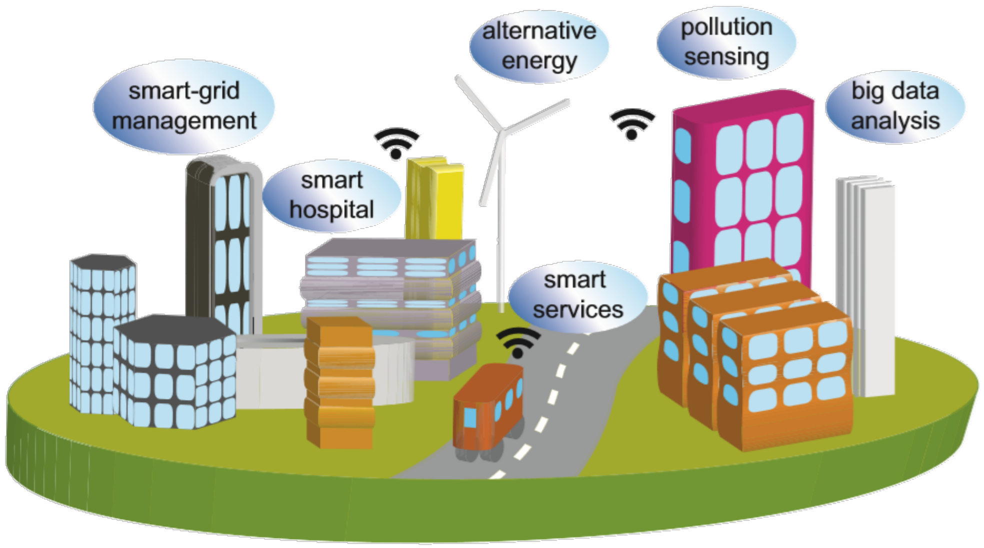
Autonomous devices for IoT



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1. Introduction

1.1 What is IoT

1.2 What do smart things communicate?

1.3 Considerations in developing IoT

1.4 What are the main IoT issues?

1.5 Some examples of IoT devices

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1.1 What is IoT?

- The term was firsty used by **Kevin Ashton** (MIT) in **1999**
- It is a new way of exploiting the **Internet**:
  - In **1990** the first IoT device from **John Romkey**:

Dan Lynch, President of Interop challenged Romkey to "bring up his toaster on the Net". He presented a toaster that was connected to a computer with TCP/IP networking. It then used an information base (SNMP MIB) to turn the power on.

***IoT** is a **network** of smart devices which are uniquely identified and can **communicate** through the Internet.*

*A **smart device** is an electronic **device**, generally connected to other devices or networks via different **wireless protocols** that **can** operate to some extent interactively and autonomously.*

1.2 What do smart things communicate?

In God we trust, all others must bring data

[W. Edwards Deming (possibly)]

- Smart things can communicate different **kinds of data**:

  - **Environmental** monitoring: humidity, temperature, air quality, strength of electromagnetic fields…
  - **Structural** monitoring: accelerations, shocks, stress/strain…
  - **Human** monitoring: position, health parameters (body temperature, blood pressure, position)…
  - Or just their **existence** in one specific position and/or in one network.

- In order to communicate they can use different **layers/technologies**: WiFi, Cellular, Bluetooth, NFC, RFID, ZigBee, Lora

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1.3 Considerations in developing IoT

- **What** do I want to build? Choice of proper sensors / components
- **Where** should my IoT device work? Choice of communication infrastructure and installation features
- **How many** data do I need to communicate? Choice of communication protocol and energy considerations
- **How much** energy does my device need?
  - Can I use batteries? (usually, **cheapest** solution)
  - How much energy is available from the ambient? In which form? (**greeneer and no-maintenance**)
  - Can I use external power (**usually avoided, not wireless**)

1.4 What are the main IoT issues?

- **Communication security:**
  - Encrypted communcations
  - Network subscription of each device through a pre-registered unique key
- **Limited AI**
  - Building of learning algorithms to make them «smarter»
- **Power need**
  - Batteries: finite lifetime, they need to be replaced, polluting, risk of explosion
  - Environmental: limited power available, not continuous, reliability issues
- **Remote collocation/ installation issues:**
  - Is power available? If not, environmental energy.
  - Is communication available? If not, need to build infrastructure.
  - Hard to reach / complex installation. Wireless device preferred

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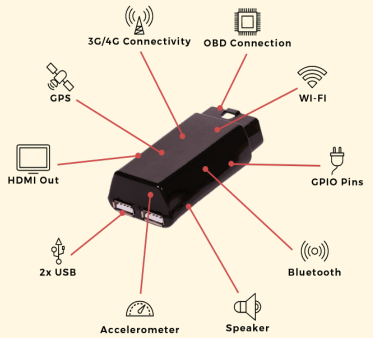
1.5 Some examples of IoT devices

Automotive



Multi-purpose sensors

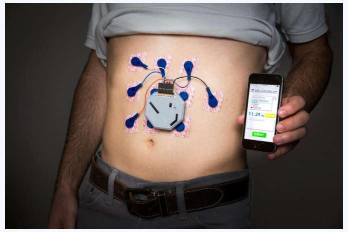
Telepass systems

GPS Trackers

Human / Pets

Children tracking

Sport monitoring



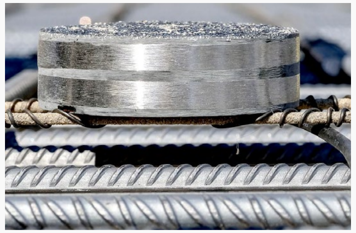
Health montoring

Pets tracking

Industrial / Structural

Motors monitoring

SH monitoring



Airports monitoring

2. Most used communication protocols

2.1 LoRa

2.2 ZigBee

2.3 Cellular (NB-IoT)

2.4 Bluetooth

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2.1 LoRa

- LoRa networks belong to the **LPWAN**: Low Power Wide Area Networks
- **LoRa** is the **physical layer**, while **LoRaWan** is the **communication protocol** defined by the LoRa Alliance Consortium.
- LoRa networks communicate on the **868MHz** (in Europe), **433MHz**, **915MHz** and **780MHz.**
- **Bytes per message (96bytes max) and messages per day (1% duty cycle) are limited**

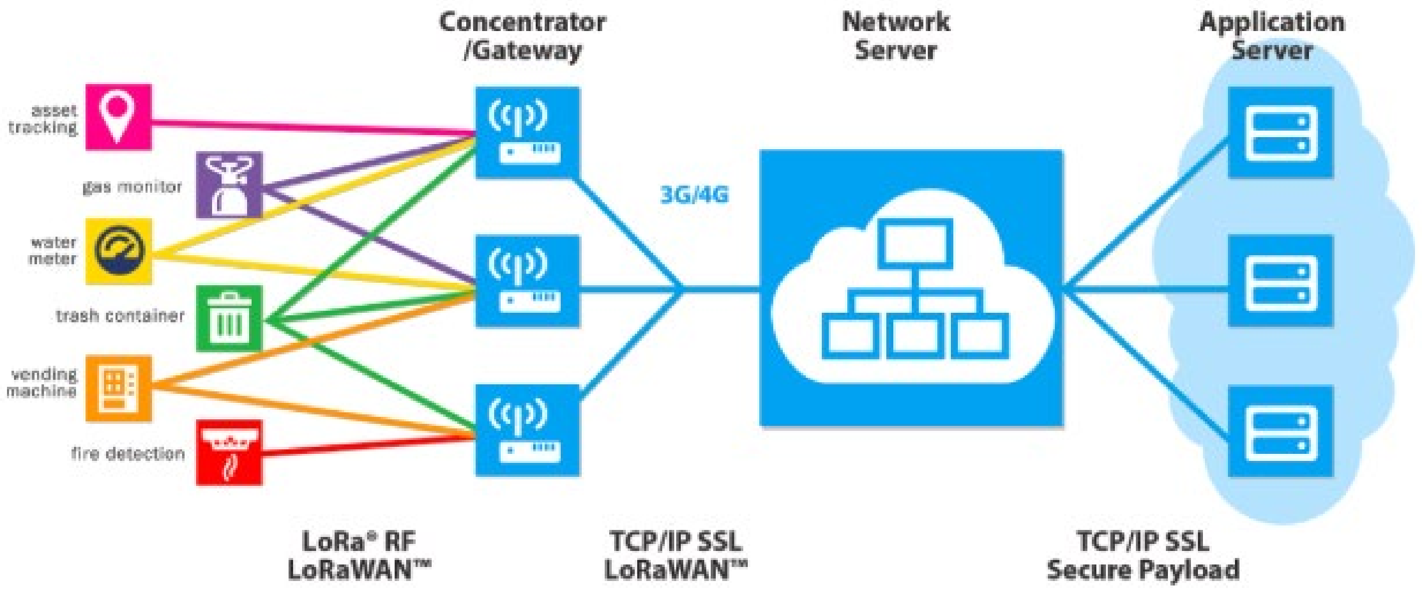
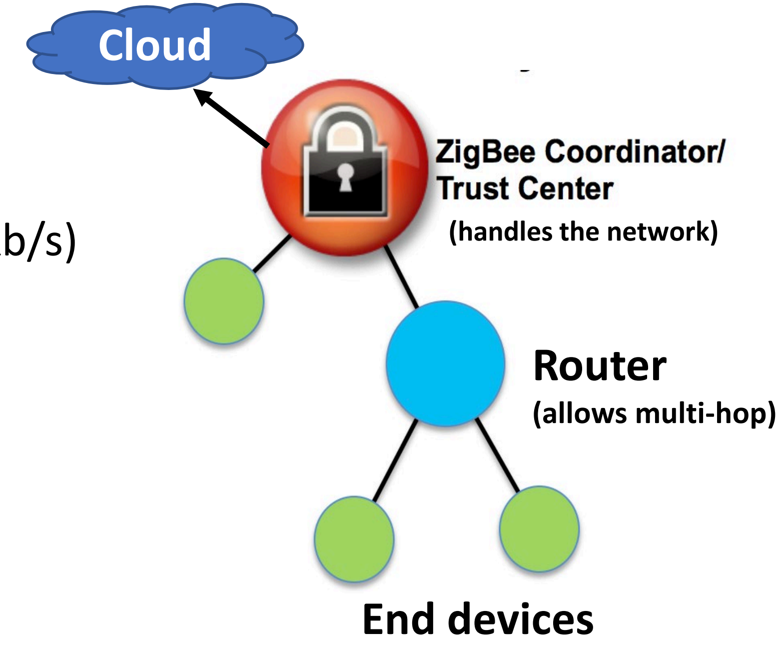


Image from medium.com

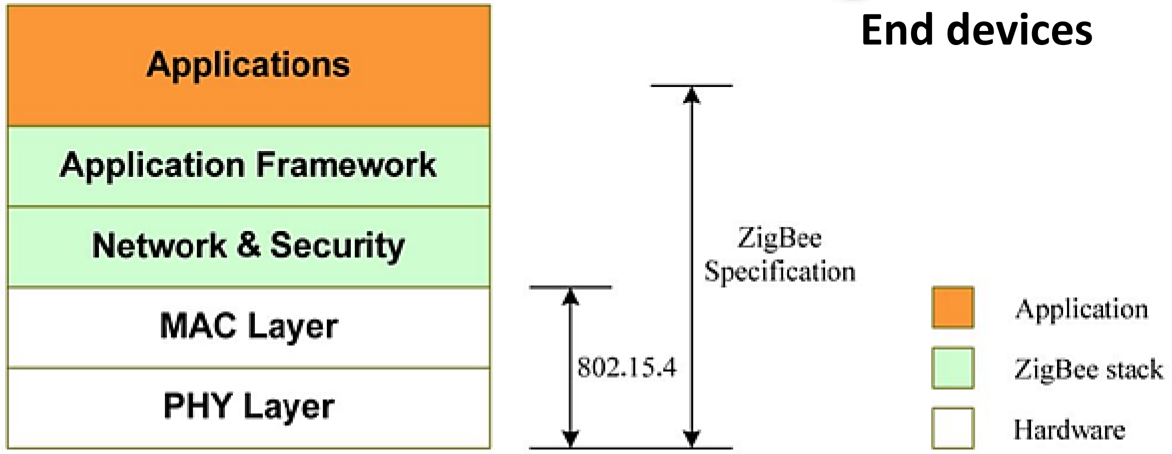
- **Network key:**
  - estabilish connection between the devices and the Network Server.
  - Integrity check on the message
- **App key:**
  - estabilish connection with the App Server
  - payload encryption
- **AES encryption** on the whole message

2.2 ZigBee



- Zigbee is a (**LR-WPAN**) Low-Rate Wireless Personal Area Networks
- Zigbee is able to communicate on **868MHz** band (20kb/s) or in **2.4GHz** band(250kb/s)
- It uses the **IEEE 802.15.4** physical and MAC layer and adds network, security and framework protocol on top of it.

- The network can be
  - **Centralized**: only the Coordinators or Trust Centers can start the networks. When a node joins it receives the network key and establish a unique TCLK (trigger clock).
  - **Distributed**: every router is able to start the network by their own. When a node joins to the network it only receives the network key (no sync).



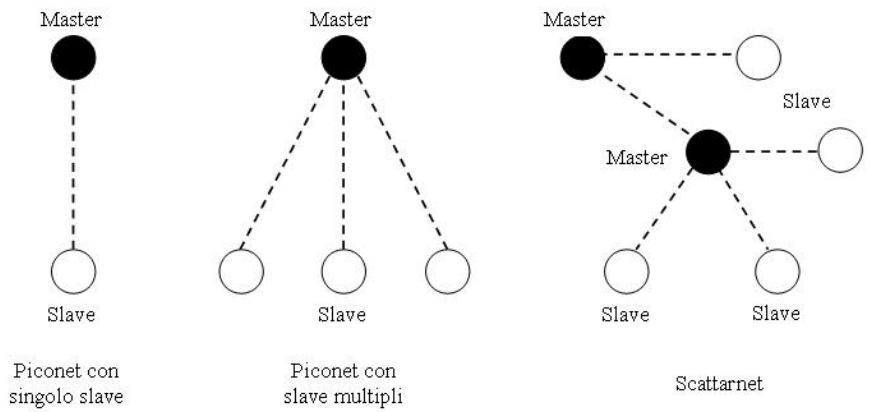
2.3 NB-IoT & Sigfox

- **NB-IoT** is a **LPWAN** (**L**ow **P**ower **W**ide **A**rea **N**etwork), based on cellular technology working at **800MHz** band.
- It needs a bandwidth of 200kHz, so it does not interfere with other cellular networks.
- Max packet length **200kb**, and throughput around **250kbps**.
- Operative in **harsh environments** (very warm or cold, very humid, in boxes, cellars…)
- NB-IoT frequencies are licensed, so a SIM card is needed to access the network.
- Best application case: few hundreds of bytes to send each time very rapidly and not frequently.
- Two different versions (Vodafone and Hwawei) that are not compatible.
- Older 4G receivers cannot handle NB-IoT transmissions.

- Sigfox is a LPWAN, working in unlicensed 868MHz band (n Europe) 433MHz (in Asia) and 915MHz (in US).
- It is unsymmetrically bidirectional (lower bandwidth for uplink than downlink)
- Maximum payload of 24bytes, with limited transmission duty cycle
- Transmission time of 1 packet is around 2s

2.3 Bluetooth

- **WPAN W**ireless **P**ersonal **A**rea **N**etwork, **2.4GHz**
- Very **low range** <100m in Class 1 and <1m class 3
- Two main data transferring ways:
  - **Connectionless**: the joined devices can start send data at any moment
  - **Connected**: The device need to connect before sending data
- Can be **bi-directional or asymmetrical** (but asymmetrical is faster)



Class	Tx Power		Distance
	(mW)	(dBm)	(m)
1	100	20	~100
2	2,5	4	~10
3	1	0	~1
4	0,5	-3	~0,5

3. Powering a IoT autonomous device

3.1 General structure of device

3.2 Solar energy harvesting

3.2 Vibrational energy harvesting: electromagnetic

3.3 Vibrational energy harvesting: piezoelectric

3.4 Harvesting from real vibrations

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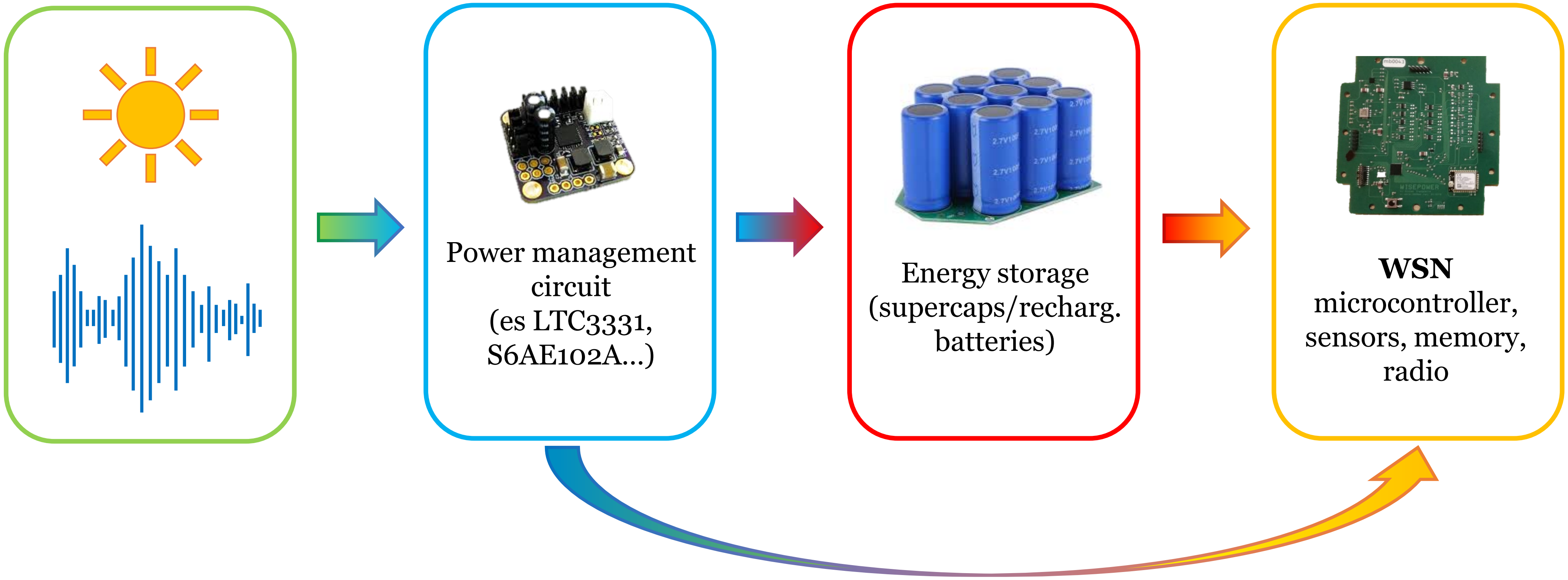
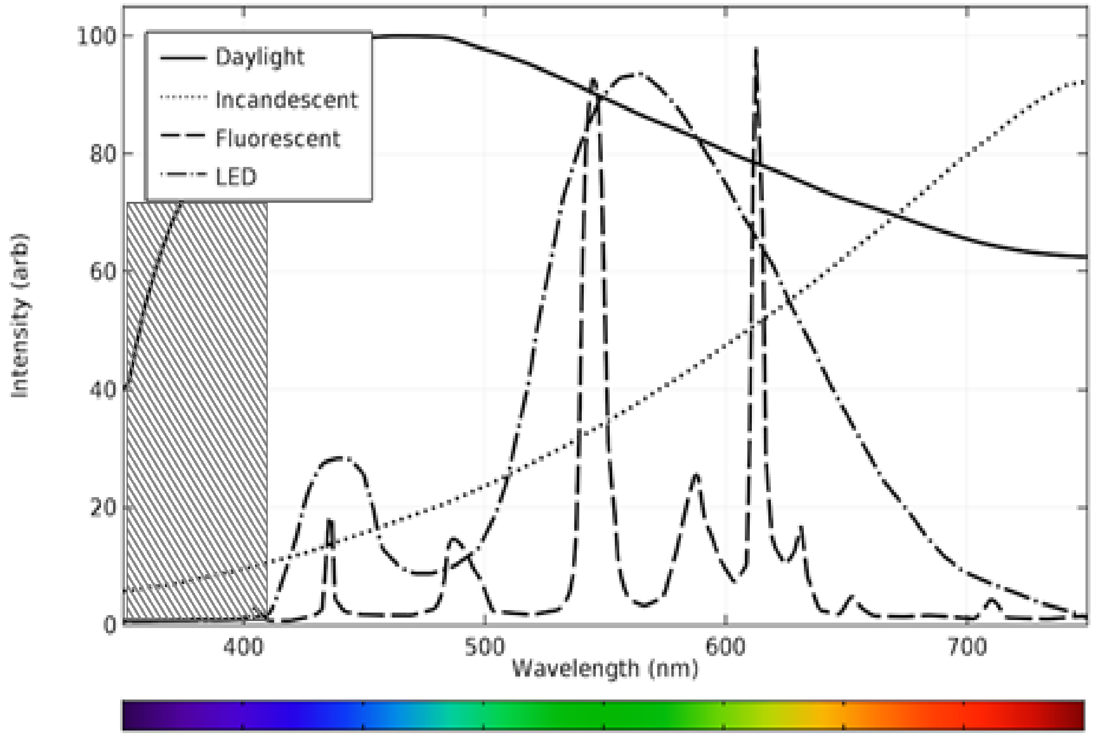
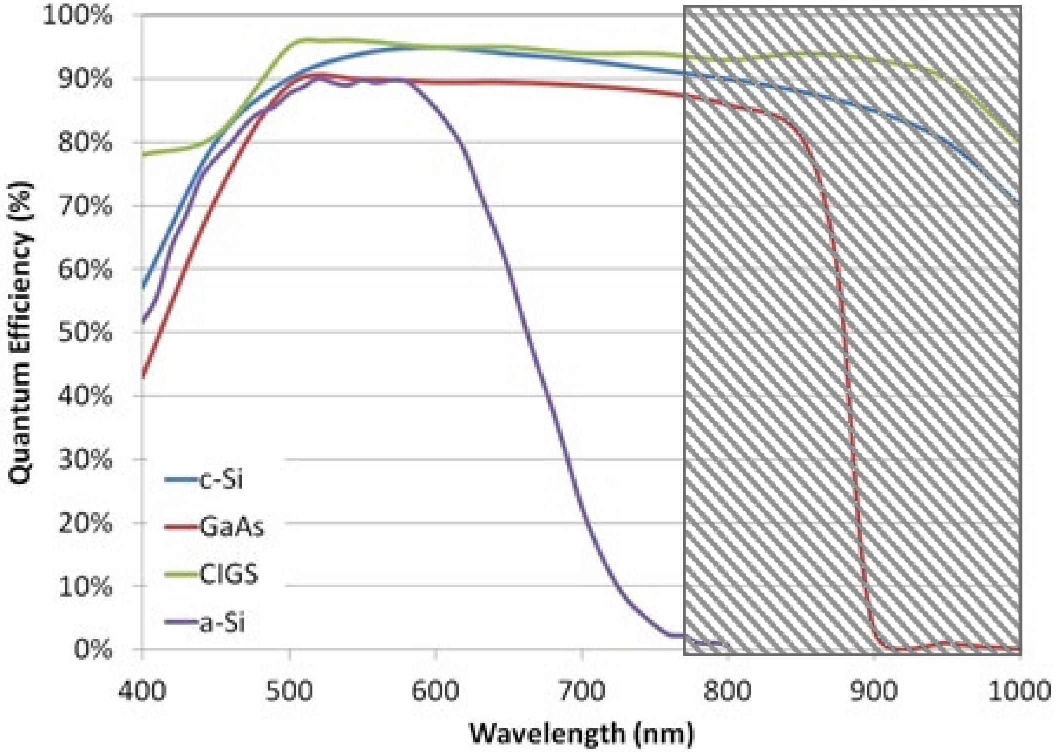
3.1 General structure of device

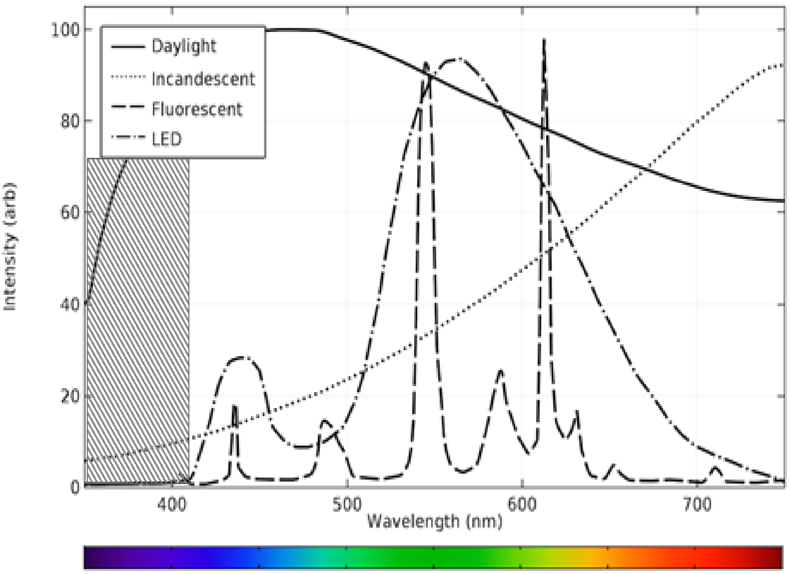


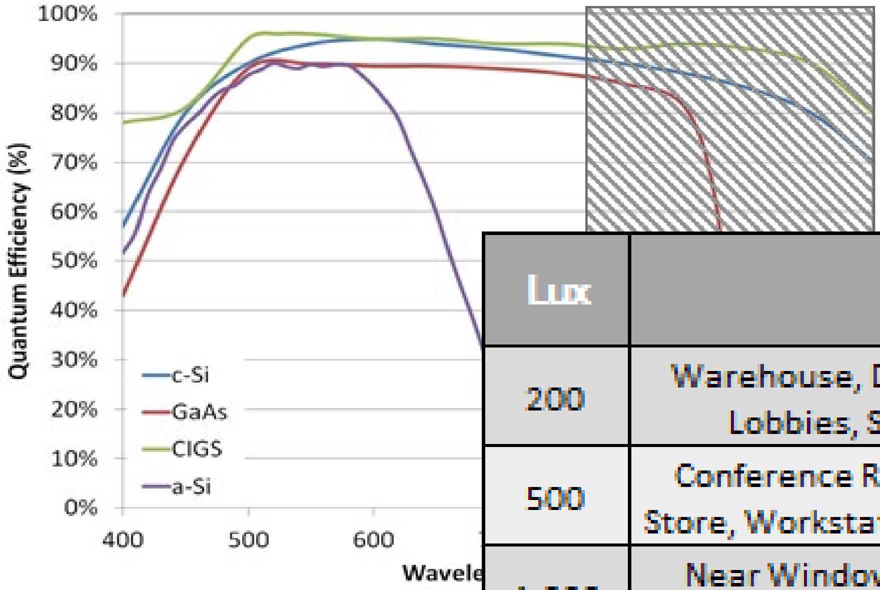
3.2 Solar energy harvesting





3.2 Solar energy harvesting

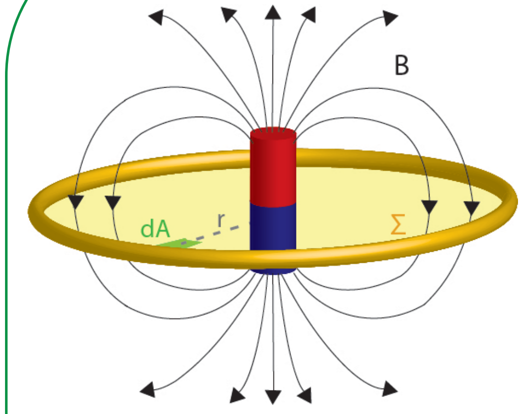




Lux	Area	Power Produced (uW/cm^2)
200	Warehouse, Dining Area, Auditorium, Lobbies, Stairwells, Corridors.	6
500	Conference Room, Office Desk, Retail Store, Workstation, Library, Living Room.	17
1,000	Near Windows, Directly Underneath Light Fixtures, Detailed Workstation.	35
10,000	Outdoor Overcast, Shaded Areas.	400
25,000	Light Overcast, Indirect Sunlight.	1,000
100,000	Direct Sunlight	4,200

3.3 Vibrational energy harvesting: electromagnetic

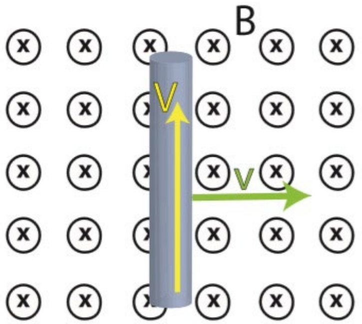
THEORY



- Variable magnetic field, steady conductor

$$\epsilon_i = -\frac{d\Phi(\boldsymbol{B})}{dt}$$

$$\Phi(\boldsymbol{B}) = \int\int_{\Sigma} \boldsymbol{B}(\boldsymbol{r}, t) \cdot d\boldsymbol{A}$$

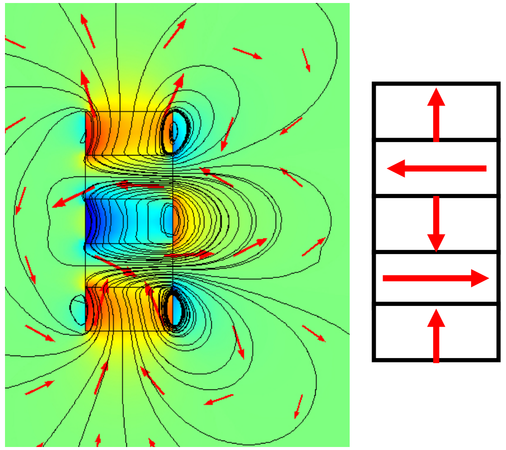


- Moving conductor, constant magnetic field

$$\boldsymbol{F_L} = e\boldsymbol{v} \times \boldsymbol{B}$$

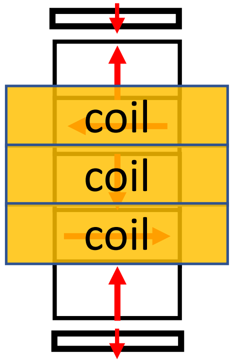
TRANSDUCERS

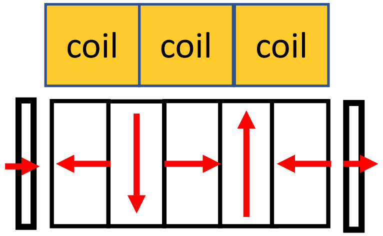
- Methods



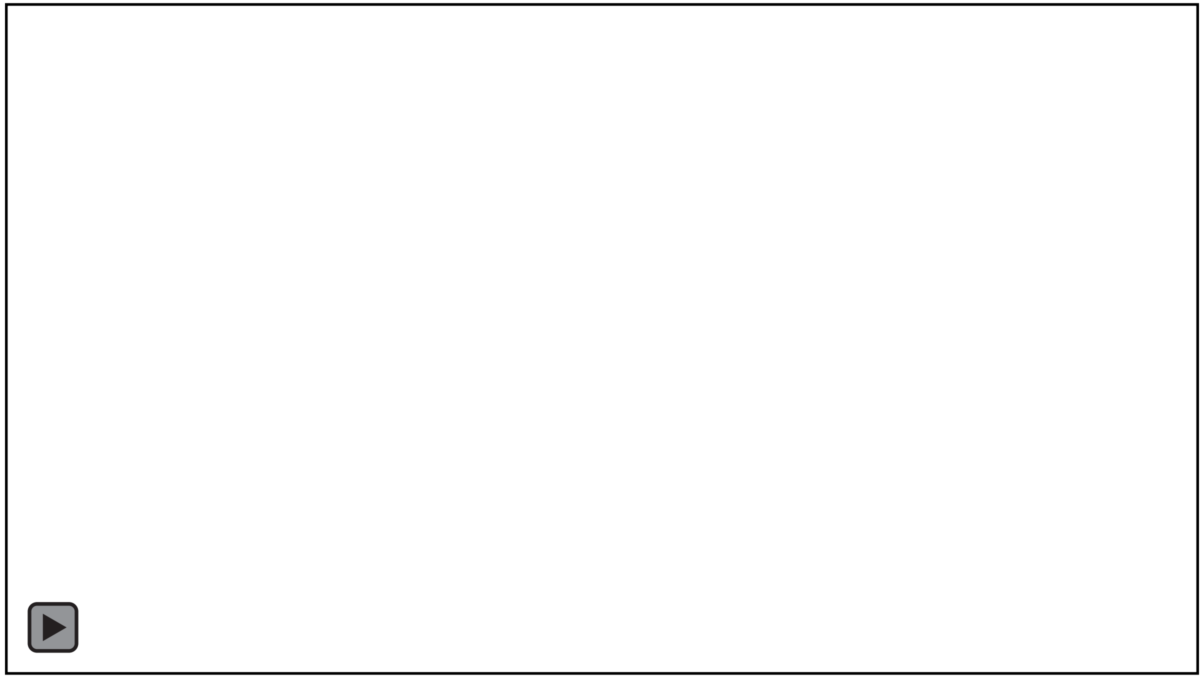
Halbach stacks are used to enhance magnetic field in a small volume.

- Geometries





Strong side exploit., use of magnetic springs.

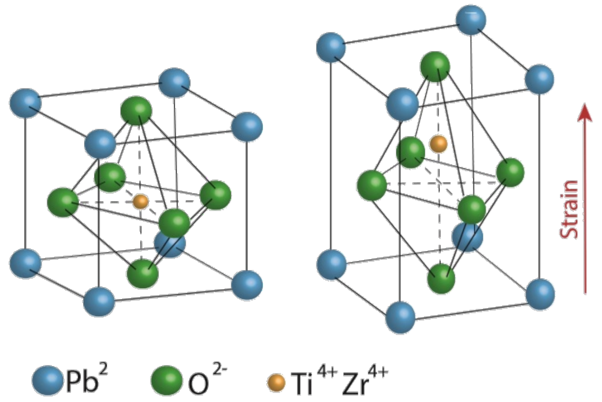


3.4 Vibrational energy harvesting: piezoelectric

THEORY

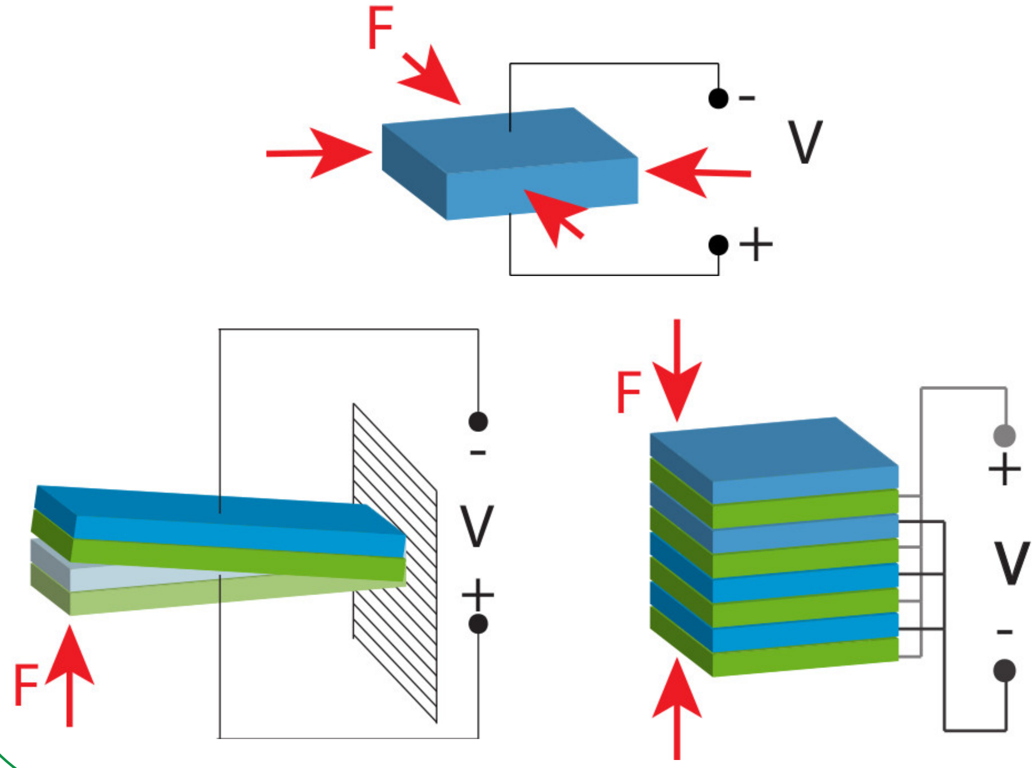
- presence of electric dipoles in the lattice
- asymmetry in electronic charges in the unit cell of piezoelectric materials is present
- when subjected to a mechanical distortion, dipoles are formed

parallel electric field opposing to the length variation

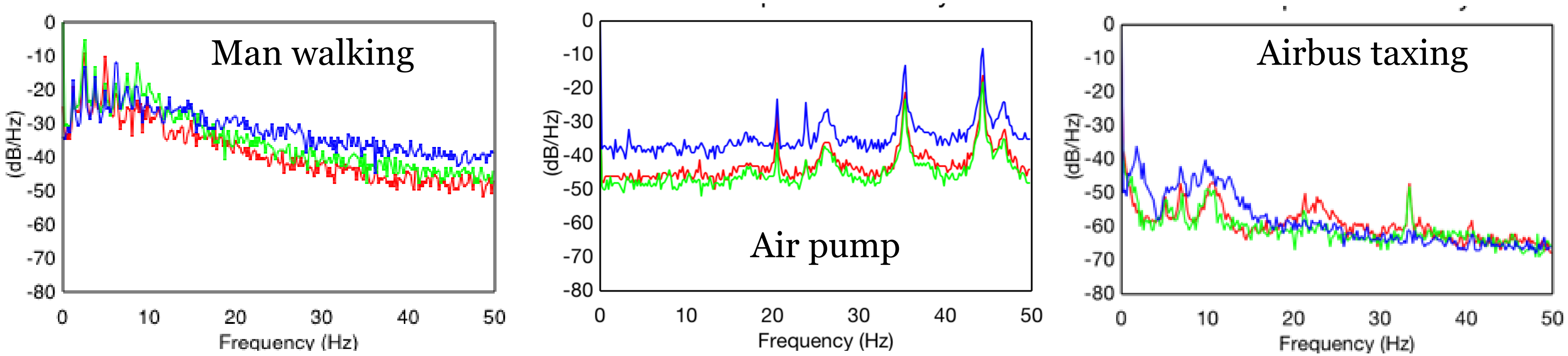


$$\begin{cases} \boldsymbol{S} = s^E \boldsymbol{T} + d\boldsymbol{E} \\ \boldsymbol{D} = d\boldsymbol{T} + \epsilon^T \boldsymbol{E} \end{cases}$$

TRANSDUCERS



3.5 Harvesting from real vibrations



- Different frequency components
- Low-frequency, large peaks

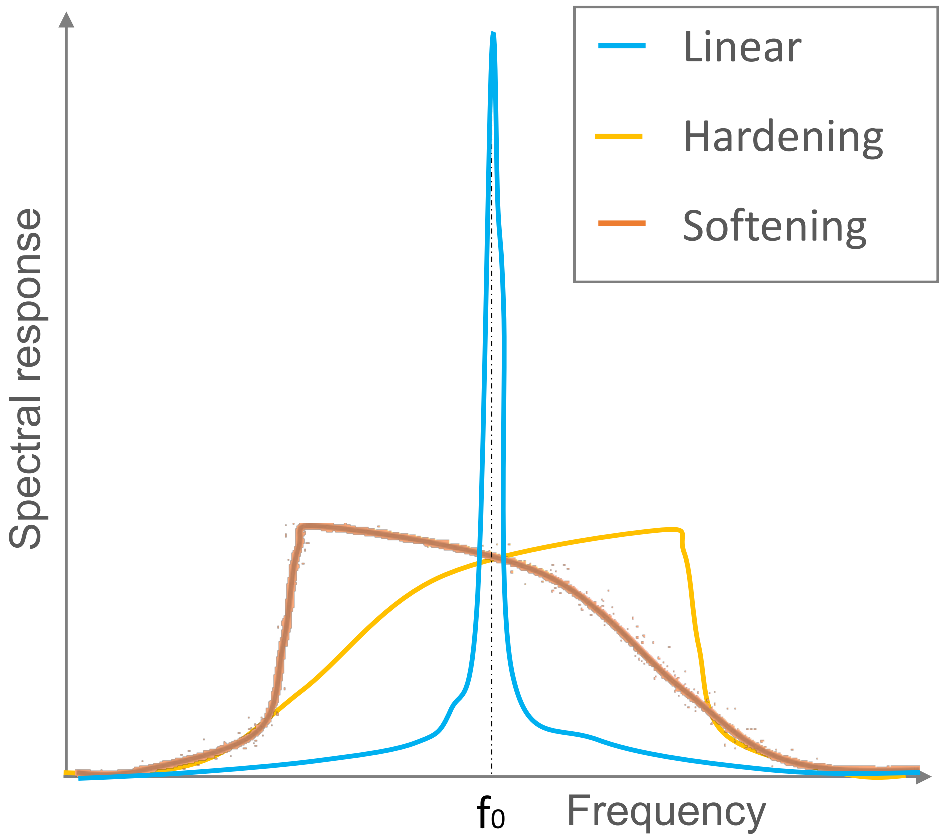
The majority of the energy is dissipated in a broad spectrum

Linear systems

- They respond very well at **resonant** (natural) frequency.
- Best possible solution if harvesting from an **harmonic signals**. In case of more than one harmonic component, arrays of linear harvesters can be used.

Non-linear systems

- They are able to respond to a **broader spectrum**
- Less need for tuning, and higher performance when harvesting from broad-band signals
- Different non-linearities:
  - **Bistability** (mainly for piezoelectric): amplifies the displacement
  - **Hardening** (magnetic springs and impacts): bends the response toward higher frequencies
  - **Softening** (nonlinear springs or loss of contact with linear springs): bends the response towards lower frequencies



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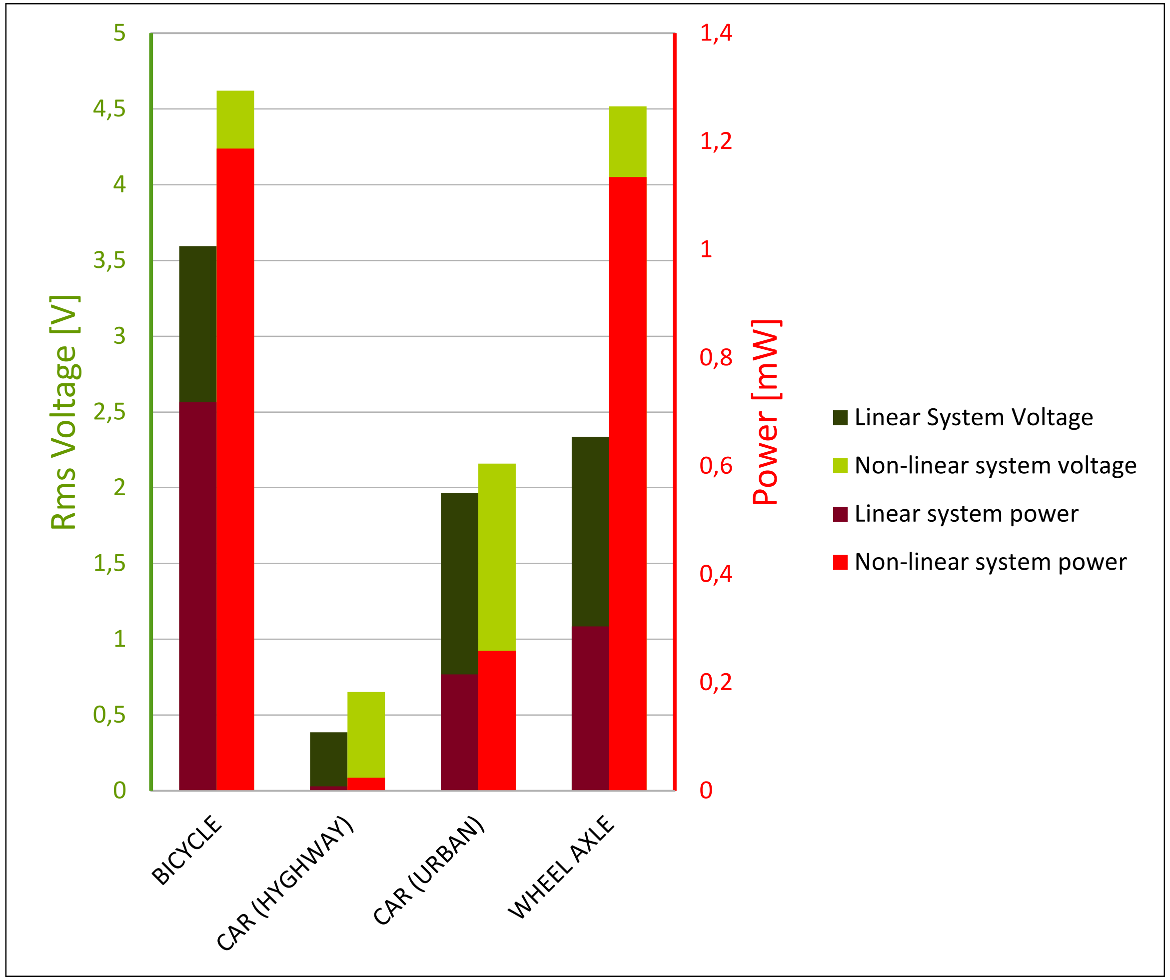

4. Application insights:

4.1 Human motion monitoring device
4.2 SHM for bridges and wind turbines
4.3 Monitoring of high voltage cables

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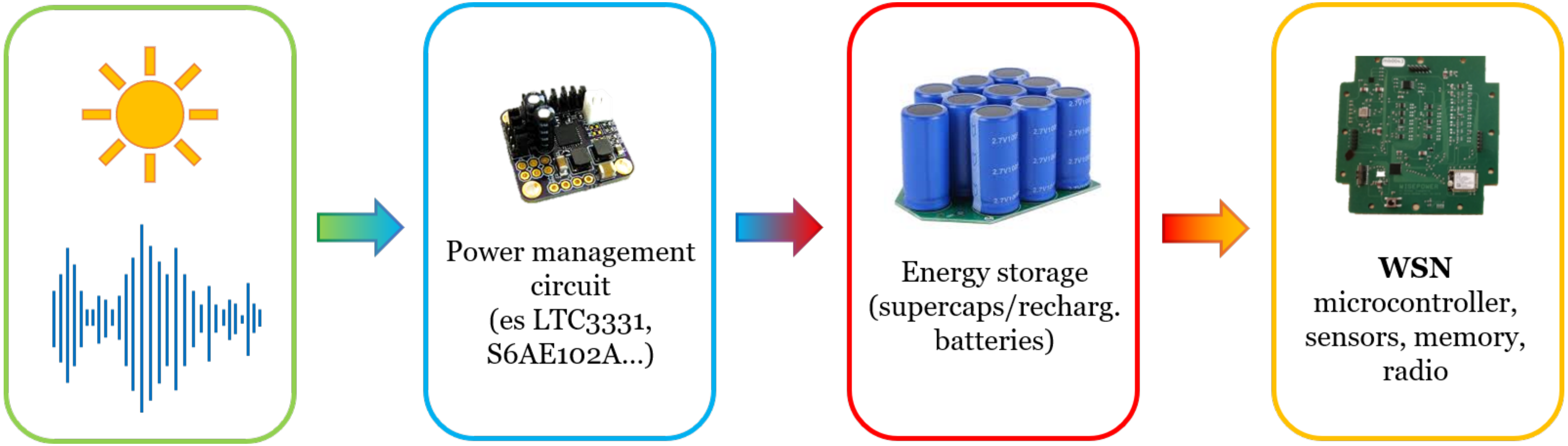
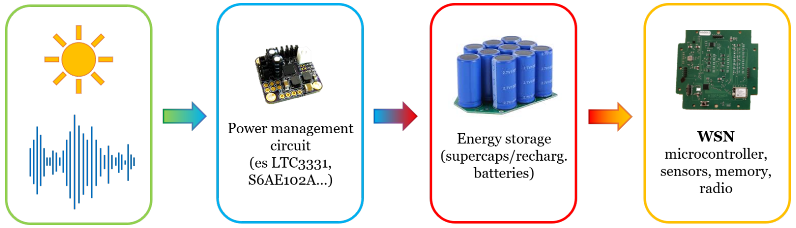
4.1 Application insight: Position monitoring

- On people, monitoring is used for:
  - Medical reasons: monitoring of not self-sufficient people who can get lost or in danger
  - Commercial reasons: monitoring of popular area at exhibitions
  - Safety reasons: monitoring of number / location of people in a crowded event

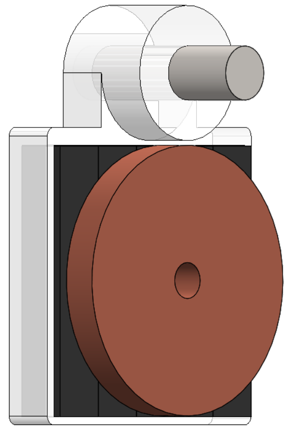
- Other usages:
  - Pet monitoring
  - Farm animals monitoring
  - Monitoring of stockhouses

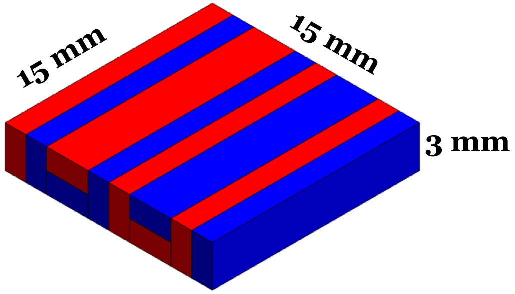

Power management
circuit
(es LTC3331,
S6AE102A…)
Energy storage
(supercaps/recharg.
batteries)
WSN
microcontroller,
sensors, memory,
radio

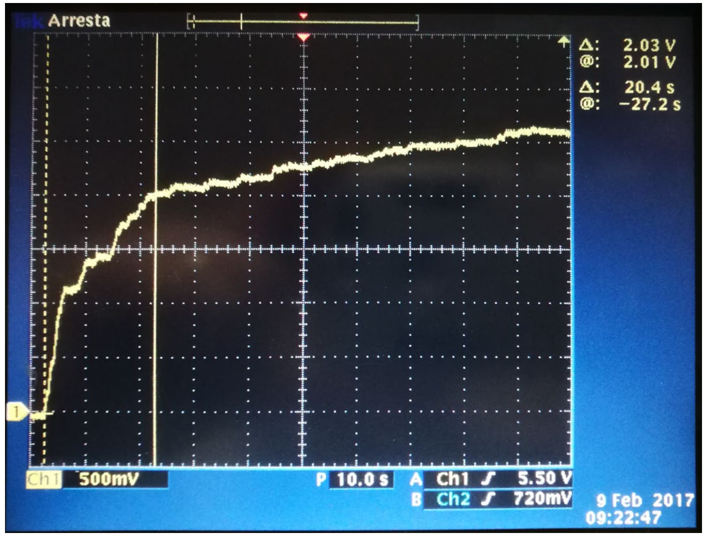


Man walking

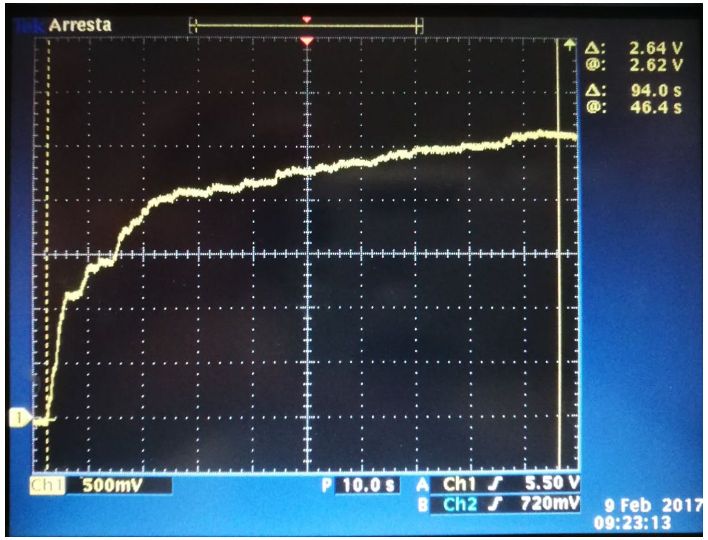
(device wore on chest)







20'' → 2.0V → E = 800 mJ



90'' → 2.6V → E = 1350 mJ

Harvesting

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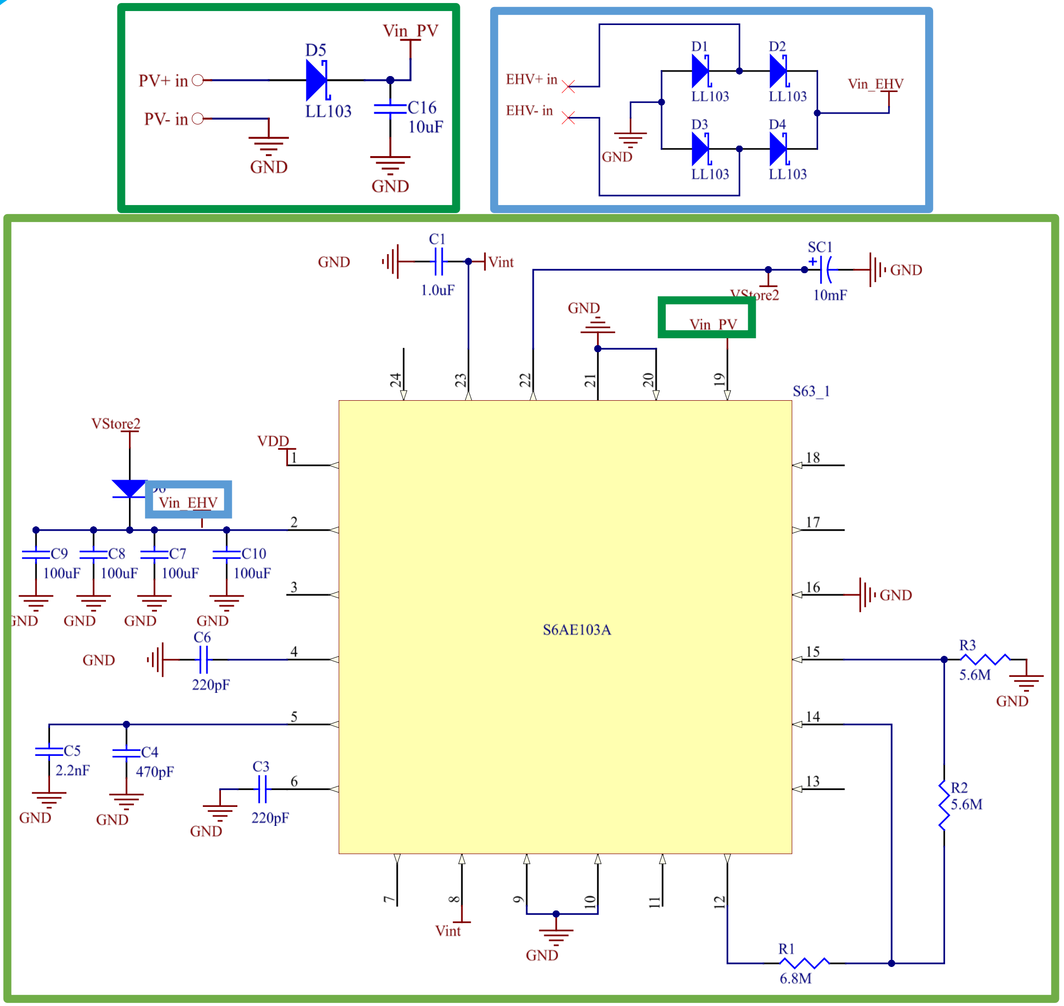
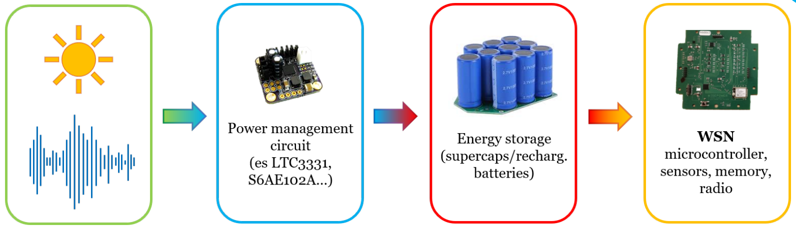
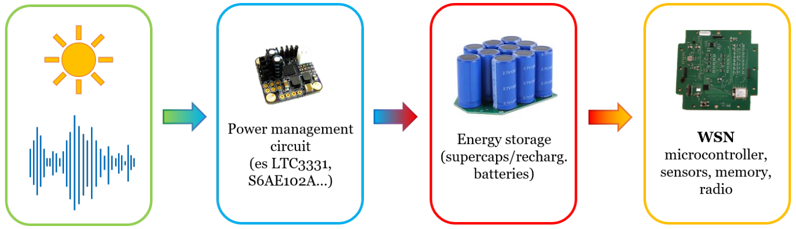
Power management

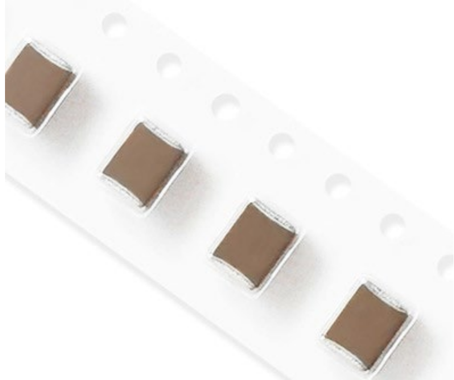




- Minimum input power 1.2 μW
- Average current : 280 nA
- Low-consumption current LDO : 400 nA
- Low-consumption current Timer: 30 nA



Energy storage



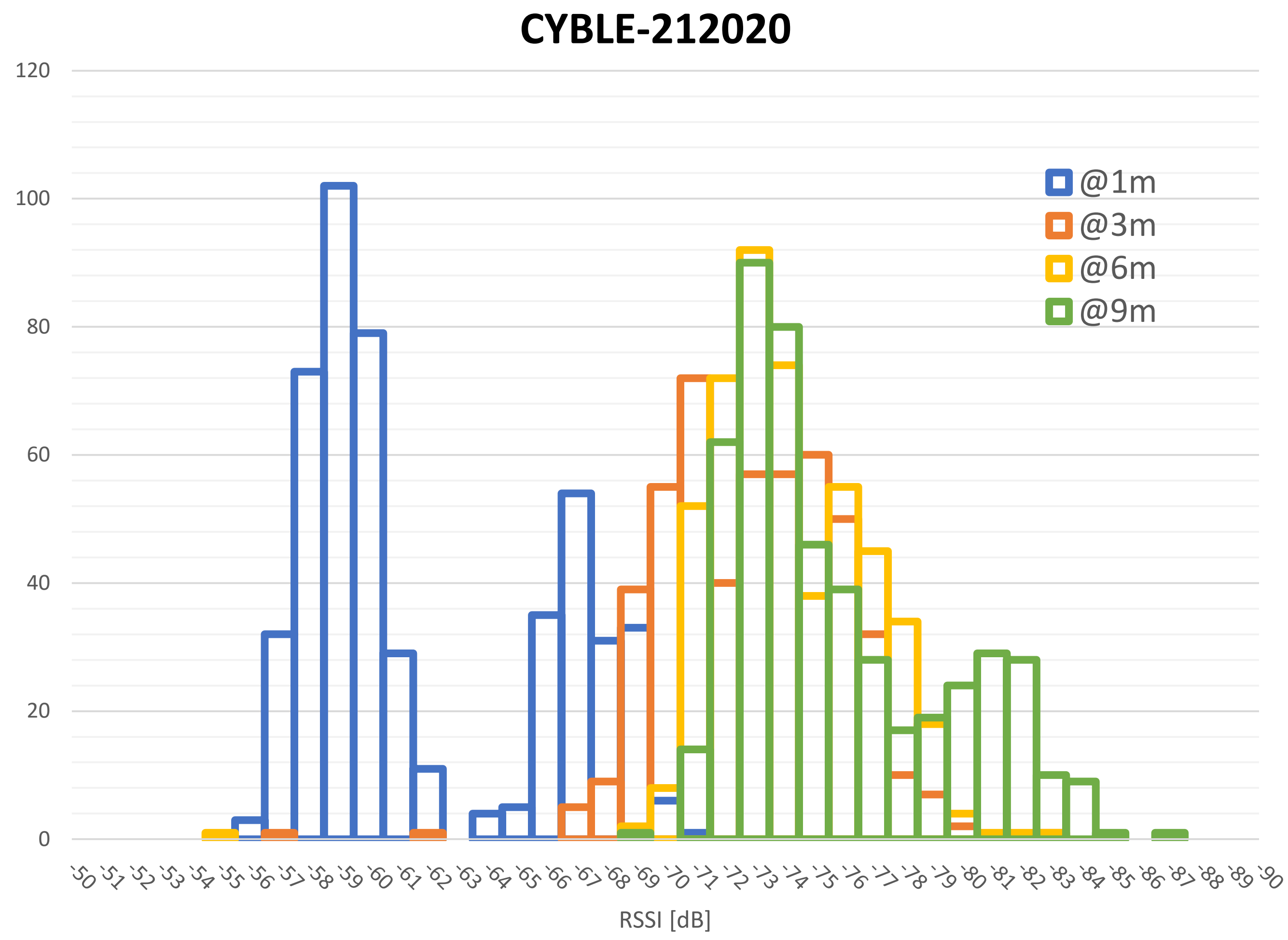
400 uF capacitor

1 transmission every 5s

Wireless BLE node

Output Power: 3 dBm
Sensitivity: - 91 dBm
Frequency: 2.4 GHz
Height: 0.75 mm
Length: 19.2 mm

4.1.1 An example of data



4.2 Application insight: SHM for bridges and wind turbines

- SHM is performed to **prevent** catastrophic events and manage maintenance

- Two different kind of monitoring

  - **Static**: inclination of the structure and its variation Resolution in commercial products from 0.1° to 0.01°.

  - **Dynamic**: vibration frequencies and/or amplitudes and their variation, shocks. Sensitivity in commercial devices from 1mg to 1ug.

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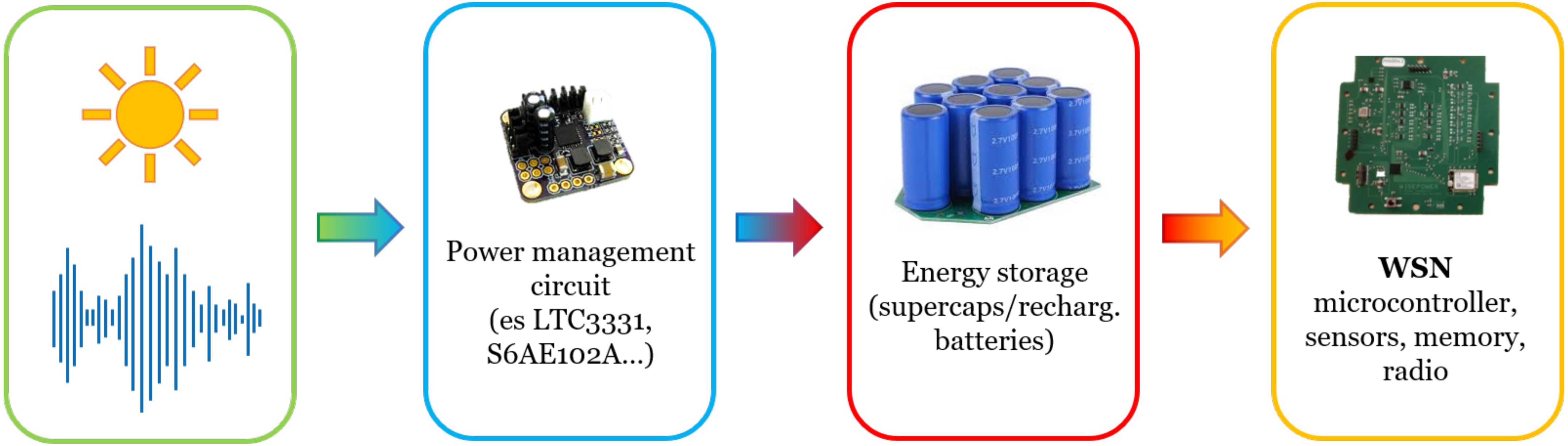
For static SHM the rms values of acceleration and inclinations are enough: a communication protocol like LoRa can be exploited. For dynamic SHM the time series are needed: a communication protocol that allows long/many transmissions has to be used (as ZigBee or Cellular)



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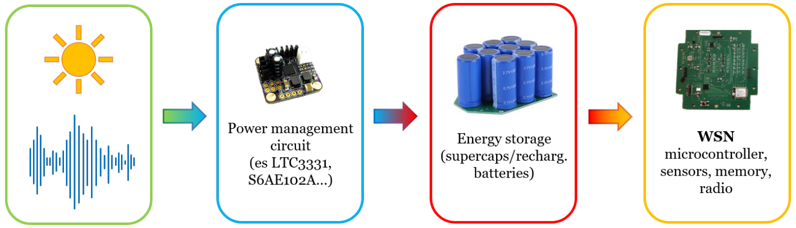
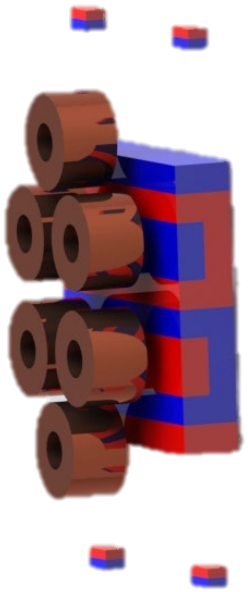
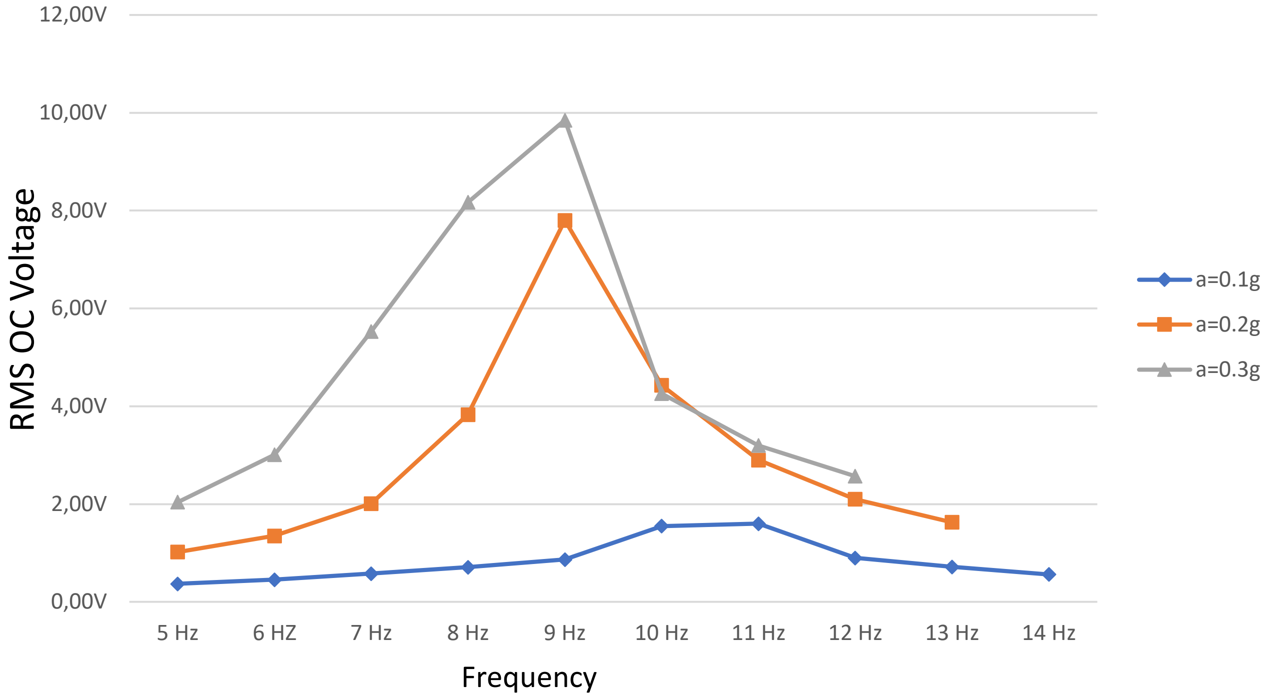
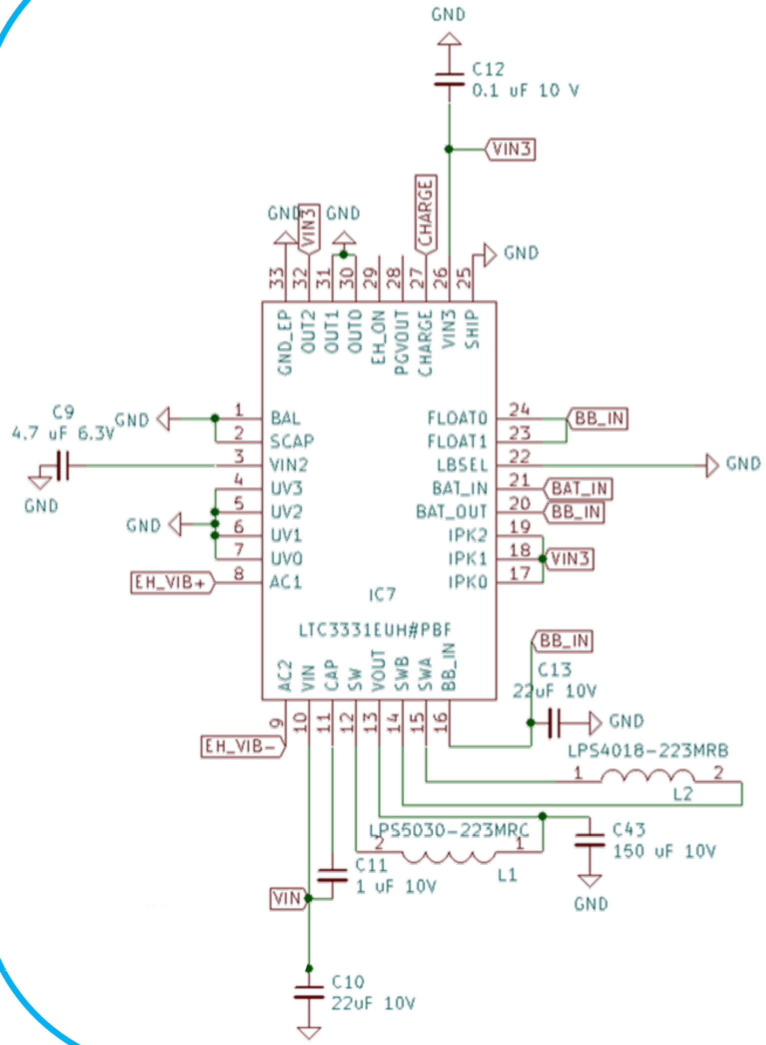
- •Open Circuit Voltage: 7.7V
- •Peak Voltage: 6.5V
- •Peak Current: 180mA
- •Peak Power: 1.2W

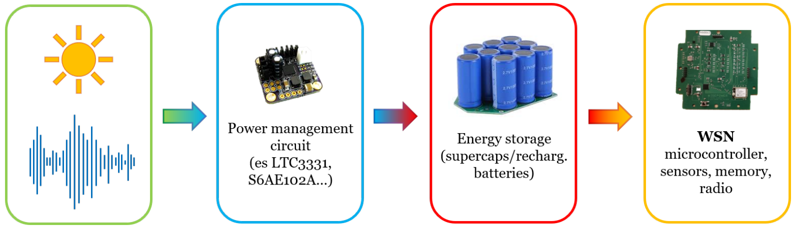






Harvesting

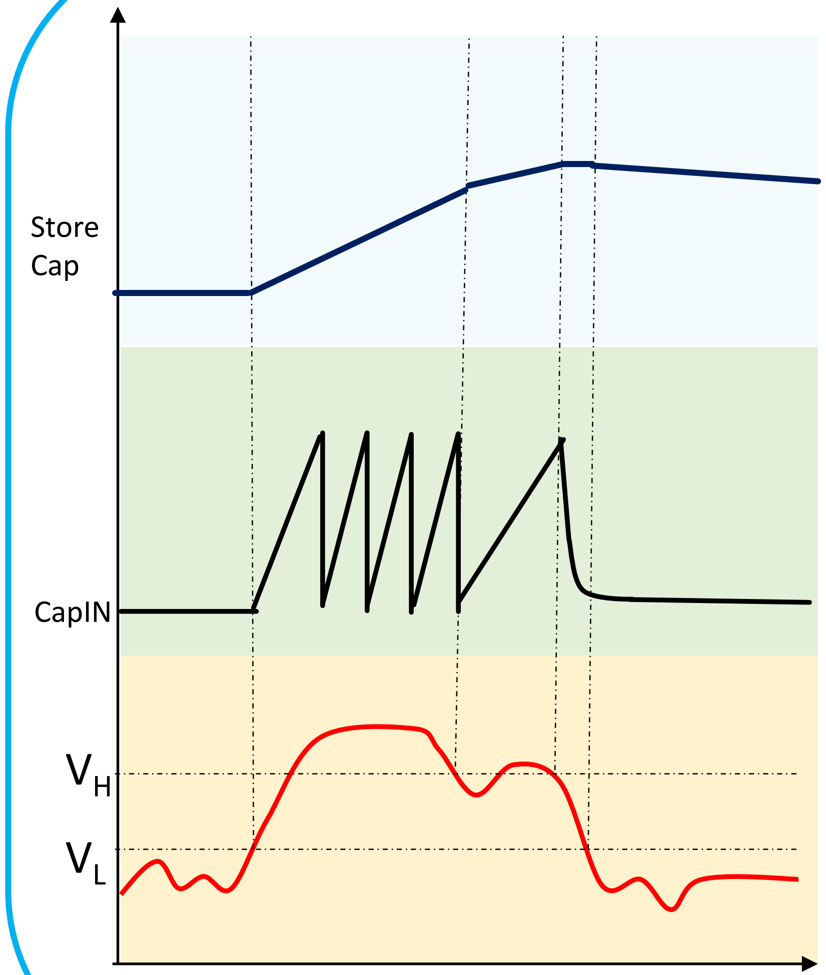


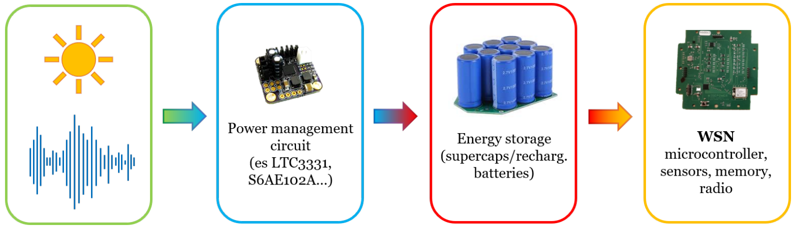


LTC3331 Buck-Boost voltage regulator

One of the (not so) many….

- Dual Input, Single Output DC/DCs with Input Prioritizer
- Energy Harvesting Input: 3.0V to 19V Buck DC/DC
- Battery Input: Up to 4.2V Buck-Boost DC/DC
- 10mA Shunt Battery Charger
- Low Battery Disconnect
- Quiescent Current: 950nA at no Load
- Max output Current: 50mA
- Integrated Low-Loss Full-Wave Bridge Rectifier





LTC3331 Buck-Boost voltage regulator

One of the (not so) many....

- Dual Input, Single Output DC/DCs with Input Prioritizer
- Energy Harvesting Input: 3.0V to 19V Buck DC/DC
- Battery Input: Up to 4.2V Buck-Boost DC/DC
- 10mA Shunt Battery Charger
- Low Battery Disconnect
- Quiescent Current: 950nA at no Load
- Max output Current: 50mA
- Integrated Low-Loss Full-Wave Bridge Rectifier

The store capacitor is charged up to the desired output voltage. When charged, on the input capacitor there is a constant voltage (rectified input) and no more energy is transferred.

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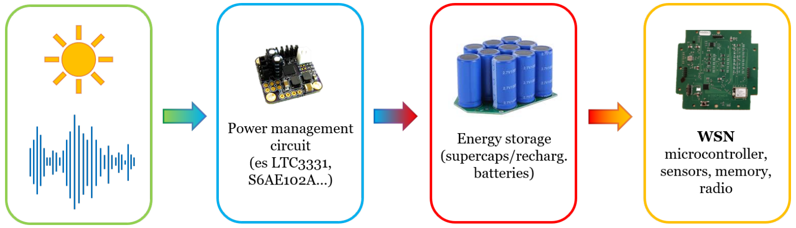
Energy storage



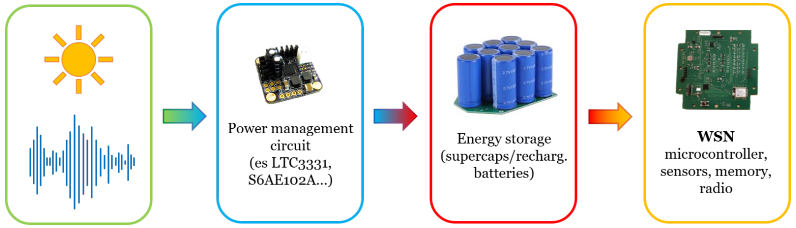
Nominal Voltage	3.7V
Capacity	2.6Ah
Chemistry	Lithium-Ion
Size	19 (Dia.) x 69 mm
Operating Temperature Range	-20 → +60°C
Number of Cells	1

- Using a rechargeable Li-Ion battery is **equivalent to using a super-cap**
- Higher stored energy with **lower dimensions**
- Batteries have a **finite** number of charge-decharge cycles. Super-caps do not

- SHM accelerometer
  - Sleep mode: 21uA -> 69.3uW
  - Active mode: 200uA -> 0.66mW
  - Noise density (all axes): 20 µg/√Hz
  - Max sensitivity: 400mV/g

- Shock accelerometer
  - Stanby mode: 10nA -> 33nW
  - Motion wake-up mode: 270nA -> 89.1uW
  - noise density: 175 µg/√Hz
  - Max sensitivity: 1 mg/LSB

- Temperature and Humidity sensor
  - Sleep mode: 100nA -> 330nW
  - Measurement: 1.3uA -> 4.29uW
  - Realtive humidity accuracy: 2%
  - Temperature accuracy: ±0.2°C



Wireless sensor node

- Zigbee Module
  - Transmission: 40 mA at 8 dBm -> 132mW
  - Receive: 17 mA -> 56mw
  - Sleep 2 uA

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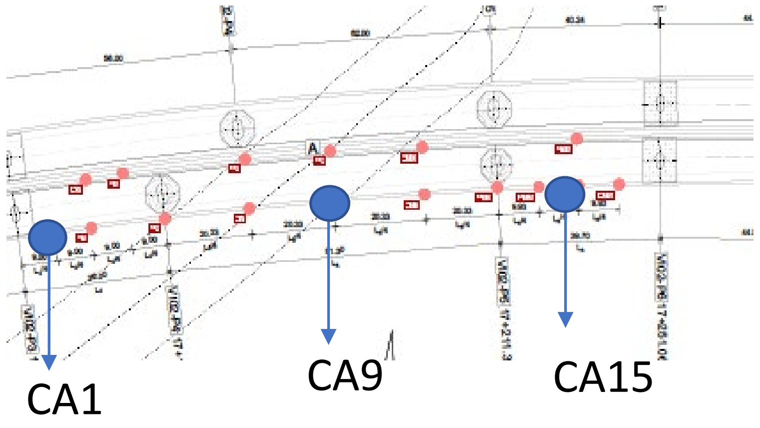
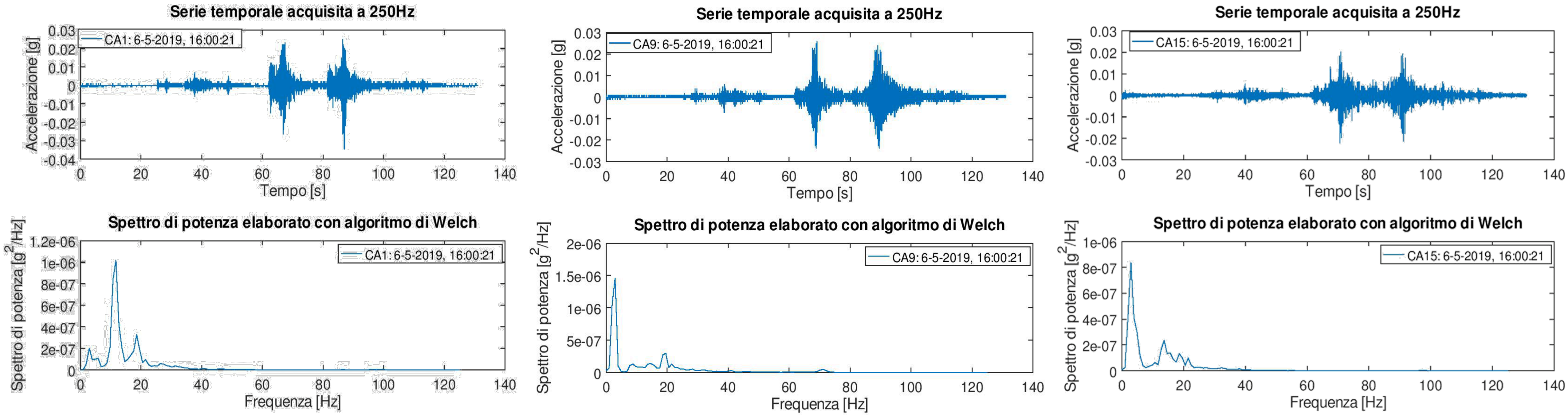
4.2.1 An example of data





4.3 Application insight: monitoring of high-voltage cables

- SHM is performed to check the **quality** of the current transmission (frequency, intensity), and to monitor the **structural parameters** in order to allow maintenance.

- Parameters monitored:
  - **Inclination** of the cable and its variation. High temperature, or to ice forming on the cable lowers it, sometimes leading to breakdowns.
  - **Shocks and 3-axis rms acceleration**: sudden hits on the cables or high wind.
  - **Magnetic field in cable's proximity**: it allows to calculate electromagnetic pollution at ground level
  - **Intensity of the current**: from magnetic field
  - **Temperature and humidity**: to be used in combination with inclination

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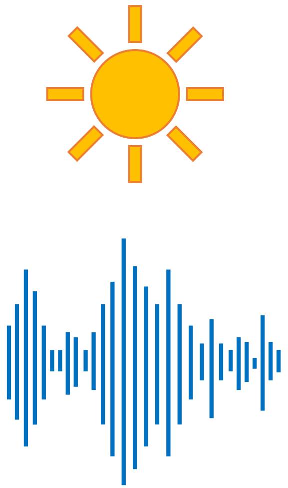
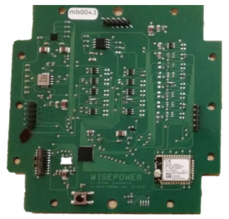
Solar is optional



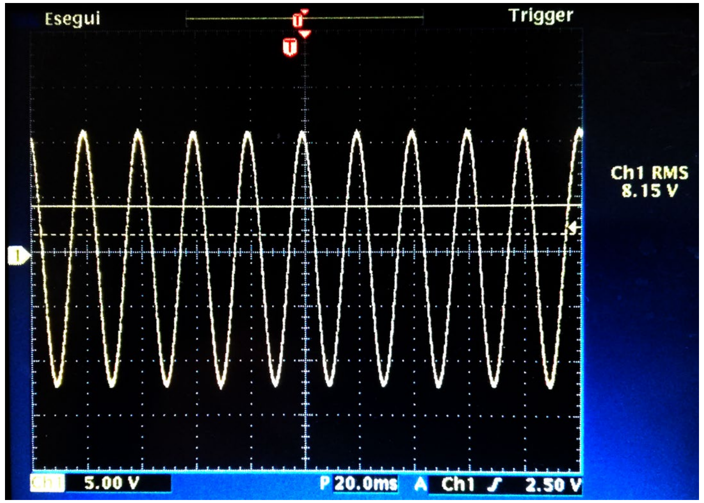
Same as SHM

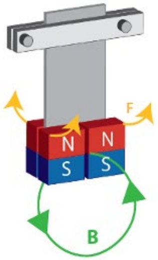
Power management circuit
(es LTC3331, S6AE102A…)

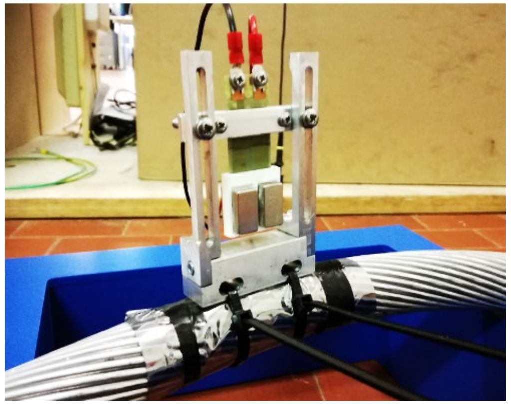
Energy storage
(supercaps/recharg. batteries)

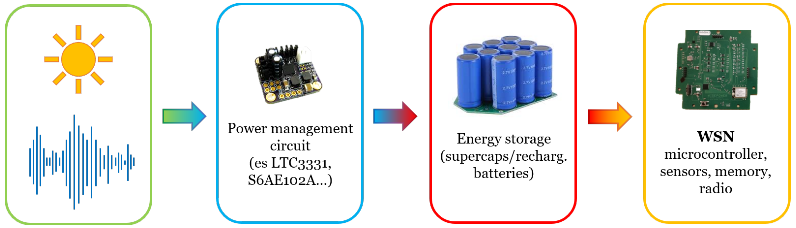


WSN
microcontroller, sensors, memory, radio









- The oscillation of the magnetic field can be converted to oscillation of a piezoelectric cantilever by exoploiting magnets in different configurations.
- The oscillation is at a very **stable frequency**: linear harvesters can be exploited
- Using a double conversion **B -> dx -> dV** helps decoupling the converted energy from the current on the cable: a cantilever is a pass-band filter!
- Solar can be added to extend operation during power outages.

Harvesting