Design flow for energy harvesting enabled devices

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Index

- What's System Integration?
- Why Energy Harvesting?
- Sources of energy
- Powering issues
- Mechanical design
- An examples of integrated system

What's system integration?

Not

Article | Talk | Read | Edit | View his

WIKIPEDIA
The Free Encyclopedia

- Main page
- Contents
- Featured content
- Current events
- Random article
- Donate to Wikipedia
- Wikipedia store

Interaction

- Help
- About Wikipedia
- Community portal
- Recent changes
- Contact page

Tools

- What links here

System integration

From Wikipedia, the free encyclopedia

System integration is defined in engineering as the process of bringing together the component sub-systems into one system (an aggregation of subsystems cooperating so that the system is able to deliver the overarching functionality) and ensuring that the subsystems function together as a system,[1] and in information technology[2] as the process of linking together different computing systems and software applications physically or functionally,[3] to act as a coordinated whole.

The system integrator integrates discrete systems utilizing a variety of techniques such as computer networking, enterprise application integration, business process management or manual programming.[4]

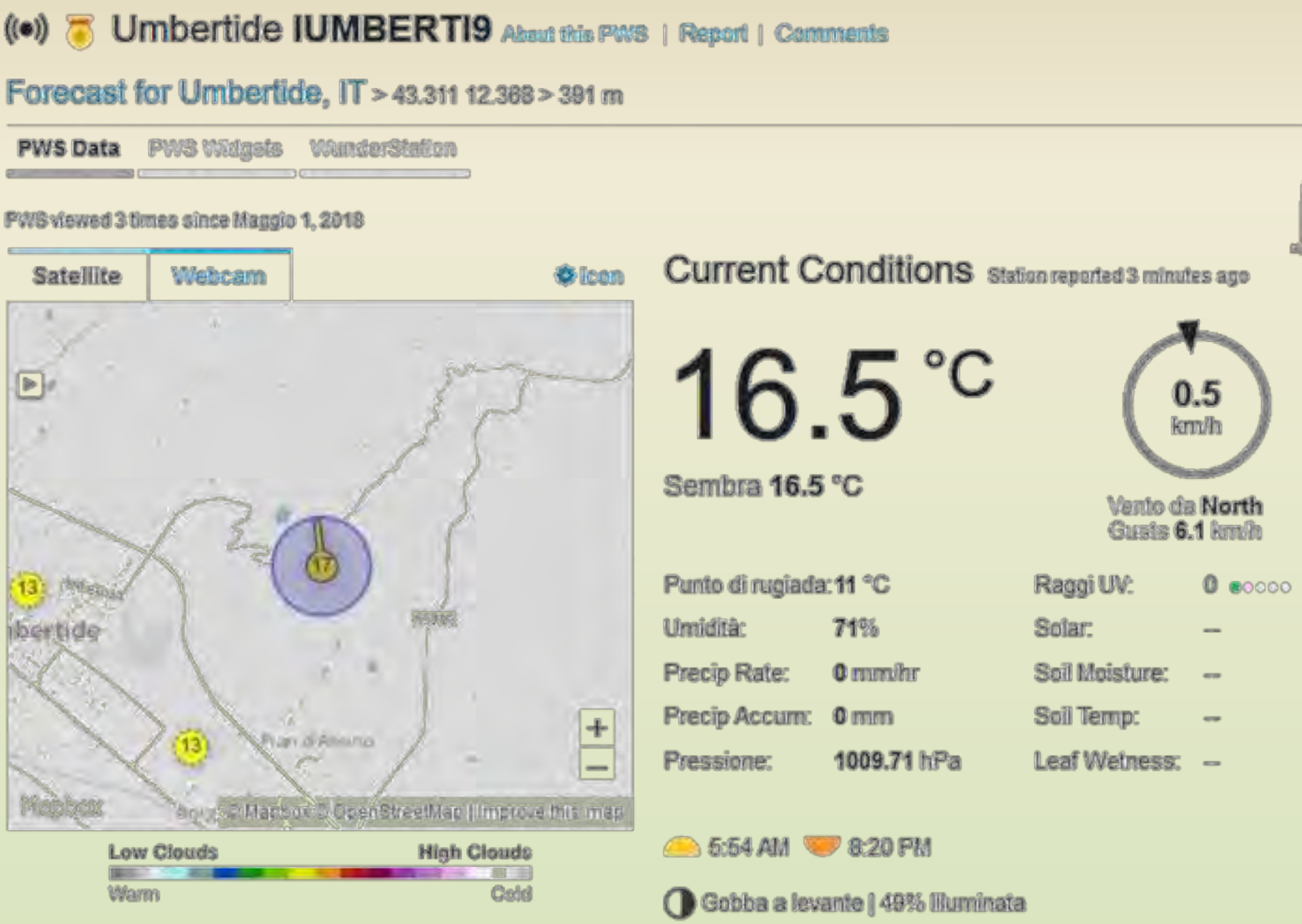
System integration involves integrating existing, often disparate systems in such a way "that focuses on increasing value to the customer"[5] (e.g., improved product quality and performance) while at the same time providing value to the company (e.g., reducing operational costs and improving response time).[5] In the modern world connected by Internet, the role of system integration engineers is important: more and more systems are designed to connect, both within the system under construction and to systems that are already deployed.[6]

What's system integration?

Ex. 1: fitness tracker

What's system integration?

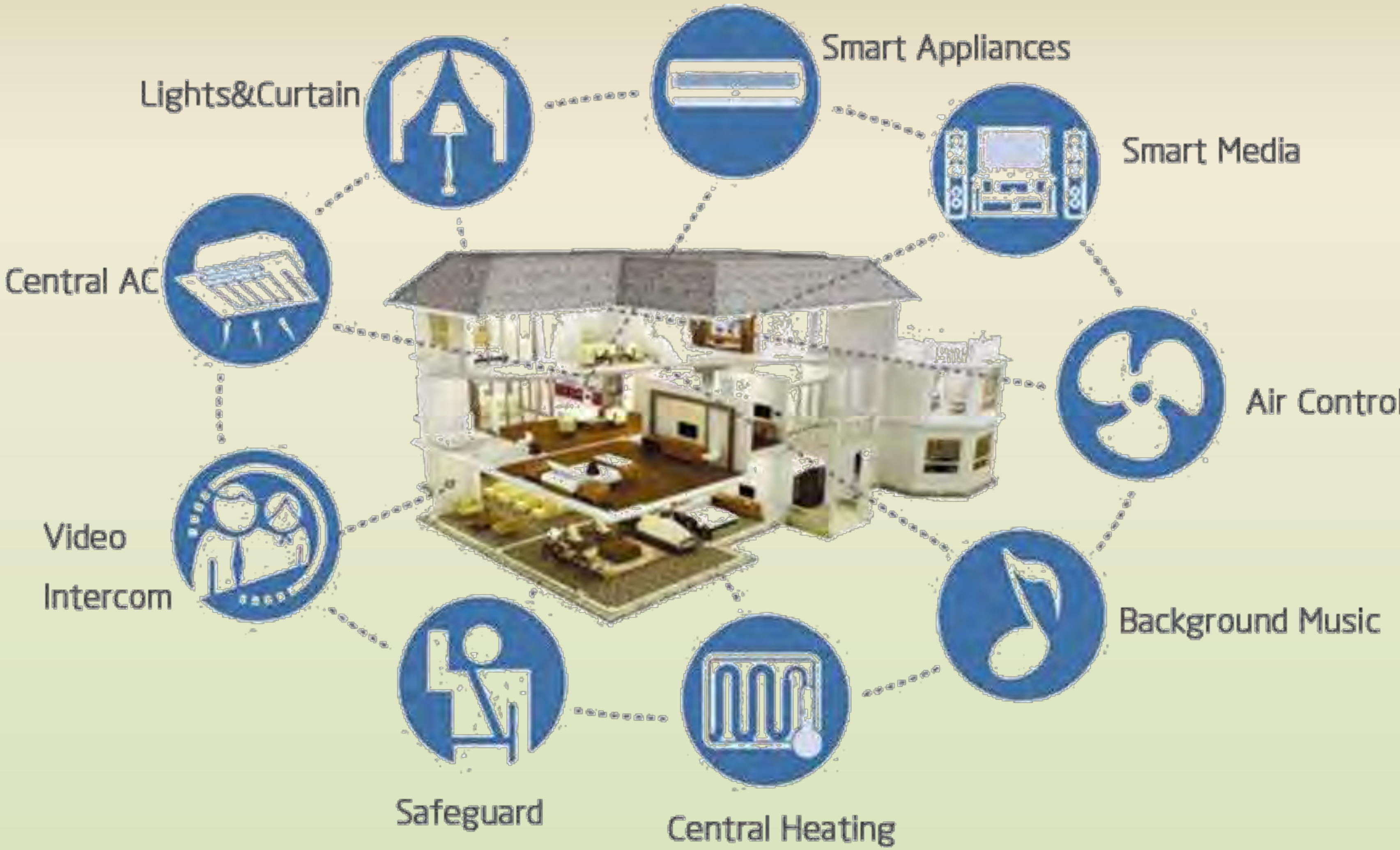
Ex. 2: weather station - sensors



https://www.wunderground.com/personal-weather-station/dashboard?ID=IUMBERTI9

What's system integration?

Ex. 3: smart homes

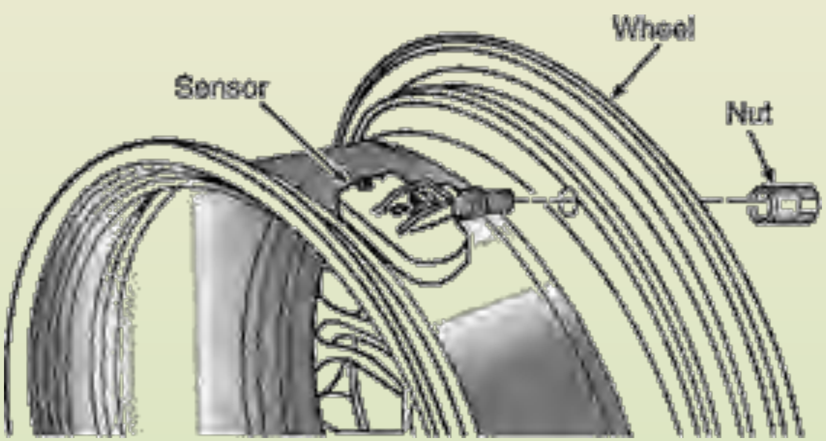


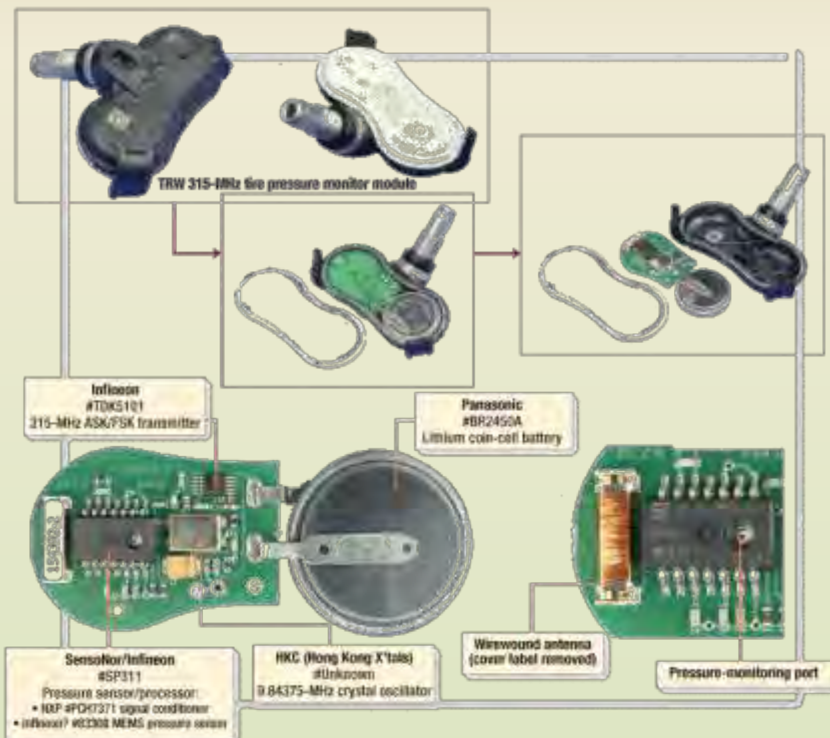
Index

- What's System Integration?
- Why Energy Harvesting?
- Sources of energy
- Powering issues
- Mechanical design
- An examples of integrated system

Why Energy Harvesting?

Ex. 1: tyre pressure monitoring





Why Energy Harvesting?

Ex. 2: extended structures monitoring

Golden Gate Bridge, San Francisco, California, USA
Total length: 8.981 ft (2,737.4 m)
Height: 746 ft (227.4 m)

Why Energy Harvesting?

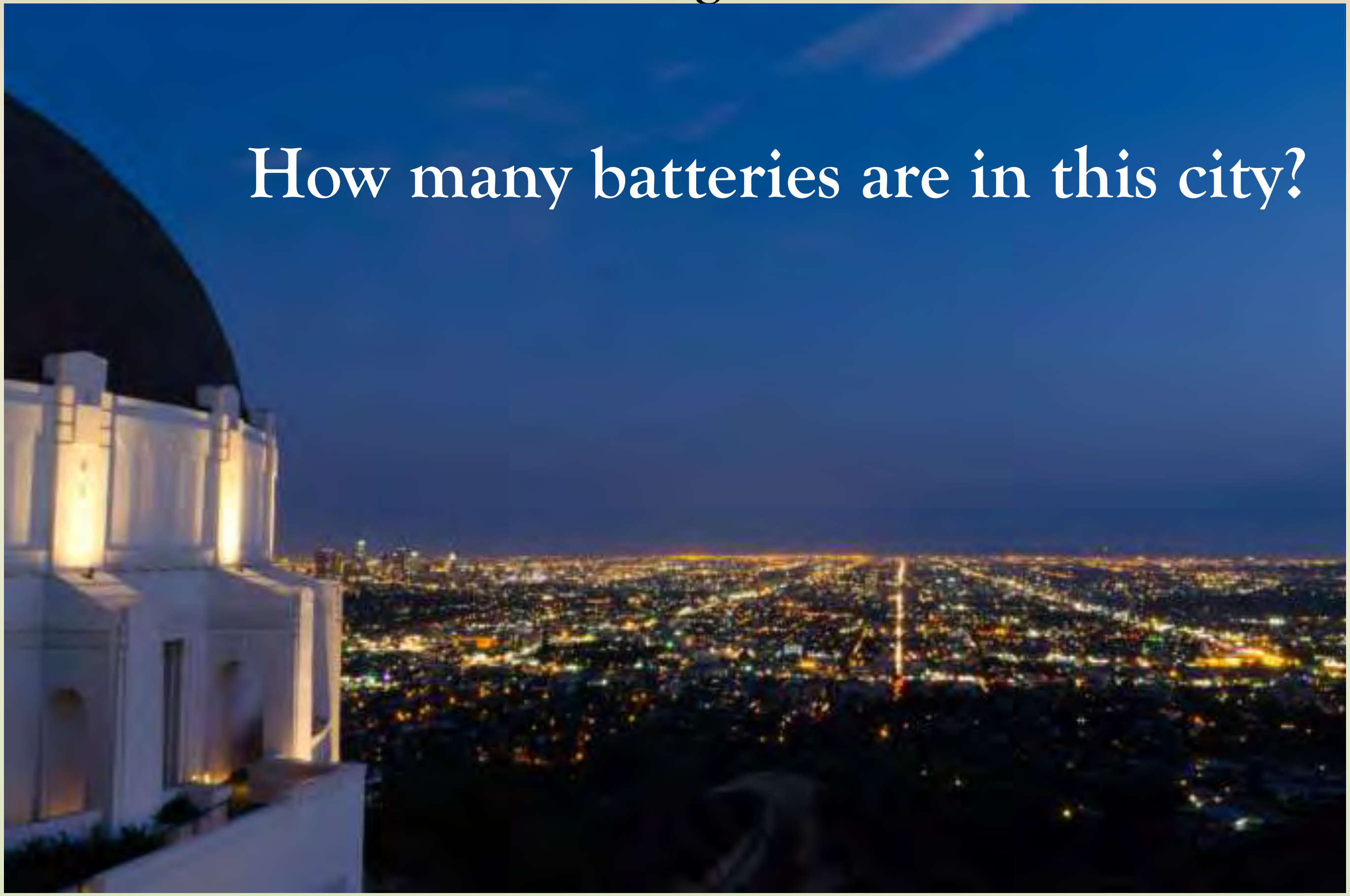
Ex. 3: large open and wild area

Point Reyes National Seashore, California, USA

Area: 111 mi^2 (71,028 acres - 287.44 km^2)[

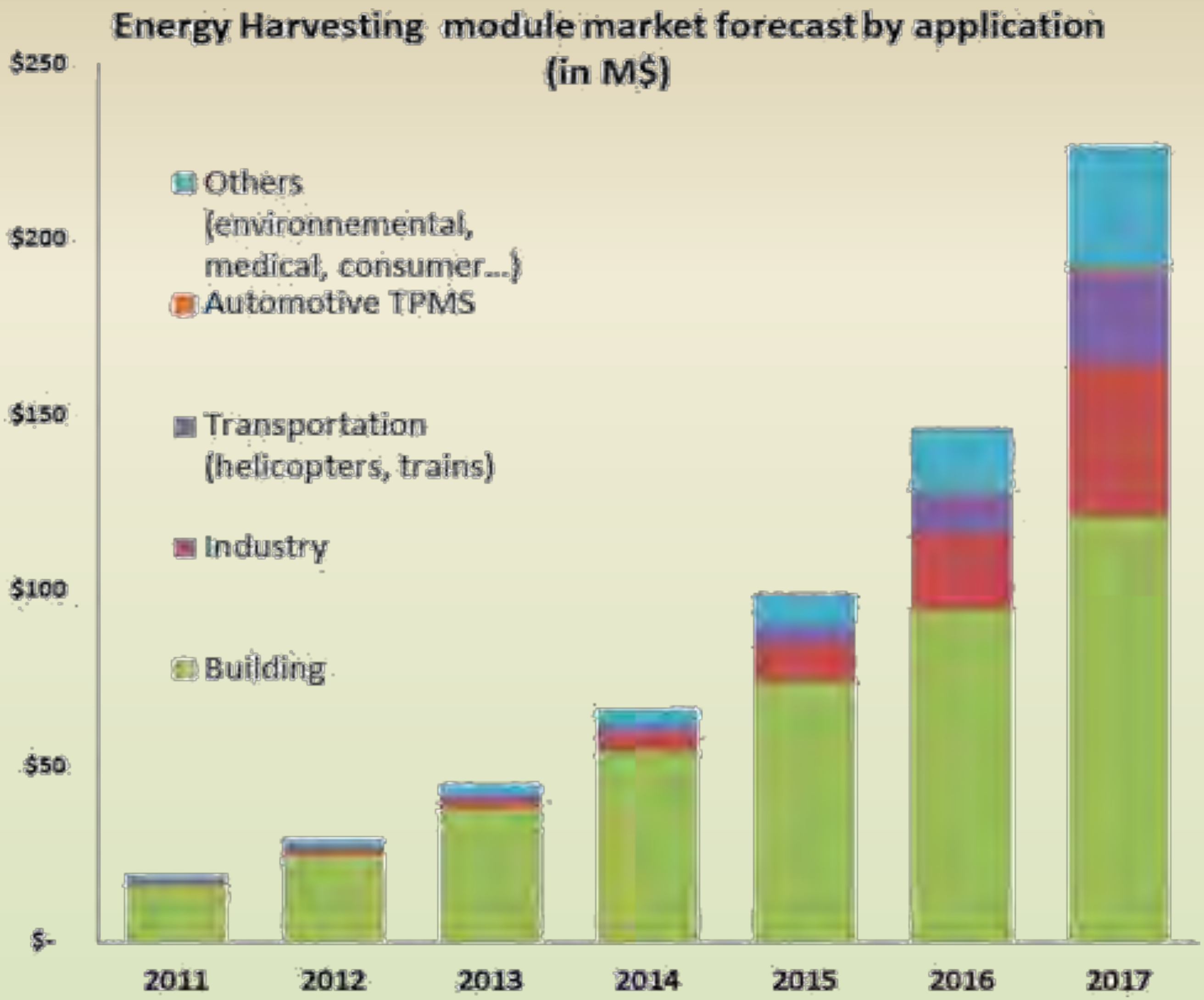
Why Energy Harvesting?

Ex. 4: big cities



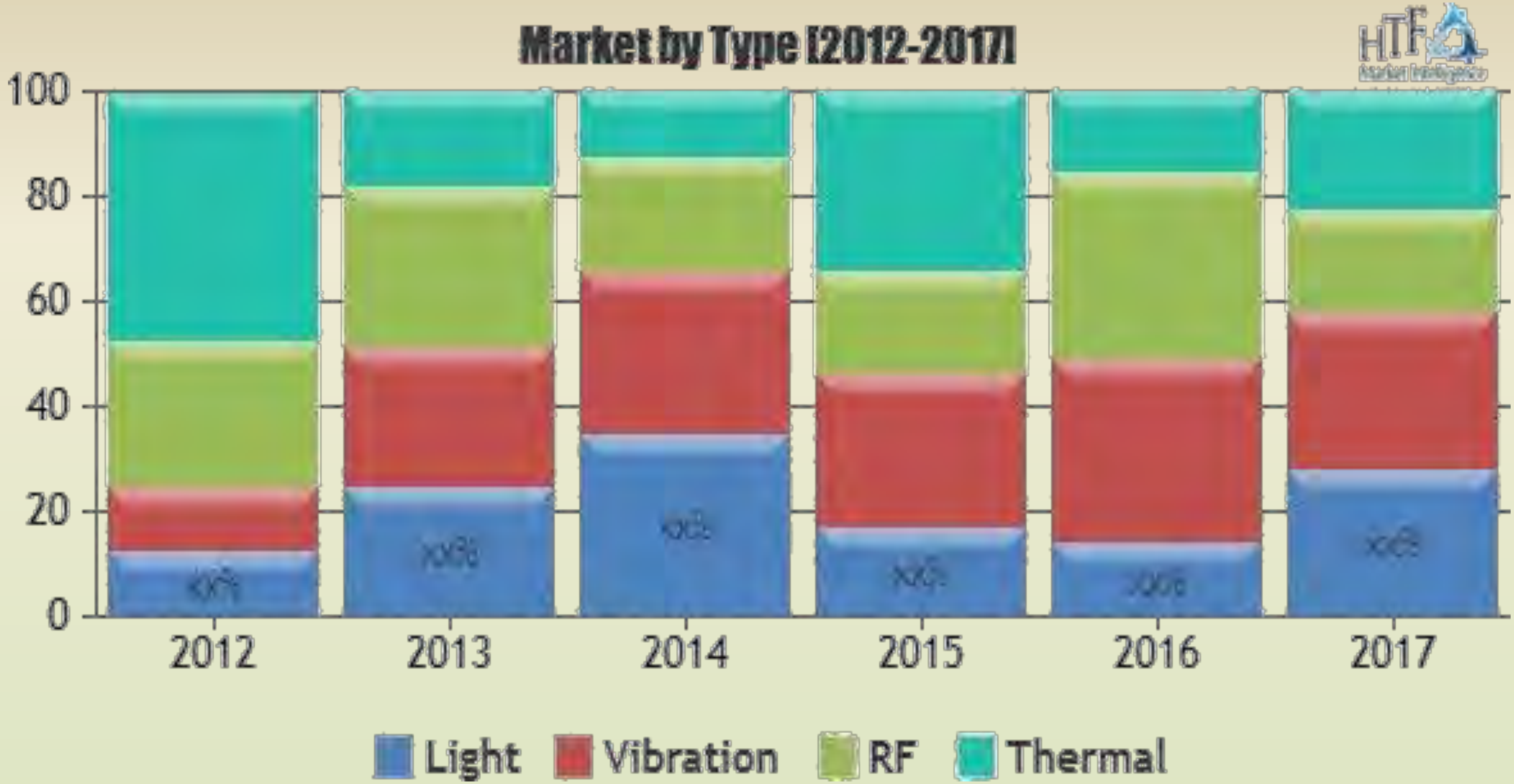
Los Angeles, California, USA
Area: 503 mi^2 (1302 km^2) - Population (2015) 18,679,763

Why Energy Harvesting?



https://www.i-micronews.com/category-listing/product/emerging-energy-harvesting-devices.html

Why Energy Harvesting?



https://industrytoday.co.uk/agriculture/energy-harvesting-system-market-demand--growth-factors--latest-rising-trend---forecast-to-2025

https://www.i-micronews.com/category-listing/product/emerging-energy-harvesting-devices.html

Index

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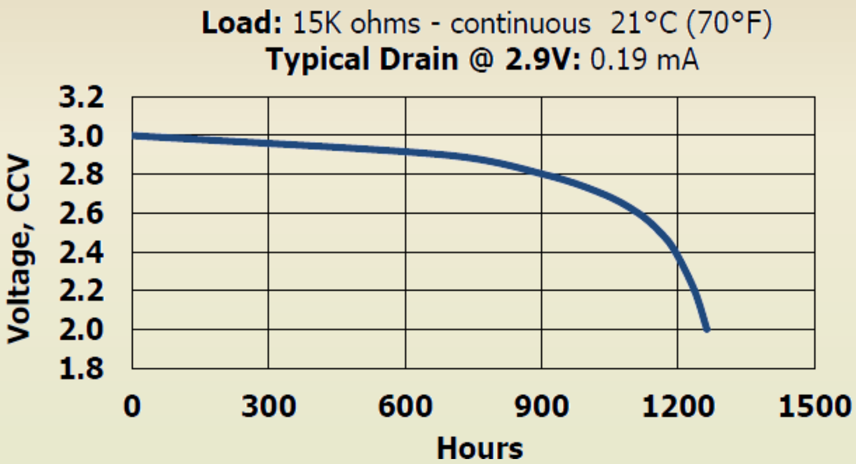
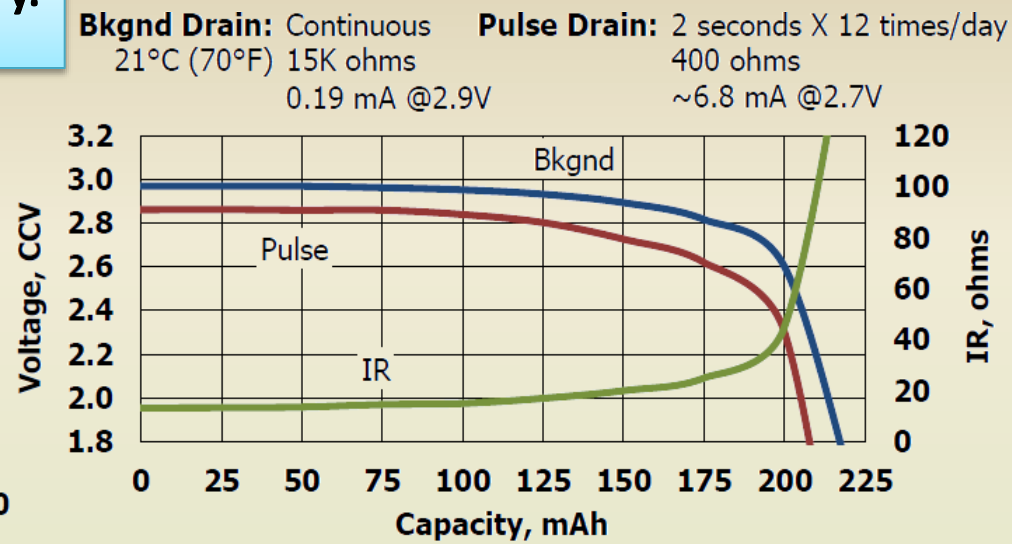
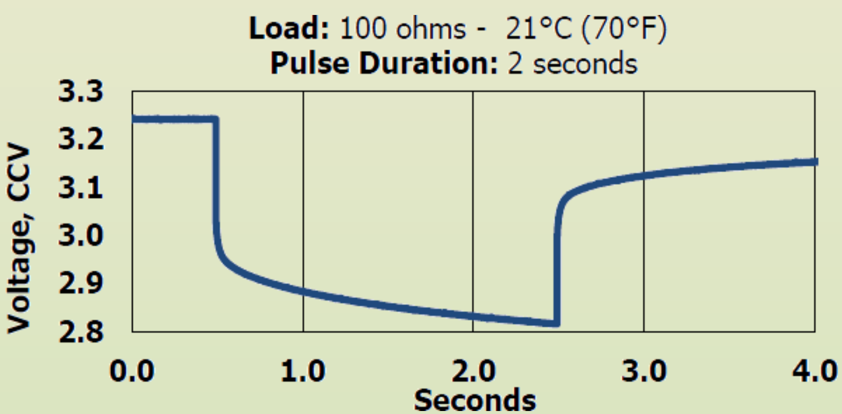
- Why Energy Harvesting?
- Sources of energy
- Powering issues
- Mechanical design
- An example of integrated system

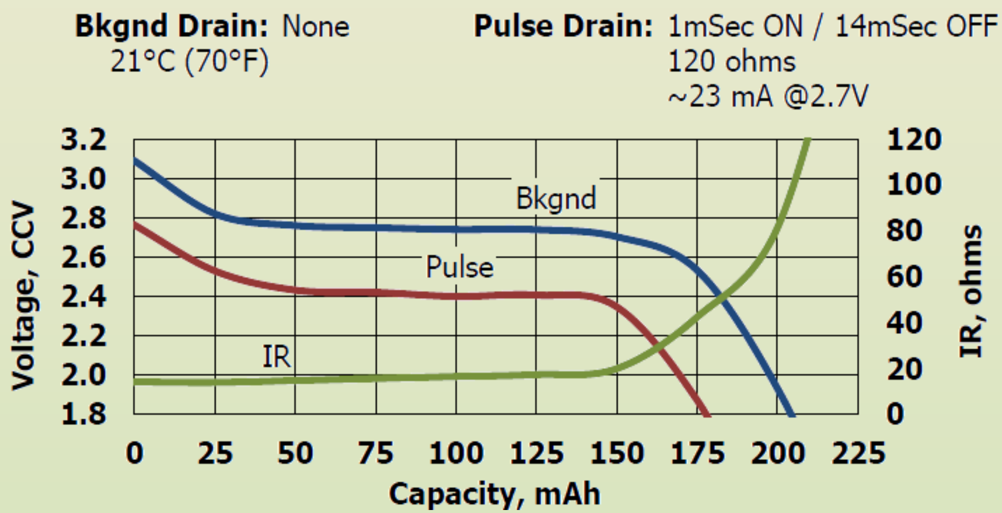
Sources of energy

Discharge characteristic of a CR2032 battery.
(from ENERGIZER CR2032 datasheet)

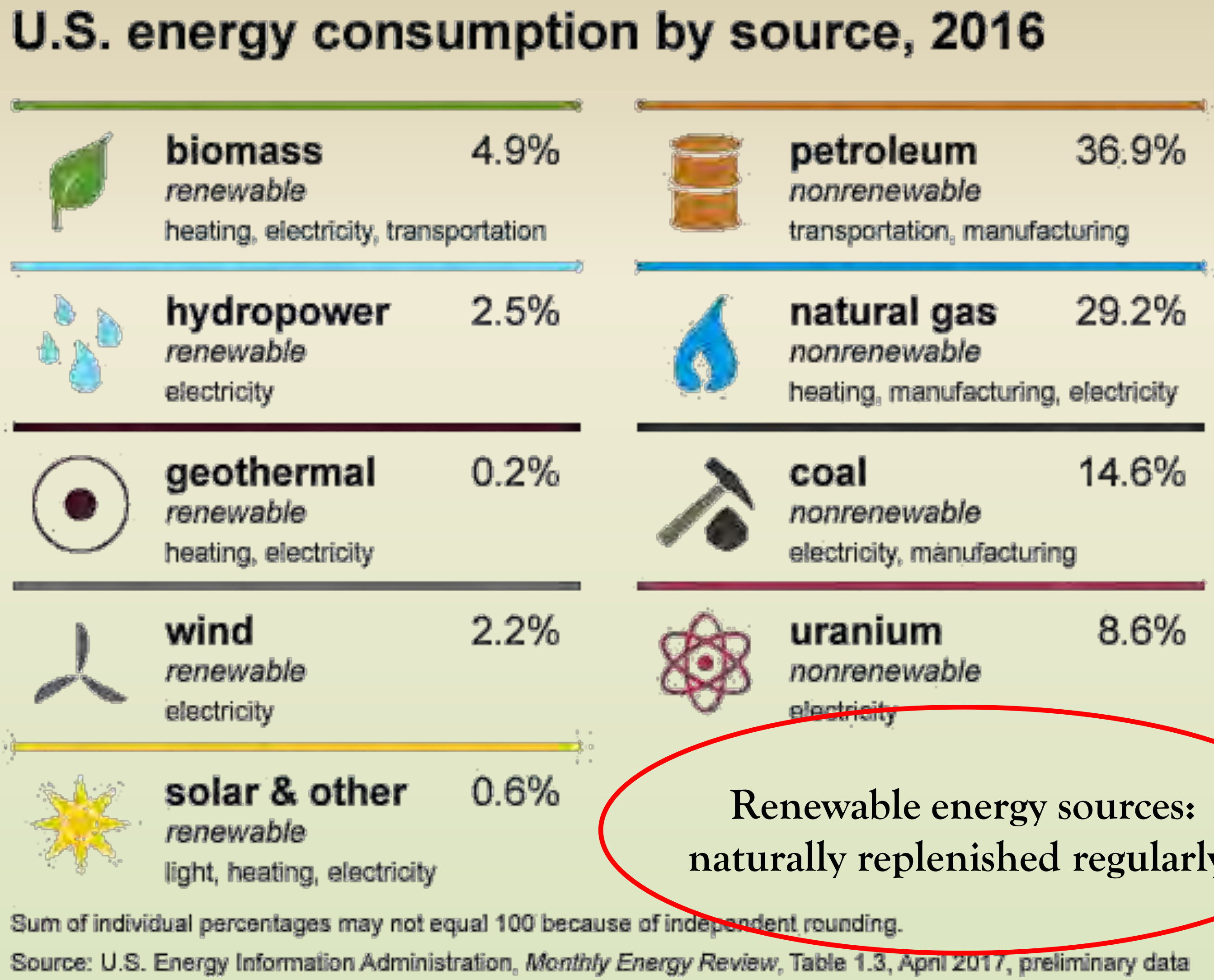








Sources of energy



Renewable energy sources: naturally replenished regularly!

https://www.eia.gov/energyexplained/index.php?page=about_sources_of_energy

Sources of energy

What about EH sources?

Energy Source	Challenge	Typical Electrical Impedance	Typical Voltage	Typical Power Output
Light 	Conform to small surface area; wide input voltage range	*Varies with light input* *Low kΩ to 10s of kΩ*	*DC: 0.5V to 5V [Depends on number of cells in array]*	10µW-15mW (Outdoors: 0.15mW-15mW) (Indoors: <500µW)
Vibrational 	Variability of vibrational frequency	*Constant impedance* *10s of kΩ to 100kΩ*	*AC: 10s of volts*	1µW-20mW
Thermal 	Small thermal gradients; efficient heat sinking	*Constant impedance* *1Ω to 100s of Ω*	*DC: 10s of mV to 10V*	0.5mW-10mW (20°C gradient)
RF & Inductive 	Coupling & rectification	*Constant impedance* *Low kΩs*	*AC: Varies with distance and power* *0.5V to 5V*	Wide range

Sources of energy

- **Typical Energy Harvester Output Power**
  - RF: 0.1µW/cm²
  - Vibration: 1nW/cm²
  - Thermal: 10mW/cm²
  - Photovoltaic: 100mW/cm²

- **Typical Energy Harvester Voltages**
  - RF: 0.01mV
  - Vibration: 0.1 ~ 0.4 V
  - Thermal: 0.02 ~ 1.0 V
  - Photovoltaic: 0.5 ~ 0.7 V typ./cell

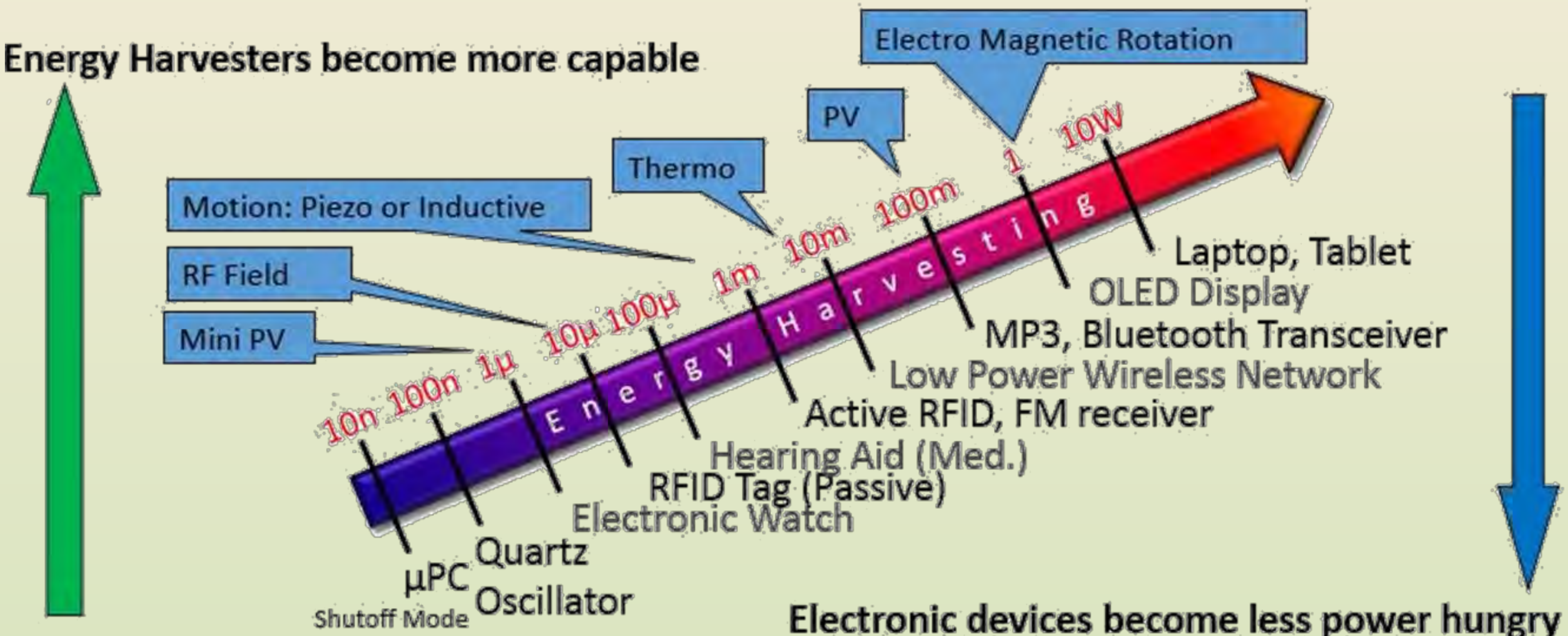
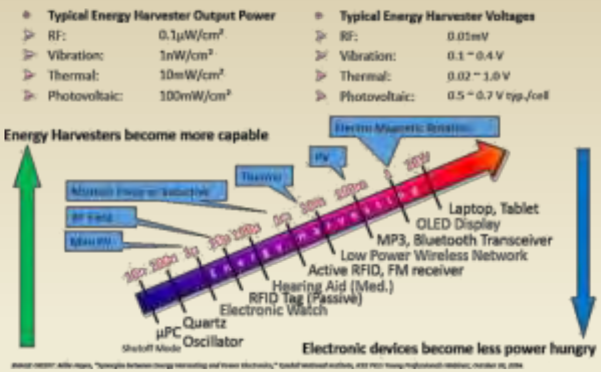
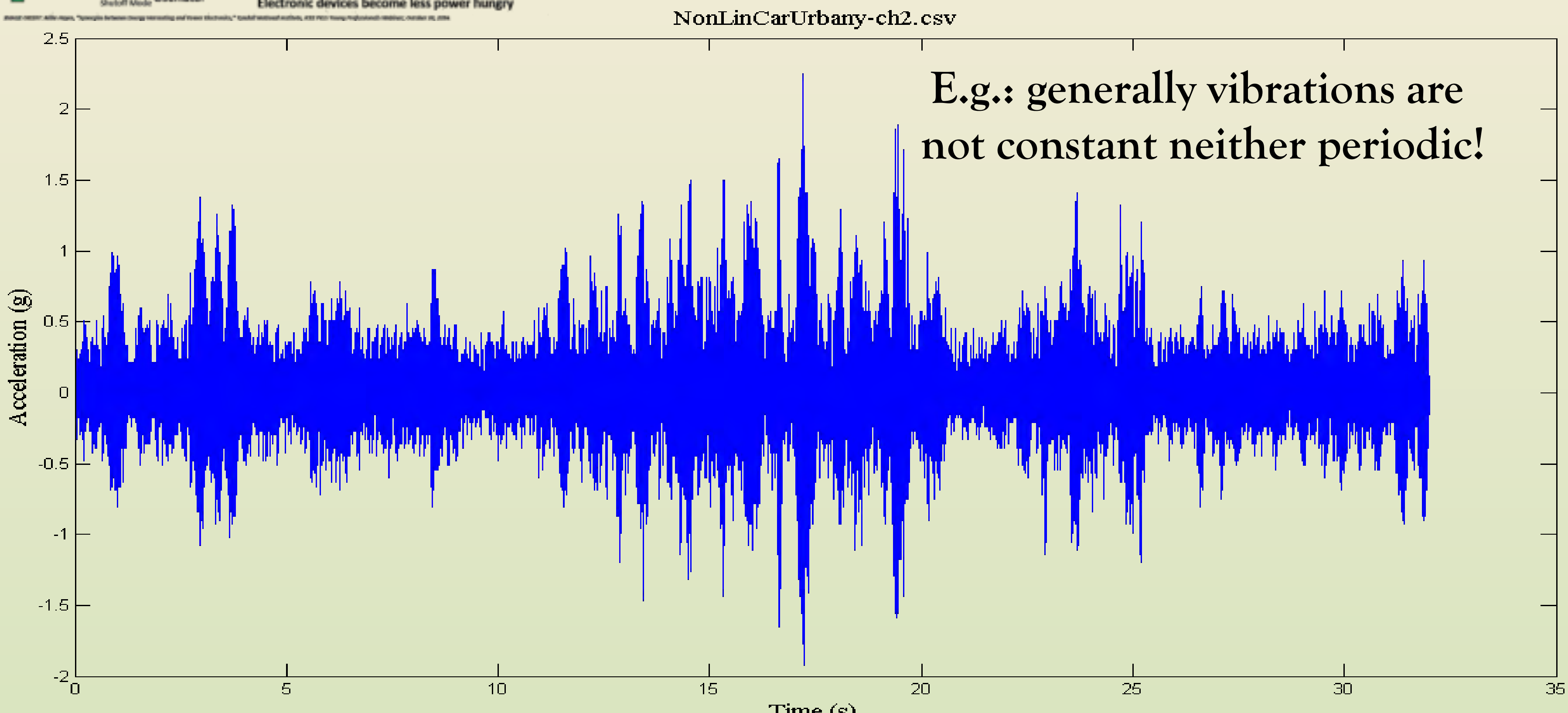


IMAGE CREDIT: Mike Hayes, "Synergies between Energy Harvesting and Power Electronics," Tyndall National Institute, IEEE PELS Young Professionals Webinar, October 20, 2016.

Sources of energy



Are these sources constant in time?

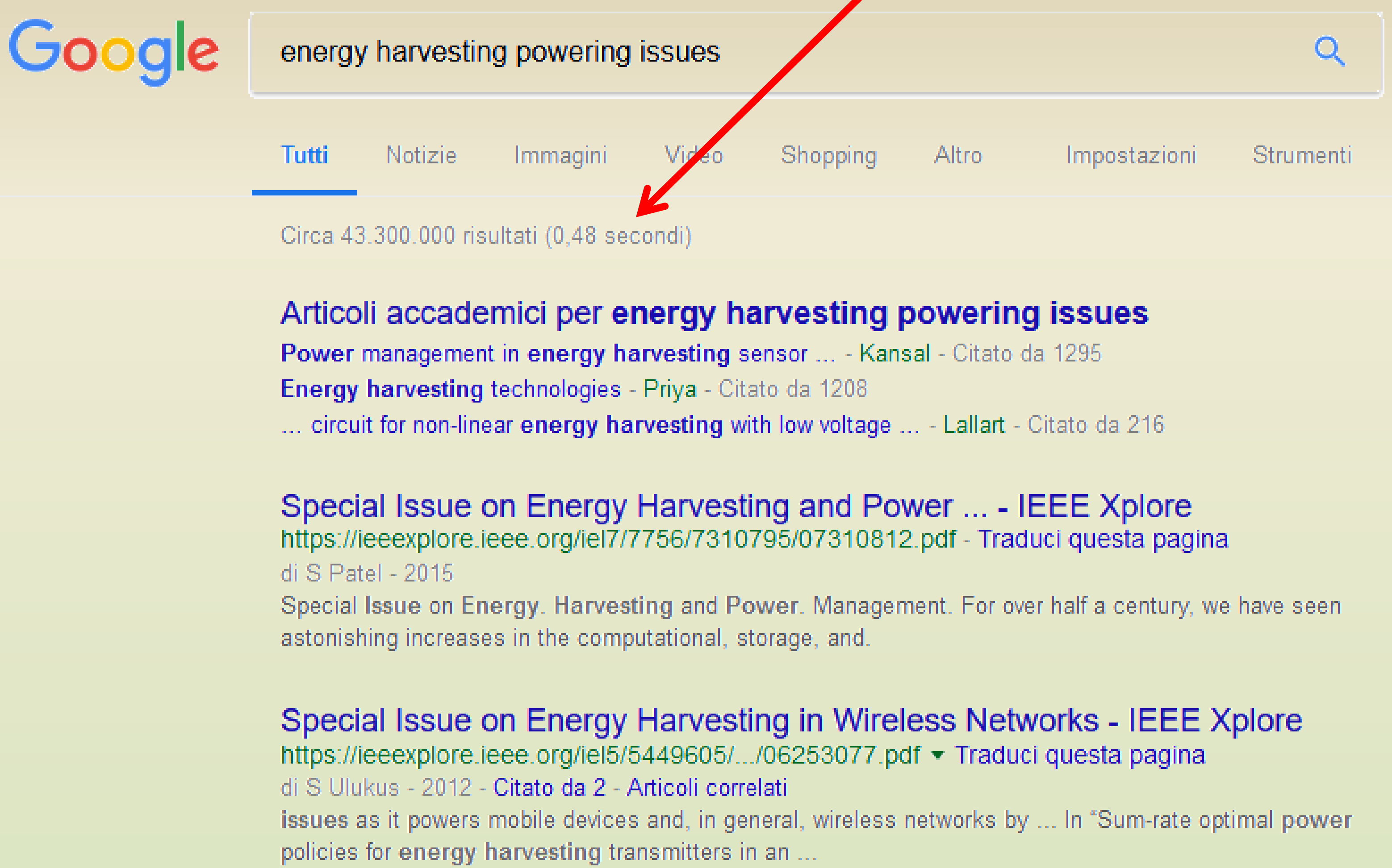


Index

- What's IoT – Internet of Things?
- Why Energy Harvesting?
- Sources of energy
- Powering issues
- Power management
- An example from the market

Powering issues

43.300.000 pages!!!



Powering issues

Power requirements for different RF technologies.

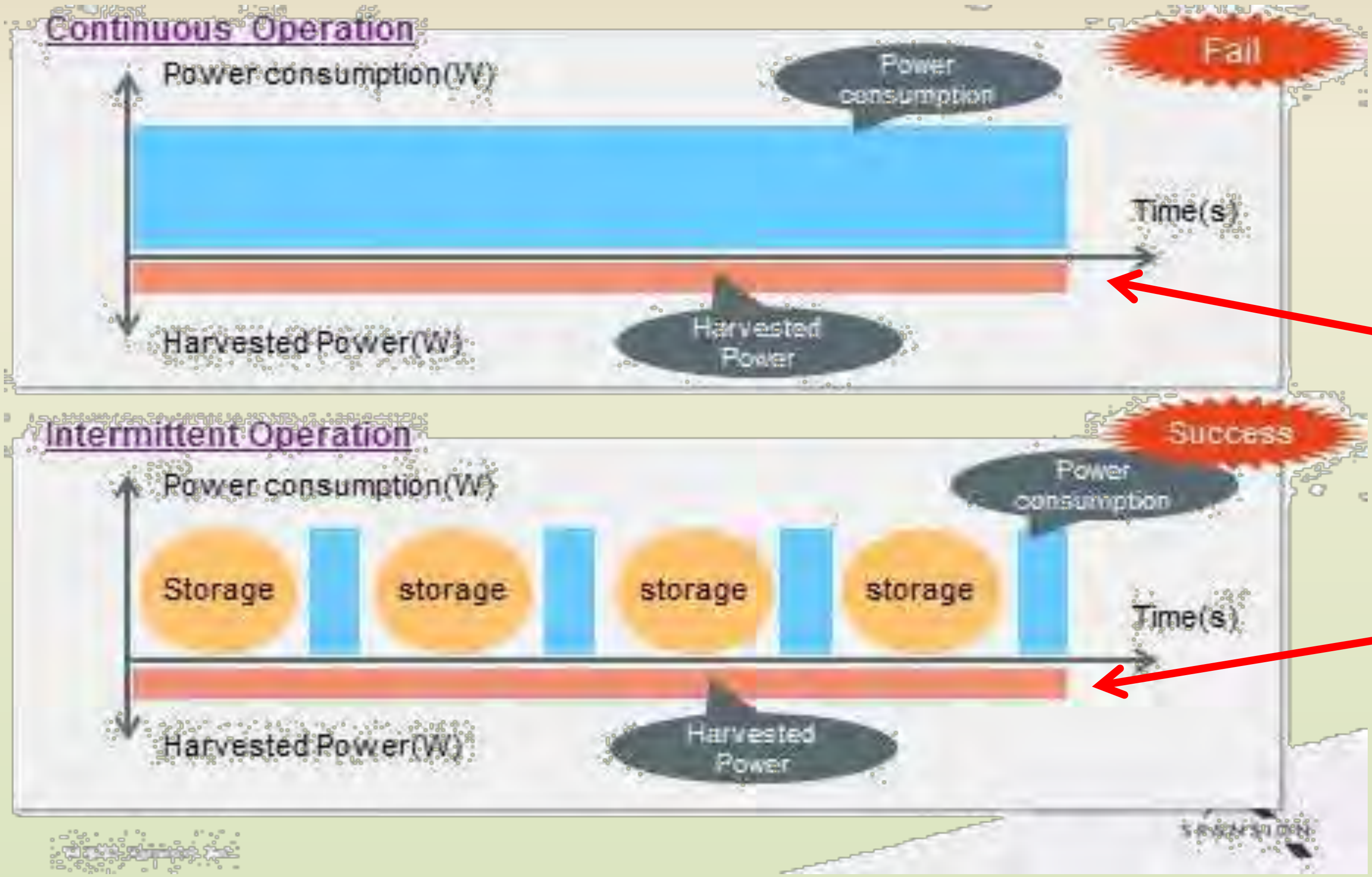
	EnOcean	Z-Wave	ZigBee	Wireless Hart	Bluetooth LE	Bluetooth	Wi-Fi
Industry Organizations	EnOcean Alliance	Z-Wave Alliance	ZigBee Alliance	HART	Bluetooth SIG	Bluetooth SIG	Wi-Fi Alliance
Frequency Band	315MHz, 868MHz, 900MHz, 920MHz	900MHz	868MHz, 915MHz, 2.4GHz	2.4GHz	2.4GHz	2.4GHz	2.4GHz,5.8GHz
Data Rate	Low	Low	Low	Low	Medium	High	Very High
Range (Depends on RF power)	~50m,~300m	~30m	~100m	~250m	~50m	~100m	~100m
Power Consumption	Very Low	Medium	Very Low	Very Low	Very Low	Low	High
Application	HEMS, BEMS	Sensor NW, HEMS	Sensor NW, HEMS,BEMS, Factory Automation	Factory Automation	NotePC, Smart Phone, Wearable, Medical, Sensor NW, HEMS, BEMS	NotePC, Smart Phone, PC peripheral	PC, Smart Phone, Digital AV, Indoor/Outdoor NW
Suitable for Energy Harvesting?	Very Good	Good	Very Good	Very Good	Very Good	Not Bad	Bad

HEMS : Home Energy Management System BEMS : Building Energy Management System

http://core.spansion.com/article/energy-harvesting-devices-replace-batteries-in-iot-sensors/#.WvKtApdx202

Powering issues

1st: reduce the power required by your application!

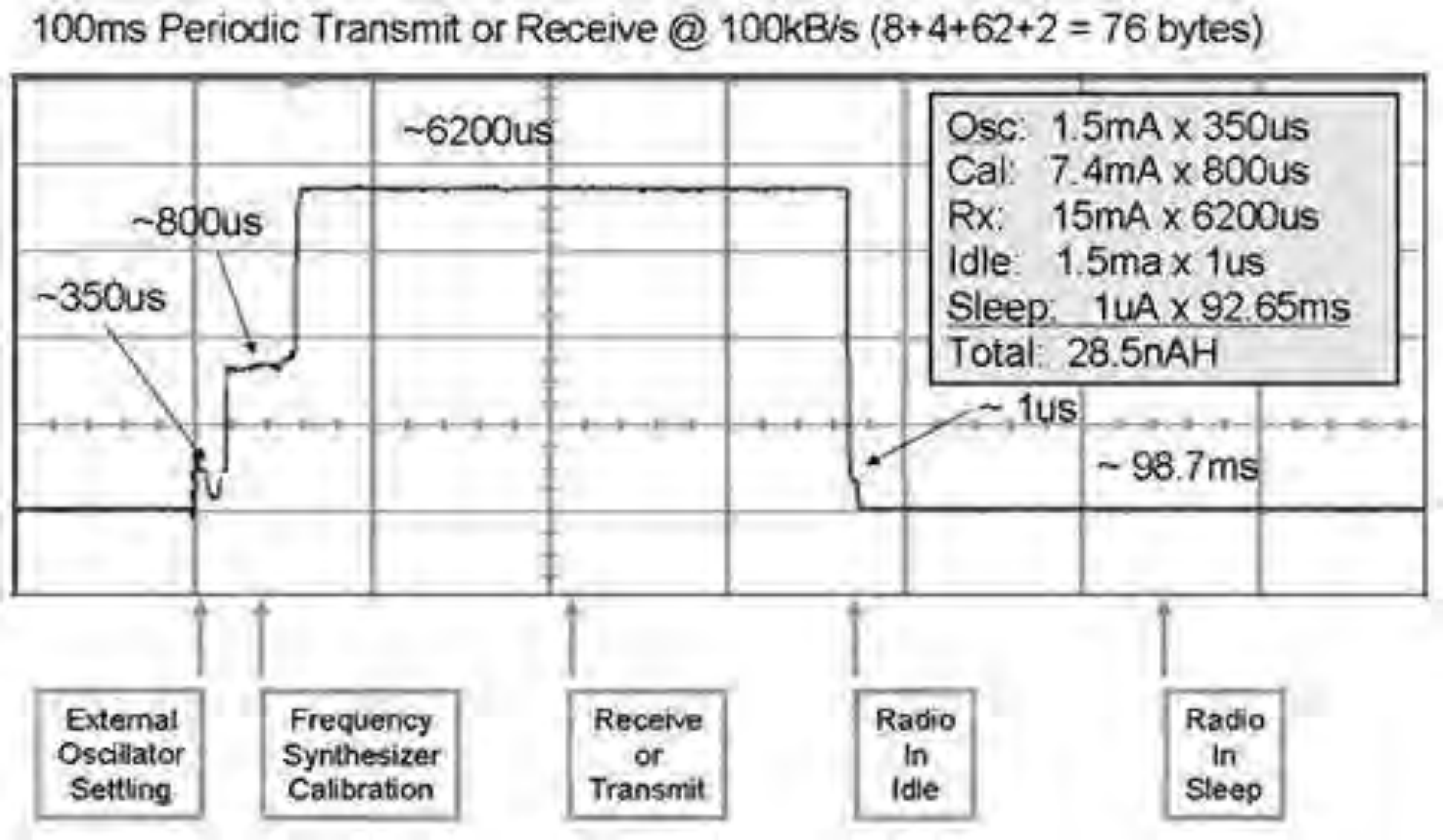


Ideal situation: constant power from the EH.

http://core.spansion.com/article/energy-harvesting-devices-replace-batteries-in-iot-sensors/#.WvKtApdx202

Powering issues

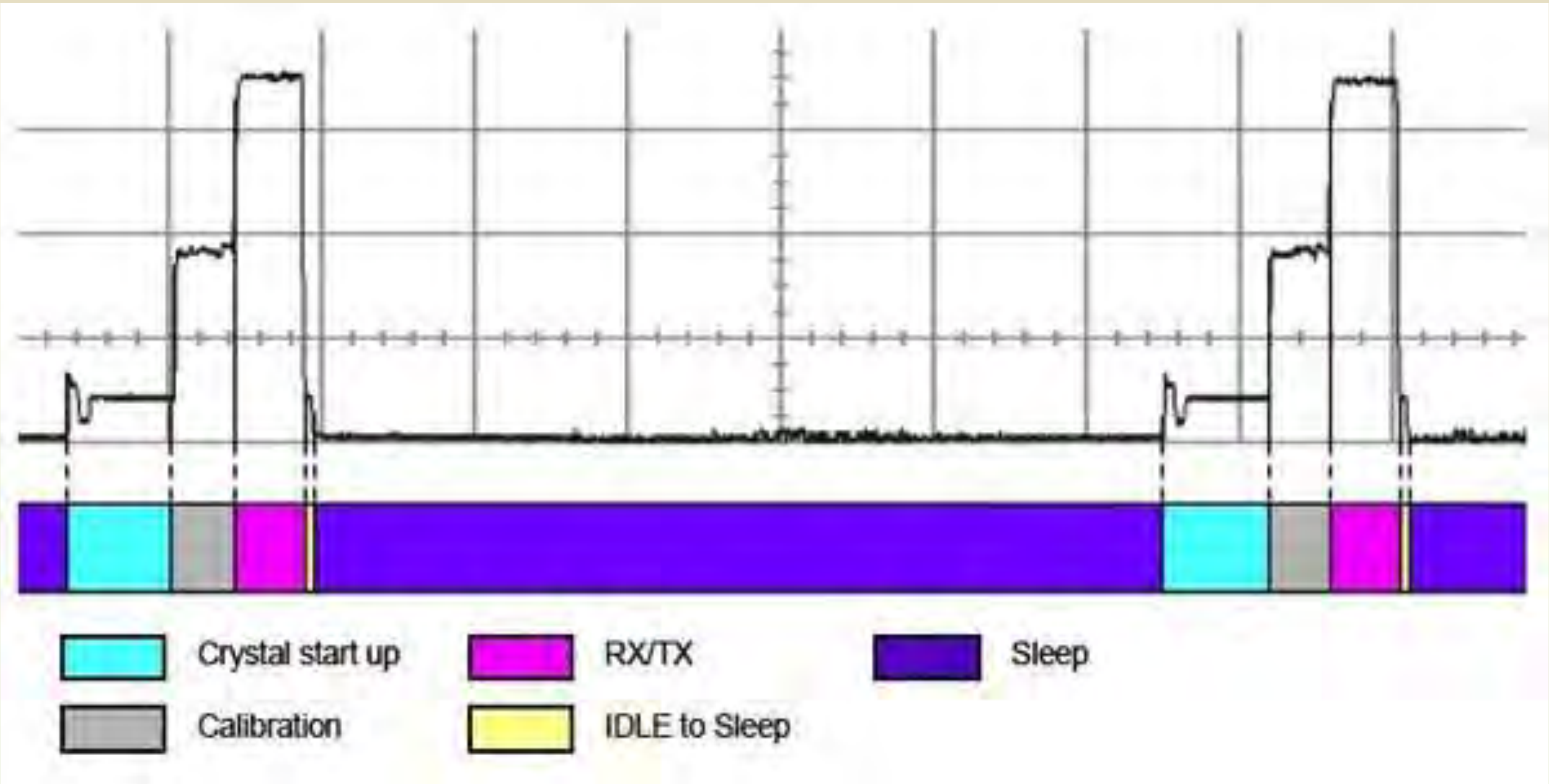
1st: reduce the power required by your application!



https://www.digikey.lv/en/articles/techzone/2014/oct/using-energy-harvesting-techniques-with-ultra-low-power-ics-to-meet-the-power-demands-of-wearables

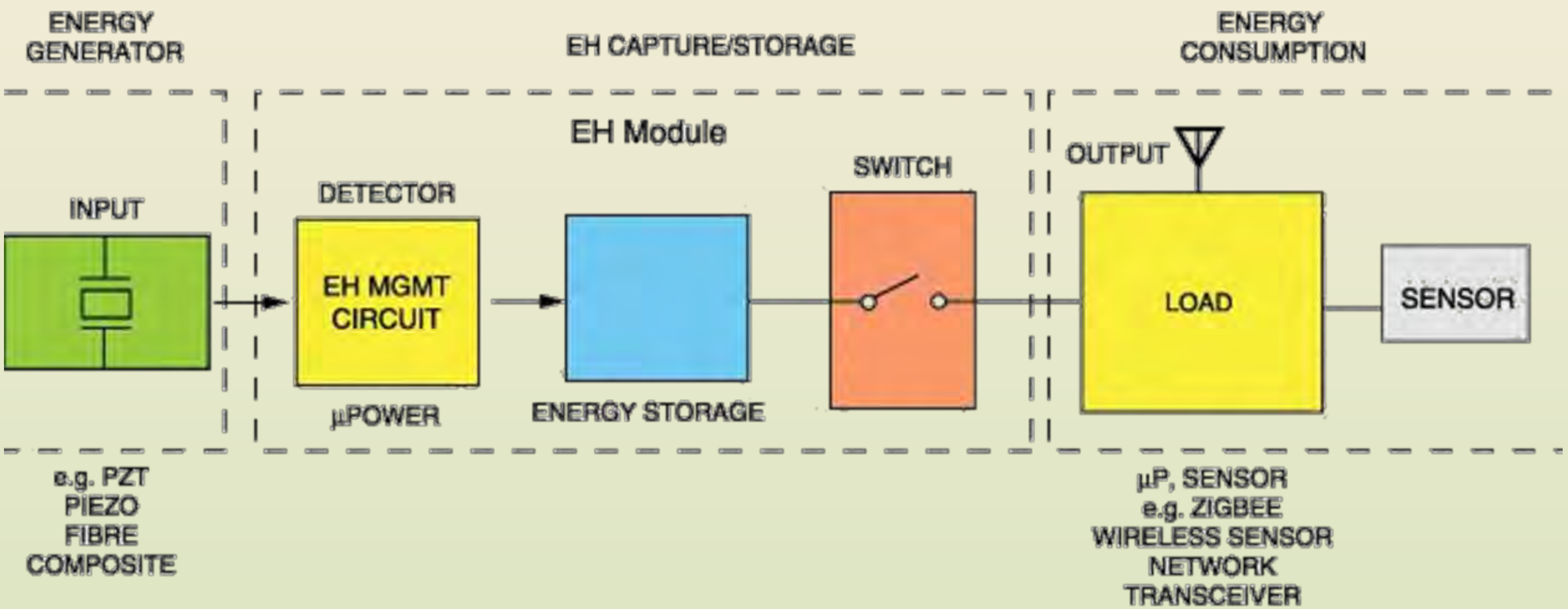
Powering issues

1st: reduce the power required by your application!



Powering issues

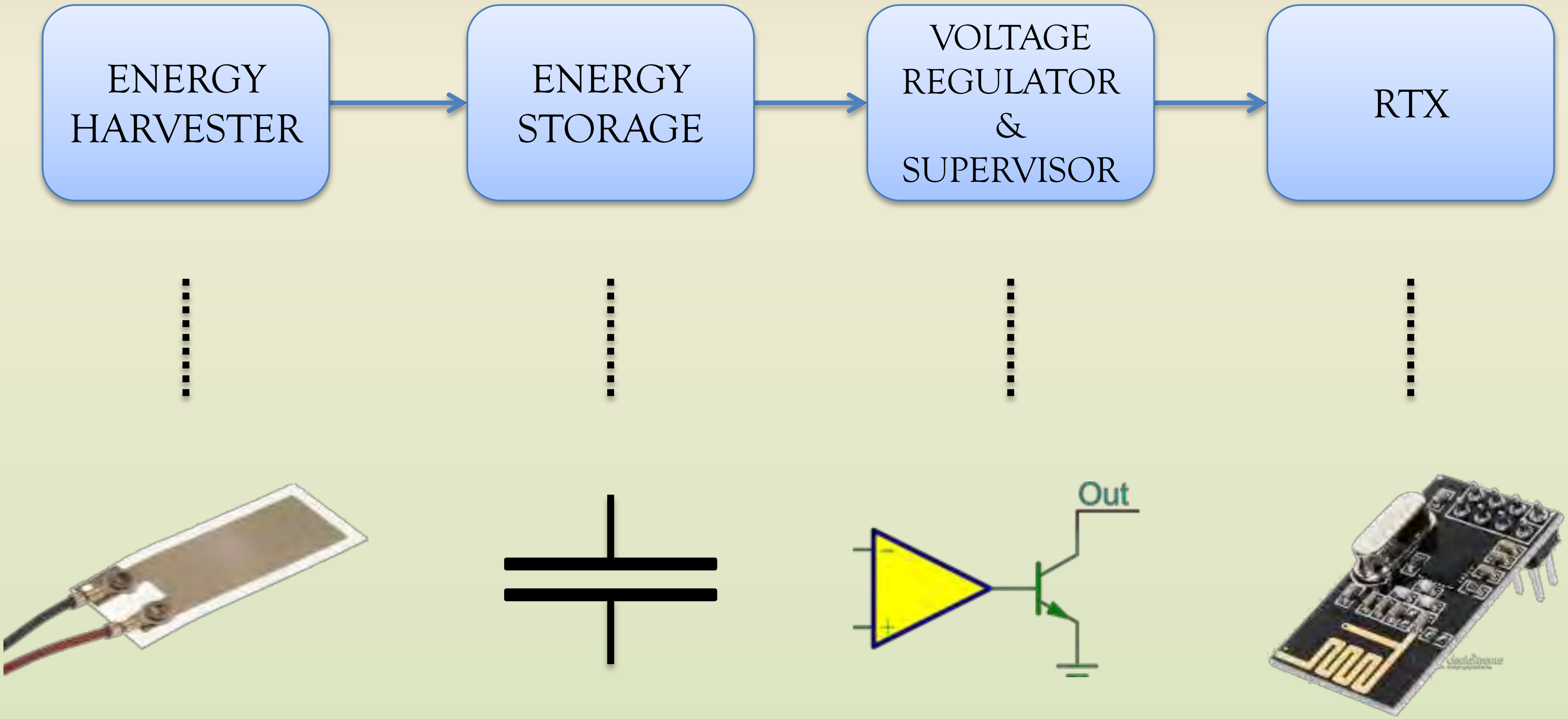
2nd: try to optimize the energy conversion, storage and usage!



Powering issues

2nd: try to optimize the energy conversion, storage and usage!

Energy is a limited quantity!



Power management

All applications generally require DC voltage supply.

AC – DC Converter

Piezoelectric EH

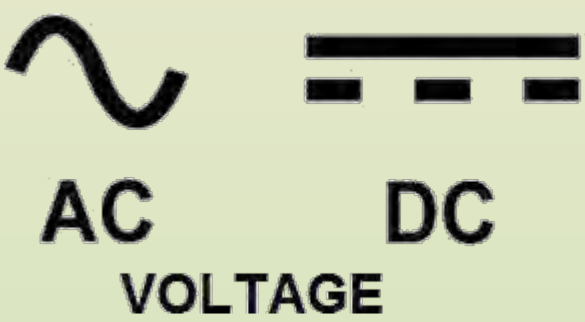
Electromechanical EH

RF EH

DC – DC Converter

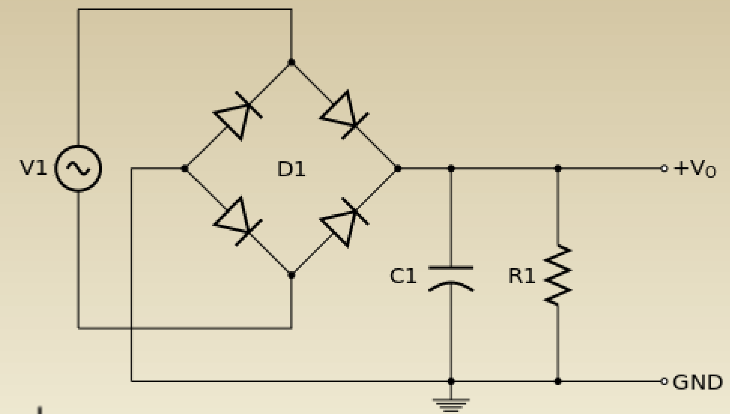
Solar EH

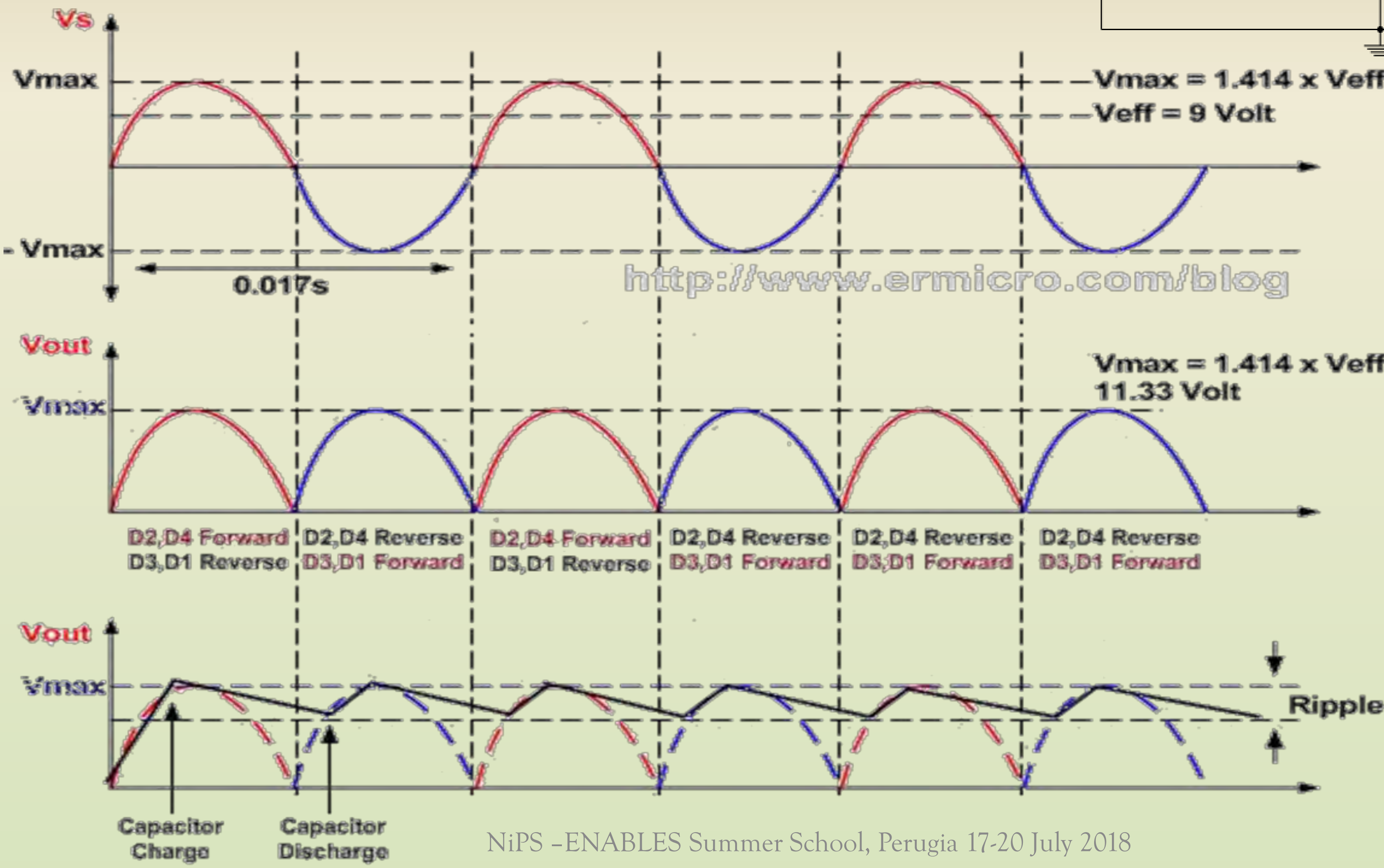
TEG EH



Power management

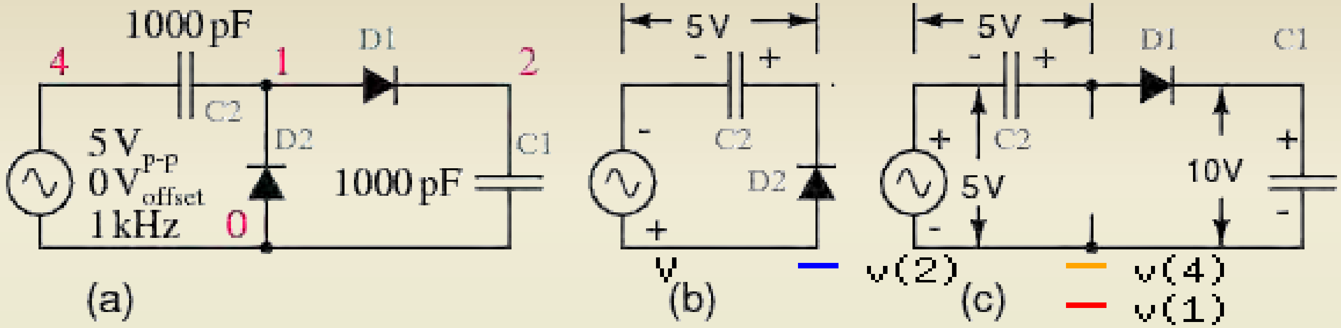
AC - DC converter (1)

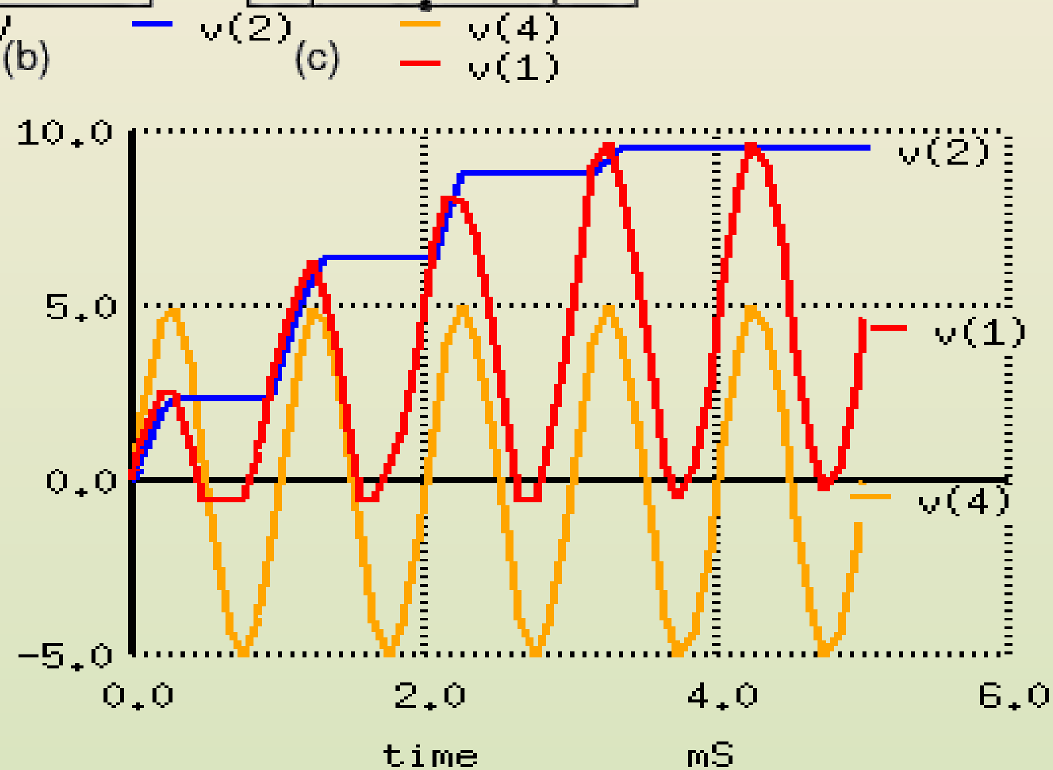




Power management

AC – DC converter (2): voltage doubler



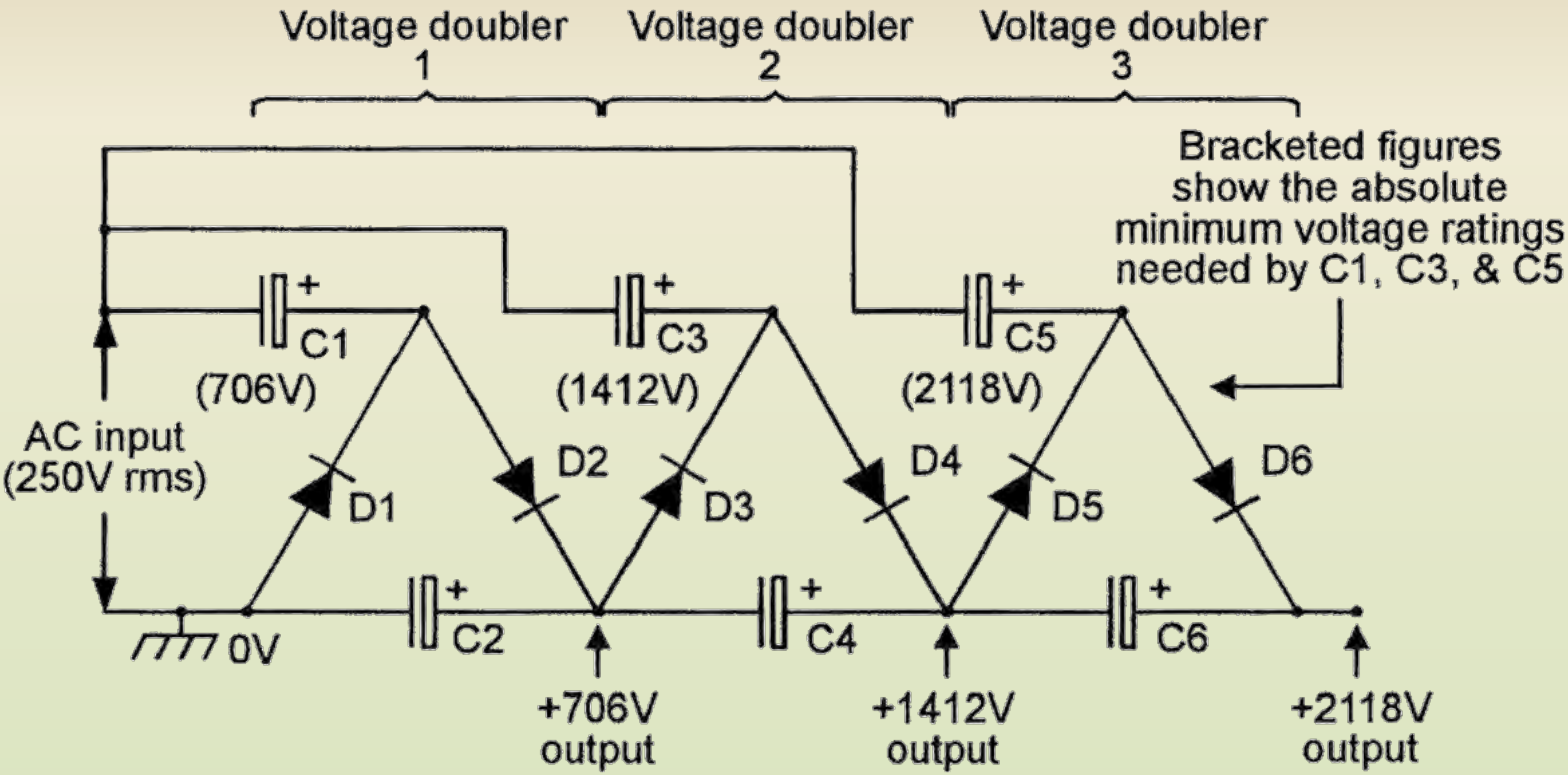


Mainly used for RF EH

https://www.allaboutcircuits.com/textbook/semiconductors/chpt-3/voltage-multipliers/

Power management

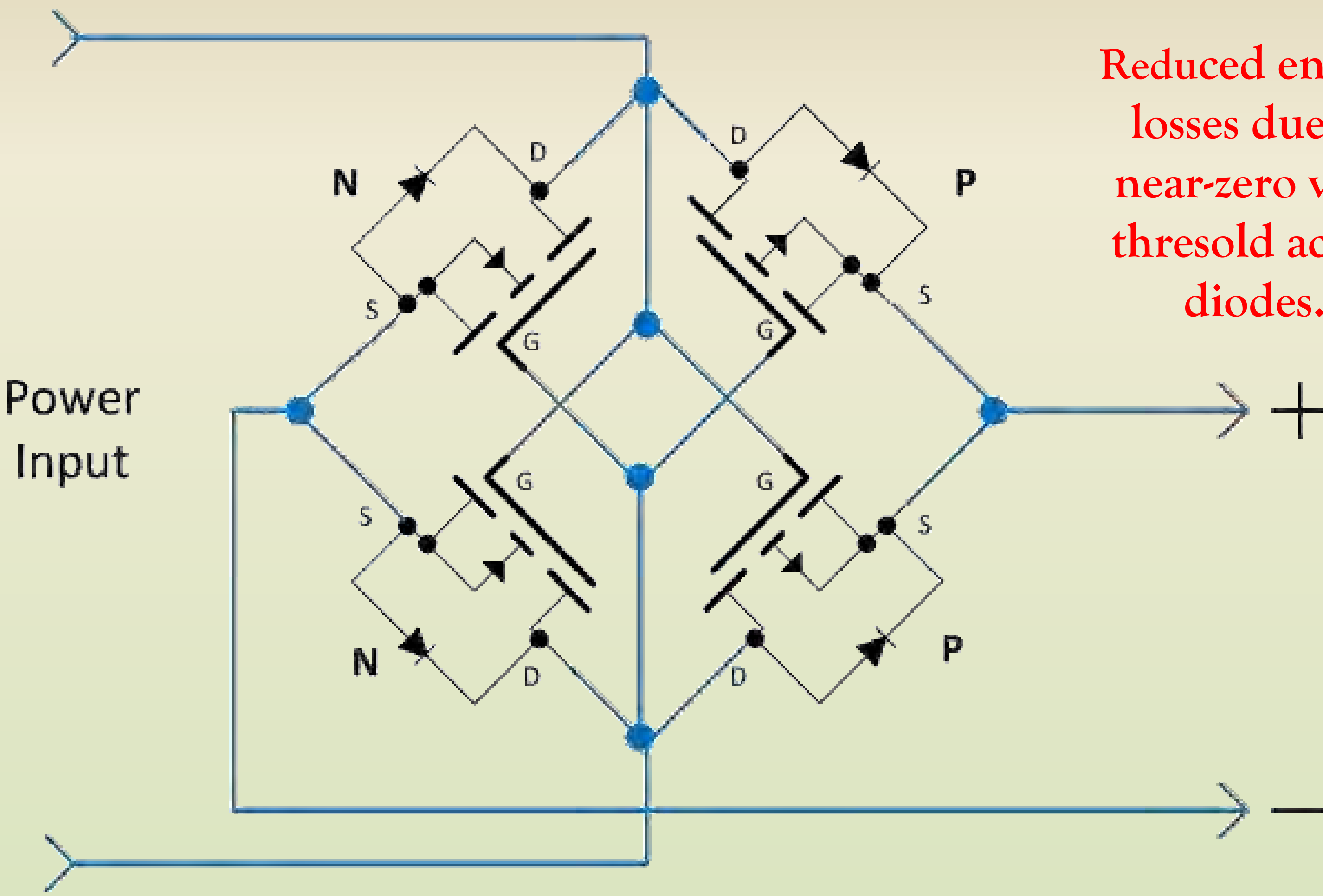
AC – DC converter (3): multiplier



http://www.nutsvolts.com/magazine/article/dc-voltage-converter-circuits

Power management

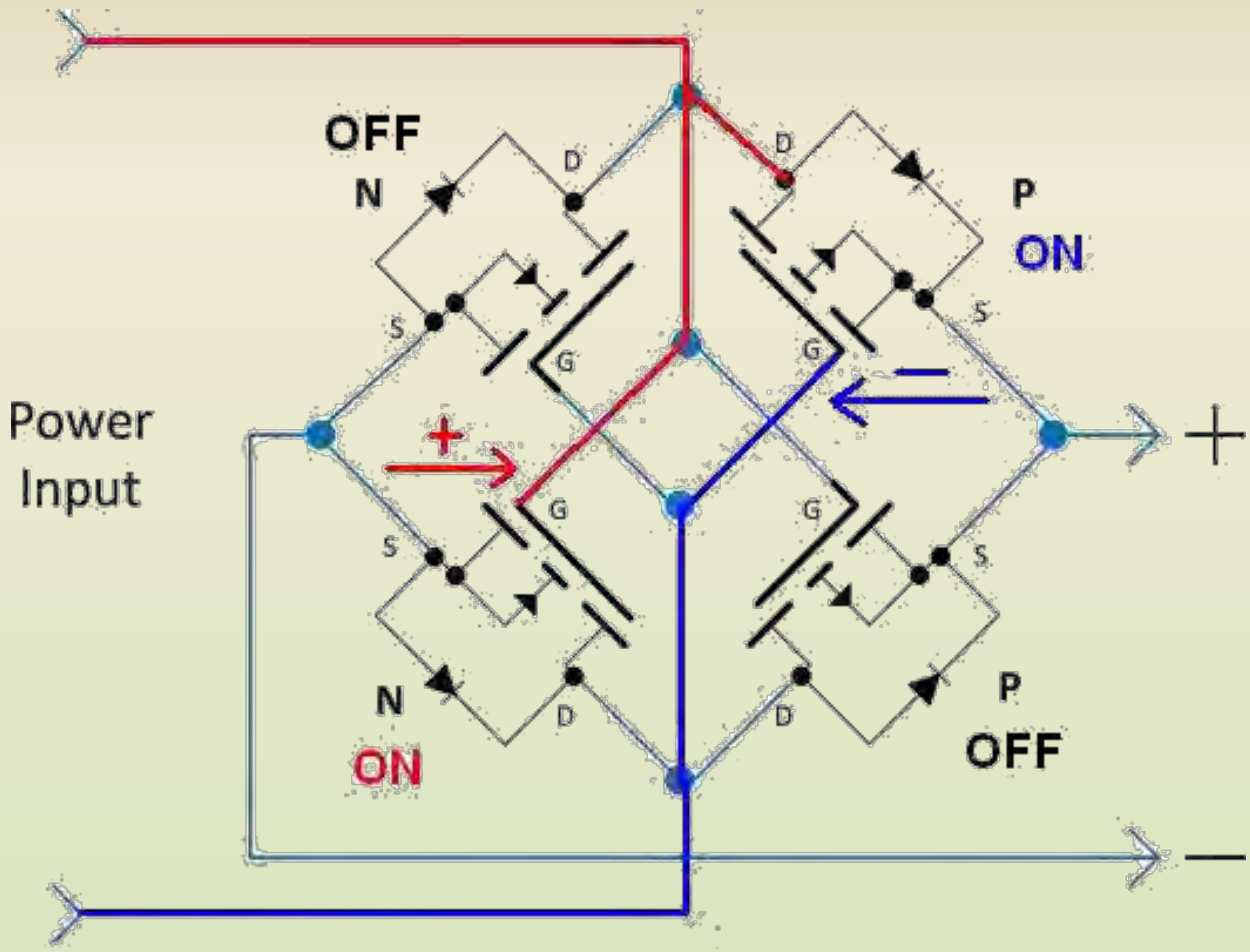
AC – DC converter (4): diodes are replaced by MOSFET



Reduced energy losses due to near-zero volt thresold active diodes.

Power management

AC – DC converter (4): diodes are replaced by MOSFET



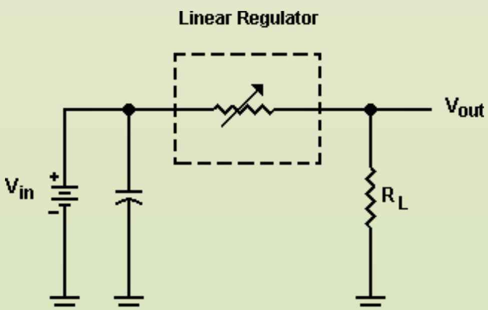
Power management

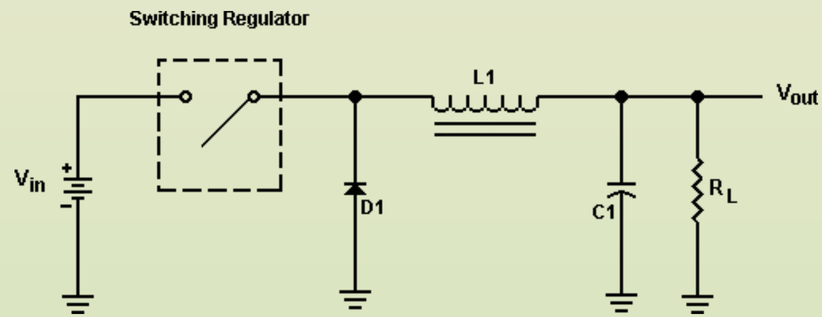
After an AC – DC and a DC – DC converters

a voltage regulator is generally required!

Linear

Switching





Power management

Linear converters

Pros of Linear Power Supply

- No ripple and low noise
- Low in cost and complexity
- Better response time to line and load transients

Cons of Linear Power Supply

- Low efficiency
- High weight due to larger components
- Low load protection in case of failure

Power management

Linear voltage regulators: efficiency

$$P = \Delta V \cdot I \quad [W]$$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{out} \cdot I_{out}}{V_{in} \cdot I_{in}}$$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{out} \cdot I_{out}}{V_{in} \cdot I_{in}} = \frac{V_{out}}{V_{in}}$$

$$since\ for\ a\ linear\ regulator\ \ I_{out} = I_{in}$$

Power management

Switching converters

Pros of Switching Power Supply

- Higher efficiency
- Low weight and size due to smaller components (conversion performed at high frequency)
- High load protection in case of failure

Cons of Switching Power Supply

- Ripple at switching frequency
- Possible emission of EM noise
- High in cost and complexity compared to linear PS
- Limited bandwidth to 1/10th of switching frequency

Power management

Switching converters

Most commonly used switching converter types:

- **Buck** – used to reduce a DC voltage to a lower DC voltage.
- **Boost** – provides an output voltage that is higher than the input.
- **Buck-Boost** – the output voltage can be lower or higher than the input one.
- **Flyback** – an output voltage that is less than or greater than the input can be generated, as well as
- **Push-Pull** – A two-transistor converter that is especially efficient at low input voltages.
- **Half-Bridge** – A two-transistor converter used in many offline applications.
- **Full-Bridge** – A four-transistor converter that can generate the highest output power of all the types.

http://www.ti.com/general/docs/lit/getliterature.tsp?baseLiteratureNumber=snva559&fileType=pdf

Index

- What's IoT – Internet of Things?
- Why Energy Harvesting?
- Sources of energy
- Powering issues
- Mechanical design
- An example of integrated system

Mechanical design

Several constraints:

- Volume
- Shape
- Weight
- Color
- Material - many standards (RoHS, RAEE, LVD e REACH...)
- Impact resistance - EN 62-262 European standard
- Tightness - Ingress Protection (IPxy)
- Cost!

http://www.ti.com/general/docs/lit/getliterature.tsp?baseLiteratureNumber=snva559&fileType=pdf

Mechanical design

IK impact resistance rating

IK00	Not protected
IK01	Protected against **0.14 joules** impact Equivalent to impact of 0.25kg mass dropped from 56mm above impacted surface.
IK02	Protected against **0.2 joules** impact Equivalent to impact of 0.25kg mass dropped from 80mm above impacted surface.
IK03	Protected against **0.35 joules** impact Equivalent to impact of 0.25kg mass dropped from 140mm above impacted surface.
IK04	Protected against **0.5 joules** impact Equivalent to impact of 0.25kg mass dropped from 200mm above impacted surface.
IK05	Protected against **0.7 joules** impact Equivalent to impact of 0.25kg mass dropped from 280mm above impacted surface.
IK06	Protected against **1 joule** impact Equivalent to impact of 0.25kg mass dropped from 400mm above impacted surface.
IK07	Protected against **2 joules** impact Equivalent to impact of 0.5kg mass dropped from 400mm above impacted surface.
IK08	Protected against **5 joules** impact Equivalent to impact of 1.7kg mass dropped from 300mm above impacted surface.
IK09	Protected against **10 joules** impact Equivalent to impact of 5kg mass dropped from 200mm above impacted surface.
IK10	Protected against **20 joules** impact Equivalent to impact of 5kg mass dropped from 400mm above impacted surface.

Mechanical design

Ingress Protection IPxy

Protection Against Solid Bodies Data Table

0	Tests	No Protection
1	∅ 50 mm	Protected against solid bodies larger than 50 mm (eg. accidental contact with the hand)
2	∅ 12.5 mm	Protected against solid bodies larger than 12.5 mm (eg. finger of the hand)
3	∅ 2.5 mm	Protected against solid bodies larger than 2.5 mm (eg. tools, wires)
4	∅ 1 mm	Protected against solid bodies larger than 1 mm (eg. fine tools, small wires)
5		Protected against dust (no harmful deposit)
6		Completely protected against dust

Protection Against Liquids Data Table

0	Tests	No Protection
1		Protected against vertically-falling drops of water (condensation)
2	15°	Protected against drops of water falling at up to 15° from the vertical
3	60°	Protected against drops of water falling at up to 60° from the vertical
4		Protected against projections of water from all directions
5		Protected against jets of water from all directions
6		Completely protected against jets of water of similar force to heavy seas
7		Protected against the effects of immersion
8		Protected against effects of prolonged immersion under specific conditions

x

y

http://www.govan.com.au/wp-content/uploads/2013/11/Protection-Against-Solid-Bodies-Liquids-Data-Table_JPG.jpg

Mechanical design

Easier with a 3D printer!

http://www.govan.com.au/wp-content/uploads/2013/11/Protection-Against-Solid-Bodies-Liquids-Data-Table_JPG.jpg

Index

- What's IoT – Internet of Things?
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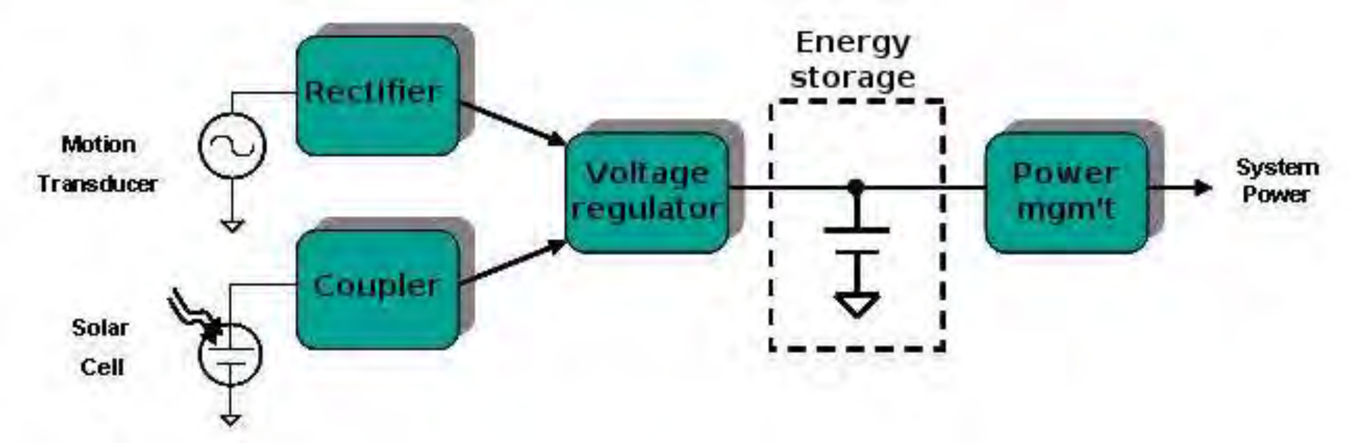
An example of integrated system

HAT2 – Hybrid Autonomous Transceiver V2

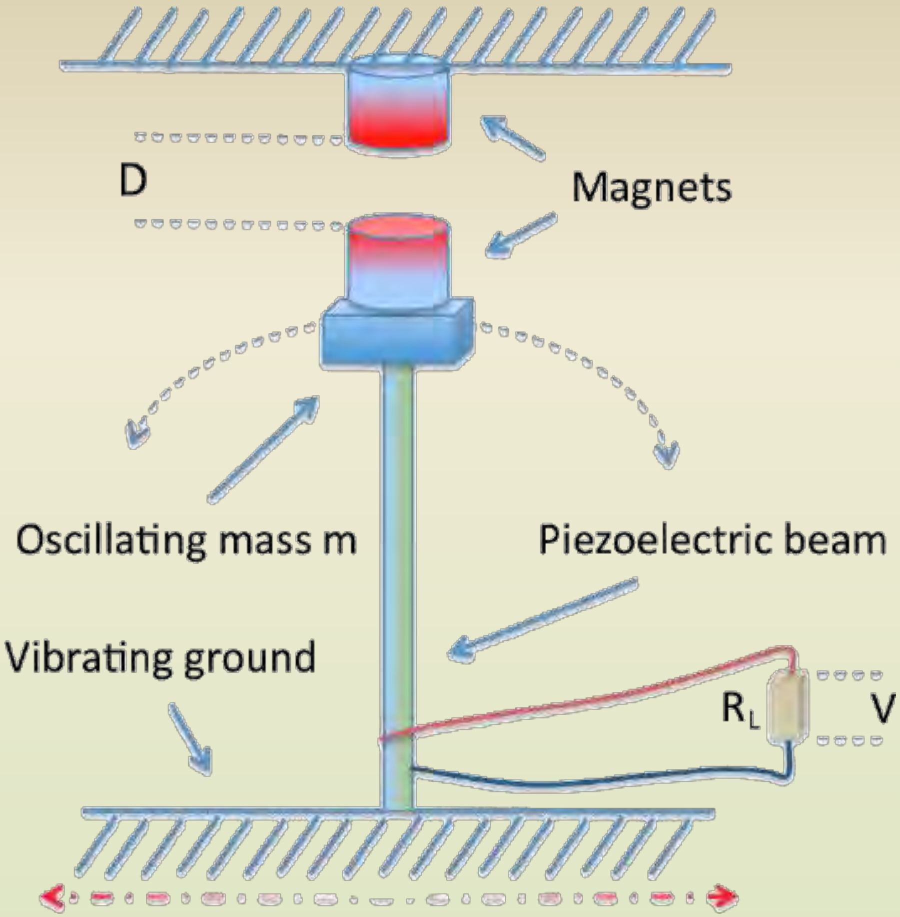
Small enclosure: 60 x 35 x 25 mm

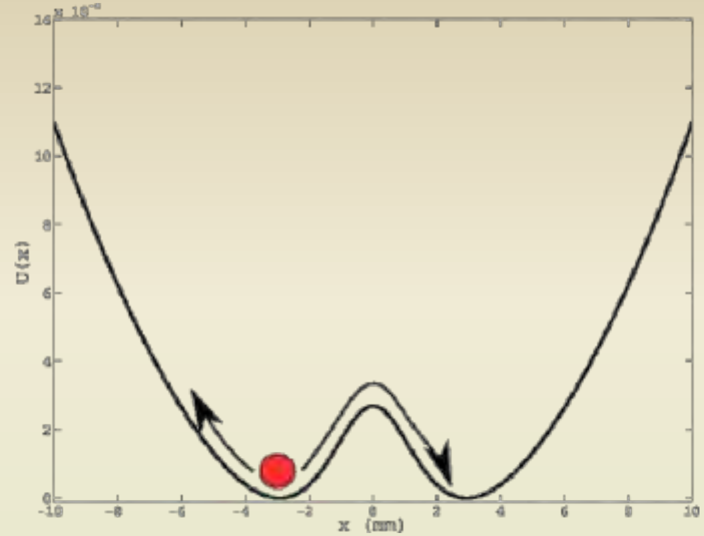
- 1 piezoelectric **non-linear vibrations energy harvester**
- 1 solar array (2 x solar cells - Pmax = 8 mW @ 3,9 V, Solar Simulator 50k LUX)
- 1 LDO voltage regulator: Vout = 3,3 Vdc, Iq = 3,2 μA
- 1 high capacitance tantalum capacitor: 1000 μF 6,3 V
- 1 NanoPower supervisory circuitry



F. Orfei, R. Mincigrucci, I. Neri, F. Travasso, H. Vocca and L. Gammaitoni, "Hybrid autonomous transceivers," Education and Research Conference (EDERC), 2012 5th European DSP, Amsterdam, 2012, pp. 173-177. doi: 10.1109/EDERC.2012.6532249 http://ieeexplore.ieee.org/document/6532249/

An example of integrated system





$$\ddot{x} = -\frac{dU(x)}{dx} - \gamma\dot{x} - K_v V - \sigma\xi(t)$$

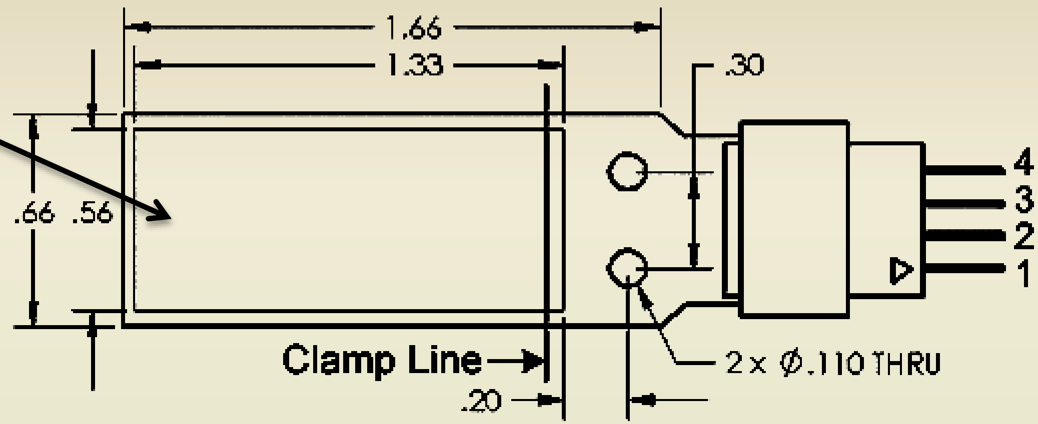
$$\dot{V} = -K_c\dot{x} - \frac{1}{\tau_p}V$$

F. Cottone, H. Vocca, L. Gammaitoni, "**Nonlinear Energy Harvesting**“
Phys. Rev. Lett. 102, 080601 (2009)

An example of integrated system

≈50 gr. Tip Mass

Resonant frequency down to 37 Hz



Harvesting Bandwidth (Hz): 3
Frequency Range (Hz): 80 - 205
Device size (in): 2.74 x 0.67 x 0.032
Device weight (oz): 0.115
Active elements: 1 stack of 2 piezos
Piezo wafer size (in): 1.40 x 0.57 x 0.008
Device capacitance: 3 - 4 nF

NOT SUITABLE FOR OUR APPLICATION!

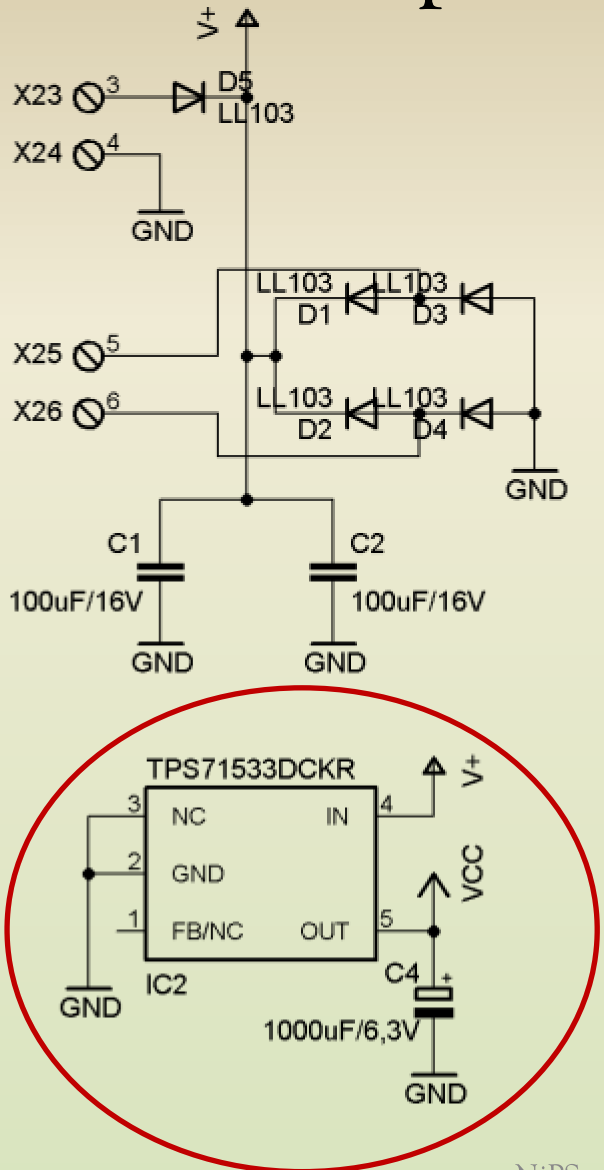
Wide Band Noise!

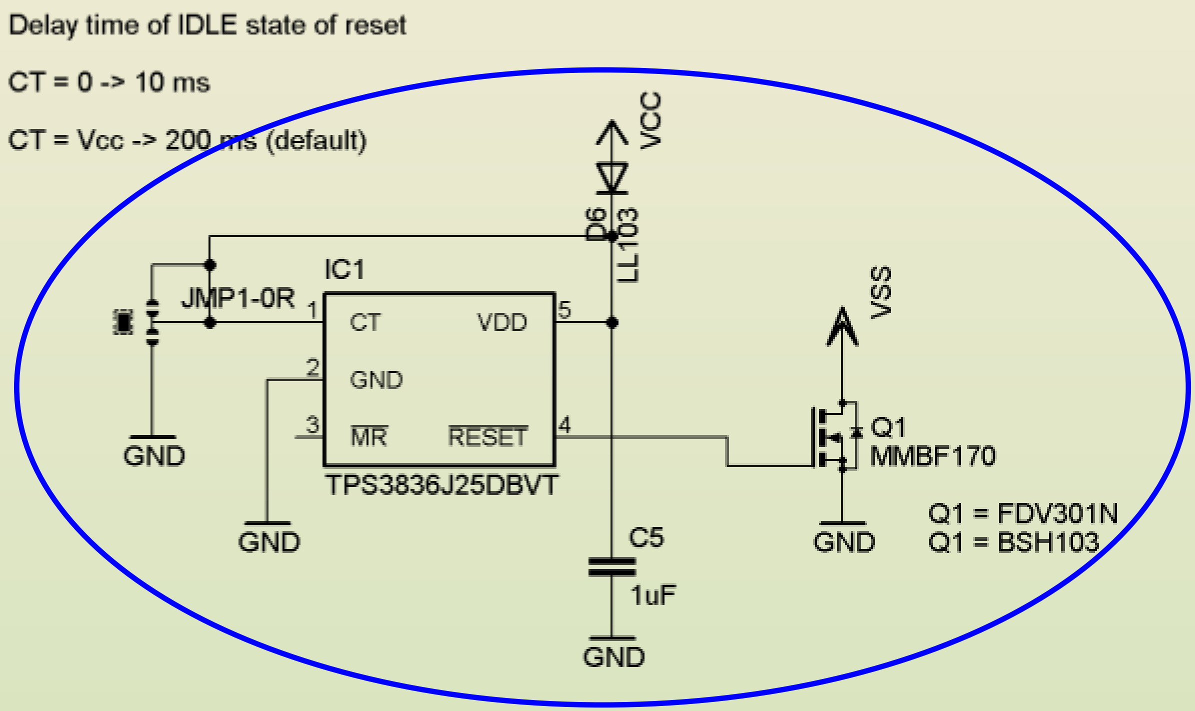
An example of integrated system

AC – DC + linear voltage regulator

Rectifier + Voltage Regulator + Supervisor

Total Current loss < 7 μA



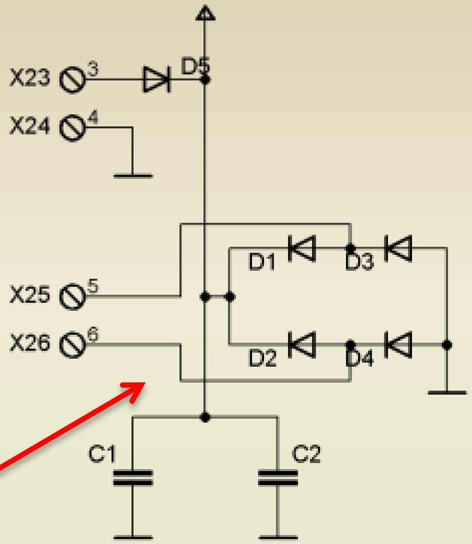


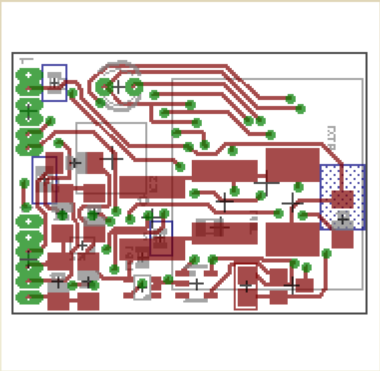
An example of integrated system

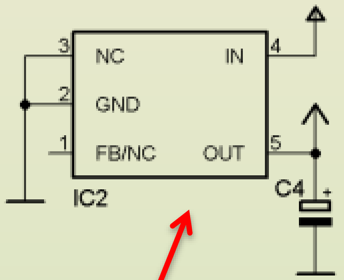
Solar

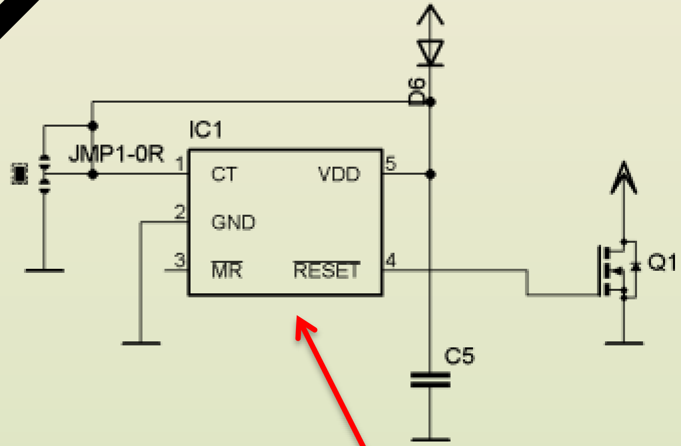
Piezo

Rectifier





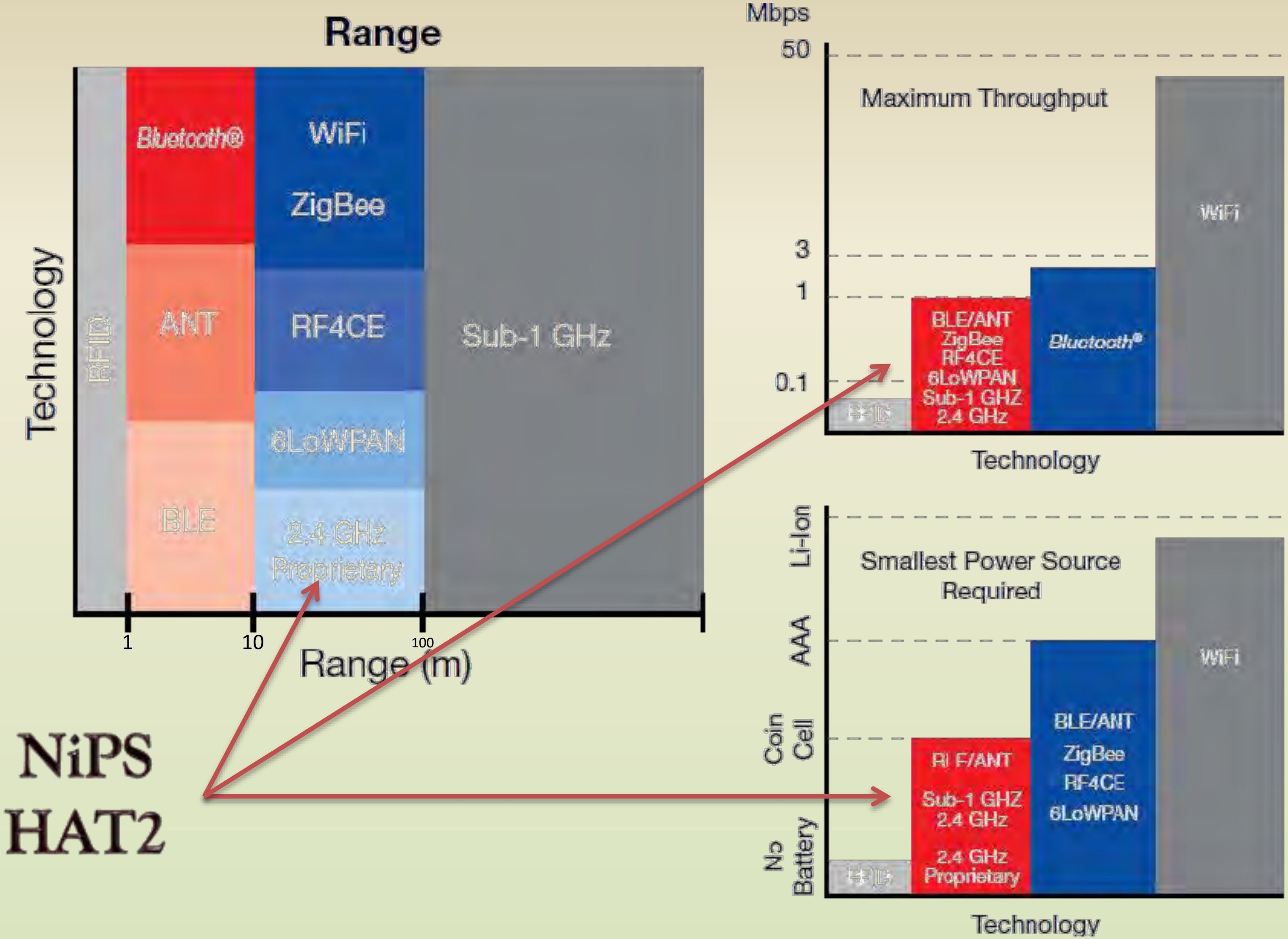




LDO

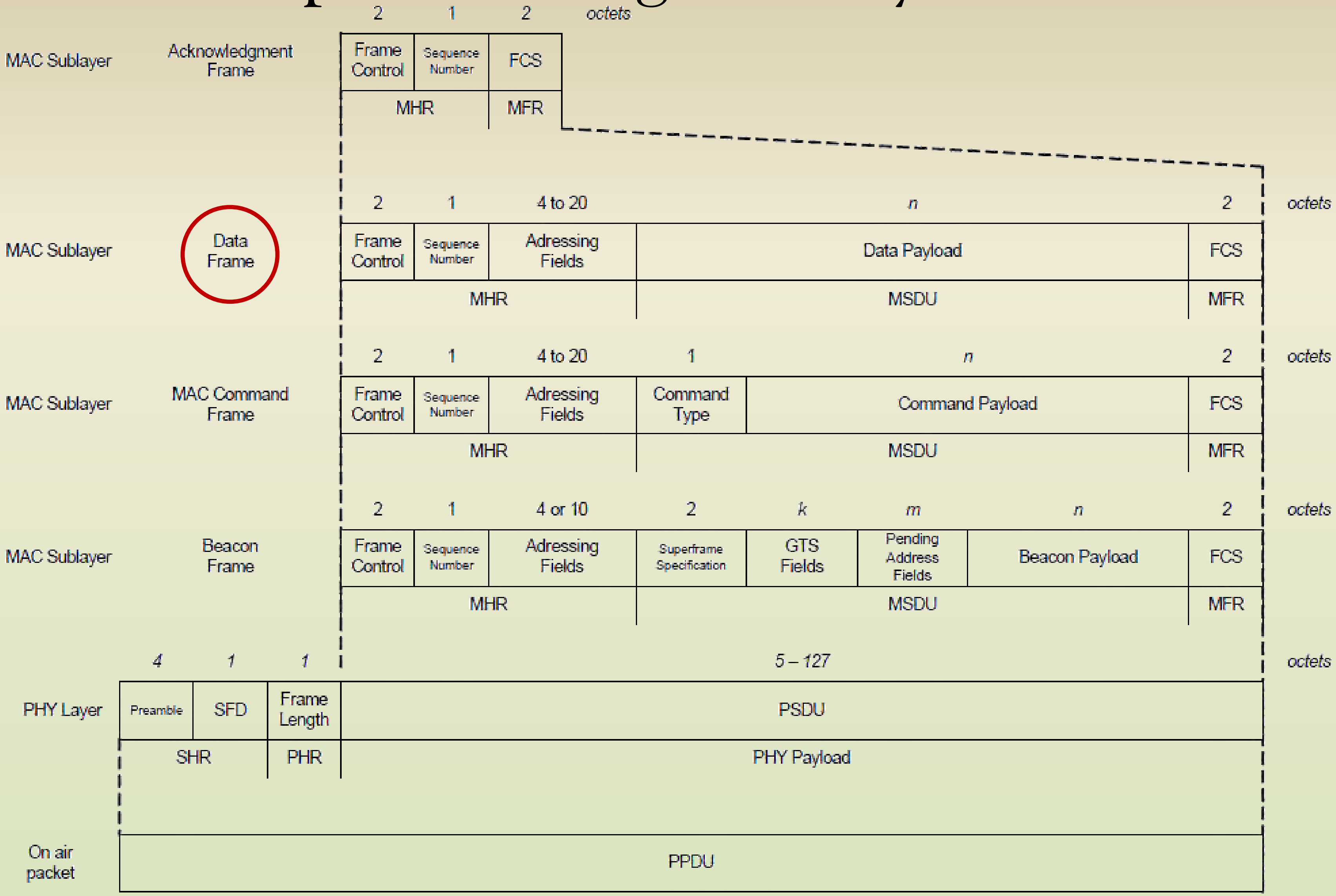
Voltage Supervisor

An example of integrated system

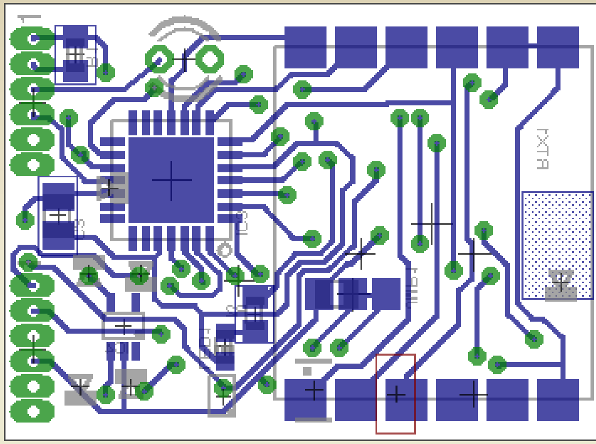


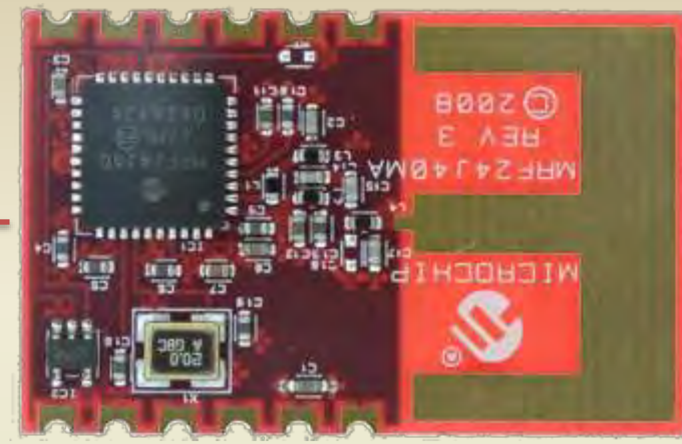
An example of integrated system

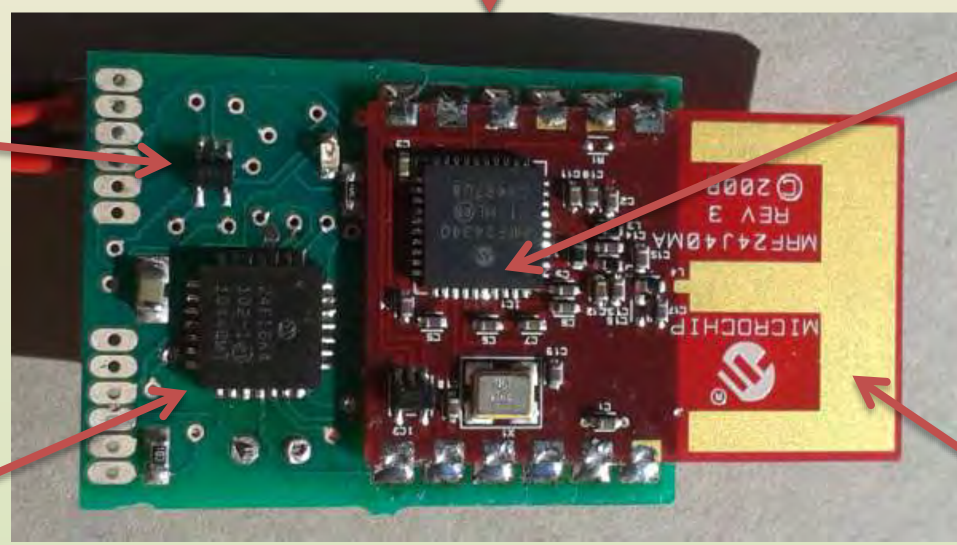
IEEE 802.15.4™ PHY PACKET AND MAC FRAME STRUCTURE.



An example of integrated system







Temperature Sensor

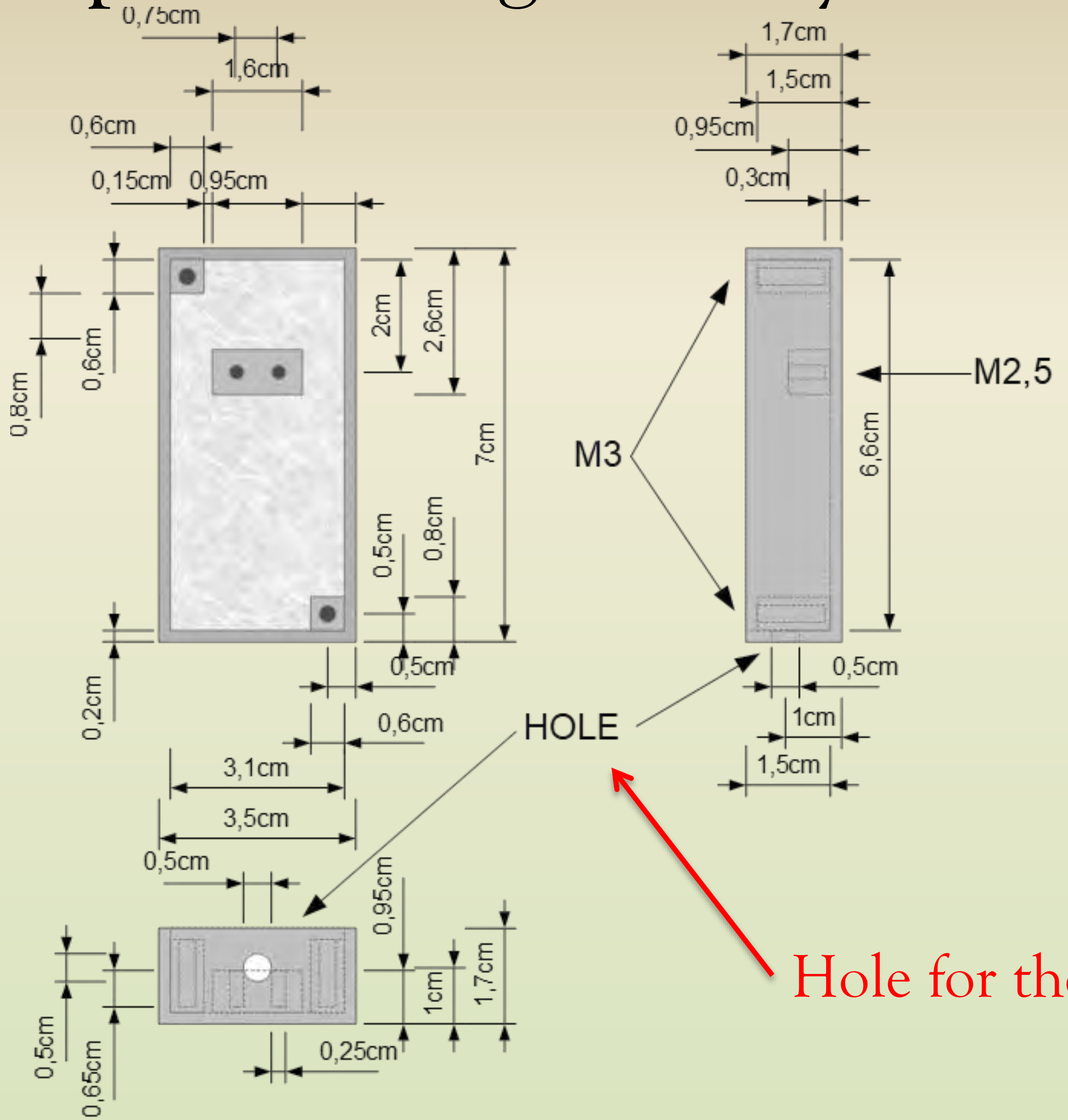
16 bit µController

2.4 GHz 802.15.4 RF Transceiver

PCB Antenna

An example of integrated system

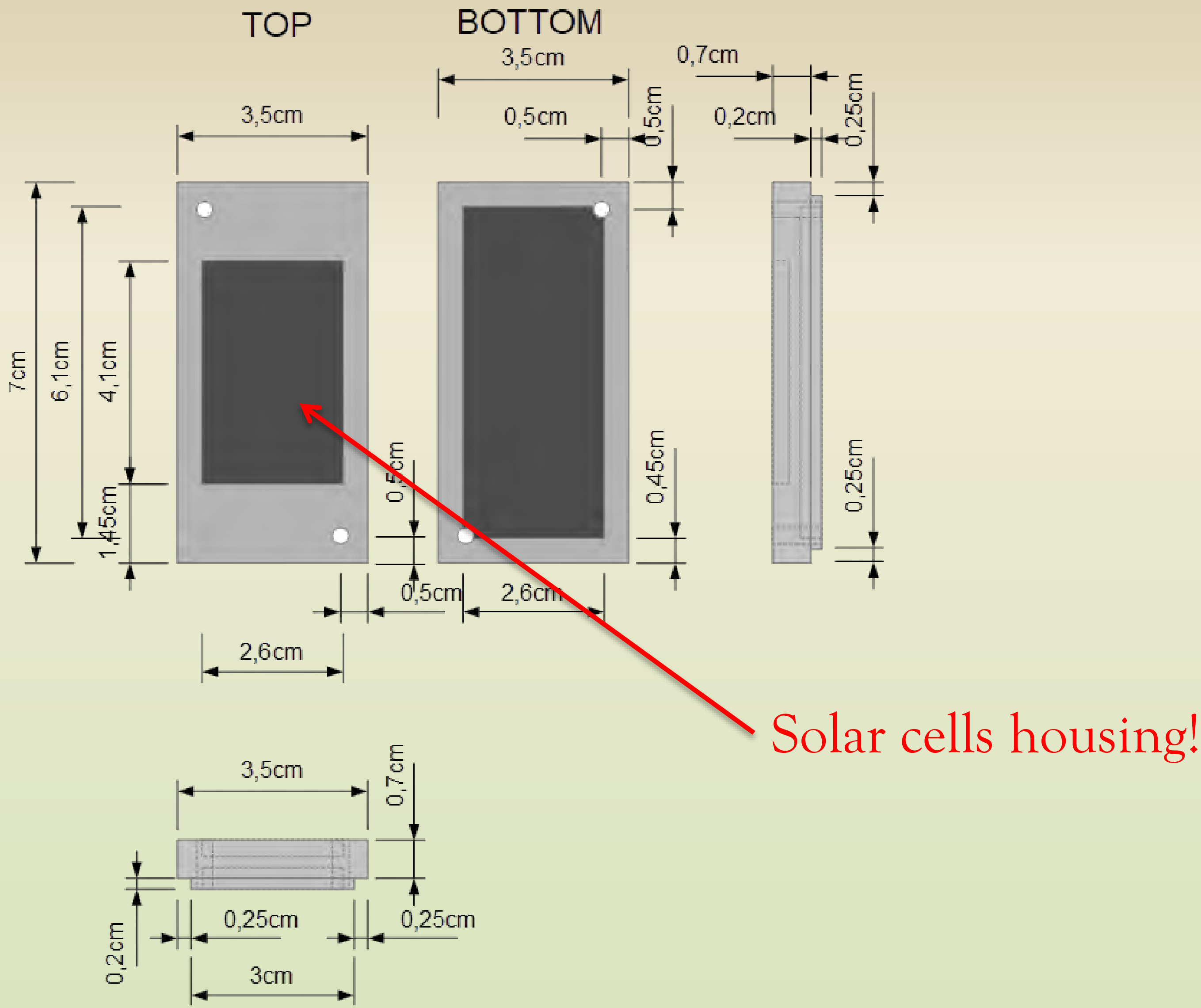
Enclosure design: body



Hole for the magnet!

An example of integrated system

Enclosure design: cover



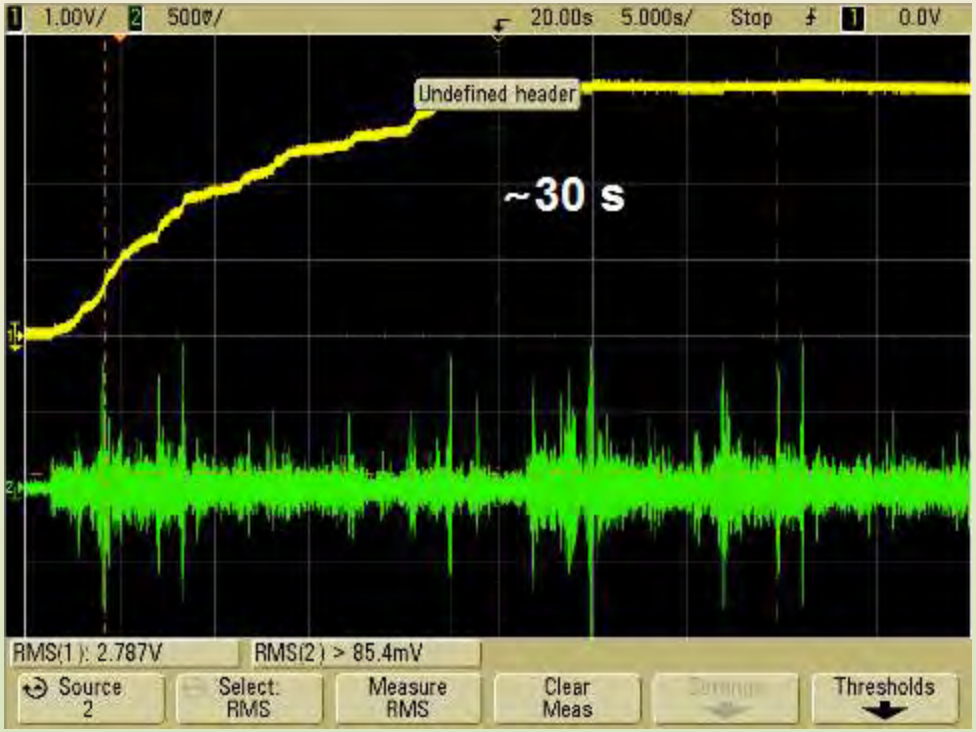
An example of integrated system

HAT2 prototype

An example of integrated system

Test on the shaker

Real vibrations can be used to evaluate the time required to charge the storage capacitor.



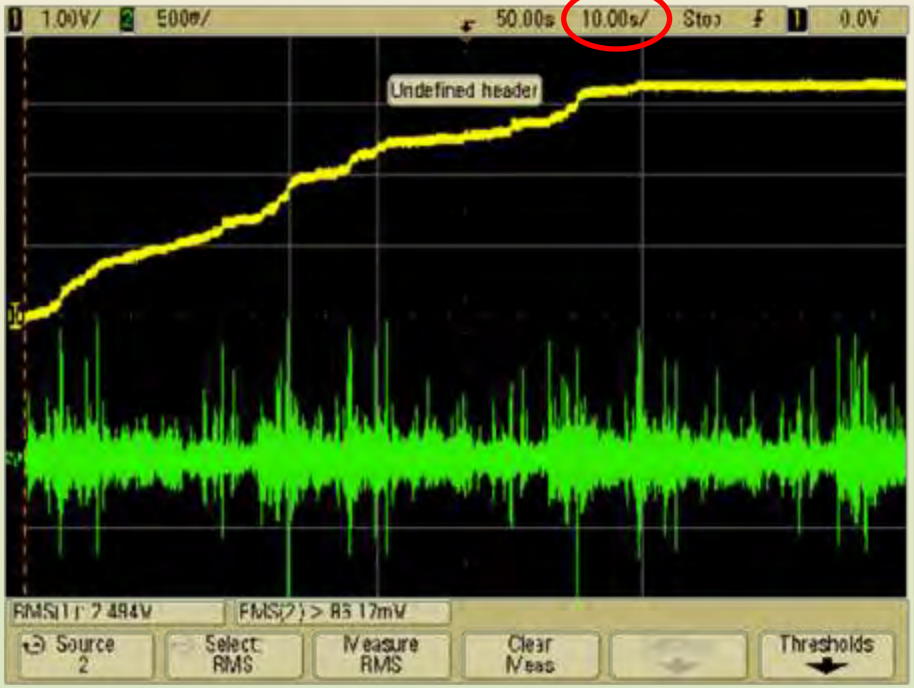
An example of integrated system

Charging a 1000 μf capacitor with a linear and

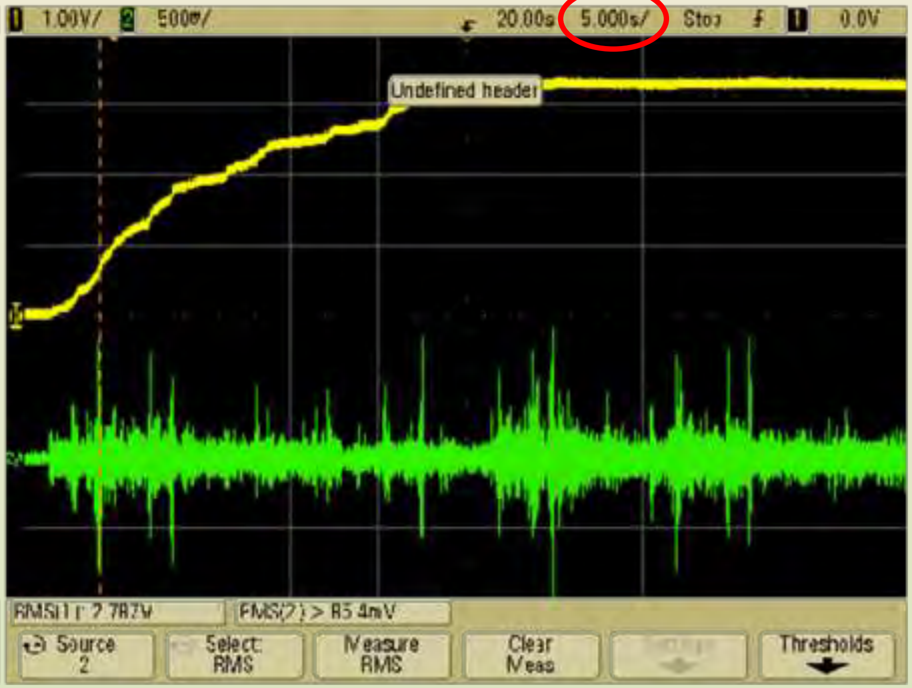
a non-linear piezoelectric vibration energy harvester up to 3.3 v

$$Q = \frac{1}{2} C V^2$$

LINEAR MODE



NON-LINEAR MODE

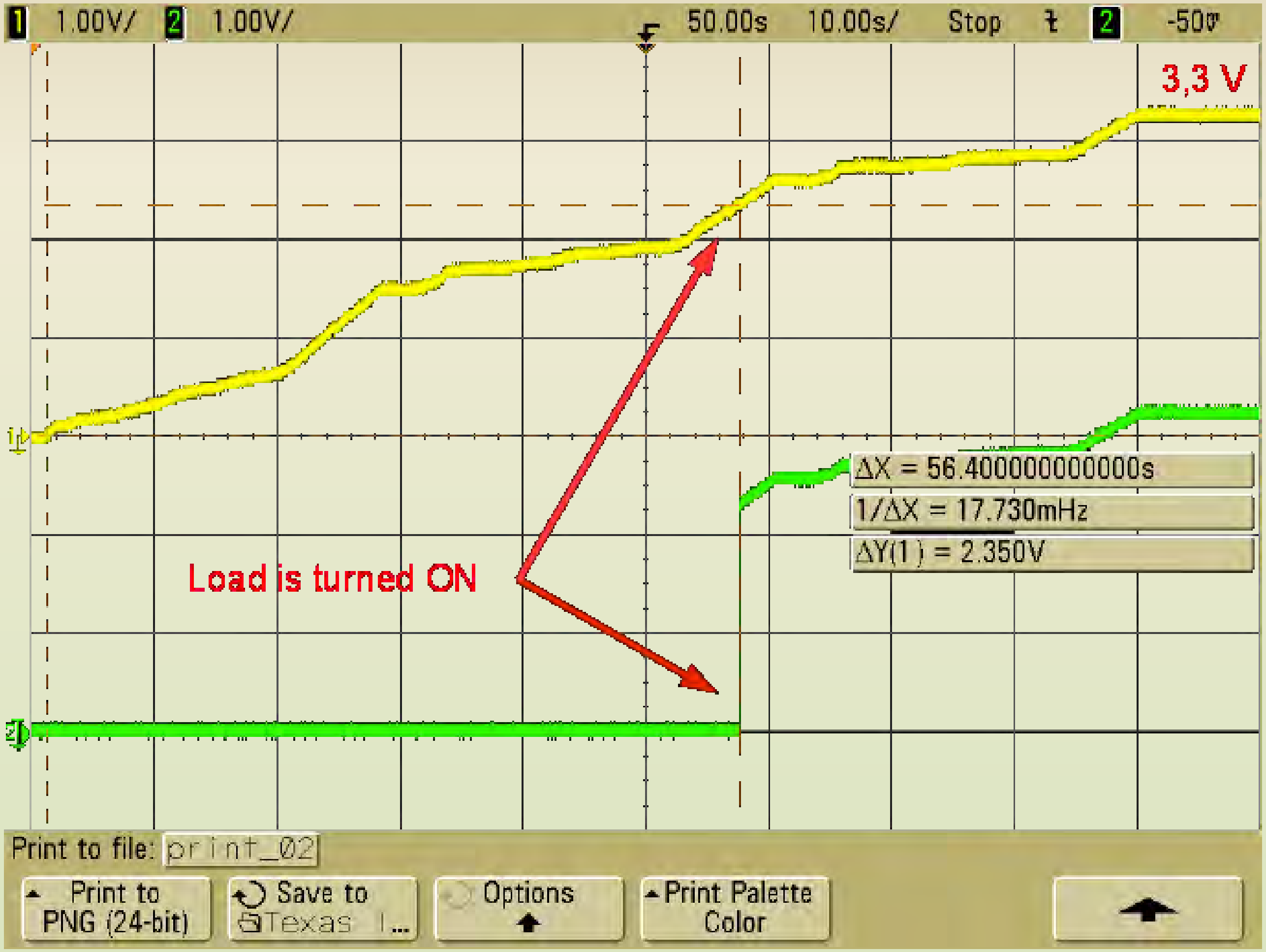


Power management

AC – DC + linear voltage regulator

Voltage across the storage capacitor

Supply voltage to the load

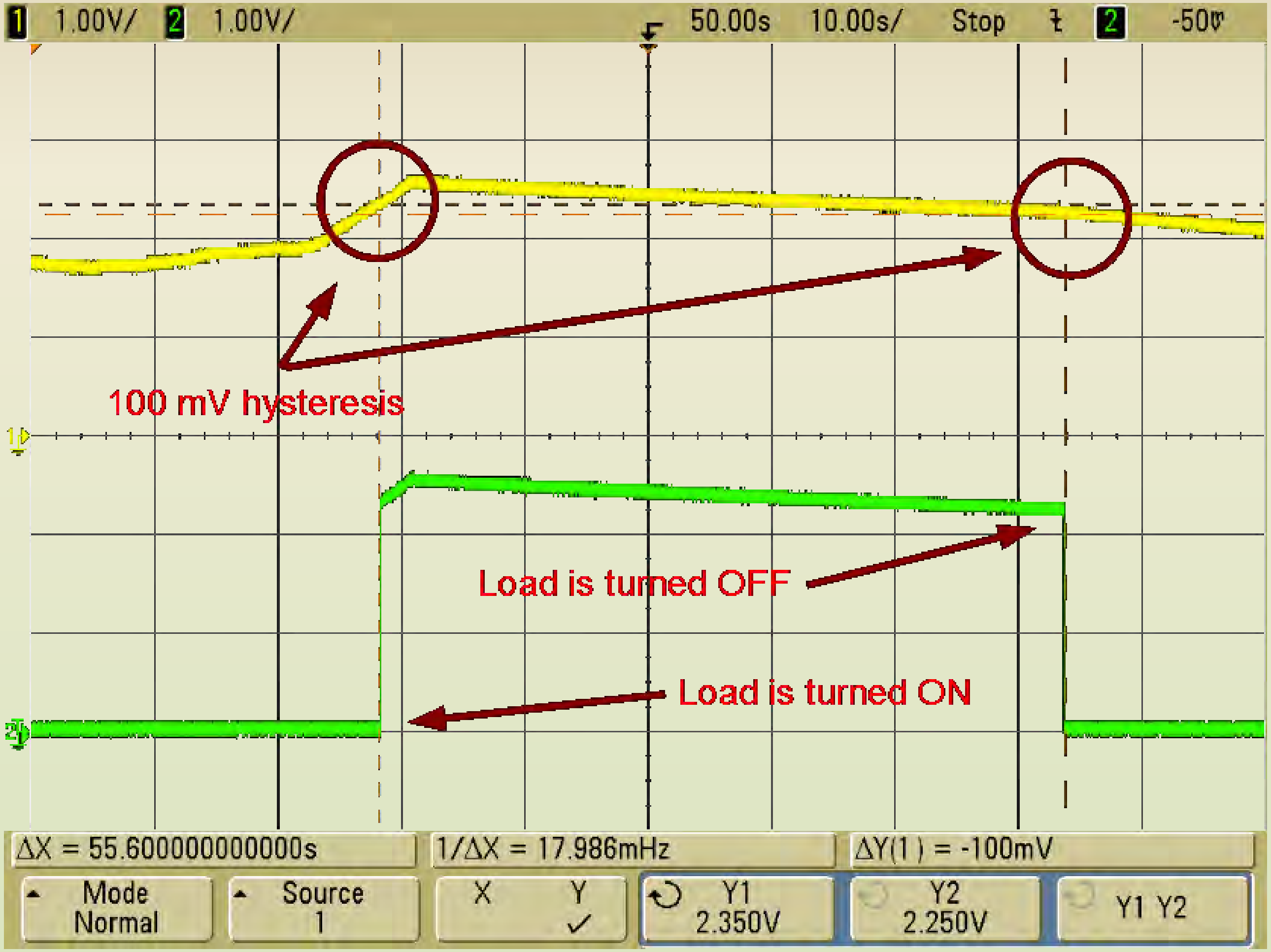


Power management

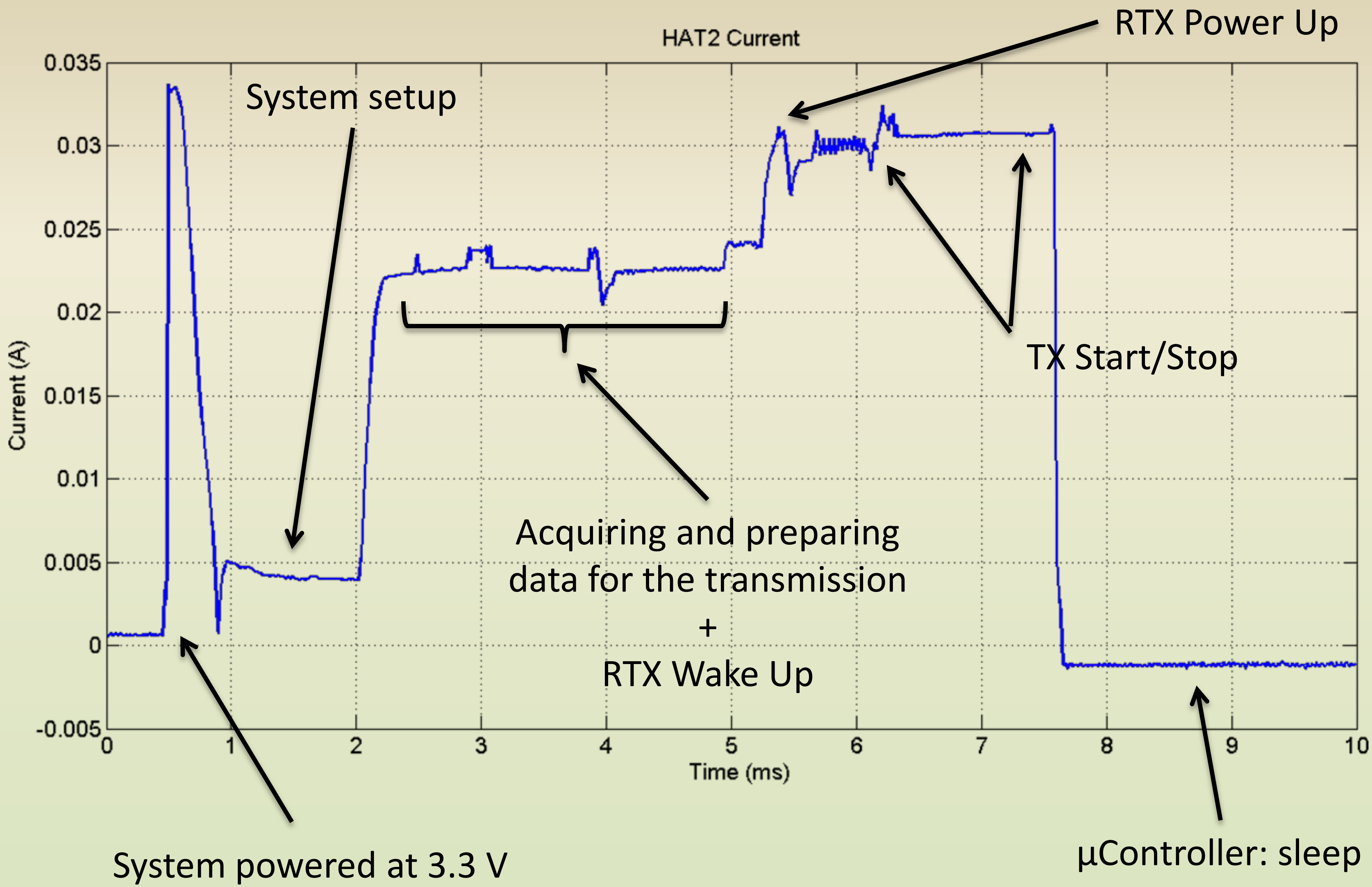
AC – DC + linear voltage regulator

Voltage across the storage capacitor

Supply voltage to the load



An example of integrated system




Questions ?