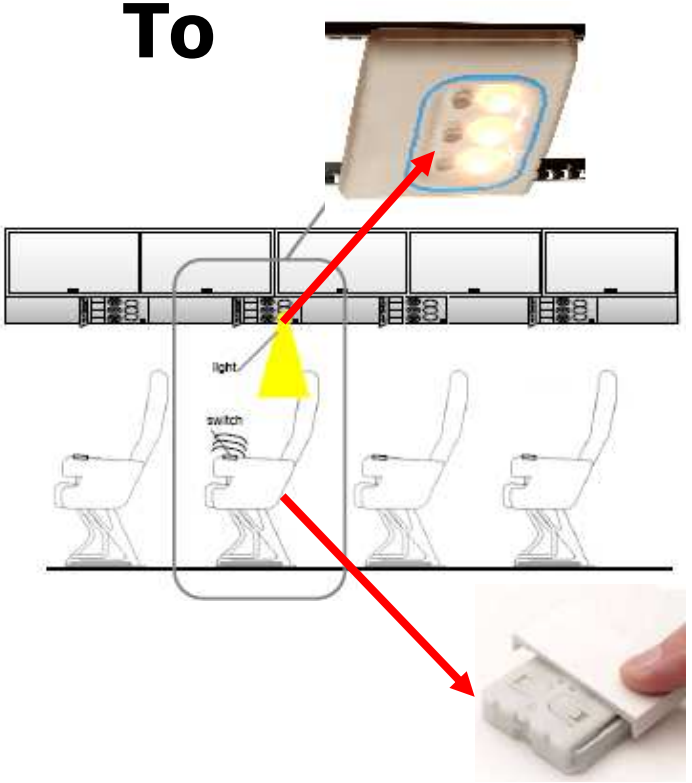
# New EH Applications - *Avionics*

**From**



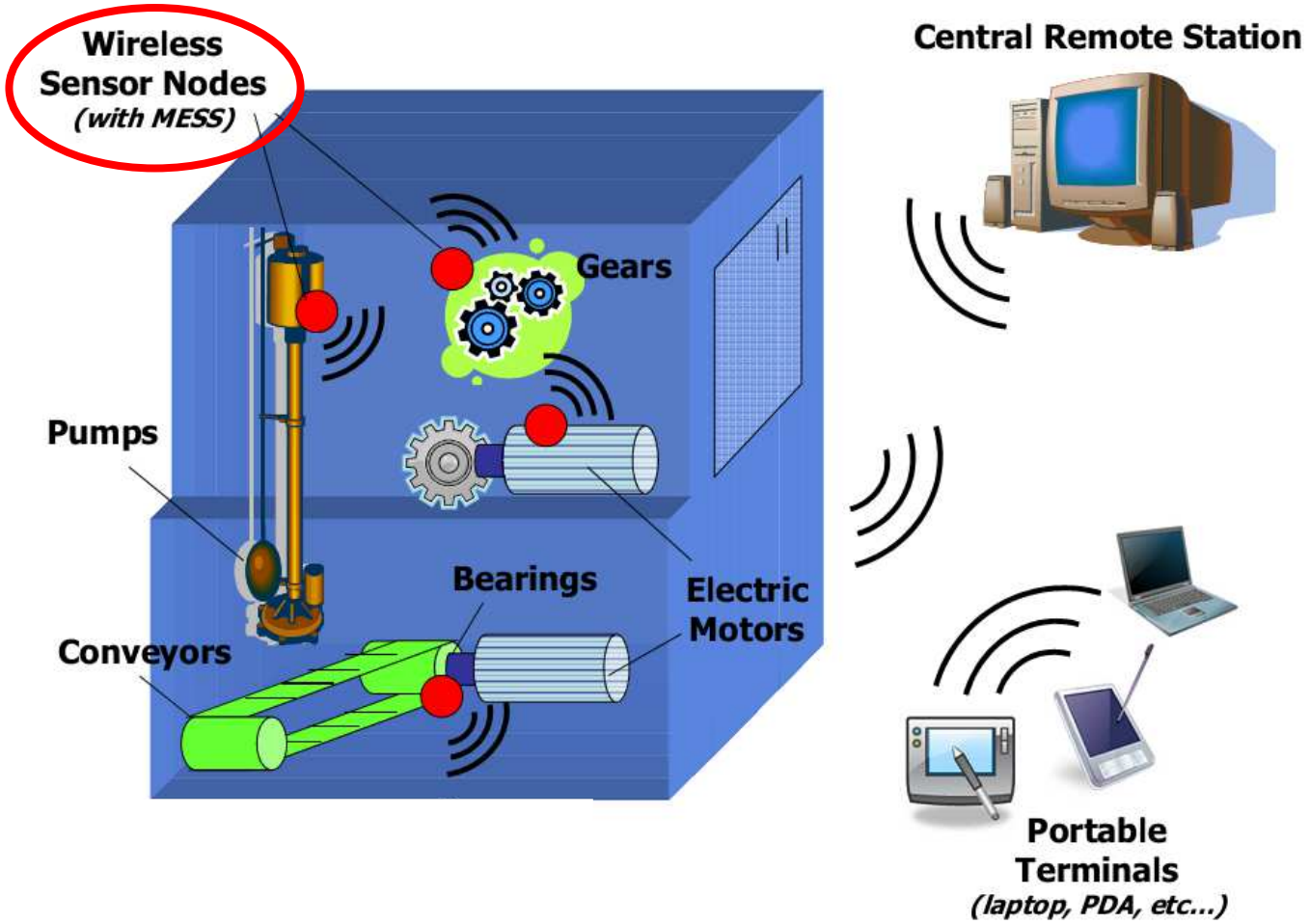

- Complex
- Expensive
- Weight

**To**




- Each Seat is a "Mini WSN"

# New EH Applications – *Automatic Machinery*



# When (Autonomous) Wireless Sensors in Automatic Machinery?

- Harvestable energy available
- Difficult to install or power devices
- Difficult to reach devices for maintenance
- Wires 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***

# Energy Harvesting Tradeoffs

- No power wires
- Easier installation
- Lower maintenance
- Environmentally friendly
- Higher uptime

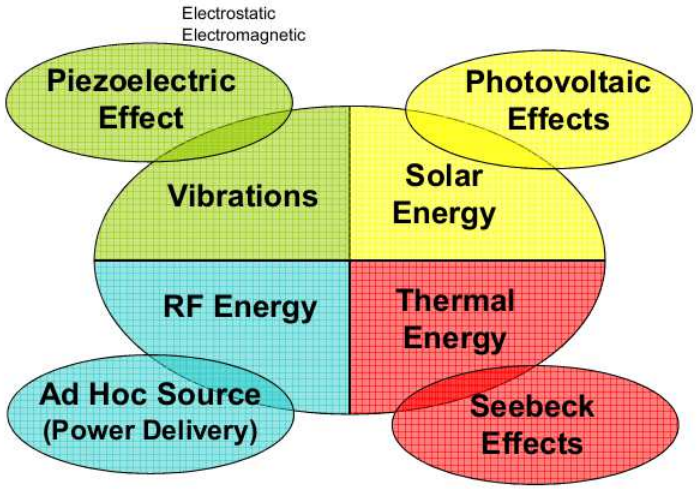
- Dependent on availability of harvestable energy source
- Strict power budget
- Less mature technology
- Upfront cost may be higher

# A different approach

**AUTONOMOUS SENSORS for WSN**

**ENERGY HARVESTING**

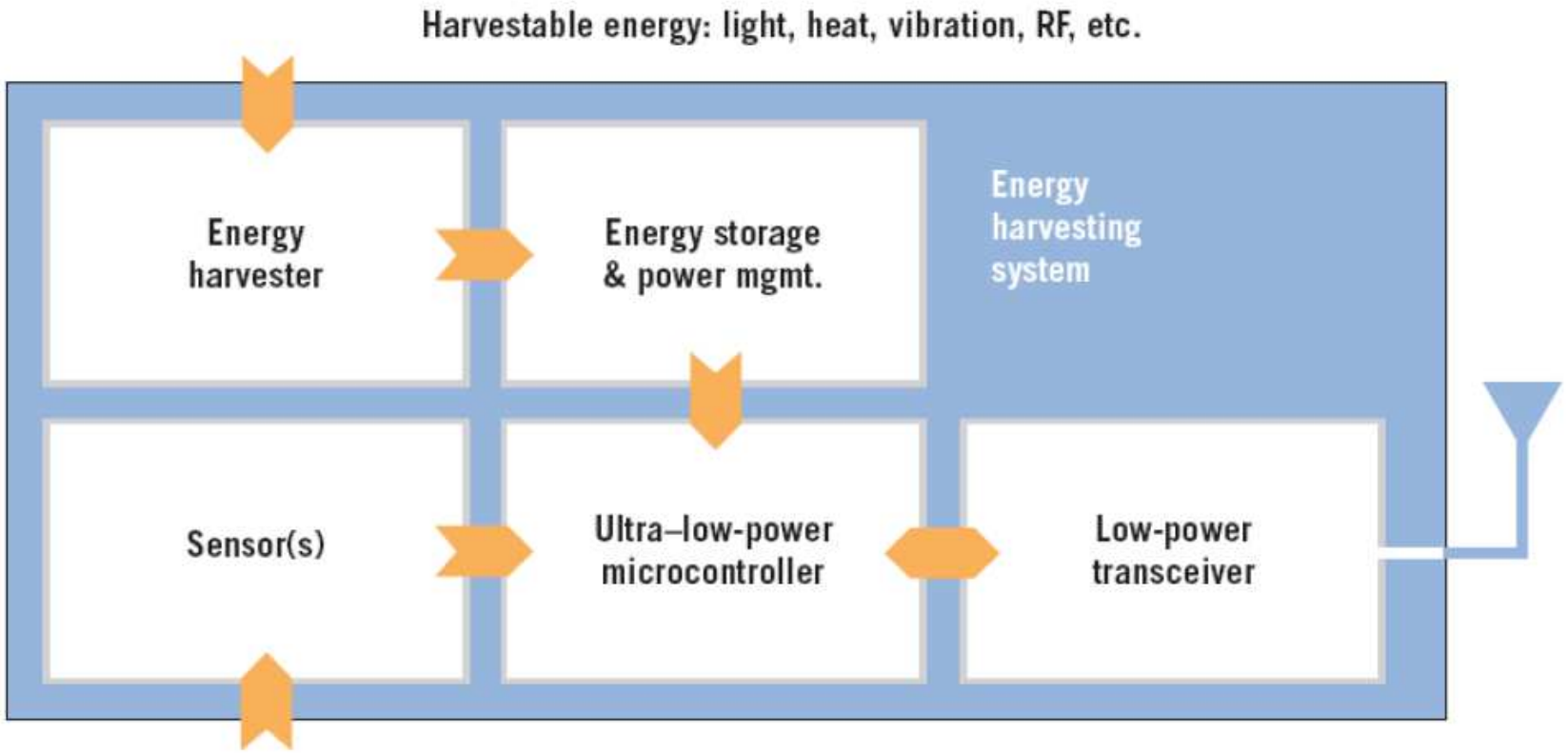
**HW/SW CODESIGN**




**Ultra Low Power Components**

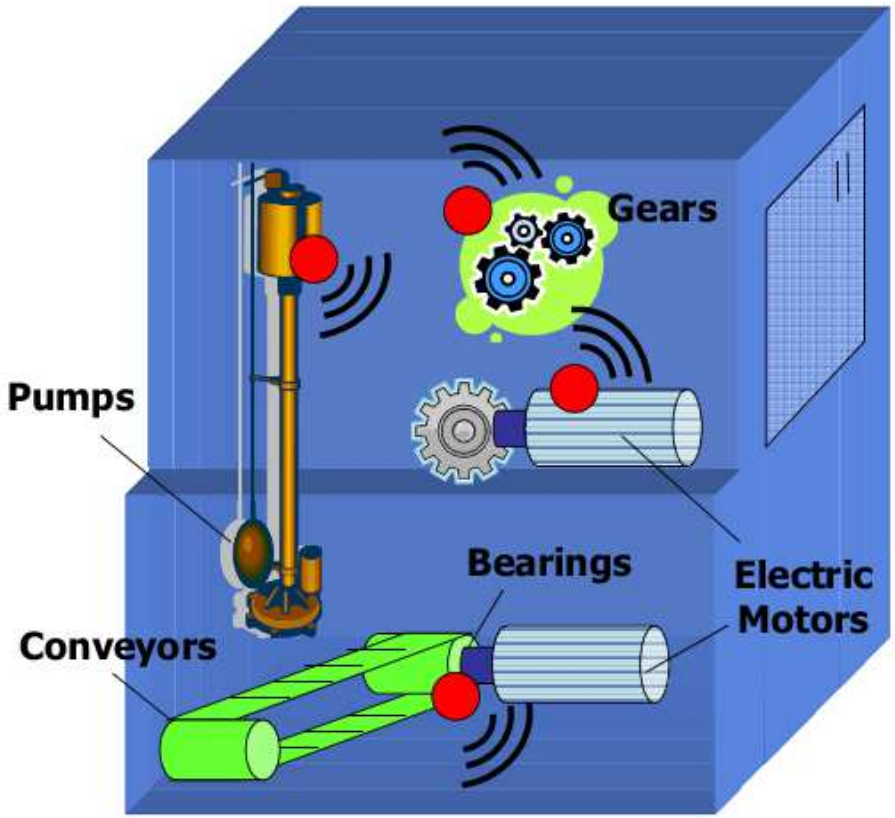
**Smart Task Manager Algorithms**

# Energy Harvesting Systems – Block Diagram




Each block have to be customized/optimized accordingly with the specific application (i.e. power budget, power consumption, etc… )

# Energy Sources in Automatic Machineries




A lot of energy is usually wasted during normal operation of the machinery

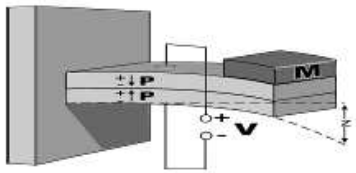
- **Vibrations**
- **Thermal Gradients**
- **Kinetic Energy**
- **(Acoustic)**

Ad-hoc Energy can be provided (Remote Powering)

- **RF signals** compliant with regulations

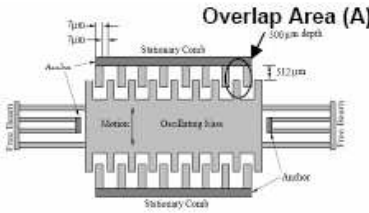
# Vibrations Energy Harvesting

## Piezoelectric




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

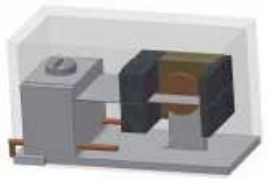
## Electrostatic




- 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



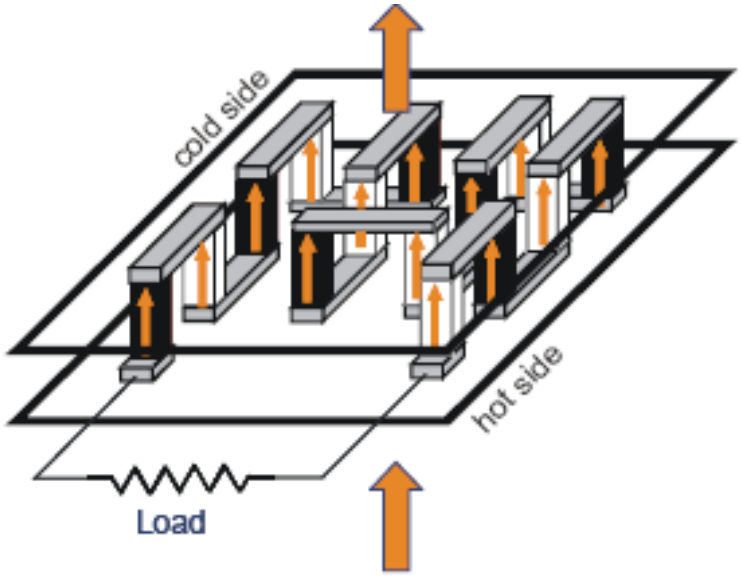
- Vibration → motion of magnetic field
- Current flows in the static copper coil

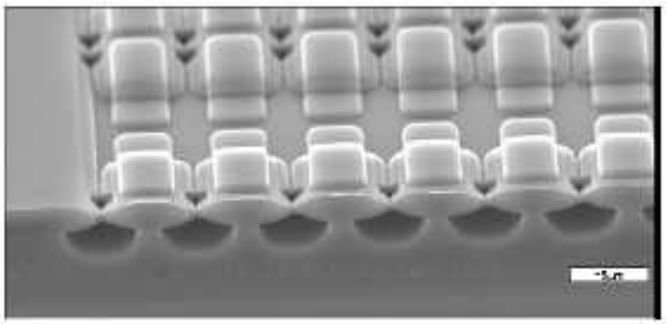
***Source: Texas Instruments***

# Thermoelectric Energy Harvesting

- Exploits the **Seebeck Effect**
  - *A voltage is developed in a loop containing two dissimilar metals, when the two junctions are exposed to different temperatures*
- ***Thermocouples are the basic element***
- ***Thermopiles are made of a large number of thermocouples connected***
  - ***thermally in parallel***
  - ***electrically in series***
- A thermoelectric generator (**TEG**) **is made of thermopiles** sandwiched between a hot and a cold plate
- ***Macro- and Microscale devices***

# Thermoelectric Energy Harvesting



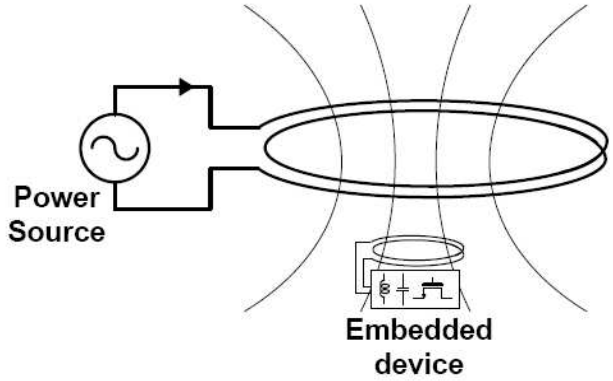
- Heat flows from the hot side to the cold side, through the pillars
- The black and white pillars represent the two types of thermoelectric materials (thermocouples)
- The metal interconnects are drawn in grey (thermopiles)

# EM & RF power delivery

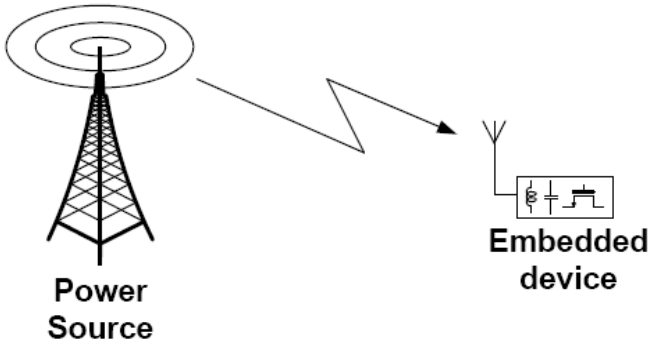
The main idea is to provide power supply through

- Generation of an Electro-Magnetic field (EM)
- Generation of an ad-hoc Radio-Frequency Signal (RF) – *Power Delivery*

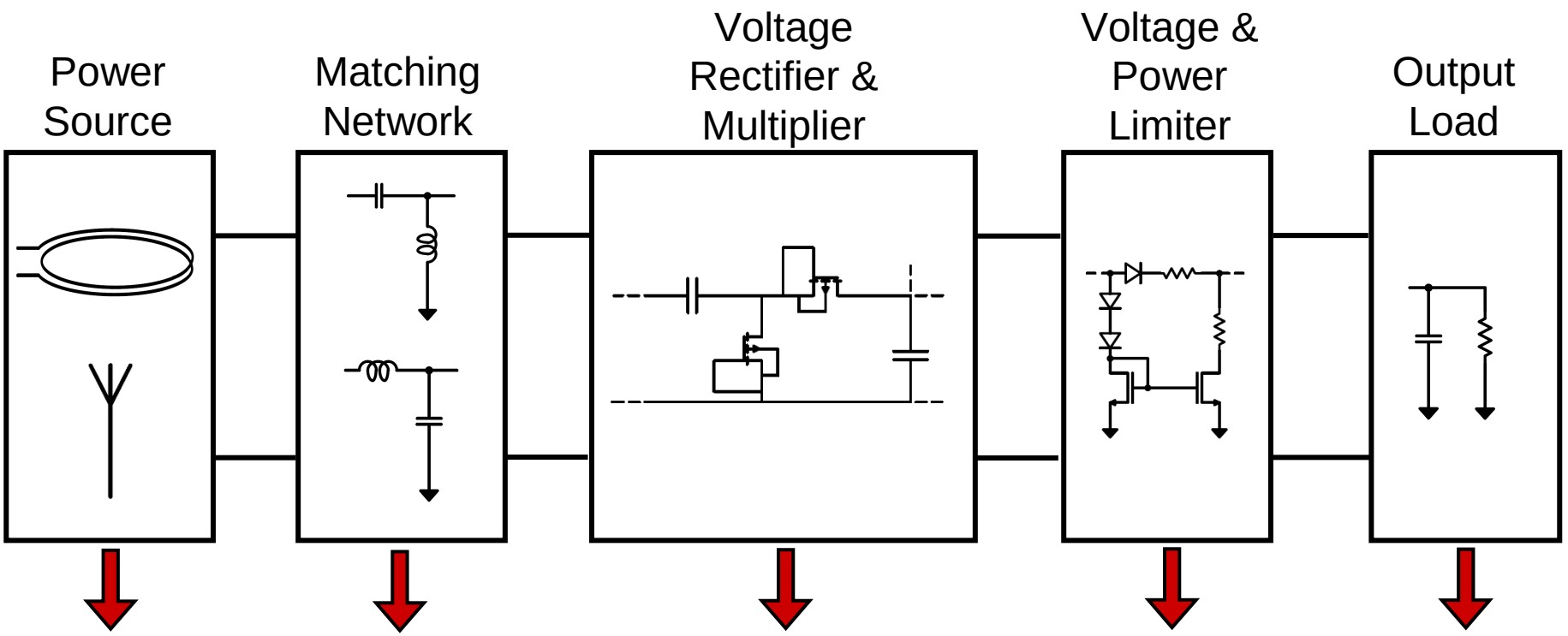
Short Range → EM Coupling



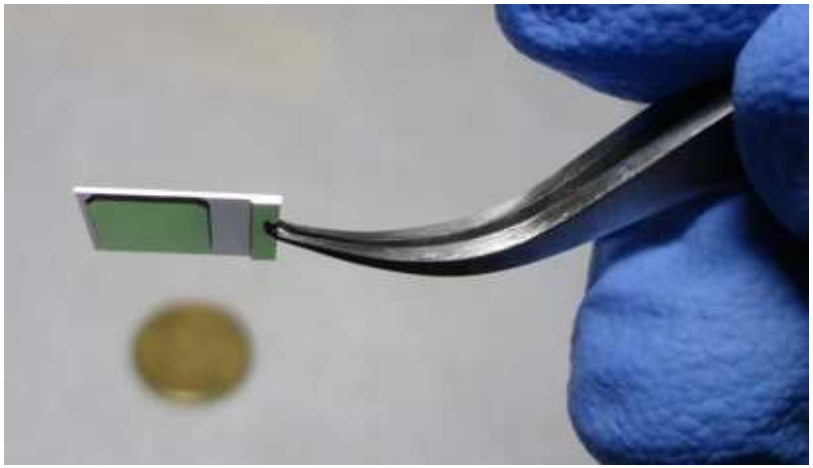

Long Range → RF

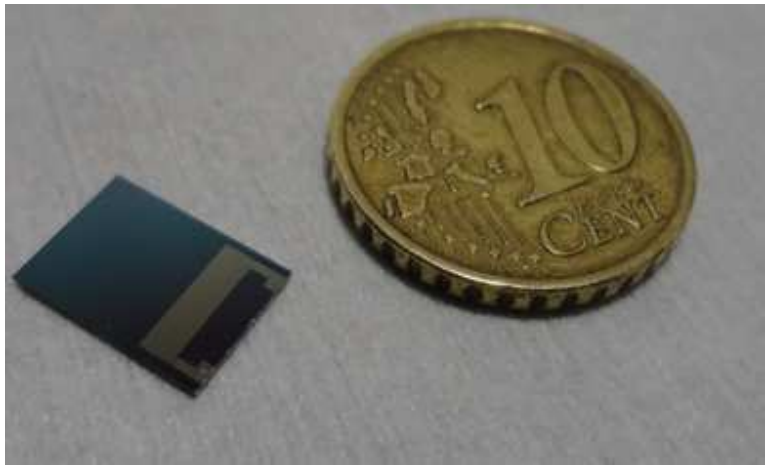


# EM/RF harvester architecture



# *EH @ UniMORE*
## Piezoelectric MEMS transducers






***Resonance @ low frequencies with MEMS scale transducers!!***

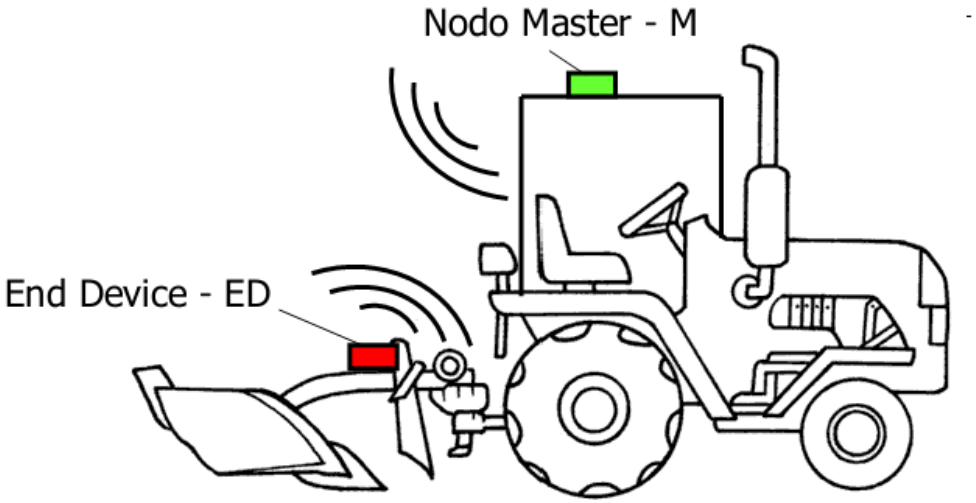
- Length **100's of µm, up to some mm**
- Width **10's of µm**
- Thickness **some µm**

**Output Power in the order of µW**

***More than one resonance frequency in the range 0-200Hz (increase of the bandwidth)***

# *EH @ UniMORE*
## Enhanced Safety in Off-Highway Vehicles

- Autonomous device for Automatic Identification of Implements or Trailers
- **Commercial** Piezoelectric Transducers
- **Customized** Low Power front-end electronics with smart power management
- **HW-SW Co-Design**



# *EH @ UniMORE*
## Enhanced Safety in Off-Highway Vehicles

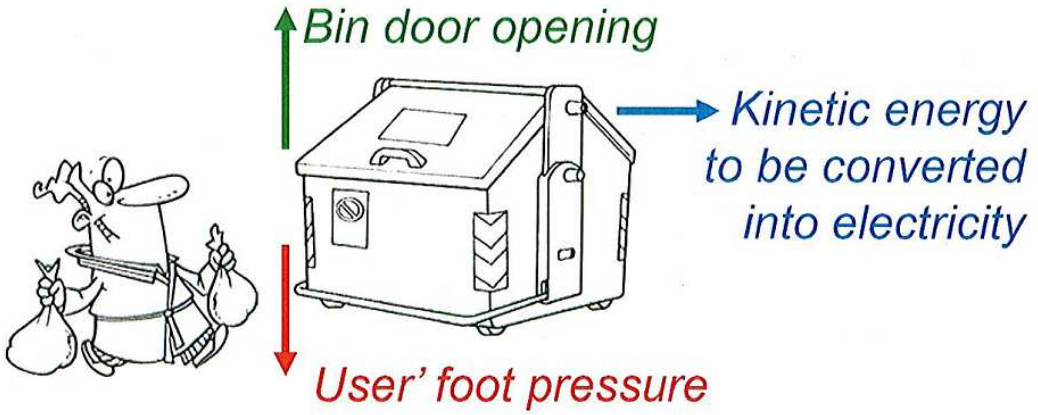
**End Device**

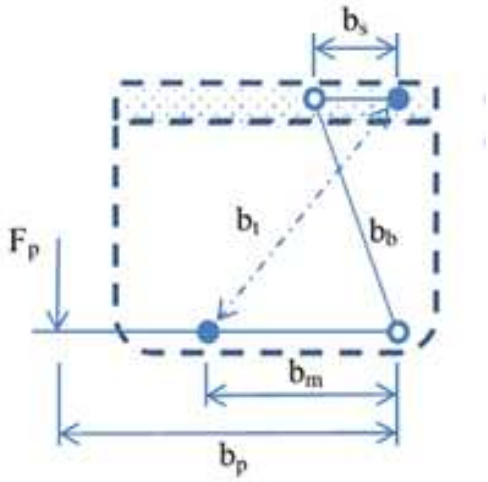
**48mm**

**35mm**

- $V_{DD}$: 2.0V÷3.3V
- $P_{STAND\text{-}BY}$: <5µW
- $P_{active\_AVG}$ µC running: <10µW
- $P_{active\_AVG}$ µC running & RF TX: 27µW
- TX @ 2.4 GHz (802.15.4 standard)

# *EH @ UniMORE*
## Kinetic Energy Harvesting



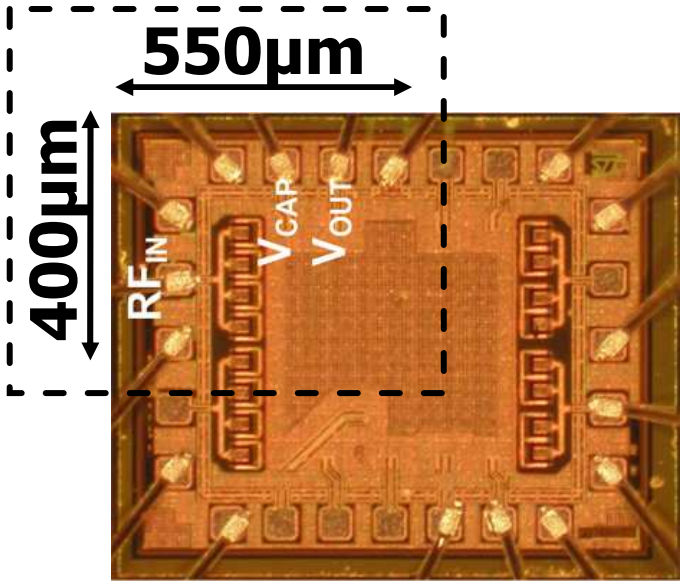




- Energy harvested from user opening and closure of urban garbage bin
- Kinematic mechanism: articulated quadrilateral
- Instantaneous $\mathbf{P_{OUT} \approx 1W}$ for each operating cycle (bin door opening & closure)

# *EH @ UniMORE*

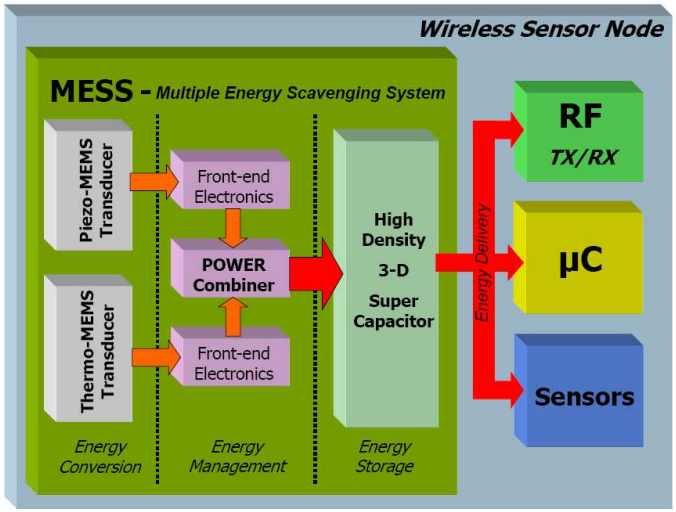
## RF EH system for power delivery in WSN nodes

- RF Harvester @868 MHz designed to power supply a TI MSP430 µC
  - $V_{DD}$: 2V÷3.6V
  - $I_{STAND-BY}$: 1.1µA
  - $I_{ON}$: 21mA
  - $t_{ON}$: 20ms
- Implemented in STM 130nm CMOS



# New research challenges

- New transduction mechanisms
- Multi-Source harvesting (power combining)
  - Solar+Vibration
  - Solar+RF
  - Solar+Thermal
  - Vibration+RF
  - **Vibration+Thermal**
  - **Vibration+Thermal+RF**



# Conclusions

- Energy Harvesting
  - Enable perpetually powered ULP systems (battery free)
  - Extend battery lifetime
- ***Efficient EH Systems have to be customized on the specific application***
- Design of high efficiency EH Systems requires
  - New MEMS/NEMS transducers
  - New Energy storage devices
  - ULP HW Components
  - ULP SW algorithms

} ***Multidisciplinary Activities***

# Thank You for Your Attention !!

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