SiNANO-NEREID Workshop:

Towards a new NanoElectronics Roadmap for Europe

Energy for Autonomous Sensors

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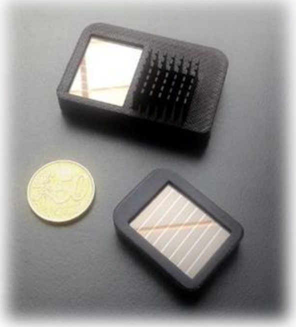
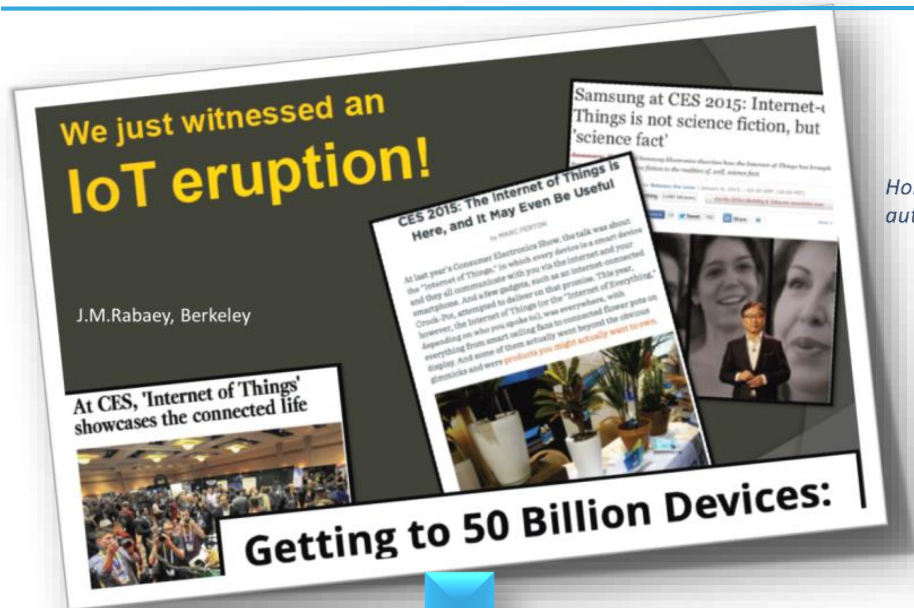


Leuven, September 11th, 2017

WP4/Task.4.2

Future IoT challenge?



Who will change the batteries ?

Who will pay for that ?

Can we do more with less energy and no batteries?
YES, WE CAN!

NEIRED WP4/Sub Task.4.2 : Energy for autonomous systems roadmap

- Among the different EH technologies, 4 were selected for the initial roadmap:
  - Experts were selected coming from Industries and Universities:

- 4 technology experts :

  - **Gustavo Ardila** – Grenoble Alpes University / Grenoble INP, France
    Mechanical energy harvesting (piezoelectric materials)
  - **Stephane Monfray** – STMicroelectronics, Crolles, France
    Thermal energy harvesting, Electrostatic energy conversion
  - **Anne Kaminski-Cachopo** – Grenoble INP, France
    Solar Energy Harvesting
  - **Aldo Romani** – University of Bologna, Italy
    Circuits for energy management

1st Domain workshop (Bertinoro, Italy, October 19th , 2016)

2nd Domain workshop (Barcelona, Spain, December 15th, 2017)

- 2017Prepare the final roadmap including the inputs from the new experts and actualize the mid-term roadmap technologies

Business opportunities for Energy autonomous IoT

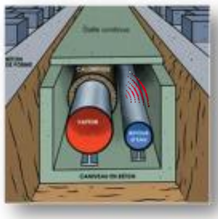
- **Home automation & Malls**:

Detect any change in the environment:
door & window opening, control of light & heat in rooms, movements, occupancy, customers traffic in malls…




- **Monitoring**:

Heat distribution to detect pipes leaks, industrial monitoring to detect anomalous variations (temperature, vibrations, movement…)



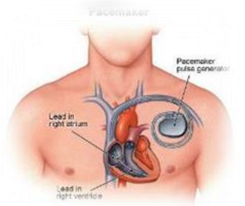

- **Transport**:

Containers & freight wagon Identification, anomalous temperature on trailer breaks…

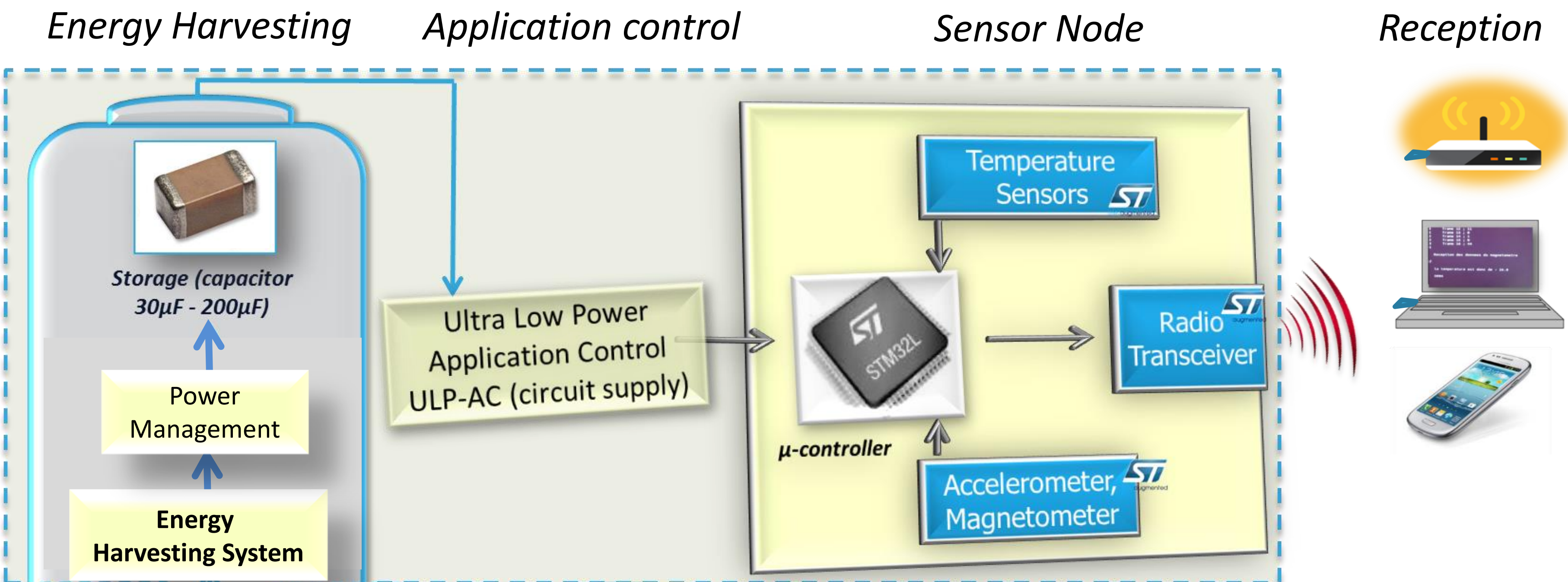

- **Wellness**:

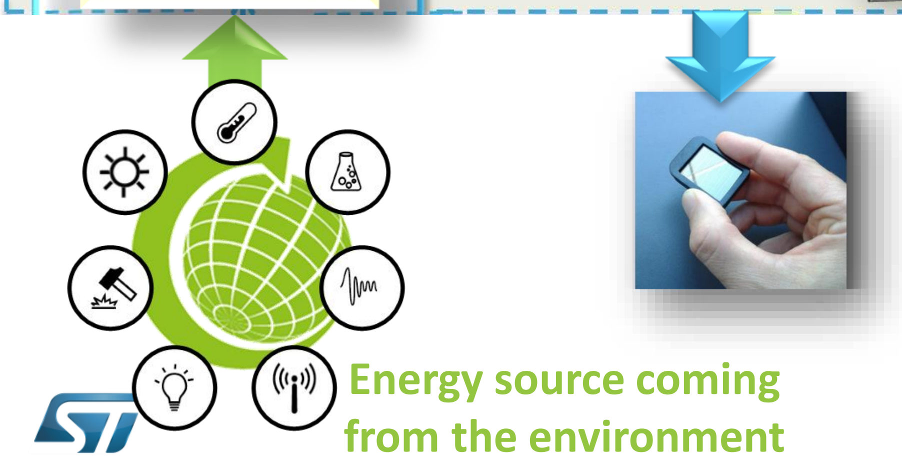
Activity monitoring for dependent people at home, intelligent ergonomic seats...



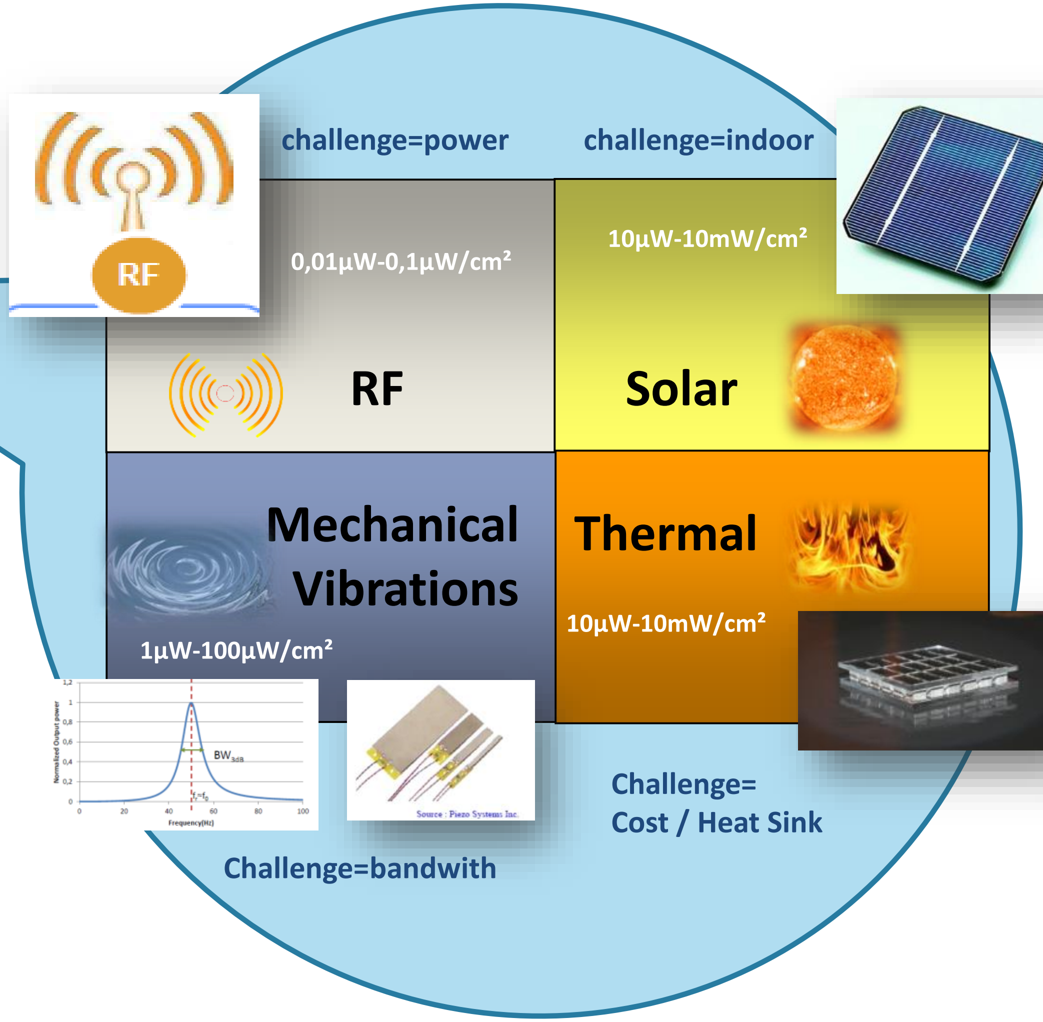


Example of System for autonomous Sensor Node





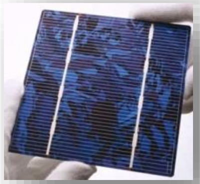
Environment Harvesting: different energy sources & performances

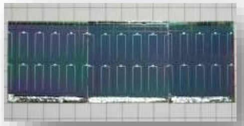


- Harvester Power can vary from 0.1µW up to 10mW/cm² depending on technologies and available energy sources
- But each approach has pro & cons -> **No Universal solution**
- Each use-case is particular
- **Energy is not always available**
- **Conventional approach= replace battery with energy harvester -> FAIL!**

Photovoltaic: Indoor performances for IoT

Technology	Efficiency under sun light at 1000 W/m²		Max available power under fluo light à 1000 lux (3)	Substrat	Cost
	Best performance for lab cell(1)	Commercial module or cells(2)			
c-Si	25.0%	12-16% (module)	≈20-60 µW/cm²	c-Si	High
c-Si back side contacted		20% (module)		c-Si	High
a-Si	10.1%	5-7% (module)	≈ 35 µW/cm²	Glass	Low
Double junction a-Si/µc-Si	11.9%	8-10% (module)		Glass	Low
CdTe (Cadmium Telluride)	16.7%	10-12% (module)		Glass	Low
CIGS (copper indium gallium selenide)	19.6%	8-13% (module)	≈30-35 µW/cm²	Glass, metal, plastic	Low
Triple junction GaInP/GaAs/Ge	32.0%	25-30% (cell)		c-Ge	very High
Organic	8.3%	1-2% (module)	≈10-20 µW/cm² (module)	Plastic	Low





- A market dominated by the Si (mature technology):
  - For *outdoor* applications, crystalline Si solar cells
  - For *indoor* applications, amorphous Si photovoltaic cells

NEIRED targets: (Indoor 300lux)

5y	10y
>20µW/cm²	>25µW/cm²

➢Define standard procedures for indoor photovoltaic cells characterization

➢Design and optimize structures for outdoor or/and indoor light (sensitivity to light sources, flexibility if necessary, Thin films, nanostructured, multi-junction solar cells, cost…)

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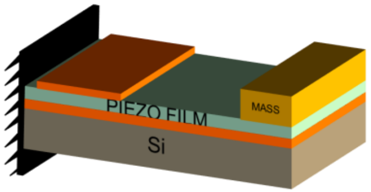
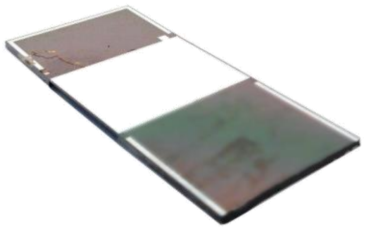
Mechanical energy harvesting: vibrations with Piezoelectric conversion

Resonant cantilever covered by a piezoelectric layer and a inertial mass attached.
As the cantilever is bent, strain is transferred to the piezo layer
-> asymmetric charge distribution (Voltage)





➢Consider new sustainable materials & piezo-composites to avoid lead based piezoelectrics

- **Efficient material : AlN thin film**

Mech. vibrations	Power
0,07G @155Hz	28µW
0,2G @155Hz	150µW

T. Ricart et al. Macro energy harvester based on Aluminium Nitride thin films, Proc. Ultrasonics 2011

- **Efficient piezoelectric structure**
- Improved cantilever shape
- High coupling bulk materials

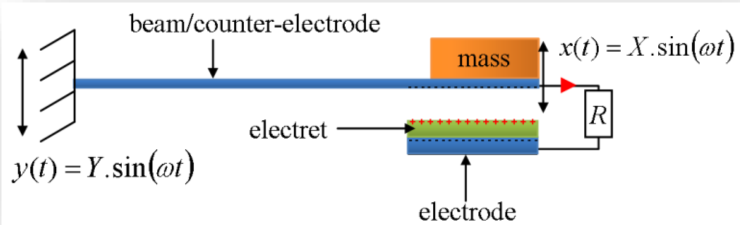
Issue=bandwith

NEIRED targets:

MEMS devices (f<300Hz, G<0.5)	5y	10y
Volume power density (mW/cm^3)	1	1.5

Mechanical energy harvesting: vibrations with Electrostatic conversion

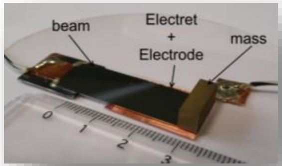
- **Electret-based harvesters**



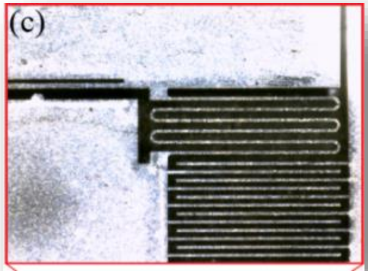
One electrode of the capacitor is charged (electret, tribolelectricity…) and the relative movement between the two electrodes causes a variation of electric capacity
-> charges movement

Mech. vibrations	Power
0,1G @50Hz (*M*=5g)	50µW

S. Boisseau et al., Cantilever-based electret energy harvesters, Smart Materials and Structures, 2011



- **MEMS electret-based harvester**



- Electrostatic converter with a comb-drive structure

Mech. vibrations	Power
2G@50Hz	1µW
2G@430Hz	6,6µW

Y. Lu et al., Proc. MEMS, 2016

- Enlarge frequency bandwidth (>50Hz)
- Reliability of materials
- Develop flexible/low cost approaches

NEIRED targets:

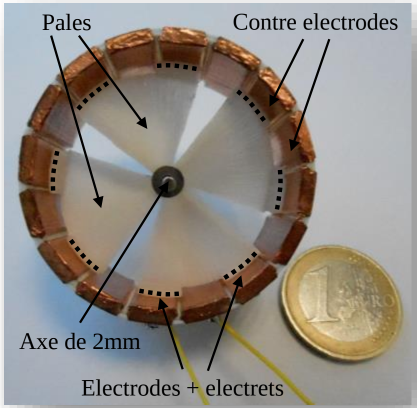
Volume power density (mW/cm^3) @1G	0.5mW/cm^3 (100Hz)	1mW/cm^3 (100Hz)

Mechanical energy harvesting: Rotations with Electromagnetic conversion

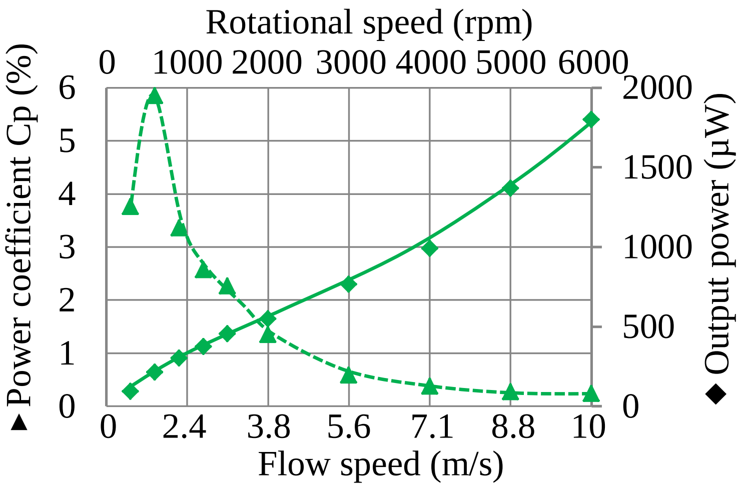
Water flow

Flow	Power
6L/min	0,2mW
20L/min	10mW

Air flow



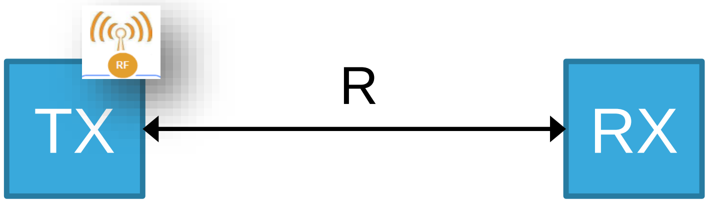
Ø4cm



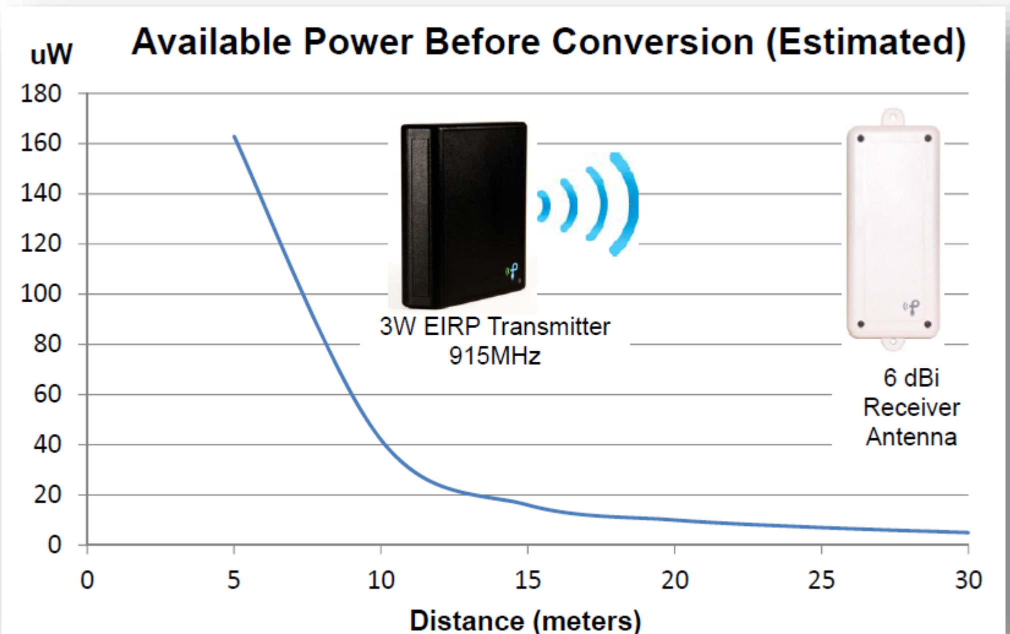
M. Perez et al., A cm scale electret-based electrostatic wind turbine for low-speed energy harvesting applications, Smart Materials and Structures, 2016.

RF Energy Harvesting

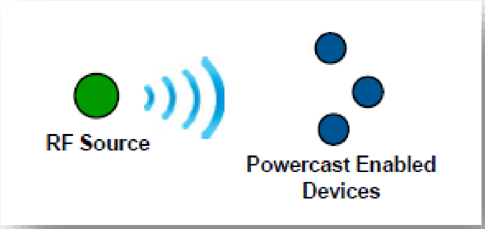
- Friis equation: transmitted power α $1/R^2$



$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi R)^2}$$



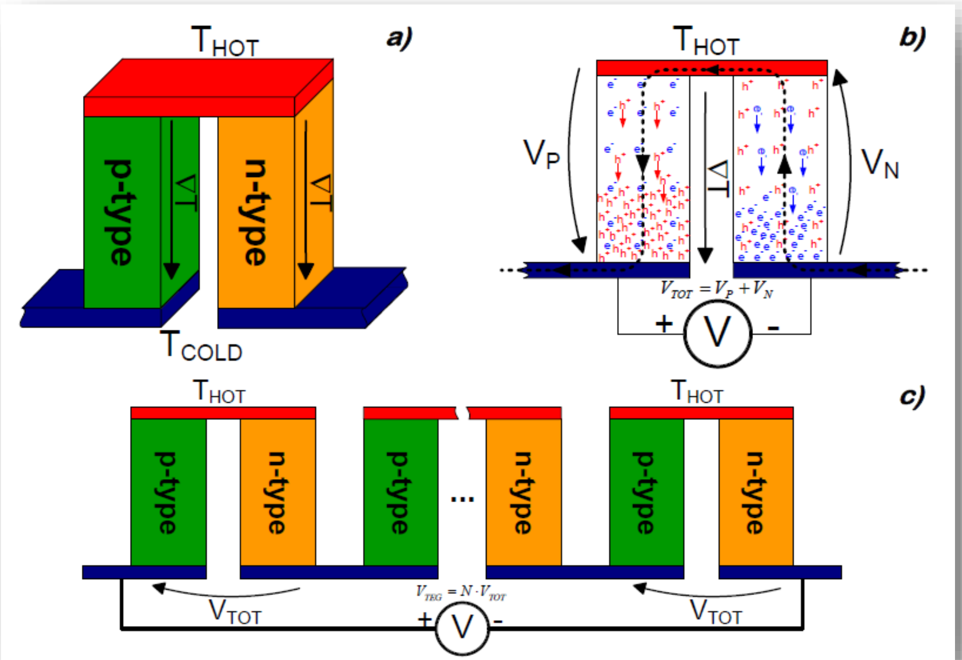
- **Very low harvested power with ambiant Harvesting**
- **10-100nW/cm²**
- **More applications for remote power use cases**

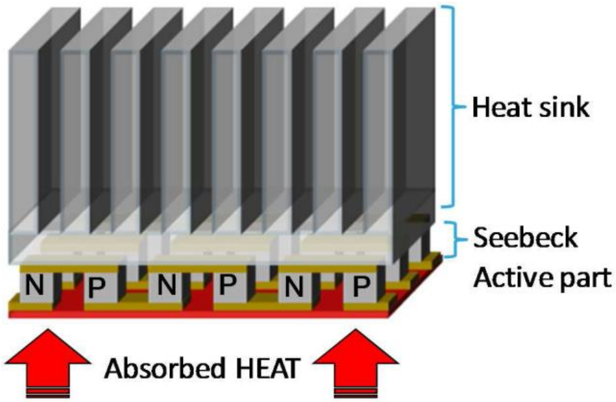


Source: powercast

Thermal Energy Harvesting: Thermoelectric Devices

Thermoelectric generator





O.Puscasu, S.Monfray, IEDM 2012

N Thermocouples

Electrically in series

Thermally in Parallel

- Seebeck effect: generation of a voltage along a conductor when it is subjected to a temperature difference: Heat Sink is mandatory

- Low voltage provided: elevator circuit needed

Industrial, Home automation, Body…

- **Material performance given by figure of merit *ZT***

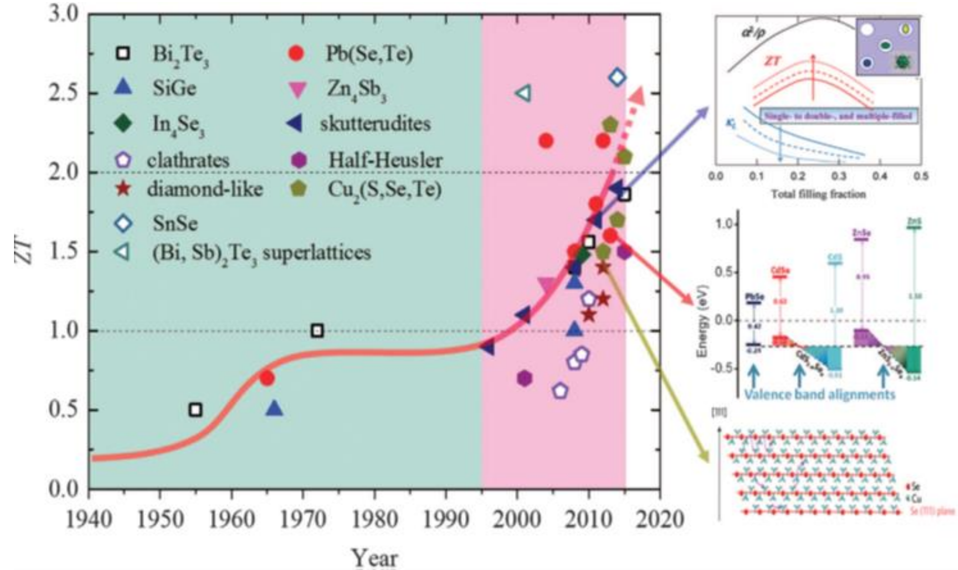
Seebeck Coef.

Electrical conductivity

$$ZT = \frac{\sigma \times \alpha^2}{\lambda} T$$

Thermal conductivity

Prediction for ZT>3 in the range 5-10 years



Nature.com, 2016

REVIEW ARTICLE OPEN

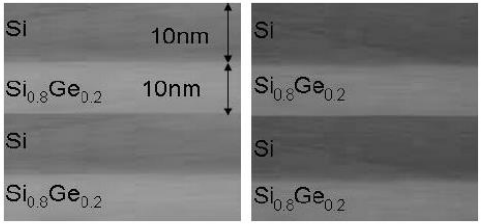
On the tuning of electrical and thermal transport in thermoelectrics: an integrated theory–experiment perspective

Jiong Yang[1], Lili Xi[2], Wujie Qiu[2,3], Lihua Wu[1], Xun Shi[2], Lidong Chen[2], Jihui Yang[4], Wenqing Zhang[1,2], Ctirad Uher[5] and David J Singh[6]

Improving ZT:

Phonon scattering:

- Reduce phonon scattering by nano particles in semiconductor matrix.
- Phonon scattering at Si/SiGe layers interfaces

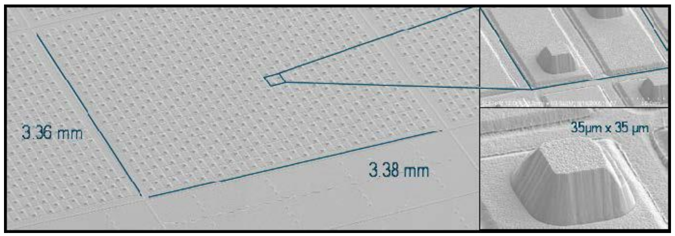


Thermal Energy Harvesting: Thermoelectric Devices

P_{max} α ΔT^2

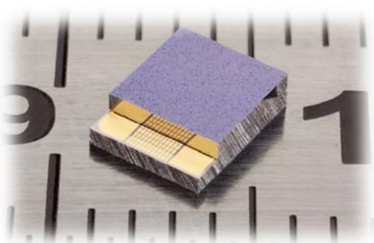
Pmax normalized in $mW/K^2/cm^2$

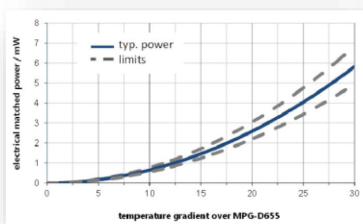
State-of-the-art ZT~1



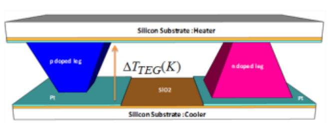
h=40µm Micropelt MPG D751 P=14mW ΔT=30K
S=0.114cm² P=123mW/cm² **P=0.13 mW/K²/cm²**

h=40µm





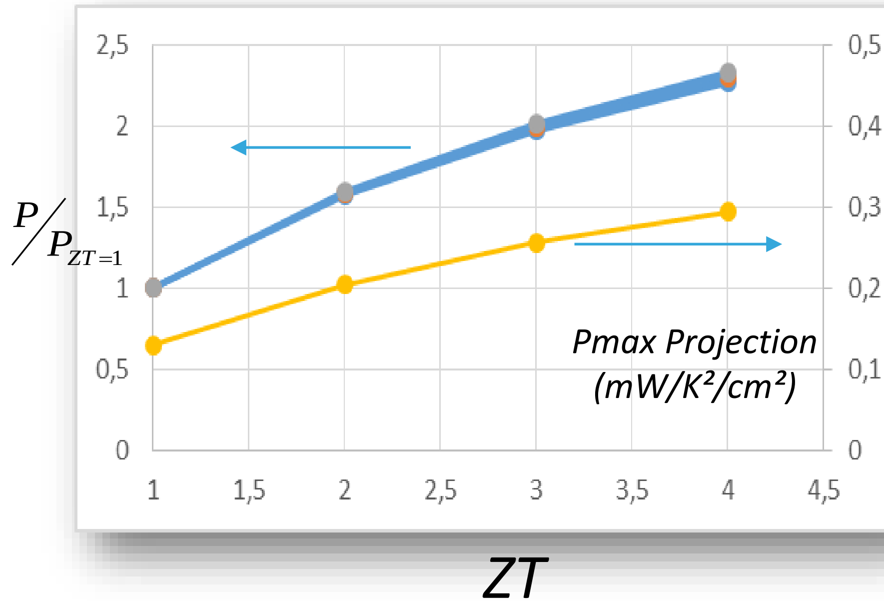
Micropelt MPG D655 P=6mW ΔT=30K
S=0.067cm² P=90mW/cm² **P=0.1 mW/K²/cm²**



h=40µm

Projections for ZT=2, 3, 4

(same fixed Heat flux) *based on MPG D751 data*



Thermal Energy Harvesting: Thermoelectric Devices

NEIRED targets:

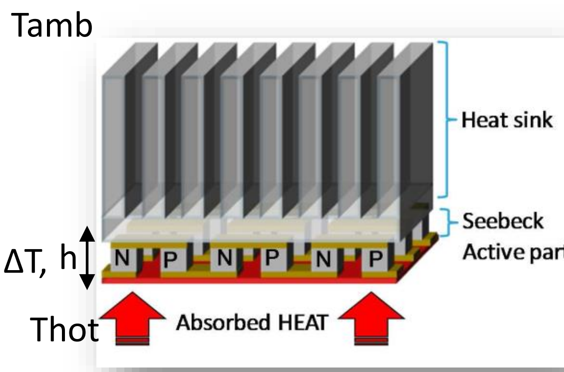
Projections allows Power output performances above 0,15mW/K²/cm²

Be aware!

ΔT corresponds to the temperature difference along the TEG, not the difference between Thot and Tambient

In order to maintain 30K of ΔT, a huge Heat Sink is mandatory!

Ex:



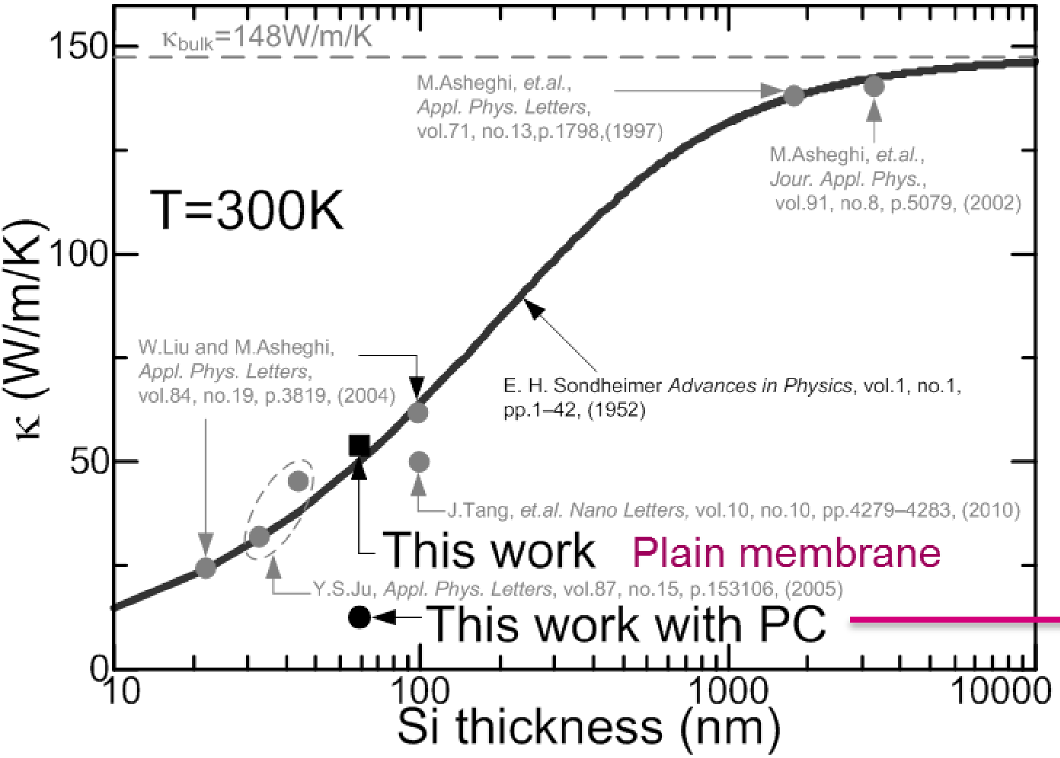
hconv=10 (ambient air convection), ΔT~0,1K (h=10µm)
hconv=10 (ambient air convection), ΔT~0,3K (h=40µm) -> P= 13µW/cm²
hconv=100 (>mm scale Heat Sink), ΔT~0,6K (h=10µm)
hconv=100 (>mm scale Heat Sink), ΔT~2,3K (h=40µm) -> P= 800µW/cm²
hconv=1000 (>cm scale Heat Sink), ΔT~5,4K (h=10µm)
hconv=1000 (>cm scale Heat Sink), ΔT~18,6K (h=40µm) -> P= 52mW/cm²

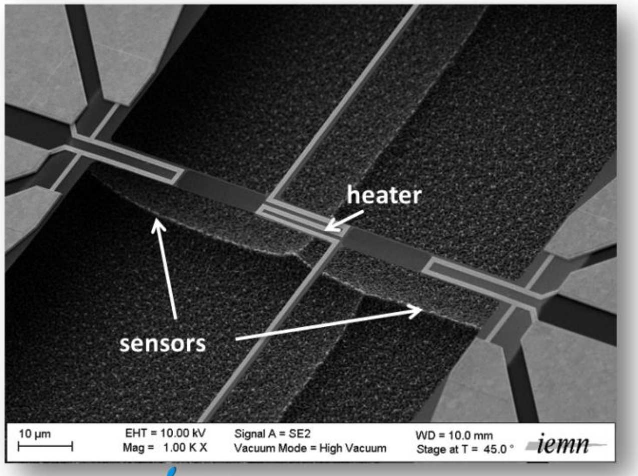
Thot=400K
Tamb=300K

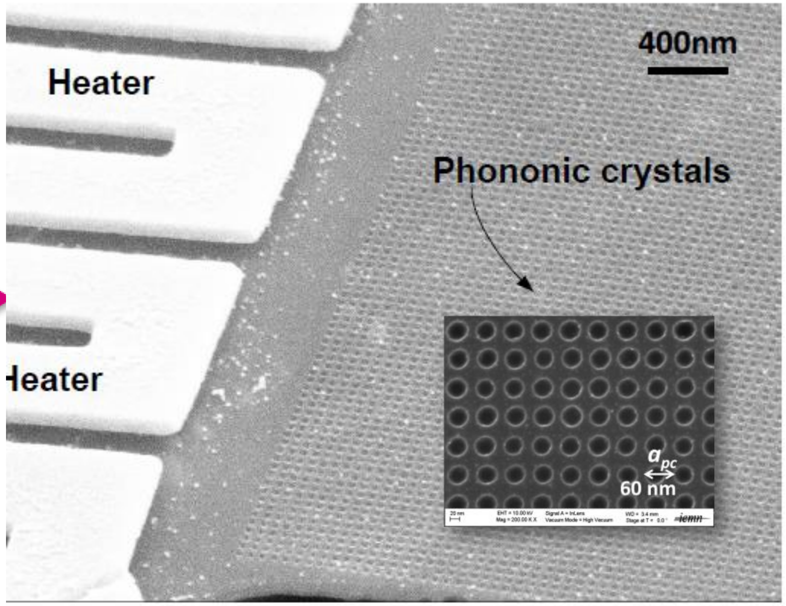
- Nanostructures for improving ZT
- Consider new sustainable materials to avoid Bi_2Te_3.
- Develop new thermal energy approaches (non Seebeck): Phase change…

Phononic Engineering: Evaluation of performances of Si based TEG

Patterned Si membranes with a_{pc} < Λ_{phonon} (mean free pass) to additionally reduce the thermal conductivity







M. Haras, Materials Letters
V. Lacatena Applied Phys. Lett.

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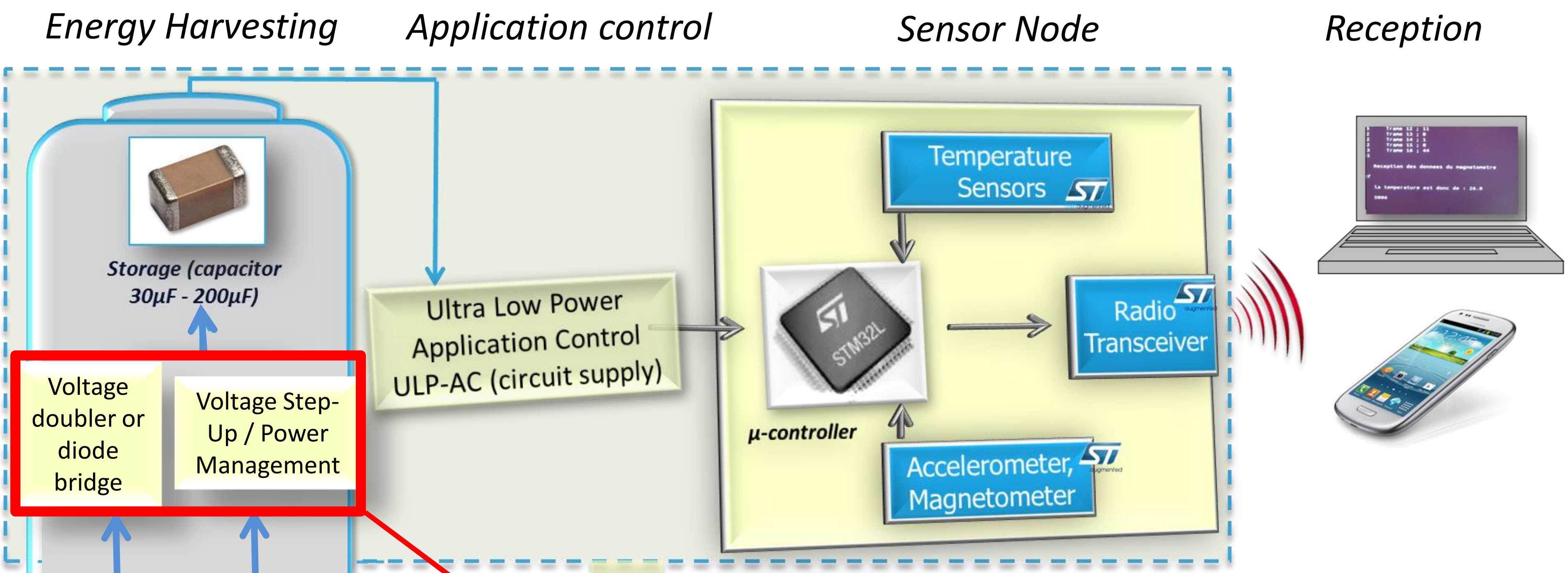
Application of ENERGY HARVESTING for IoT

System optimization to work with very few level of energy

System optimization



Multi-harvesting compatibility
-piezo (vibrations & shock)
-piezo (thermal with bimetal)
-electromagnetic
-solar
-TEG

When few power is available (below 3µW), simple and passive circuits are the best solutions instead of Power Management Circuits?

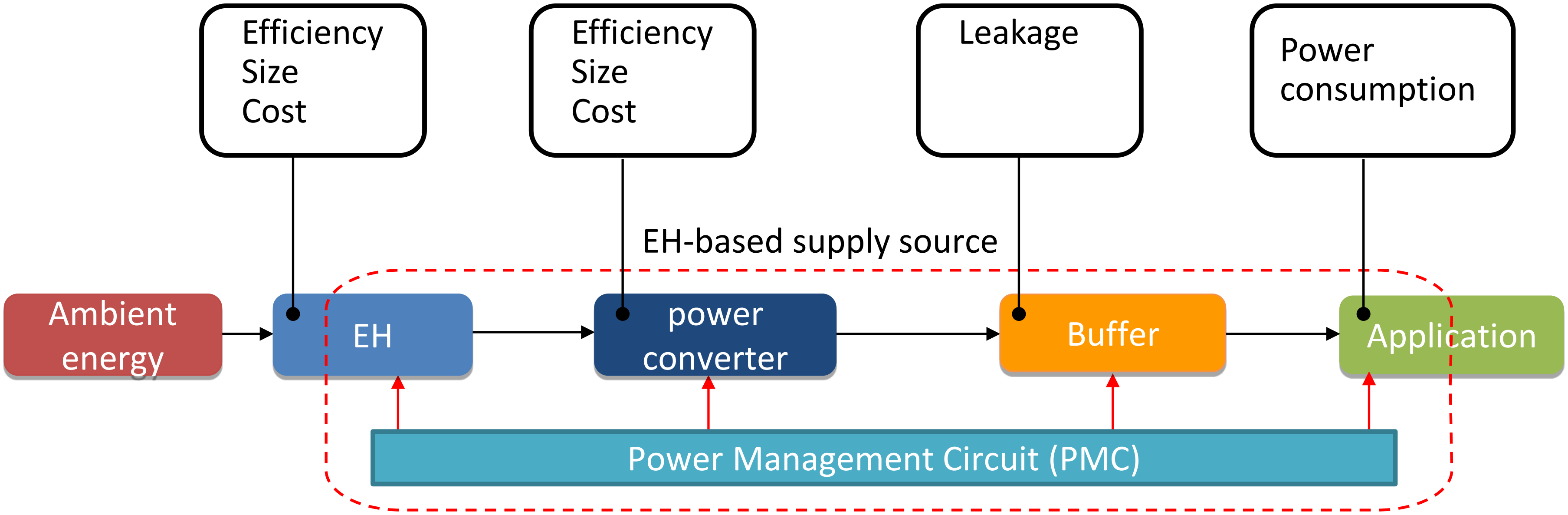
Ultra low power circuits needed!

NEIRED targets:

Medium term: 5+ : P_{IN} < 1µW (70% eff.), V_{IN} < 100 mV, Max. V=20V.

Long term: 10+ : P_{IN} < 100nW (80% eff.), V_{IN} < 10 mV, Max. V=10V.

Optimization of the whole energy harvesting chain!



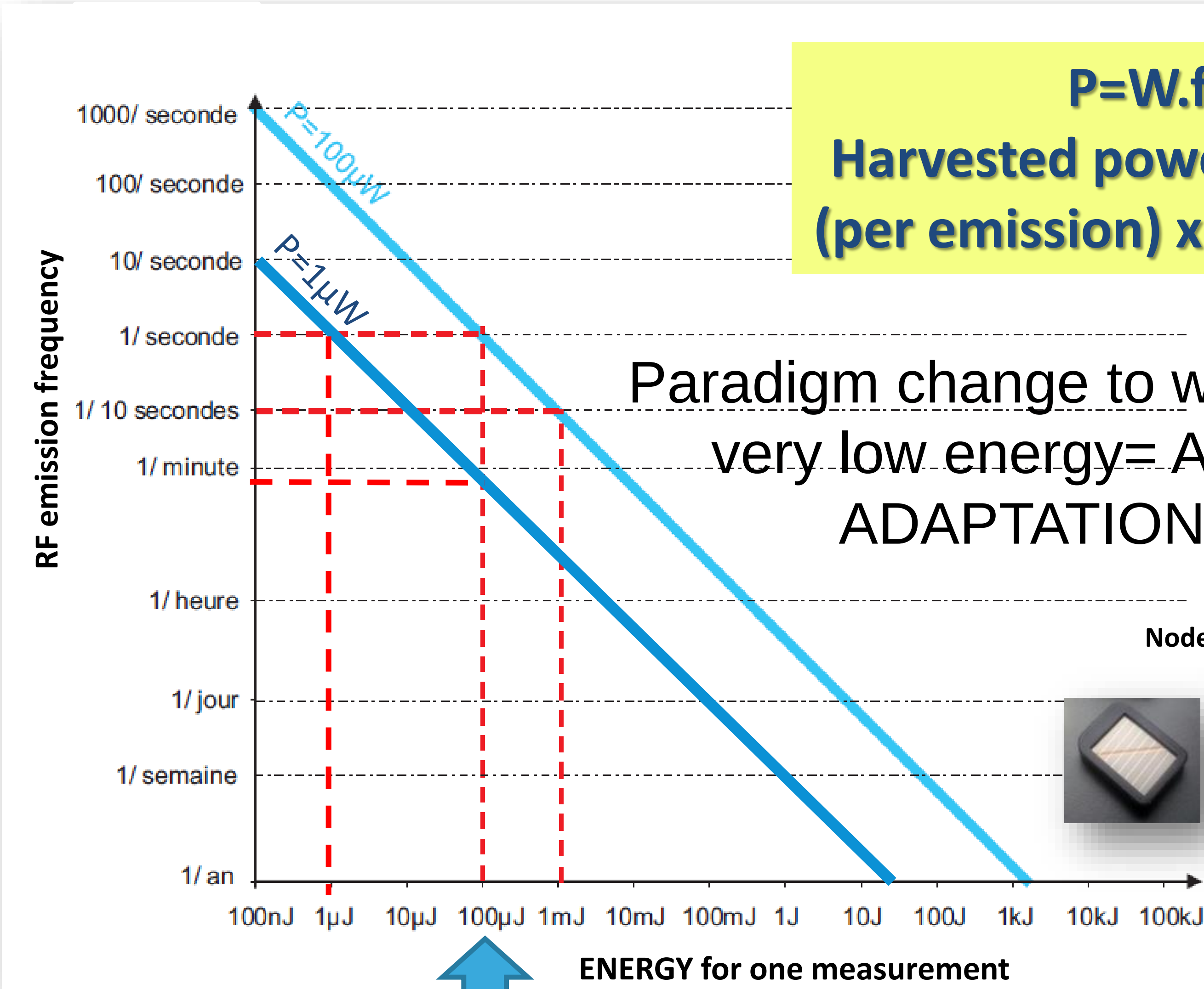
- Define trade-offs (intrinsic power consumption, efficiency, performance): energy-aware power design of circuits.
- Size reduction of inductors, planar alternatives (piezoMEMS), inductor-less converters

Asynchronous autonomous Sensor: the paradigm to work with very low energy

P=W.f

Harvested power=Energy (per emission) x frequency

Paradigm change to work with very low energy= AUTO ADAPTATION



Node powered by solar

Energy needed to measure & send a t° with IEEE.802.15.4 protocol

General Recommendations

- The development of applications is the key. IoT and energy harvesting are application-driven today, so projects should mainly focus on the development of a complete application (from harvesting to the use case).
- The improvement of the EH performance/efficiency is as important as the development of "green" materials. Replacing toxic/rare materials used nowadays (lead based piezoelectrics, Bi_2Te_3 for thermoelectrics).
- The use of nanotechnologies is foreseen to increase the performance of all the concepts in general.
- Flexible and low cost approaches for wearable applications should be developed as well.
- SYSTEM OPTIMIZATION is the MOST IMPORTANT WAY to work with ENERGY HARVESTING
- Power management circuit consumption is key