



Energy Harvesting Communication Networks: Optimization and Demonstration (e-crops) WP5: Demonstration

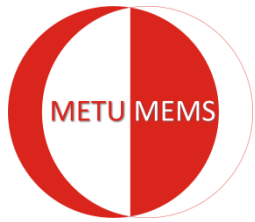
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*MEMS Research and Applications Centre
Ankara, Turkey**

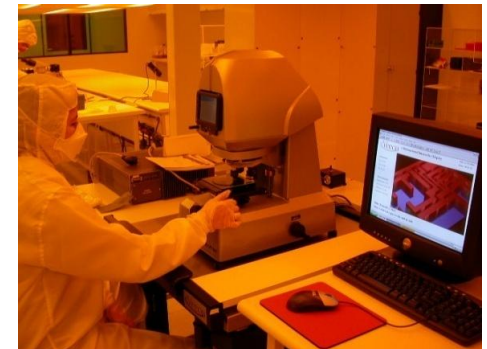
Co-PIs: Prof. Dr. Elif Uysal-Bıyıkoglu & Assoc. Prof. Dr. Haluk KÜlah

CHIST-ERA Project Seminar 2014, March 5th, 2014





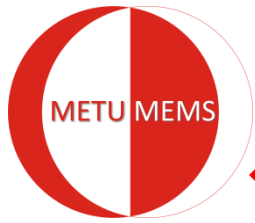
METU-MEMS Center



- Since 1995
- Developing various microsensors and systems
- > 90 People
 - 8 Faculty Members, 6 Post-Docs
 - > 45 Graduate Student
 - 26 Technical Personnel

- > 60 M.Sc., 8 Ph.D. Graduates
- 13 Patent Applications
- 3+1 Spin-offs
- National and International Research Projects
 - Intel USA, NATO, NSF, FP6, FP7, TÜBİTAK, DPT, MSB, SSM, ARÇELİK, TOFAŞ, TURKCELL

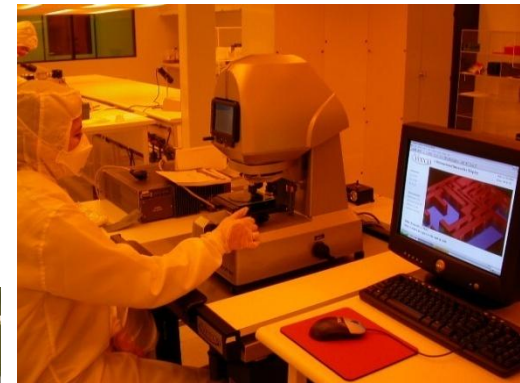
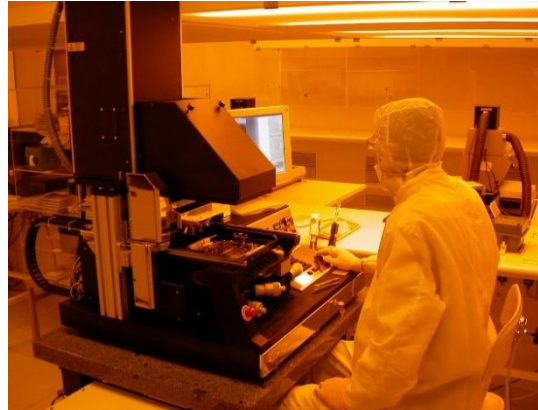


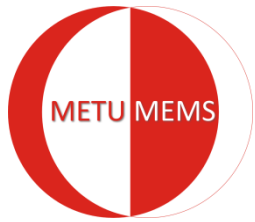


METU-MEMS Facilities

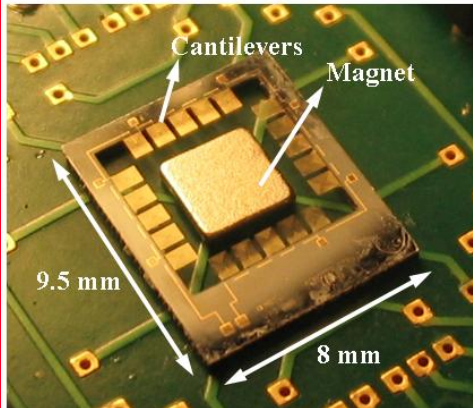
- ◆ 1300 m² clean room allowing Class 100 and 1000 process
- ◆ <0.35μm 4", 6", and 8" wafer processing

- ASML Stepper
- Suss Automatic Photoresist Coater
- EVG Double-sided aligner
- EVG Wafer bonder
- STS DRIE, RIE, PECVD, ICP RIE
- Diffusion and oxidation furnaces
- LPCVD oxide, nitride, poly
- Evaporation (Au, Ni, Cr, Cu, Ti.)
- Sputtering (Al, Cr, Ni-Cr, Cu, Ti, Ta)
- Anisotropic silicon etch (KOH, TMAH, EDP), Isotropic silicon etch
- Electrochemical etch-stop (KOH, TMAH)
- Electroplating (Ni, Cu, Au) , SU-8 Molding
- Wafer dicing (Disco DAD)
- Axis Grinder/CMP
- SEM, FESEM (JEOL) (8")
- Critical point drying
- Veeco Optical Profilometer
- Heidelberg DWL200 Mask Maker
- FTIR-VASE Spectrometer (2-33μm)
- Veeco - Dektak 8
- SUSS PAV Prober w/Polytec
- Intel Donated 8" Equipments

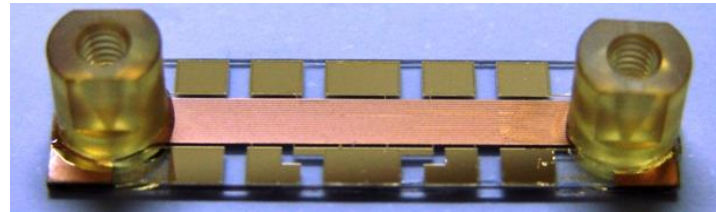




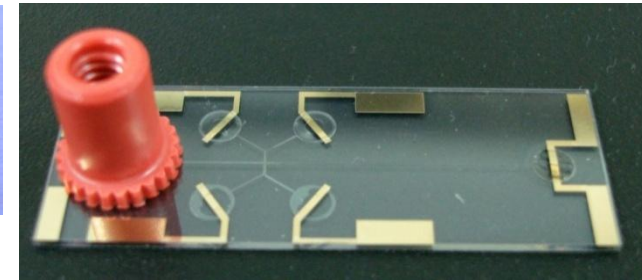
Research Achievements



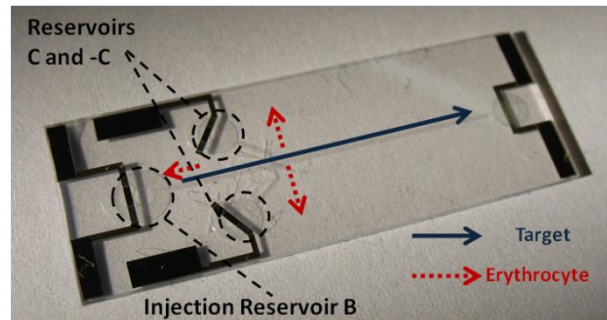
Micro Power Generators



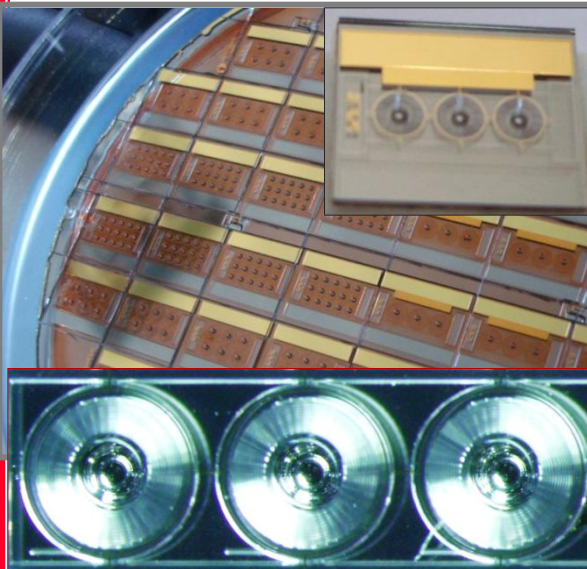
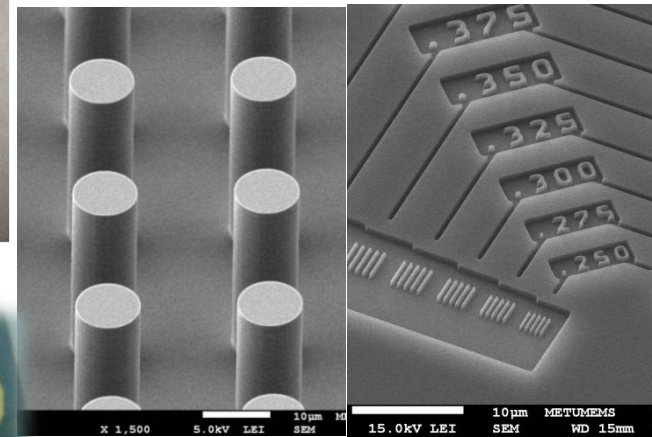
Chip-scale Cooling



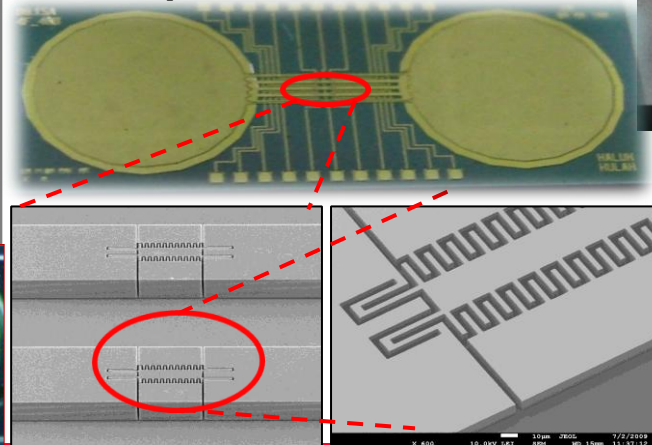
DNA & Mutation Analysis



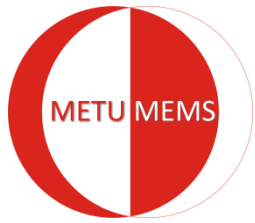
Cell Separation



Cell Sorting

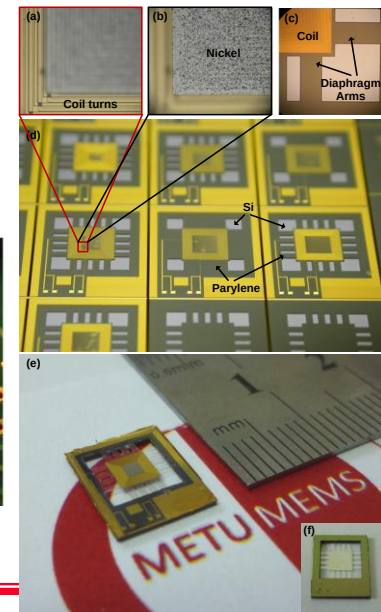
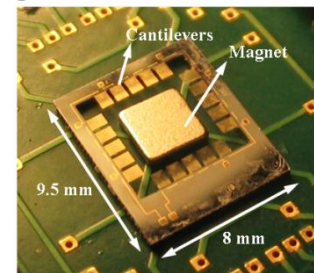
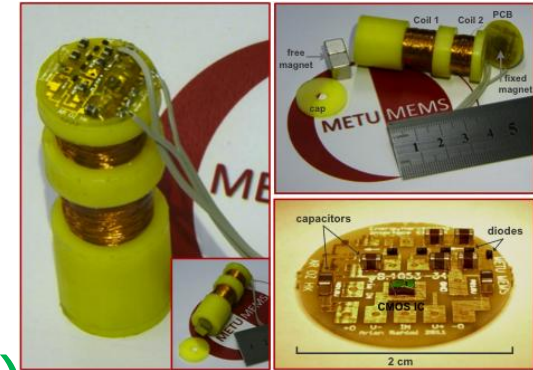


Cell Cytometry



Research Subjects

- Low-cost uncooled CMOS infrared detectors
- Gyroscopes/Accelerometers
- RF MEMS
- BioMEMS/Microfluidics
- ➔ • Energy Harvesting (PowerMEMS)
- Piezoresistive Pressure Sensors
- Capacitive Pressure Sensors
- CMOS Humidity Sensors
- CMOS Thermopiles
- CMOS Temperature Sensors



Total Budget ~ \$65 Million



Outline

➤ Introduction

- Previous approaches
- Integration of energy harvesters into WSNs

➤ Power Consumption of WSN nodes

- Measurement methods

➤ Experimental Results

- Power consumption of MicaZ
- Vibration-based electromagnetic energy harvester
- Initial combined test results

➤ Conclusion



Introduction

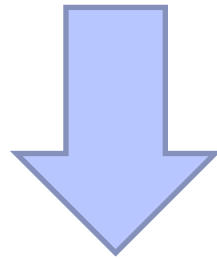
❖ Previous approaches on energy efficient WSNs

1. Architectural and algorithmic methods
 - *Transmission; communication*
2. Protocols enabling low power consumption of the terminal stations
 - *Data transfer frequency; significant data detection; averaging*
3. Models for evaluating the energy consumption of network nodes
4. Identifying the affects of WSN architecture and environmental parameters on battery performance
 - *Battery decay; temperature variations; placement of nodes*
5. Integrating energy harvesters to WSNs
 - *Using ambient energy sources for powering WSNs*



Introduction

- New interests for energy efficient communication over wired and wireless networks have been raised.
- Lifetime and the physical size of communication is limited by the battery capacity and size



Energy harvesting (EH) technology could play a significant role

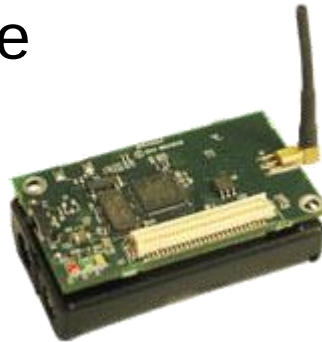


WSN Nodes and Their Energy Consumption

➤ The energy consumption $\mathcal{E}(T)$ of a node over a period of time T

- $i(t)$: current drawn by the device
- $v(t)$: supply voltage

$$\mathcal{E}(T) = \int_0^T v(t)i(t)dt$$



➤ MicaZ Motes

- Chipcon CC240 RF transceiver
- Atmega 128L micro-controller
- MTS310CB data acquisition board
- Supply: 2xAA batteries

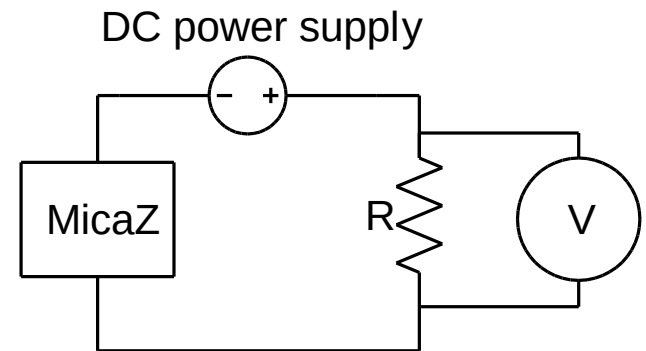
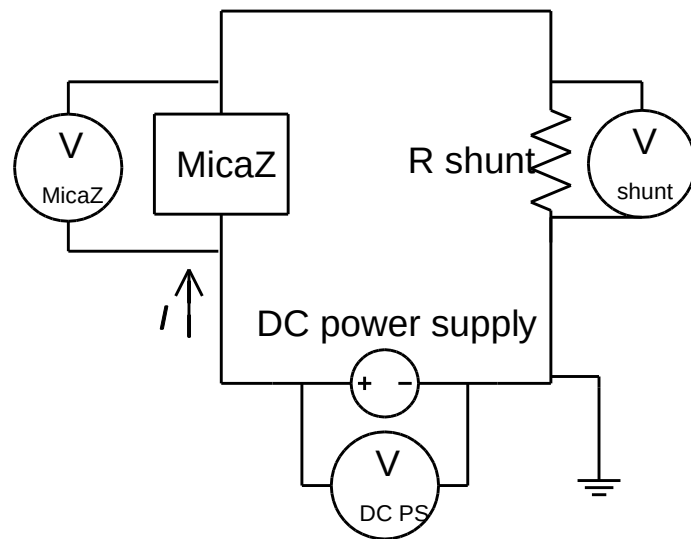
MicaZ Current Consumption

Radio Unit (mA)		MCU(mA)	
TX: 0dBm	17.2	Active	7.8
TX: -1dBm	16.2	Idle	0.024
TX: -3dBm	15.5	Standby	0.2
TX: -5dBm	13.8	Acc. Sensor	< 1mA
TX: -7dBm	12.5		
TX: -10dBm	11		
TX: -15dBm	10	LEDs	2.2 mA
TX: -25dBm	8.5		
RX	19		



Monitoring Device Current and Supply Voltage -1

- shunt resistor
- simple circuit



$$I(t) = V(t)/R$$

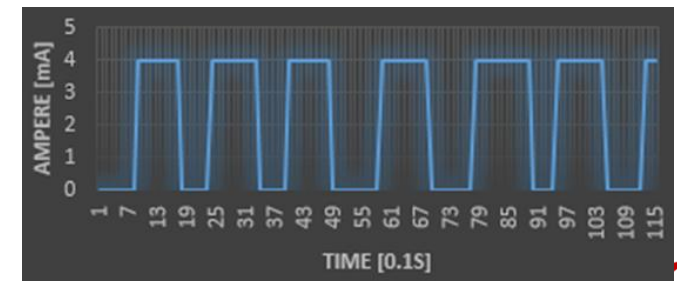
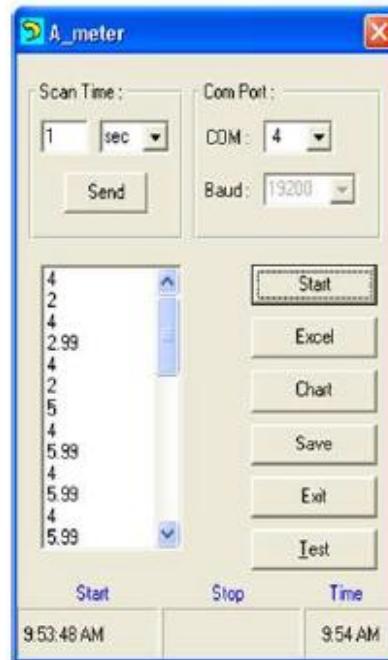
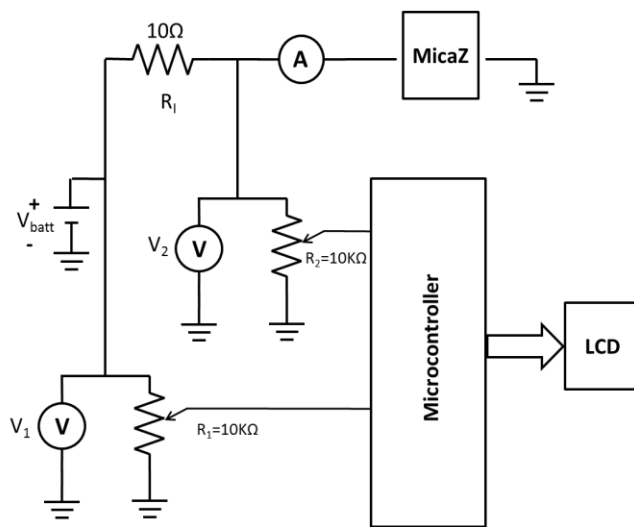
$$P(t) = (V_{supply}(t) - V_{shunt}(t)) \times \frac{V_{shunt}(t)}{R_{shunt}}$$



Monitoring Device Current and Supply Voltage -2

Constructed Setup

- Ampere meter with AVR Atmega128
- connected to a PC via a serial port



Monitoring Device Current and Supply Voltage -3

❖ Measuring battery voltage

- MicaZ has an accurate internal voltage reference V_{ref}
- compute the battery voltage from ADC reading

$$V_{batt} = V_{ref} \times ADC_FS / ADC_Count$$

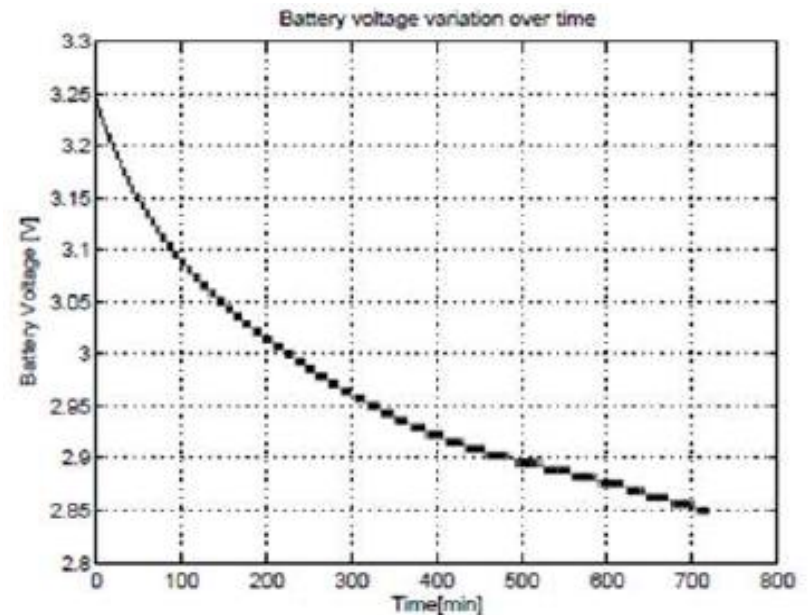
- V_{batt} =Battery voltage
- ADC_FS =1024 and
- ADC_Count is the measured ADC count



Measurements

❖ Battery decay test under full power operation

- MoteView software
- Xmesh protocol in HP (high power)
- **All the sensors are active** (on MTS310CB board)
- Transmission period: 0.3 sec, 100% duty cycle
- Red and Green **LEDs** were kept **ON**
- Yellow was kept blinking
- **RF output power: 0 dBm**
- RF channel: 2405 MHz
- Packet size: 36 Bytes
- Experiment duration: **12 hours**
- Battery voltage:
 - **Start of the test: 3.25 V**
 - **End of the test: 2.85 V**



Measurements

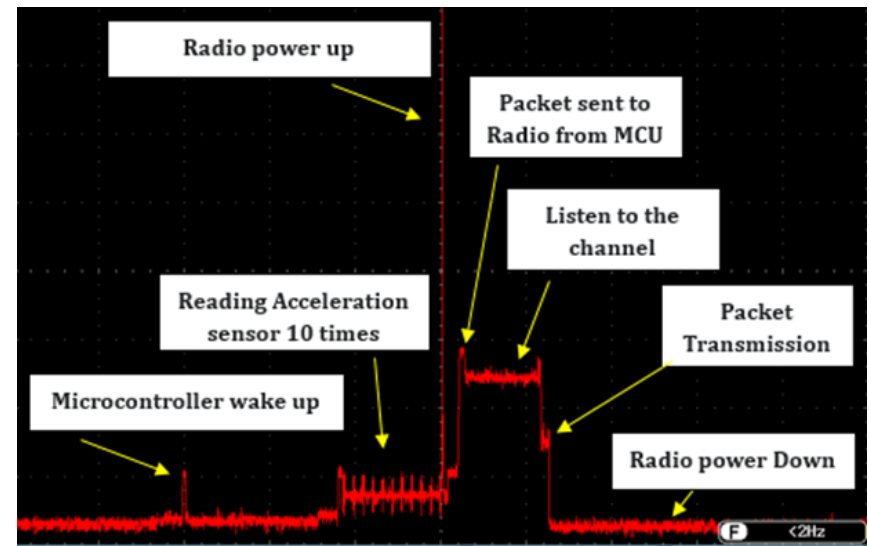
❖ Testing under low power operation

- All LEDs are OFF.
- Only accelerometer in "read" mode (10 samples and 100Hz sampling frequency)
- Reading → Radio ON → Broadcast → Radio OFF
- **Transmission power = -25 dBm** → minimum current consumption (8.5 mA)

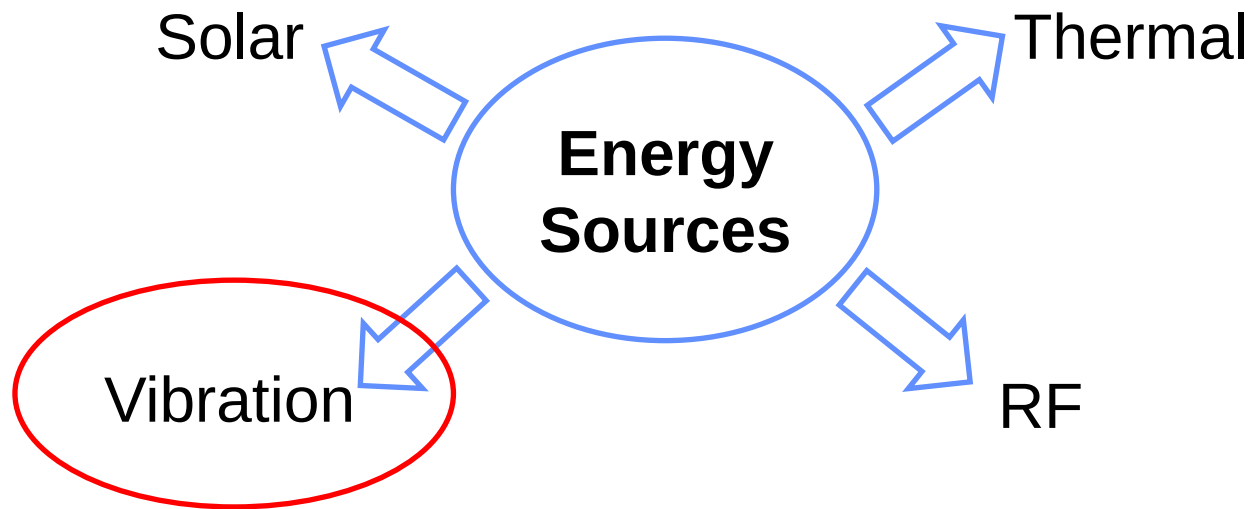
- **Current Consumption**
- Packet reception (receive mode): 19 mA
- Radio power up: 65 mA
- Microcontroller ~ 4 mA
- Packet transmit ~ 8.5 mA
- Accelerometer sensor current < 1mA

• ~ 1 mJ energy/cycle

→ 1 mW power dissipation @ 1 Hz



Different Types of Energy Sources



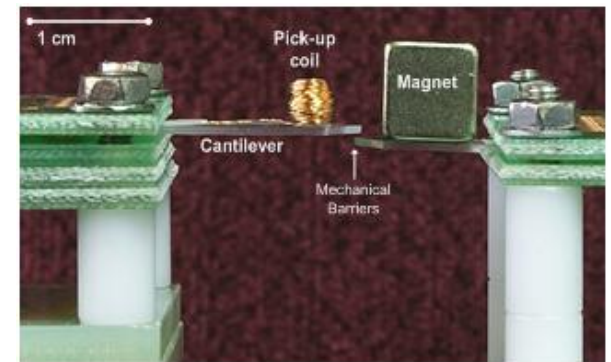
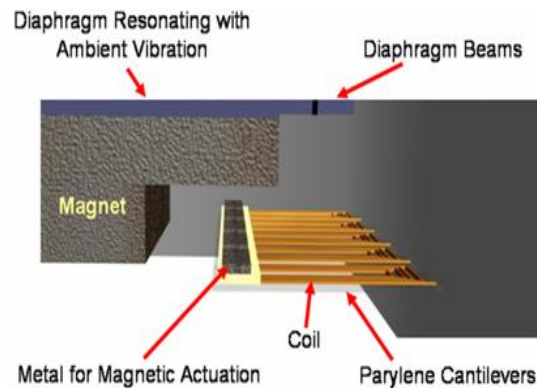
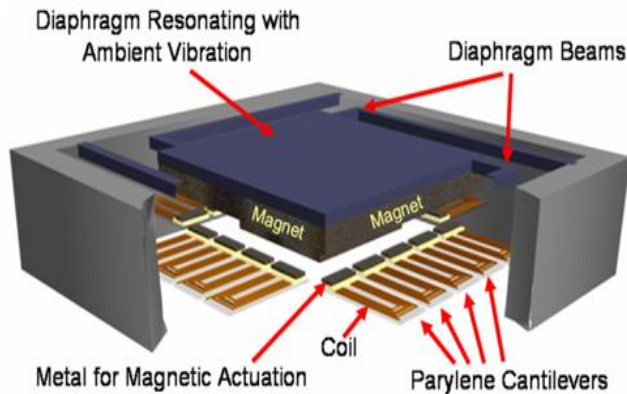
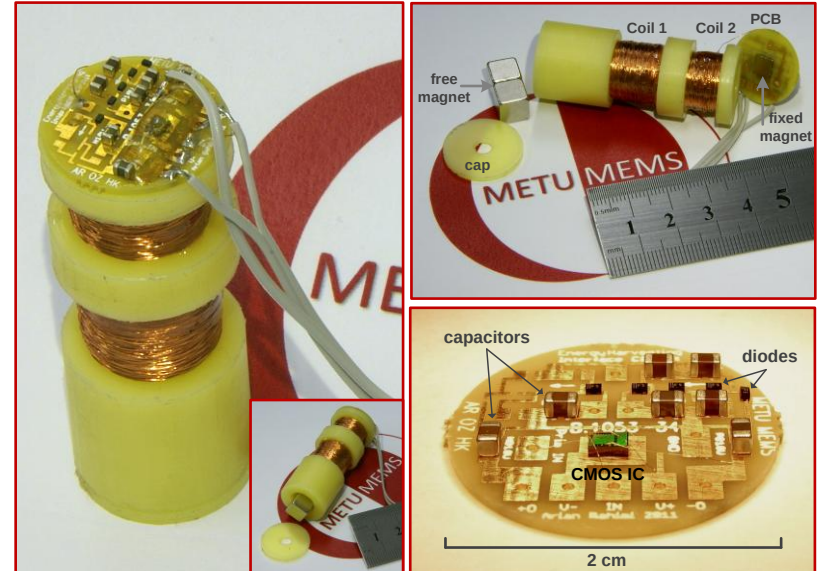
➤ Vibration-based Energy Harvesting:

- abundant in the nature
- clean
- based on simple structures



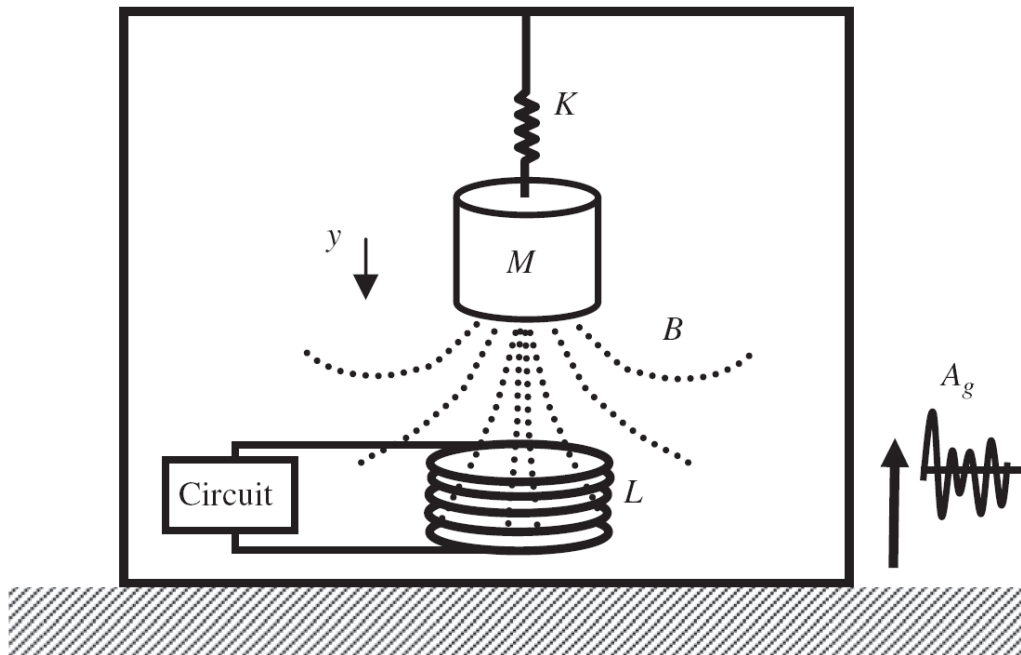
Electromagnetic Energy Harvesting

- Good candidates for low frequency **ambient** vibrations
- Simple: coil & magnet
- Low output impedance



EM Harvester Operation Principle

- The basic EM energy harvester representation



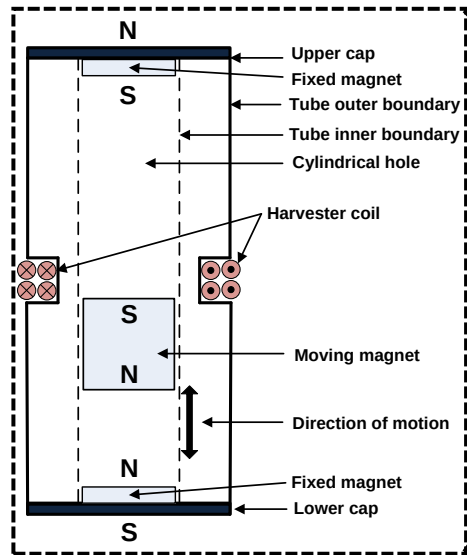
$$M\ddot{y} + D\dot{y} + Ky + F_L = -MA_g$$

$$F_L = I \int dl \times B$$

$$\varepsilon(t) = -\frac{d\Phi}{dt} = -\frac{d(\int B \cdot dA)}{dt}$$



The EM Energy Harvesting System

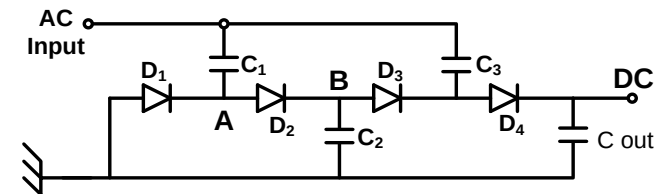


EM Energy Harvester

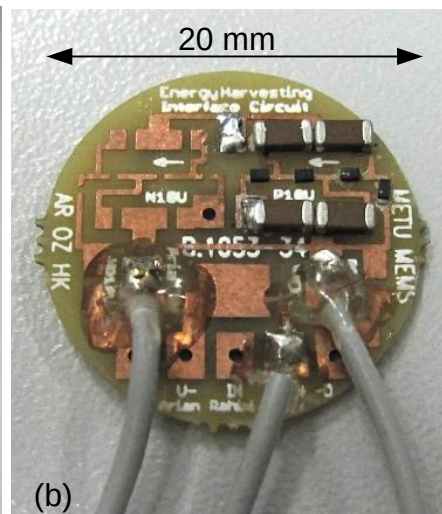
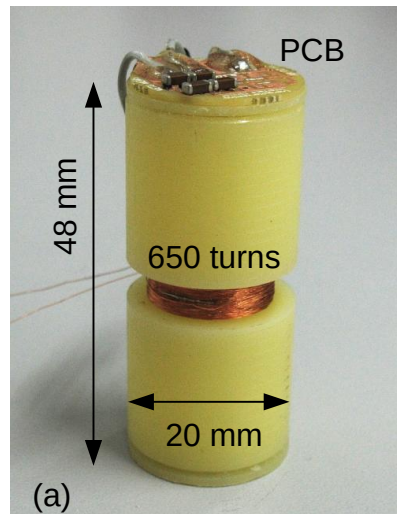
Rectification and step up

Storage Capacitor

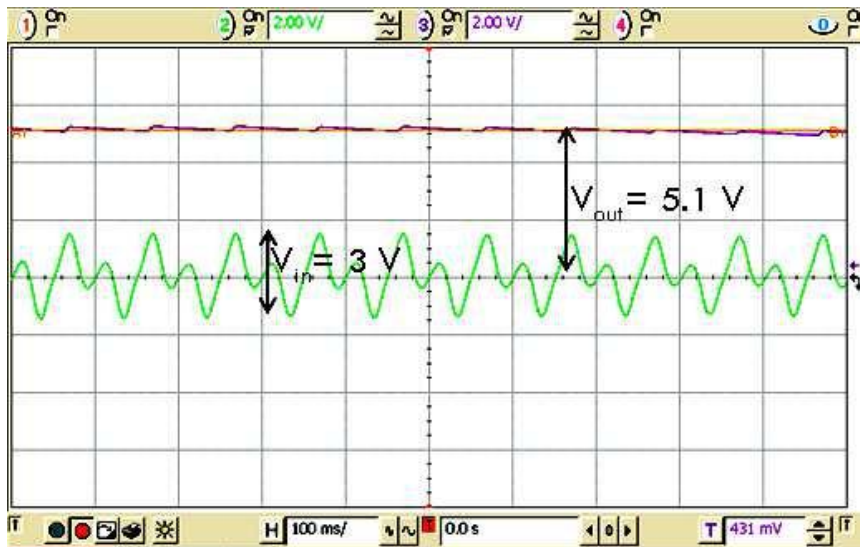
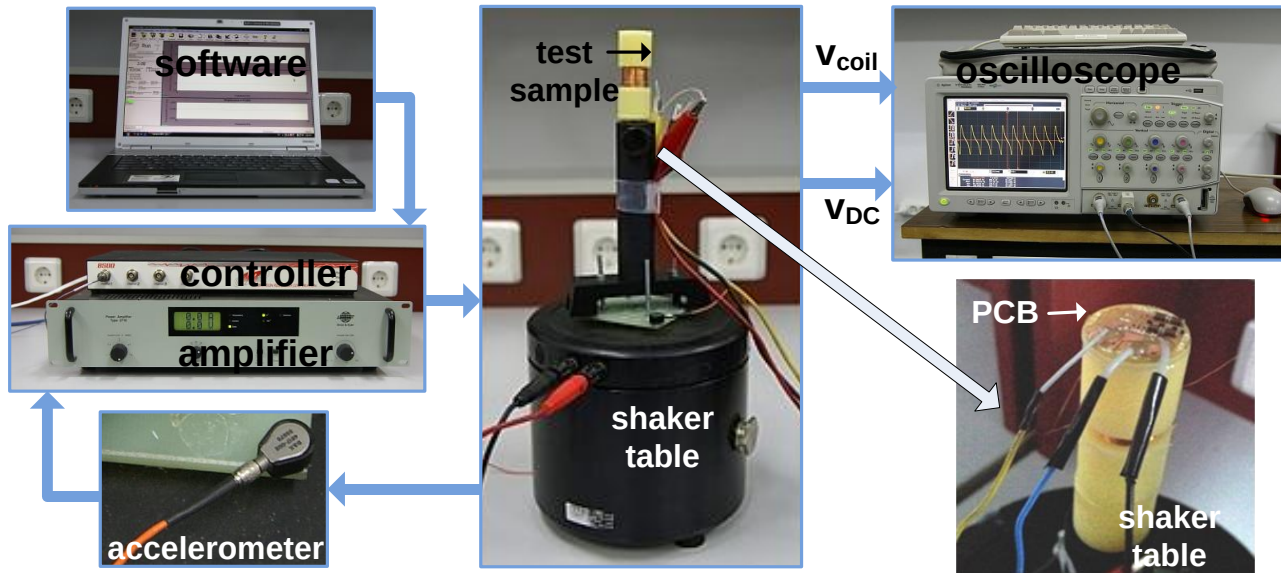
2-stage Dickson rectifier



$$V_{DC} = 4 \times (V_{AC_{peak}} - V_{th})$$



Test Setup and Results



Vibration conditions:

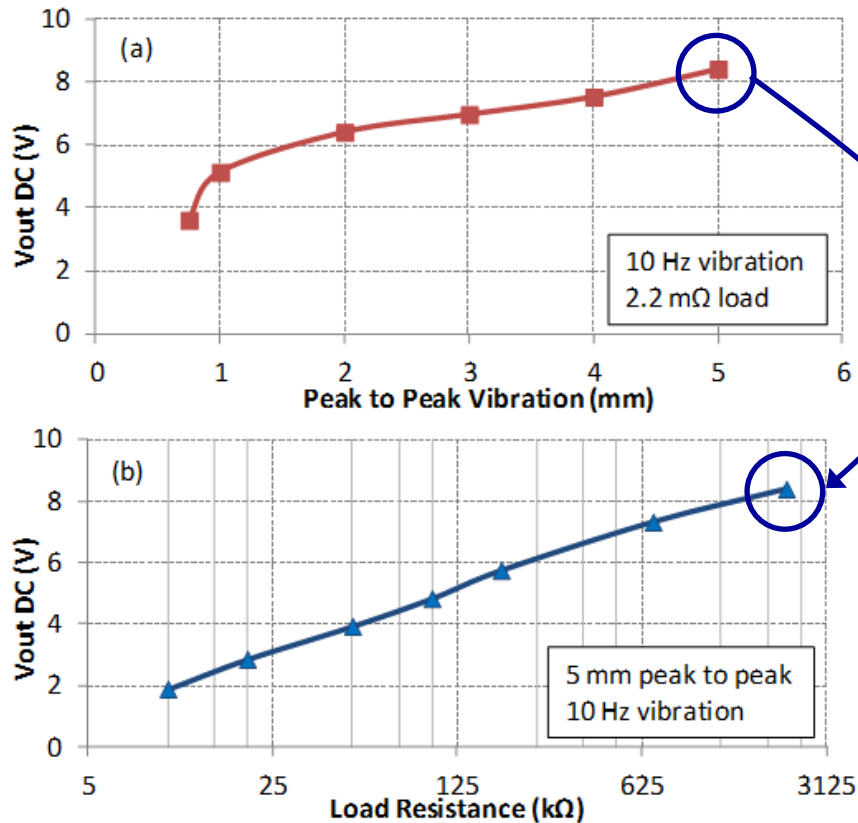
- Frequency: 10 Hz
- Acceleration: 0.5g
- Vibration amplitude: 2.5 mm peak-to-peak

$1.5 \text{ V}_{\text{peak}} \text{ AC} \rightarrow 5.1 \text{ V DC}$



Test Results

- Different vibration conditions and load resistances



V_{out} decreases for low-Z load such as:

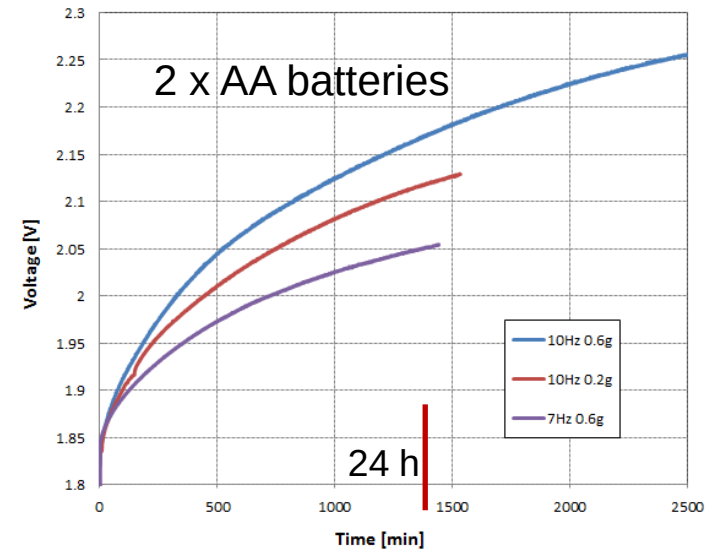
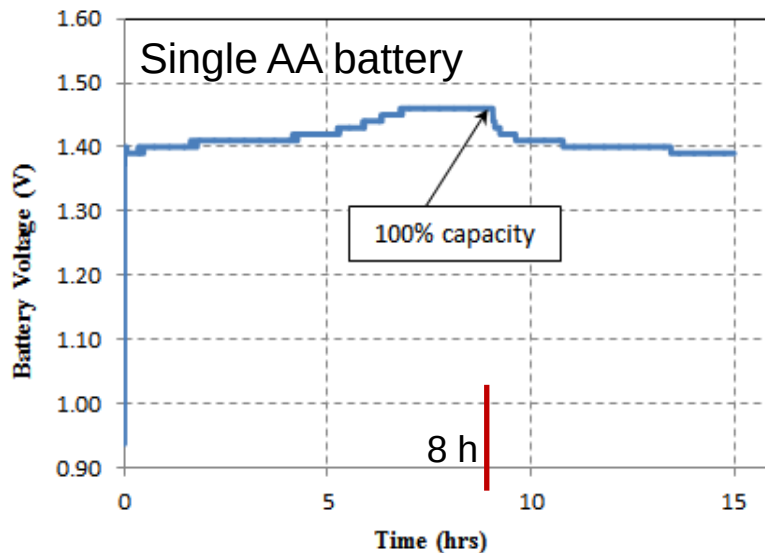
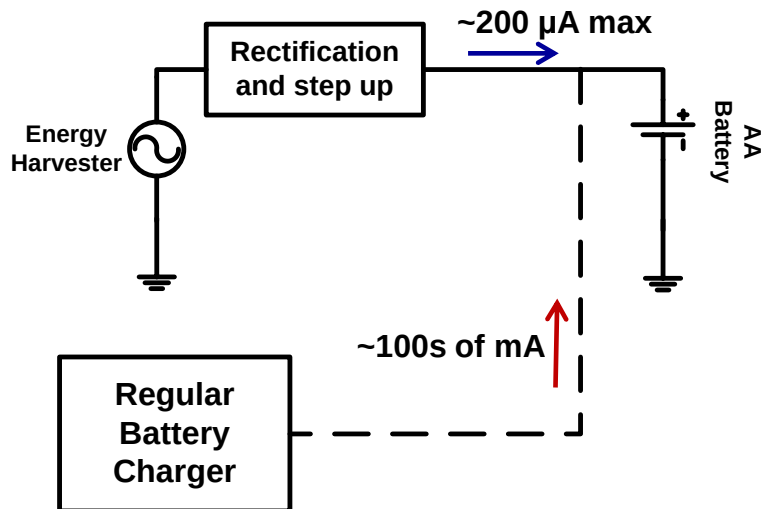
- Receive/transmit
- Battery charging

Generated DC power, P_{out}

- 100 μ W @ 5 kΩ load
- 90 μ W @ 25 kΩ load
- 50 μ W @ 125 kΩ load



Comparison of Charging Performance

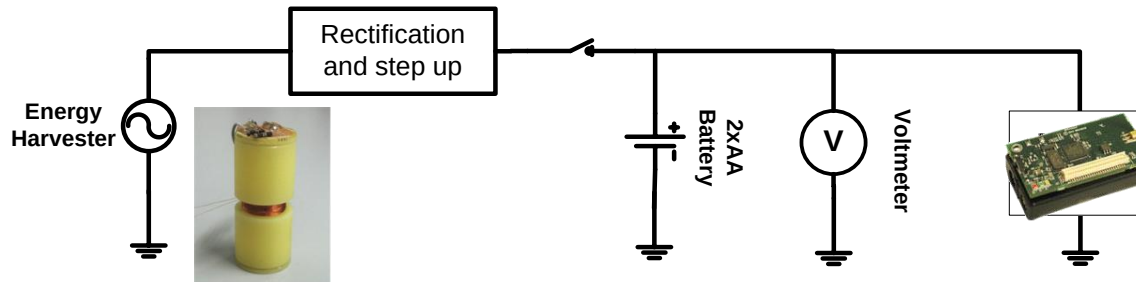


Charging with energy harvester

- ✗ Long time process (> 2 days)
- ✓ On-line charging possible
- ✓ Battery voltage can be maintained



Monitored Battery Voltage

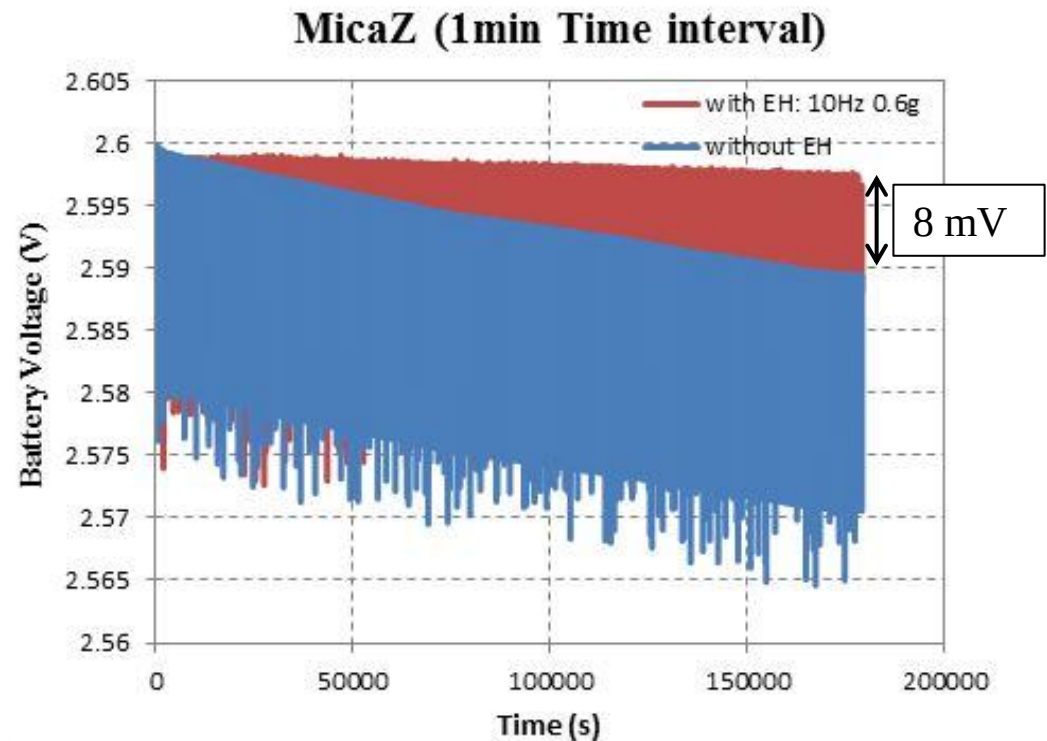


Vibration conditions:

- Frequency: 10 Hz
- Acceleration: 0.6g
- Vibration amplitude: 3 mm peak-to-peak

MicaZ operation conditions:

- Low power mode
- 1 min interval time
- Send average acceleration data (10 measurements)
- Transmitter power : -25 dBm



Conclusion

➤ Utilization of energy harvesters in WSNs

- Power consumption of MicaZ
- Vibration-based electromagnetic energy harvester
- **First experimental results showing the feasibility**
 - Energy harvester characterization
(EM harvester, low level vibrations, ~100 μ W DC)
 - Charging empty batteries with an energy harvester **(> 2 days)**
 - Comparison with a regular batter charger
(long process time, however eneables on-line charging)
 - MicaZ operation with Battery + Energy harvester
(8 mV improvement in the battery voltage)

➤ Future Work

- Energy harvester optimization (still comparable with MicaZ dimensions)
- Piezoelectric harvester vs. Electromagnetic
- More efficient interface electronics
- Statistical data collection on harvested energy

