ENERGY FOR CONNECTED OBJECTS

Energy Harvesting and Wireless Power Transfer

5ISS - I5SSEC11

Communicating systems for IoT

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Learning objectives

- Know how to power a connected object:
    - without wires
    - without batteries
    - with ambient energy harvesting
    - with wireless power transfer
    - and with (super)capacitor

- Know the good practices for the design of a low-power wireless connected object:
    - Hardware (components, routing, etc.)
    - Software (initialisation, architecture, etc.)
    - Electromagnetic (wireless communication, EMC, etc.)

- Know the state of the art of solutions to power a connected object.

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Conduct of the course

- 4 lecture sessions (5 hours)
  - From general concepts...
  - ... to the specific cases of wireless power transfer based on radiated electromagnetic waves, ...
  - ... through the energy buffers, ...
  - ... the wireless communication technologies, ...
  - ... and the most usual ambient energy harvesting techniques, ...
  - ... but also the most promising optimisation techniques, ...
  - ... and even more.

- 2 laboratory sessions (5 hours 30)
  - Design of a connected object emulator
  - Characterisation of a radiated electromagnetic energy harvester
  - Powering the emulator by ambient electromagnetic energy harvesting and by electromagnetic wireless power transfer

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Ressources

- Georgiadis A., Collado A., and Tentzeris M.M., "Energy Harvesting: Technologies, Systems, and Challenges," Cambridge Univ. Press, 2021.
- Peruzzi G., and Pozzebon A., "A review of energy harvesting techniques for Low Power Wide Area Networks (LPWANs)," Energies, vol. 13, no. 13, p. 3433, 2020.
- Ma D., Lan G., Hassan M., Hu W., and Das S. K., "Sensing, computing, and communications for energy harvesting iots: A survey," IEEE Comm. Surveys & Tutorials, vol. 22, no. 2, pp. 1222-1250, 2019.
- Boyer A., "Low Power Software for IoT", INSA Toulouse course for 5ESPE, 2021.
- Dilhac J.M., "Sources d'énergie, stockage & récupération d'énergie", INSA Toulouse course for 4AE-SE, 2021.

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Evaluation

Lab report and attendance

A report per group to be included in the portfolio.

A group is made up of two people.

The report should include:

- an introduction with the context.
- a summary of all the work carried out during the sessions (explanations of the concepts covered, justification of the choices made, problems encountered and solutions implemented, etc.).
- a conclusion with an analysis of your work and of the knowledge and skills developed during this course.

Study of the energy autonomy in your innovative project

Investigate the possibility to use battery-free systems in your innovative project based on ambient energy harvesting and/or Wireless Power Transfer.

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Terminology

Connected objects *(or communicating objects)*

Objects able to communicate, *i.e.* to send and receive information

Examples

Satellite, aircraft, car, UAV, rocket, secure camera, gate, shutters, lock, parking meter, ATM, laptop, smartphone, smart watch, headphones, hoover, electricity meter, weather station, pacemaker, etc.

Cyber-Physical Systems (CPS)

Networks able to connect the physical and digital worlds

Internet of Things (IoT)

A global cyber-physical system based on connected objects

Terminology

Communication

Transmission and reception of something (material, information, energy) from one point to another or others

Wireless communications

Communications that do not require wires

Telecommunications

Communication of information by means of electromagnetic signals

Radiocommunications

Telecommunication using radiated electromagnetic waves

Terminology

Embedded systems

Electronic systems...
driven by software for specific tasks...
which are fully integrated with the system it controls...
and which usually have limited resources (data storage, energy, processing, etc.)...

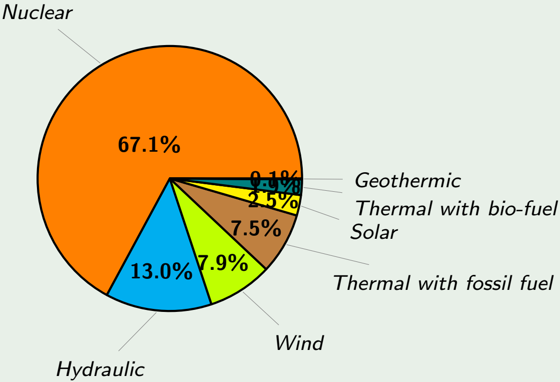
Connected objects (and embedded systems) are not necessary wireless!
But these require direct current (DC) electrical power to operate!

Mains supply

- ✔ Almost unlimited source
- ✘ Wire solution, not available everywhere, no mobility

In France, in 2020

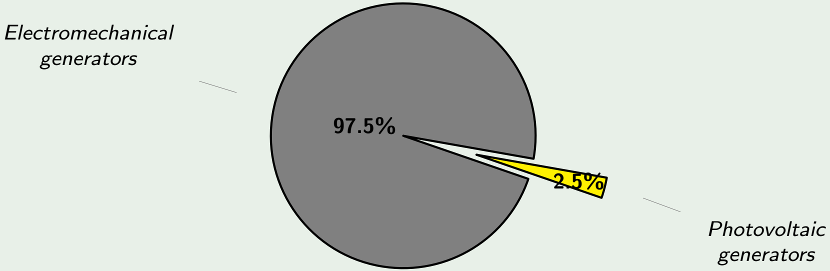
500.1 TWh



Thermal with fossil fuel: coal (0.3%), oil (0.3%), gas (6.9%)
Thermal with bio-fuel: biogas (0.6%), biomass (0.5%), non-renewable household waste (0.4%), renewable household waste (0.4%)

In France in 2020

500.1 TWh



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Direct storage of electricity

Electricity is difficult to store in electrical form!

- Electricity can be stored as current in inductors, *i.e.* in an **electrodynamics** form, but for short times (mainly used for transient storage in static converters).
- Electricity can be stored as voltage in capacitors, *i.e.* in an **electrostatic** form, but for limited times.

Indirect storage of electricity

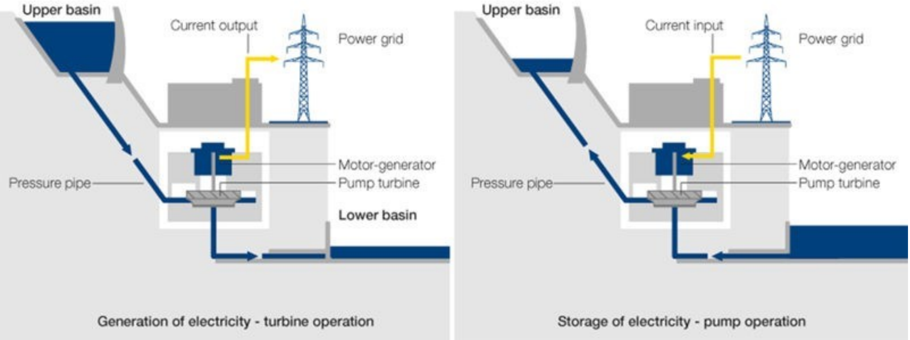
Electricity can be easily stored in chemical and physical forms!

- Fuel cells, batteries, supercapacitors, and capacitors!
  - ✔ Wireless solution, usable almost everywhere, with mobility
  - ✘ Limited source (even if rechargeable)
- These technologies are very old at the microelectronics scale.

Electricity can be stored in the form of:

- gravitational potential energy in the case of hydraulic dams: pumped-storage hydroelectricity
- heat: thermophotovoltaic systems and thermoionic converters
- mechanical motion: inertial wheel

Pumped-storage hydroelectricity



Physical quantities

Energy

Is expressed in Joules (J (SI), or $kg \cdot m^2 \cdot s^{-2}$) or in Watt·hour (W·h).
Energy = Power · Time

Power

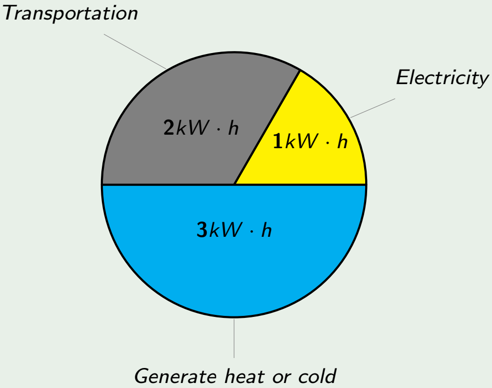
Is expressed in Watts (W (SI), or $kg \cdot m^2 \cdot s^{-3}$)
Power = Energy / Time
Power = Voltage · Current
Average_power = Σ [Instantaneous_power · Time] / Full_time

Capacity

Is expressed in Joules (J (SI), or $kg \cdot m^2 \cdot s^{-2}$) or Amps · hour (A · h)
Capacity = Nominal_voltage · Current · Time
Capacity = Current · Time

Putting into perspective

On average, worldwide, for 6 $kW \cdot h$ consumed:



Putting into perspective

1 $kW \cdot h$ allows:

- To melt 1 kg of water ice.
- To drive 1 or 2 km by car.
- To drive 200 m by truck.
- To transport a person by plane for 1 or 2 km.
- To run a class 1 refrigerator for 2 days.
- To light a house for an evening.
- To heat a room for 1 hour.

Parameters to consider

Parameters

Technology	Each system requires specific use conditions (e.g. for discharge and charge).
Recycling	Issue now unavoidable.
Capacity	Expressed in J or $A \cdot h$
Energy density	Expressed in $J \cdot kg^{-1}$, $J \cdot l^{-1}$, $W \cdot h \cdot kg^{-1}$, or $W \cdot h \cdot l^{-1}$
Power density	Expressed in $W \cdot kg^{-1}$, or $W \cdot l^{-1}$
Lifetime	A function of various parameters.

Parameters to consider

Parameters

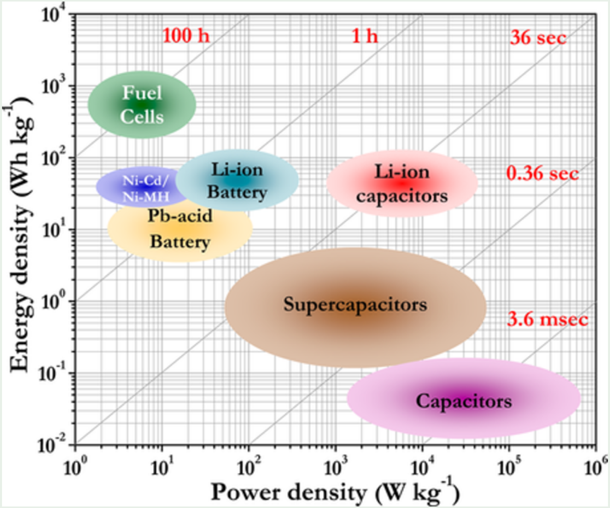
Use voltages	Expressed in V. Differ in open circuit and on load. Are also a function of the series/parallel arrangement of the basic cells.
Electrical Serial Resistance (ESR)	Expressed in Ω. Limits the efficiency and the power density.
Self-discharge	Only losses.
Residual energy	Cannot be used.
Use temperatures	Limit the use.
Storage time	A function of various parameters.

Ragone plot

Useful to compare the performances of energy storage technologies.
The different technologies are placed in a plane according to their performances in terms of **stored energy density** (ability to store a large amount of energy) and **available power density** (ability to redeliver the stored energy quickly).
Both mass and volume densities can be considered.

Ragone plot

Power density versus energy density



Power density versus energy density.

Putting into perspective

Primary lithium battery	$2\ MJ \cdot kg^{-1}$
TNT	$4.6\ MJ \cdot kg^{-1}$
Petrol	$50\ MJ \cdot kg^{-1}$
Liquid hydrogen	$140\ MJ \cdot kg^{-1}$
Nuclear fission	$80\ TJ \cdot kg^{-1}$
Nuclear fusion	$330\ TJ \cdot kg^{-1}$
$E = m \cdot c^2$ (matter and antimatter)	$90\ PJ \cdot kg^{-1}$

Considering the energy density of TNT (only five times that of a primary lithium battery), it is unlikely that technological progress will go very far on this parameter.

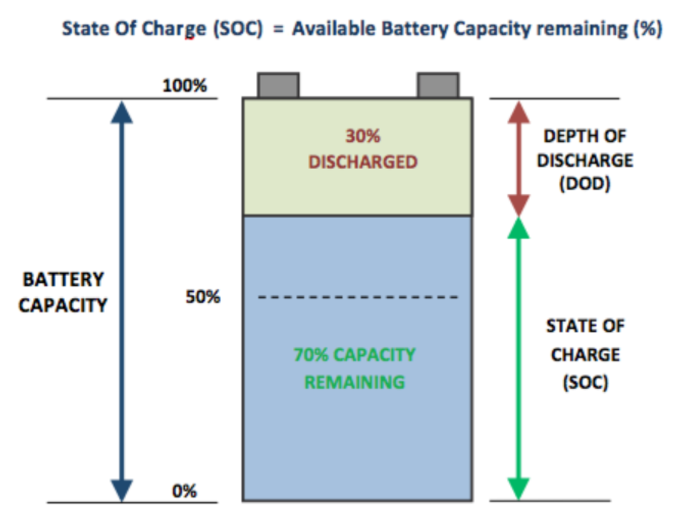
Electrochemical batteries

Based on an oxidation-reduction (redox) reaction.
Composed of an anode, a cathode, an electrolyte and a separator.
Store energy within a volume.

Have normalized sizes (among hundreds), including those standardised by the *American National Standards Institute* (ANSI) and the *Commission Electrotechnique Internationale* (CEI):

CEI battery type	ANSI battery type	Nominal voltage (V)	Rates capacity ($A \cdot h$)	Voltage cut-off (V)	Rated load (Ω)	Discharge C-rate
6(L)R61	9V	9	0.570	4.8	620	0.025
(L)R03	AAA	1.5	1.150	0.8	75	0.017
(L)R6	AA	1.5	2.870	0.8	75	0.007
(L)R14	C	1.5	7.800	0.8	39	0.005
(L)R20	D	1.5	17.000	0.8	39	0.0022

State of charge



Discharge (and charge) rate

The (dis)charge rate (C-charge) -noted C- is defined as the ratio of the (dis)charge current (A) to the battery capacity ($A \cdot h$), and is expressed in h^{-1}.

E.g.: for a battery of 1.6 $A \cdot h$ and a discharge current of 1.6 A, the discharge rate is 1 h^{-1}
A discharge at 0.1 C will correspond to a current of 0.16 A... but unfortunately not usually for 10 hours!

N.B.: Secondary batteries age according to the number of cycles they undergo and the higher the discharge rate, the faster they age.

Fuel cells

Need an external supply, like oxygen and/or hydrogen.

- ✔ Half-generator, half-storage device.
- ✔ Very high energy density.
- ✔ Long lifetime.
- ✘ High cost.
- ✘ Require a specific environment.

Examples

Polymer electrolyte membrane, proton exchange membrane, direct methanol, alkaline, sulfuric acid, phosphoric acid molted carbonate, solid polymer, solid oxide, etc.

Thermal batteries

Use an electrolyte that is solid and inactive at ambient temperatures.
Need a pyrotechnic heat source to start,.
Provide full power in an instant when required.

- ✔ Can be stored for long-time (over 50 years), even in harsh environments.
- ✔ Provide a burst of high power (W to kW) for a short period (a few tens of seconds to more than 1 hour).
- ✔ High energy density.
- ✔ High power density.
- ✘ Single use.
- ✘ Expensive because custom-made.

Examples

Military use...

Primary batteries

Use an electrolyte that is liquid.

- ✔ Very usual.
- ✔ Low self-discharge.
- ✔ High energy density.
- ✔ Low cost.
- ? Recyclable.
- ✘ High electrical serial resistance.
- ✘ Limited lifetime because single use.

Examples

Leclanché type (C-Zn)	Cheapest but prone to electrolyte leaks
Alkakine-Mn	Higher power and energy densities
Lithium (Li)	Best energy density, designed for special purposes
Others	Zn, Mn, Pb, Ni, Li, etc.

Secondary batteries

Use an electrolyte that is liquid.

- ✔ Rechargeable.
- ? Medium self-discharge.
- ? Medium energy density.
- ? Medium cost.
- ✘ Technology specific charge procedure.
- ✘ Limited lifetime because limited cycles.

Examples

Lead-Acid	Very mature. Low cost. Bad use tolerant. Pollutant.
Nickel-Cadmium (NiCd)	Mature. High C-rate. High lifetime. Pollutant.
Nickel Metal Hybrid (NiMH)	Better energy density. Less unstable and. expensive than Li-ion. High self-discharge.
Lithium-ions (Li-ion)	Most recent technology. Best energy density. Environment friendly. Numerous subfamilies.

Charge procedure for NiMH batteries

Complicated charge management: deterioration in case of overcharge (except by a very low trickle current, inferior than 0.05 C).
Traditionally: 0.1 C-rate using a timer. However, does not work well for partially discharged batteries.
In practice: use of a charger that automatically detects the end of charge. But the detection is only reliable (voltage drop of a few mV) for a fast charge of 1 C or even 4 C.
Optimal charger: combines fast charging ($t < 1h$), end-of-charge detection by ($\delta v/\delta t < 0$) (or by the inflection point), noise filtering on the voltage signal, battery temperature monitoring, safety delay, detection of defective batteries.

Charge procedure for Li-ion batteries

Complicated charge management: destruction in case of overcharge (even with a very low trickle current), bad charge procedure, but also deep discharge, use outside the temperature range, incorrect balancing, manufacturing or design defect, etc.

Stage 1: Constant current charge (the voltage rises)

Stage 2: Saturation charge (the voltage peaks and the current decreases). End of charge when the current is inferior than 3 % of the rated current.

Stage 3: Ready, with no current and self-discharge.

Stage 4: In case of batteries permanently connected to a charger: standby mode (occasional topping charge with a small current each time the open circuit voltage falls below a threshold)

It is not recommended to leave the battery connected to the charger when it is also connected to a load.

Li-ion batteries hardly suffer from the lazy battery effect caused by repeated identical partial discharges, which eventually impose a low level.

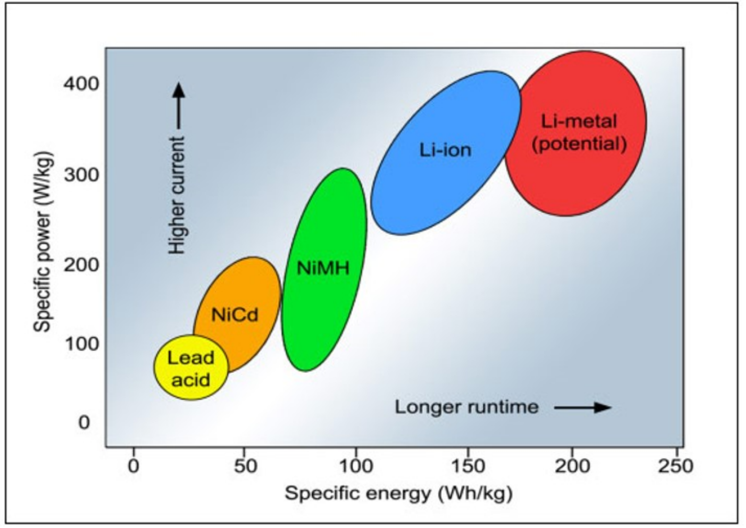
Electrochemical batteries

Comparison of secondary batteries

Specifications	Lead Acid	NiCd	NiMH	Li-ion		
				Cobalt	Manganese	Phosphate
Specific energy density (Wh/kg)	30–50	45–80	60–120	150–190	100–135	90–120
Internal resistance[1] (mΩ)	<100 12V pack	100–200 6V pack	200–300 6V pack	150–300 7.2V	25–75[2] per cell	25–50[2] per cell
Cycle life[4] (80% discharge)	200–300	1000[3]	300–500[3]	500–1,000	500–1,000	1,000–2,000
Fast-charge time	8–16h	1h typical	2–4h	2–4h	1h or less	1h or less
Overcharge tolerance	High	Moderate	Low	Low. Cannot tolerate trickle charge		
Self-discharge/ month (room temp)	5%	20%[5]	30%[5]	<10%[6]		
Cell voltage (nominal)	2V	1.2V[7]	1.2V[7]	3.6V[8]	3.8V[8]	3.3V
Peak load current Best result	5C[9] 0.2C	20C 1C	5C 0.5C	>3C <1C	>30C <10C	>30C <10C
Operating temp.[10] (discharge only)	–20 to 60°C	–40 to 60°C	–20 to 60°C	–20 to 60°C		
Maintenance requirement	3–6 months[11]	30–60 days	60–90 days	Not required		
Safety requirements	Thermally stable	Thermally stable, fuse protection common		Protection circuit mandatory		
In use since	Late 1800s	1950	1990	1991	1996	2006
Toxicity	Very high	Very high	Low	Low		

1 Internal resistance of a battery pack varies with milliampere-hour (mAh) rating, wiring and number of cells. Protection circuit of lithium-ion adds about 100mW.
2 Based on 18650 cell size. Cell size and design determines internal resistance.
3 Cycle life is based on battery receiving regular maintenance.
4 Cycle life is based on the depth of discharge (DoD). Shallow DoD improves cycle life.
5 Self-discharge is highest immediately after charge. NiCd loses 10% in the first 24 hours, then declines to 10% every 30 days. High temperature increases self-discharge.
6 Internal protection circuits typically consume 3% of the stored energy per month.
7 The traditional voltage is 1.25V; 1.2V is more commonly used.
8 Low internal resistance reduces the voltage drop under load and Li-ion is often rated higher than 3.6V/cell. Cells marked 3.7V and 3.8V are fully compatible with 3.6V.
9 Capable of high current pulses; needs time to recuperate.
10 Applies to discharge only; charge temperature is more confined.
11 Maintenance may be in the form of equalizing or topping charge to prevent sulfation.

Ragone plot of secondary batteries



Supercapacitors

Composed of two electrodes separated by a dielectric separator.
Store energy in a electrostatic way.
Store energy within a volume.
Employ a solid dielectric (non-polarized) or a liquid dielectric (polarized).
From a few mF to several F.

- ✔ Long lifetime, expressed in millions of cycles.
- ✔ High power density and low electrical serial resistance.
- ✔ Fast and simple charge.
- ? Best trade-off between energy and power densities.
- ✘ Low energy density.
- ✘ High non-linear self-discharge and residual energy.
- ✘ Non-constant output voltage (required a regulator).
- ✘ High cost.

Can be combined with an electrochemical battery.

Capacitors

Composed of two electrodes separated by a dielectric separator.
Store energy in a electrostatic way.
Store energy within a surface.
Employ a solid dielectric (um-polarized) or a liquid dielectric (polarized).
respectively from pF to µF, and from a few µF to mF.

- ✔ Long lifetime, expressed in millions of cycles.
- ✔ Very high power density and low electrical serial resistance.
- ✔ Fast and simple charge.
- ✔ Low cost.
- ✘ Very low energy density.
- ✘ Very high non-linear self-discharge.
- ✘ Non-constant output voltage (required a regulator).

Technologies: electrochemical or electrolytic, ceramic, aluminium, polymer, tantalum, thin film, etc.)

Supercapacitors and capacitors

Stored energy

$E = \frac{1}{2} \cdot C \cdot (V_{max}^2 - V_{min}^2)$

Charge procedure

A (super)capacitor behaves almost like a voltage generator and when initially discharged is almost equivalent to a short circuit. If it is charged by a converter acting as a voltage generator, the initial current is then limited only by the series resistance of the (super)capacitor. Thus, the converter must be able to handle the current draw, without going into an oscillating state or being destroyed.

The solution may be to charge at constant current, then to regulate the voltage when the maximum permissible voltage at the terminals of the (super)capacitor is reached.

Cells association

Unit cells can be combine:

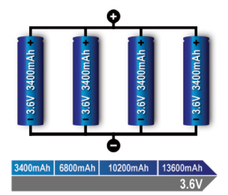
- in series, to increase the nominal voltage

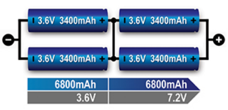
  and/or

- in parallel, to increase the capacity

Cells must be balanced, to compensate the manufacturing dispersion, and also avoid overcharging and deep-discharge.
The SP code is used.

Examples





Balancing for in series configuration

Can be passive (with high value parallel resistances, which impose an high time constant) or active (by adding a follower circuit between the high value parallel resistances and the energy storage devices, which consumes more).

(Super)capacitors association

For a same stored energy (e.g. a 4S2P and a 8S1P), the available energy is not the same. Usually, the configuration with the highest voltage is privileged over the configuration with the highest capacity because providing the more energy. Nevertheless, as the current losses are a function of the voltage, the time of charge will be longest.
For a targeted energy, a trade-off between the lowest capacity (lower residual energy) and the lowest maximum voltage (faster charging time) must be found.

Conclusion

Several solutions: fuel cells, thermal cells, primary cells, and secondary cells which can be assembled in batteries, or supercapacitors and capacitors which can be assembled in banks, but also the possibility to merge supercapacitor and battery to form an hybrid electricity energy storage device.

But always with limited runtime and capacity (recharge or replacement required), but also sometimes non-adapted to harsh, secure or inaccessible environments, and pollutants.

So, why not collecting the energy available in the near environment?

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Ambient energy harvesting

Definition of ambient energy harvesting

Collecting/scavenging/harvesting as much as possible the ambient/environmental/existing energy which is usually only lost/wasted, and convert and/or store it in the electric form.

- ✔ Use of the unlimited and available power
- ✘ Environment dependent, fluctuating, uncontrollable and unpredictable

There are four main types of ambient energies that can be harvested and converted into electricity:

Light   Mechanical (or kinetic)   Thermal   Electromagnetic

Hybrid approaches are also possible.

Even if light can be considered as an electromagnetic wave, a distinction is done here.

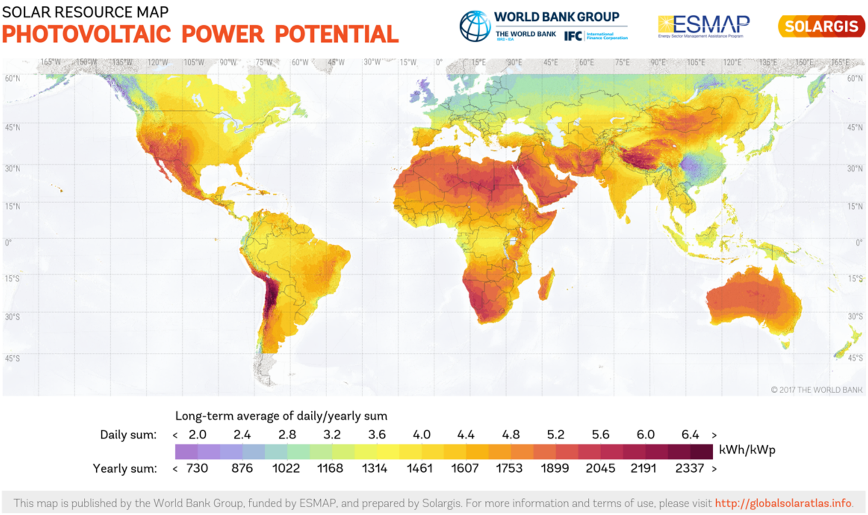
Ambient light energy harvesting

Based on the photovoltaic effect, which converts both solar and artificial lights into direct-current electricity.

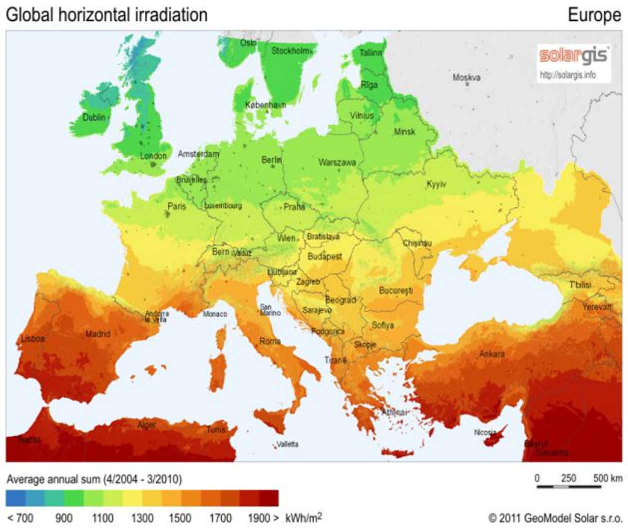
- ✔ Most abundant ambient energy sources (solar and artificial lights).
- ✔ Most common, usual, used and well-known harvesting technique
- ✘ Environment dependent (day-night cycle, location, indoors versus outdoors, etc.).

Harvesters: photodiodes or solar/photovoltaic cells.

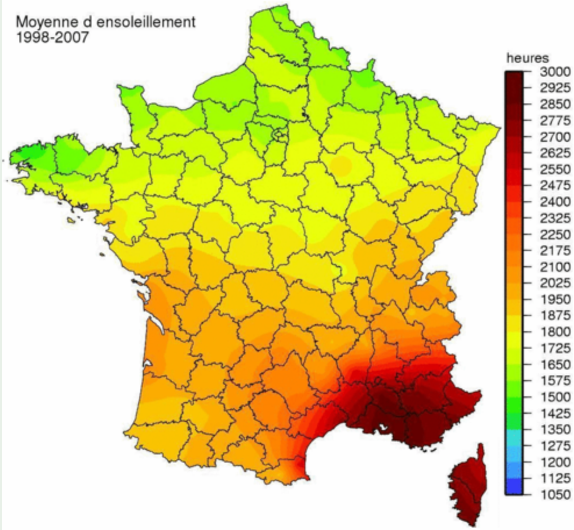
Ambient solar light worldwide



Ambient solar light in Europe



Ambient solar light in France



Efficiency of the photovoltaic cells

According to the properties of the used semiconductor and of the radiating light, the electrical properties vary as well as the efficiency (defined as the ratio between the generated electrical power and the incident light power).

Test conditions: AM1.5G standard at 25°C; i.e. air mass of 1.5 for a global terrestrial solar irradiance distribution, that corresponds to the solar irradiance at the surface of the Earth from a solar zenith angle of 48.18°, that is 1 $kW \cdot m^{-2}$

Efficiency of the photovoltaic cells

Silicon (more common semiconductor for photovoltaic applications) maximum measured and theoretical efficiencies:

- Monocrystalline: 26.7 %
- Multi-crystalline: 22.3 %
- Amourphous: 14.0 %
- Theoretical ultimate efficiency: 44 %
- Detailed balance limit: 29.5 %

Highest efficiency for single cell:

- Gallium-Arsenide (GaAs) thin film solution: 29.1 %

Others technologies: Copper-Indium-Gallium-di-Selenide (CIGS), Cadmium-Telluride (CdTe), Perovskite, dye sensitive, organic, quantum-dots, etc.

Optimization of the photovoltaic cells

Main techniques:

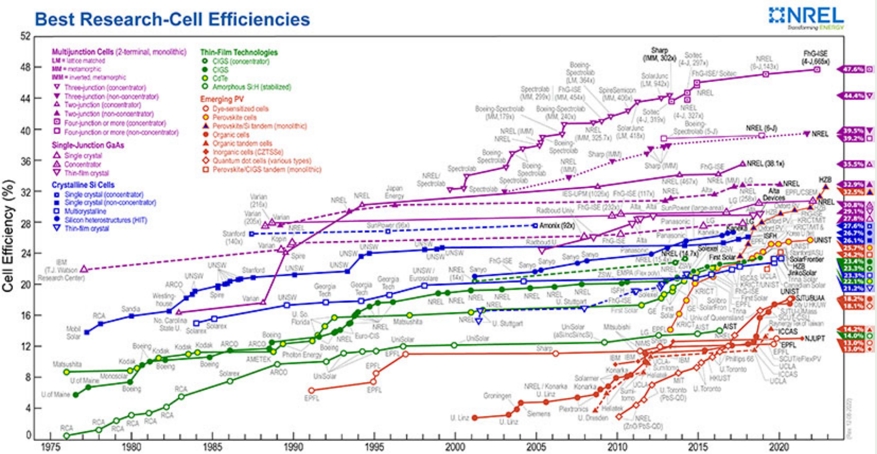
- Light concentrator
- Multijunction or tandem topology
- Network (serial and parallel topologies)

Highest efficiency:

- Six-junction and a concentrator: 47.1 %

Objectives: low cost, high efficiency and eco-friendly.

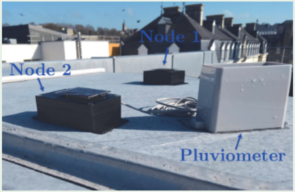
Maximum efficiencies of the photovoltaic cells in function of their technology and over time

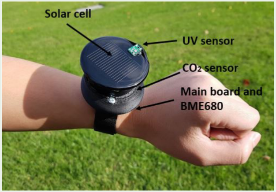


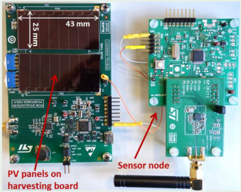
https://www.nrel.gov/pv/interactive-cell-efficiency.html

Ambient light energy harvesting: examples









Ambient mechanical or kinetic energy harvesting

Energy due to the movement of material particles such as vibrations, displacements, fluid flows and pressures (or forces).
Can be harvested with:

- electrostatic (capacitive) and triboelectric transducers (e.g. electret)
- electromagnetic or inductive transducers (e.g. dynamo or alternator)
- piezoelectric transducers

✔ Electromagnetic or inductive transducers widely used, common, usual and well-known for large scale energy production plants.

? Generate direct or alternative current.

✘ Frequencies must be coupled.

✘ Environment dependant (natural frequency, etc.).

✘ Anisotropy.

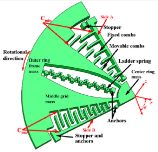
✘ Limited lifetime because of mobile elements.

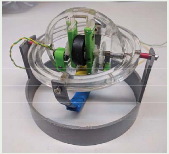
Optimization of the mechanical or kinetic harvesters

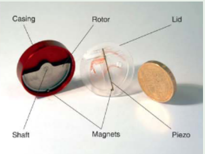
Main techniques:

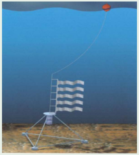
- Hybrid tranducers.
- Use of a cantilever and a adapted mass (vibrations).
- Mechanical or electrical tuning, adaptive tuning or self-tuning.
- Multiband or wideband topology
- Network (serial and parallel topologies)

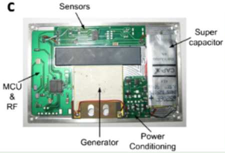
Ambient mechanical or kinetic energy harvesting: examples

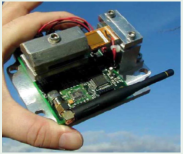


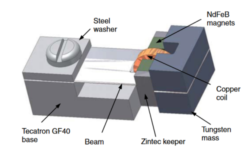


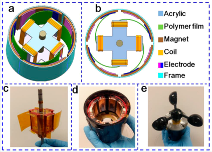












Ambient thermal energy harvesting

Energy due to a variation or a gradient of temperature.
Can be harvested with:

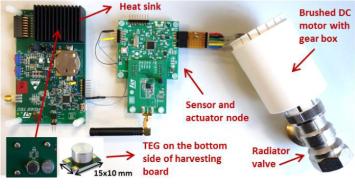
- pyroelectric transducers
- thermoelectrics transducers (Seebeck effect)

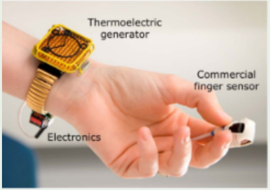
✔ Long lifetime (no mobile element).
✘ Pollutant and availability.
✘ Environment dependant (large temperature gradient required, etc.).
✘ Cost.

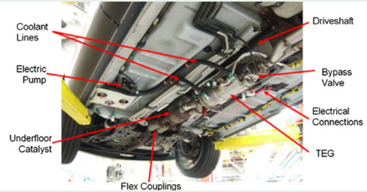
Optimization technique:

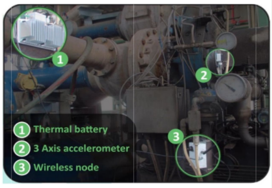
Network (serial and parallel topologies)

Ambient thermal energy harvesting: examples









Ambient electromagnetic energy harvesting

Energy due to electromagnetic fields.

Can be harvested with:

- capacitive transducers (near-field, electrostatic field)
- inductive transducers (near-field, magnetic field)
- radiative transducers (far-field, waves)

✔ High potential.

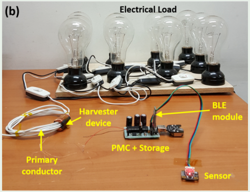
✘ Provide alternative current.

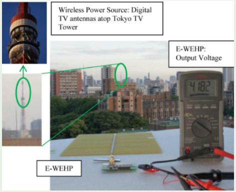
✘ Environment dependant (human activities, high fields required, etc.).

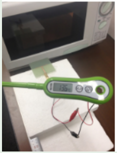
Optimization technique:

Hybrid trandducers
Multiband or wideband topology
Network (serial and parallel topologies)

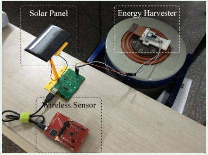
Ambient electromagnetic energy harvesting: examples

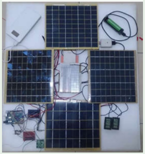


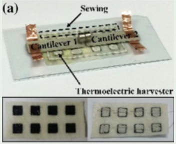


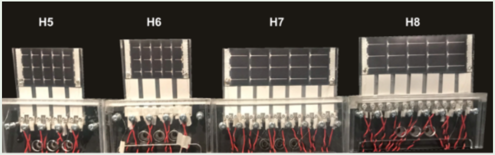


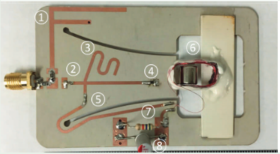
Hybrid transducers: examples

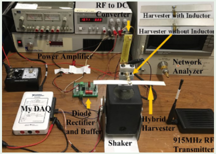


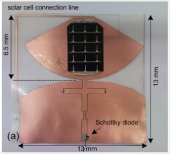


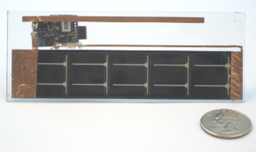


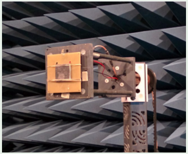












Order of magnitude of the power density for ambient energy sources

Light

Indoors

between 3 and 400 $\mu W \cdot cm^{-3}$

Outdoors

between 150 $nW \cdot cm^{-3}$ and 10 $mW \cdot cm^{-3}$

Mechanical or kinetic

between 1 and 800 $\mu W \cdot cm^{-3}$

Thermal

Variations around 10 $\mu W \cdot cm^{-3}$

Gradient between 10 $\mu W \cdot cm^{-3}$ and 10 $mW \cdot cm^{-3}$

Electromagnetic

between 80 $pW \cdot cm^{-3}$ and 100 $nW \cdot cm^{-3}$

Conclusion

Several solutions: light, mechanical or kinetic, thermal and electromagnetic, which can be combined.

But very low levels of ambient energy, highly environment dependant, low efficiency and fluctuating, uncontrollable and unpredictable.

So, why not wirelessly transferring the required power?

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Definition of wireless power transfer

Remote and wireless transmission of power in order to collect/scavenge/harvest as much as possible the energy provided by the dedicated source(s), and convert and/or store it in the electric form.

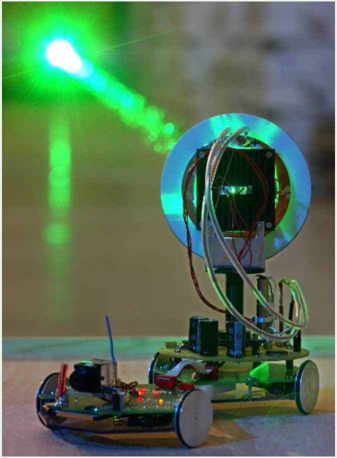
- ✔ Environment independent and low fluctuating, controllable and predictable.
- ✔ Same harvesters as for ambient energy harvesting.
- ✘ Need of controlled and dedicated source(s).

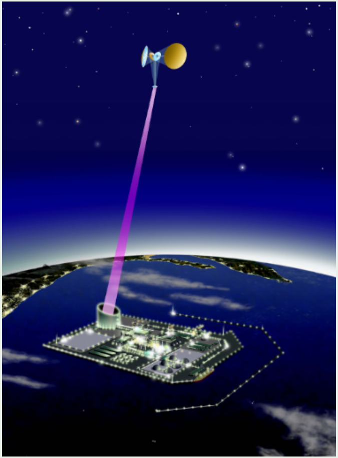
There are three main techniques of wireless power transfer:

Light	**Mechanical (or kinetic)**	**Electromagnetic**
Optical	Acoustic	Capacitive (near-field)
Laser	Ultrasonic	Inductive (near-field)
Infrared		Radiative (far-field)

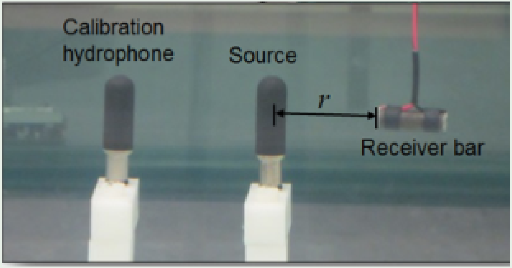
Even if light can be considered as an electromagnetic wave, a distinction is done here.

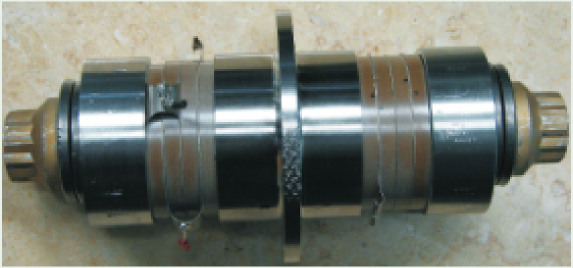
Wireless power transfer of light: examples



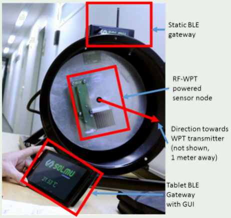


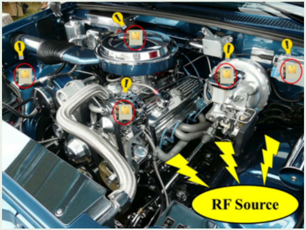
Mechanical or kinetic wireless power transfer: examples

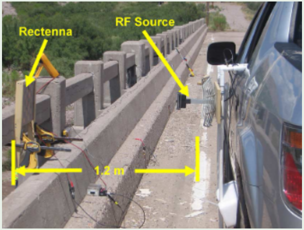




Electromagntic wireless power transfer: examples







Simultaneous Wireless Information and Power Transmission (SWIPT)

- Temporal multiplexing
- Frequenty multiplexing
- Spatial multiplexing
- Power splitting
- Functions discrimination

Optimization of the wireless power transfer

For the harvester:

- Fine tuning
- Use of concentrators
- Multiband or wideband topology
- Networks

For the source:

- Beamforming techniques
- Frequency diverse arrays techniques
- Use of relays
- Optimization of the waveform

Objectives: more efficient, low cost, green generation of power, recycling or biodegradable systems, etc.

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Near-field and far-field

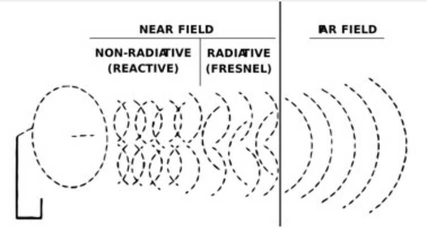
Near-field:

Distances lower than $\frac{\lambda}{2 \cdot \pi}$

Far-field:

Distances higher than $\frac{2 \cdot D^2}{\lambda}$

With λ the wavelength in the propagation medium and D the physical length of the antenna



Near-field and far-field wireless power transfer

Near-field			Far-field	
Capacitive coupling	Non-resonant inductive coupling	Resonant inductive coupling	Radiative (radiofrequency/ microwave)	Laser
		Wireless Power Consortium (Qi) and Airfuel Alliance	Airfuel Alliance	
Electric field	Magnetic field	Magnetic field	Electromagnetic waves	Light
Metal plates forming a capacitor	Coupled inductors	Coupled inductors resonant with capacitors	Rectenna	Photodiode

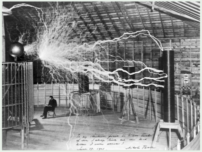
Ambient energy harvesting and wireless power transfer: focus on electromagnetic solutions

Near-field and far-field wireless power transfer

Near-field			Far-field	
Capacitive coupling	Non-resonant inductive coupling	Resonant inductive coupling	Radiative (radiofrequency/ microwave)	Laser
- Very short ranges - Very high voltages + Very good efficiency (>90 %) + Passes obstacles whose metal + Misalignement insensitive + Little interferences ? Safety	- Short ranges - Sensitive to metal - Sensitive to misalignement + Very good efficiency (>90 %) ? Safety	- Short to medium ranges - Sensitive to metal - Sensitive to misalignement + Very good efficiency (>90 %) ? Safety + SWIPT	+ Large ranges + Good efficiency - Line of sight required - Interferences - Maturity - Electromagnetic compatibilities ? Safety + SWIPT	+ Very large ranges + Decent efficiency - Line of sight required - Interferences - Maturity ? Safety + SWIPT

History of the radiative electromagnetic wireless power transfer

Nikola Tesla - 1899-1906

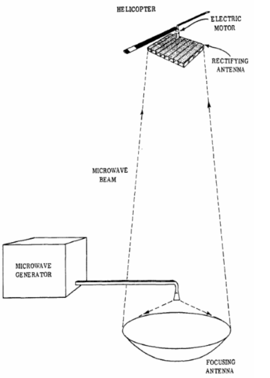


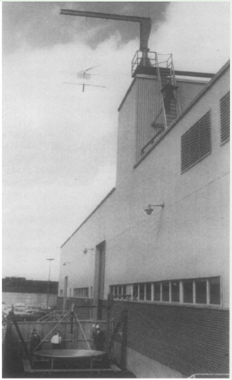
History of the radiative electromagnetic wireless power transfer

First implementation - 1959

History of the radiative electromagnetic wireless power transfer

First use of microwave (2.45 GHz, 15 m, 13 %) - 1964 - William C. Brown



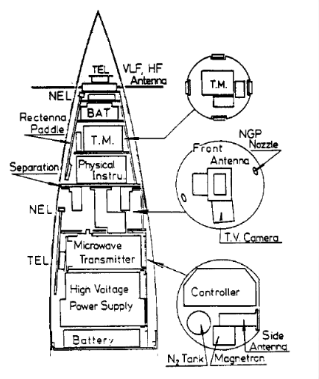


History of the radiative electromagnetic wireless power transfer

Long distance (1.54 km, 2.388 GHz, 30.4 kW 80 %) - 1975

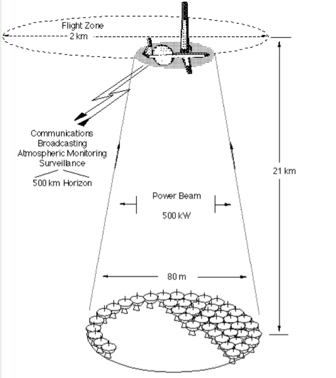
History of the radiative electromagnetic wireless power transfer

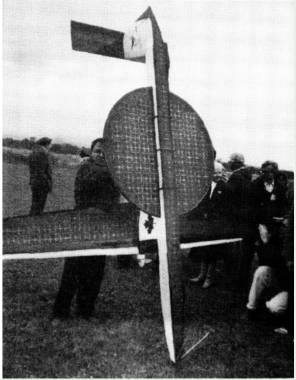
First spatial application (JAXA) - 1983



History of the radiative electromagnetic wireless power transfer

First use for UAV - 1987



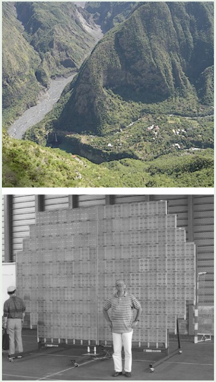


History of the radiative electromagnetic wireless power transfer

First use of beamforming - 1992 - Noaki Shinohara

History of the radiative electromagnetic wireless power transfer

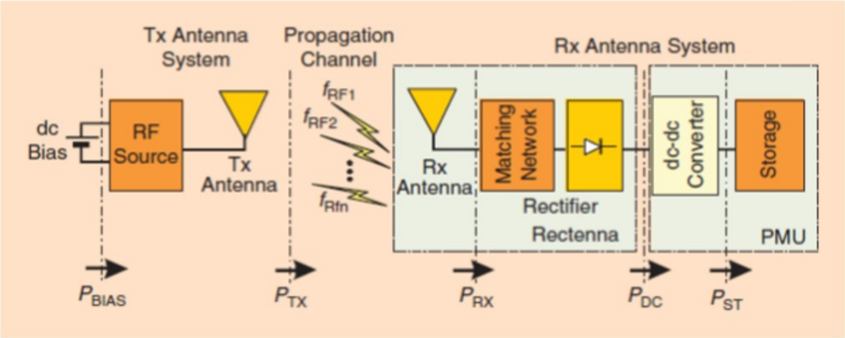
Long distance (700 m, 26 %) - 2001



History of the radiative electromagnetic wireless power transfer

Distance record (20 W at 148 km) - 2008

Diagram of the system



Relevant relations

Friis equation:

$$P_{Rx} = P_{Tx} + G_{Tx} + G_{Rx} - L_{propagation} - L_{various} \text{ (dB)}$$

Direct current power:

$$P_{DC} = \eta \cdot P_{Rx} \text{ (W)}$$

Model of free space losses for a line of sight propagation:

$$L_{propagation} = 20 \cdot log(\frac{4 \cdot \pi \cdot d \cdot f}{c}) \text{ (dB)}$$

Choice of frequency

The free space losses are dependent of the choose frequency.

A maximum equivalent isotropic radiated power (EIRP) is allowed by regulators in each frequency band, for the terrestrial applications (not for the spatial ones).

The choose frequency constraints the maximum range between the power source and the harvester, but also the size of the antenna.

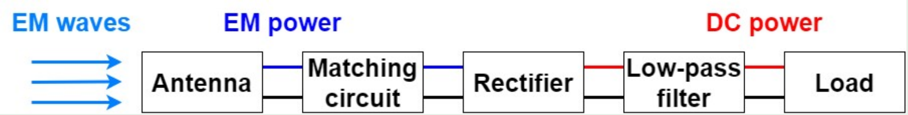
Industrial, Scientific, and Medical (ISM) frequency bands

Central frequency	13.56 MHz	433 MHz	868 MHz	2.45 GHz	5.8 GHz
Wavelength in the air	2.21 m	69.2 cm	34.4 cm	12.2 cm	5.2 cm
Bandwidth	14 kHz	1.74 MHz	5 MHz	100 MHz	150 MHz
Maximal EIRP	/	10 mW +10 dBm	2 W +33 dBm	100 mW 20 dBm	200 mW +23 dBm 1 W +30 dBm
Free space losses at 1 m	/	25.17 dBm	31.21 dBm	40.23 dBm	47.71 dBm
Free space losses at 5 m	/	39.15 dBm	45.19 dBm	54.20 dBm	61.69 dBm
Theoretical range for P_{IN} =+0 dBm	/	17 cm	123 cm	9 cm	6 cm 13 cm
Theoretical range for P_{IN} =-10 dBm	/	55 cm	388 cm	30 cm	18 cm 41 cm
Theoretical range for P_{IN} =-14 dBm	/	87 cm	615 cm	48 cm	29 cm 65 cm

Rectenna

A harvester for electromagntic waves made of:

- Antenna
- Matching network for the impedance adaptation in power
- RF-to-DC rectifier with a non-linear element
- Low-pass filter



Rectenna

The **optimal rectenna design** (Topology choice, impedance matching, harmonics deletion, bandwidth, etc.) is not necessary the combination of:

- **the optimal antenna** (High gain, compact size, controlled radiation pattern shape and polarization, input impedance easy to match with the rectifier, etc.)

  and

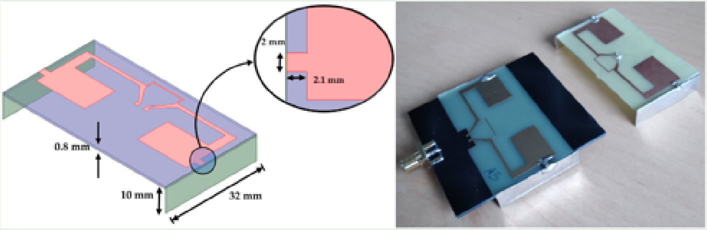
- **the optimal rectifier/non-linear element** (Low series resistance and junction capacitances, low forward/threshold voltage and high breakdown voltage, input impedance easy to match with the antenna, etc.)

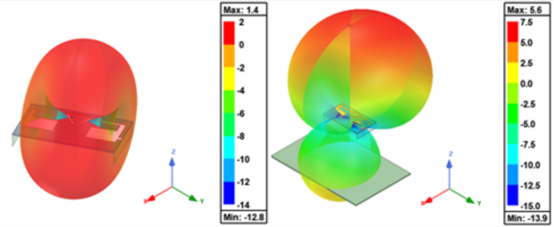
Antenna

The choise of the antenna will be based on:

- its **central frequency** (matched with the electromagnetic waves specifically generated and/or from the environment)
- its **bandwidth(s)** (narrowband, wideband, multiband)
- its **gain**
- its **radiation pattern** and its aperture angle (directive, omnidirectionnal)
- its **size**
- its **polarisation** (linear, circular, elliptic)
- its **input impedance** (for matching the rectifier)

Antenna


2 mm
2.1 mm
0.8 mm
10 mm
32 mm


Max: 1.4
2
0
-2
-4
-6
-8
-10
-12
-14
Min: -12.8
Max: 5.6
7.5
5.0
2.5
0.0
-2.5
-5.0
-7.5
-10.0
-12.5
-15.0
Min: -13.9

Impedance matching

The impedance matching circuit can be made with:

- lumped components (e.g. capacitor, inductor, etc.)
- distributed components(e.g. line, stub, etc.)
- a hybrid circuit

in various topologies:

- 'L'
- 'T'
- 'π'
- etc.

Its objective is to optimize the power transfer between the antenna and the rectifier for a specific frequency, by employing the complex conjugate impedance matching.

Rectifier

The RF-to-DC rectifiers can be made with different non-linear device:

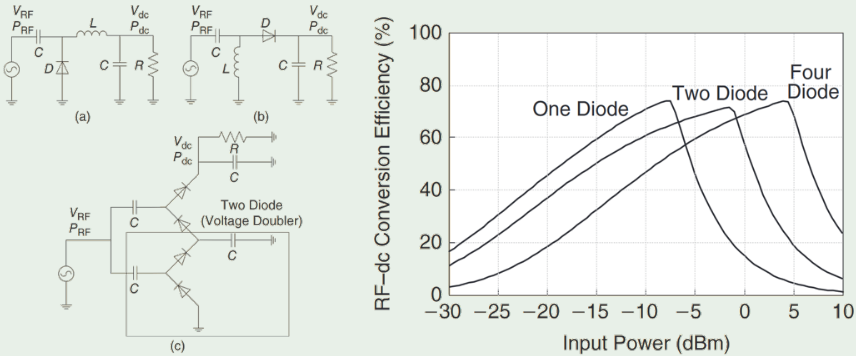
- diodes (PN, Schottky, zero-bias, backward, MIM, PIN, Spin, etc.)
- transistors in diode configuration (CMOS, etc.)
- power amplifier

in various topologies:

- single-shunt diode
- single-series diode
- voltage multiplier (2 levels, 4 levels, etc.)
- etc.

Its objective is to convert the radiofrequency power (at a specific frequency) in direct current power. The main parameters to consider are: the threshold voltage, the serial resistance, the junction capacitances, and the breakdown voltage.

Rectifier



V_{RF}
P_{RF}
L
V_{dc}
P_{dc}
C
D
R
(a)
(b)
(c)
Two Diode
(Voltage Doubler)
RF–dc Conversion Efficiency (%)
Input Power (dBm)
One Diode
Two Diode
Four Diode
100
80
60
40
20
0
−30
−25
−20
−15
−10
−5
0
5
10

Low-pass filter

It is usually based on a capacitor in series to cut the 'high' frequencies and only conserve the static part (direct current).

Rectenna efficiency

- Efficiency

$$\eta_{rectenna} = \frac{P_{DC}}{P_{RF}} = \frac{P_{DC}}{S \cdot A_{eff}} = P_{DC} \cdot \frac{16 \cdot \pi^2 \cdot d^2}{P_{Tx} \cdot G_{Tx} \cdot G_{Rx} \cdot \lambda^2} \; (\%)$$

- Effective electric field

$$E = \frac{\sqrt{30 \cdot P_{Tx} \cdot G_{Tx}}}{d} \; (V \cdot m^{-1})$$

- Incident electromagnetic power density

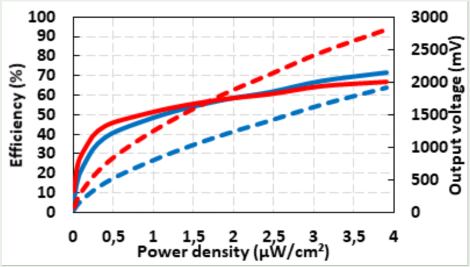
$$S = \frac{E^2}{120 \cdot \pi} = \frac{30 \cdot P_{Tx} \cdot G_{Tx}}{120 \cdot \pi \cdot d^2} = \frac{P_{Tx} \cdot G_{Tx}}{4 \cdot \pi \cdot d^2} \; (W \cdot m^{-2})$$

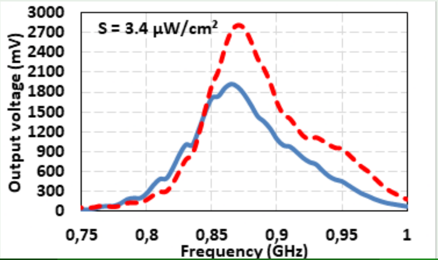
- Effective area of the antenna

$$A_{eff} = G_{Rx} \cdot \frac{\lambda^2}{4 \cdot \pi} \; (m^2)$$

Ambient energy harvesting and wireless power transfer: focus on electromagnetic solutions

Rectenna efficiency





Ambient energy harvesting and wireless power transfer: focus on electromagnetic solutions

Example

We need to power continuously, with a +14 dB electromagnetic source working in the 868 MHz band, a wireless sensor that requires a DC current of 4 mA at 3.3 V, by using a rectenna with an efficiency of 75 % and a effective surface of 100 cm^2.

- What electromagnetic power density is required? 1.76 $W \cdot m^{-2}$ or 176 $W \cdot cm^{-2}$
- What effective electric field is required? 26 $V \cdot m^{-1}$
- What range of use could be achieved? 1.15 m
- What is the global efficiency? 0.044 %
- What is the required antenna gain? +0.4 dBi

Table of contents

How-to design connected objects?

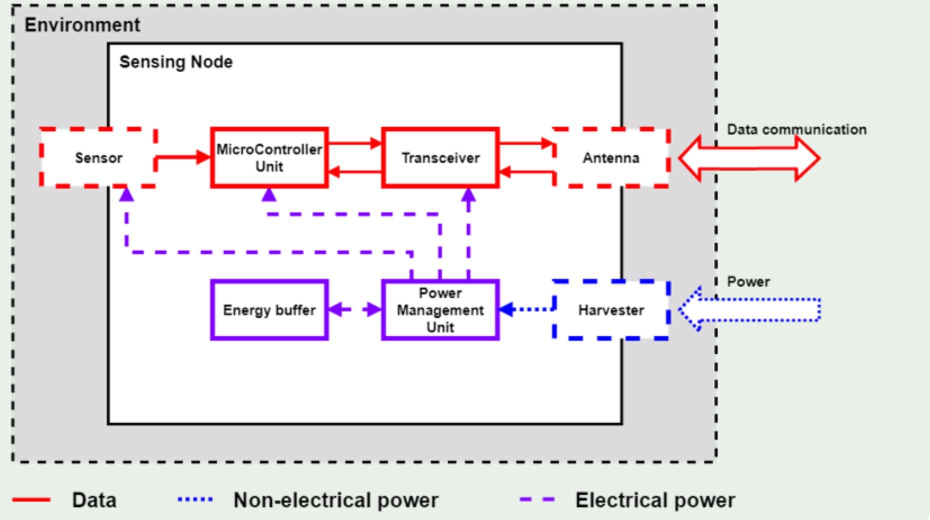
Specifications

Energy autonomous and fully wireless sensing nodes for long term use

Mains application constraints

Power/energy required by the connected object
Power available (type and quantity)
Environment
Mobility
Range of use
Periodicity of use: usualy there is a discontinuous activity with short periods of activity separated by long periods of inactivity
Size
Etc.

Generic architecture



How-to design connected objects?

Required energy or power

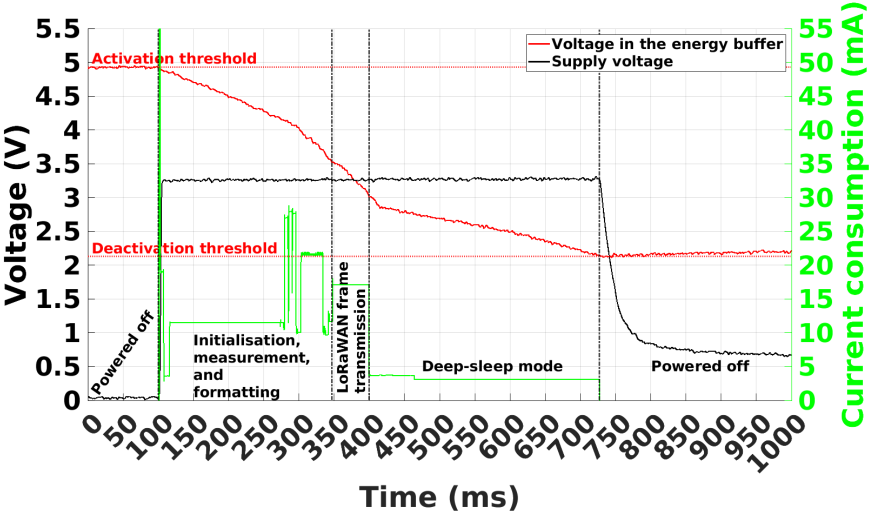
Data part = Sensor + Microcontroler Unit + Transceiver
This is application specific.

Typical power consumption

Sensors (<0.1 - 1 mW)
ADC usually embedded in the MCU or in the sensor (1 - 2 mW)
MCU operation, especially initialization and processing (1 - 10 mW)
Wireless communication device (20 - 400 mW)
for various durations...

$RF\_Tx > RF\_Rx > Wake - up\_RF > Measurement > Processing > Wake - up > Stand - by > Sleep\_mode > Deep - sleep\_mode > Stop\_mode$

Example: typical power consumption of a wireless sensing node



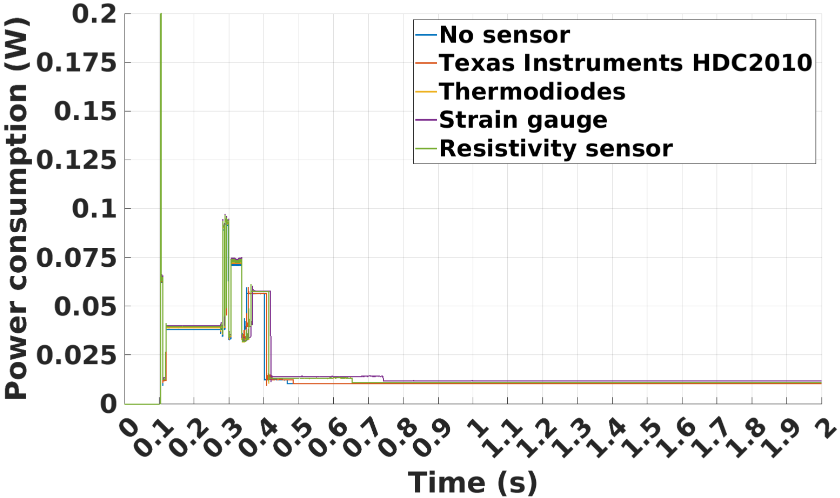
Sensors

Temperature
Relative humidity
Luminosity
Gas
Location
Orientation
Velocity
Resistivity
Deformation
Etc.

But also actuators...

Cost, consumption, power supply, interface, size, measurement performances (frequency, duration, precision, range, etc.), temperature and humidity range of use, etc.

Example: consumption of sensors

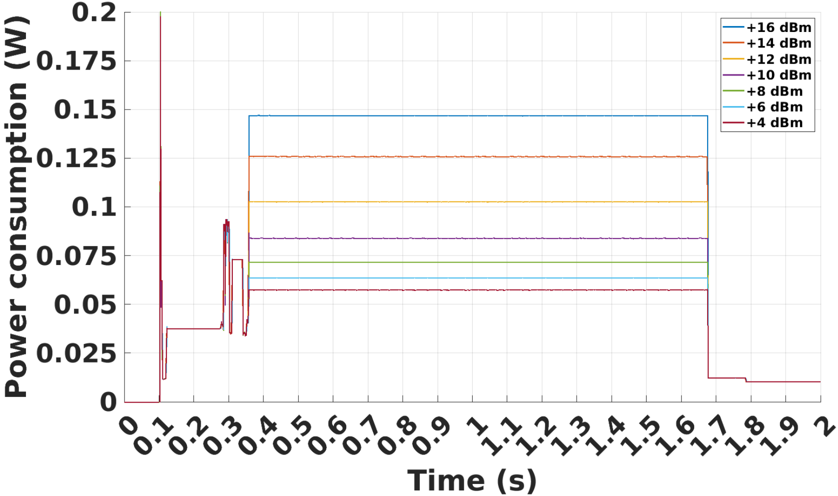


Wireless transceiver

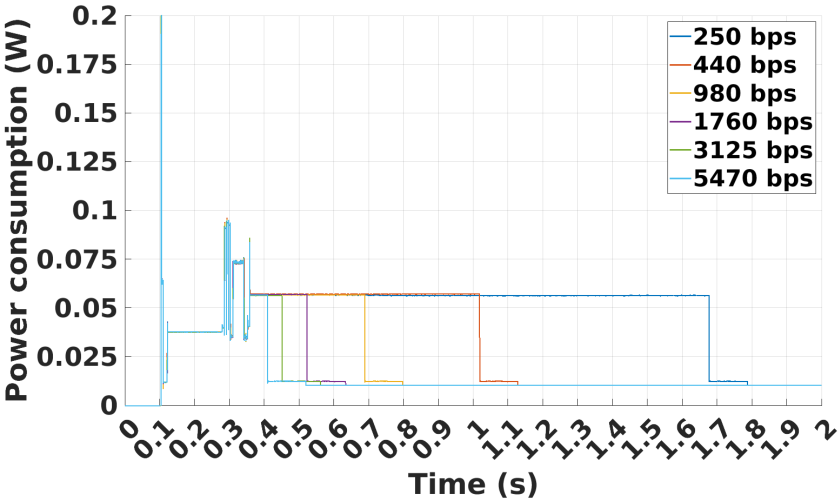
RFID
Bluetooth Low Energy (1 mJ)
ZigBee
Bluetooth
Wi-Fi
Cellular (2G/3G/4G/5G/LTE-M/NB-IoT)
LoRa/LoRaWAN (21 - 250 mJ)
DASH7
SigFox

Cost, consumption, power supply, range of communication (modulation, frequency band, directivity, sensitivity, allowed power, etc.), data-rate (bandwidth, etc.), infrastructure, latency, mobility, lifetime, etc.

Example: consumption of LoRa transceiver as a function of the output power



Example: consumption of LoRa transceiver as a function of the data-rate



Antenna

Central frequency
Bandwidth(s) (narrowband, wideband, multiband)
Gain
Radiation pattern and its aperture angle (directive, omnidirectionnal)
Size
Polarisation (linear, circular, elliptic)
Input impedance

MicroController Unit

Architecture (16 bits, 32 bits, 64 bits, etc. RISC, etc., 32 nm, 45 nm, etc.), cost, consumption, consumption modes (run, standby, sleep, deep-sleep) and wake-up mechanisms (periodic or on interruption), power supply, memory, peripherals, interfaces, size, performances (frequency, latency, real time, etc.), security, safety, temperature and humidity range of use, etc.

The consumption is due to the current:

- static: linked to the biasing, namely 'leakage current' (imperfections of CMOS transistors and presence of analog functions), impacted by the supply voltage and the temperature
- dynamic: linked to the switching activity, impacted by the frequency, preponderant

Example: STM32L476RG power consumption

Vdd = 3 V (1.2 V internal) at 25 °C

Block	Typical current consumption
CPU (from Flash + HSE + 80 MHz PLL, range 1, run mode)	10 - 11 mA
CPU (from Flash + HSE + 26 MHz PLL, range 2, run mode)	2.8 - 3.1 mA
8 MHz quartz oscillator (HSE)	0.45 mA
PLL (VCO frequency = 64 - 344 MHz)	0.2 - 0.5 mA
32 kHz quartz oscillator, medium drive (LSE)	5.1 μA
Internal RC oscillator (100 kHz - 48 MHz) - PLL mode	0.6 - 155 μA
Flash memory (write - erase mode)	3.4 mA
Flash	6.2 $\mu A \cdot MHz^{-1}$
SRAM 1 and 2	0.9 - 1.6 $\mu A \cdot MHz^{-1}$
ADC (1 MSps, fclk = 80 MHz)	0.66 mA
I2C (I/O not included)	0.4 mA
SPI (I/O not included)	0.16 mA
GPIO (10 pF load, 15 MHz)	0.45 mA
GPIO (50 pF load, 1 MHz)	0.15 mA
RTC (external 32 kHz quartz)	0.5 μA

How to reduce data part consumption?

➔ By optimally configuring all components, especially the MCU and the wireless transceiver, and their connection.

General strategies:

- Reduce the duty cycle
- Reduce the current in active mode, in standby mode, and in (deep)sleep mode of all the components and their parts
- Reduce the peak current during the initialisation and the wake-up

How-to design connected objects?

Reduce the duty cycle

- The CPU must be woke-up only when necessary.
- Peripherals (as DMA for memory management), autonomous communication interfaces (as I2C and LPUART in batch acquisition mode) and hardware accelerators (as for AES encryption) must be used to limit the interventions of the CPU.
- It is usually more relevant to increase the MCU clock frequency to increase the inactive (standby) duration than to reduce the MCU clock frequency to reduce instantaneous dynamic consumption.
- Local (e.g. for CPU, peripherals as ADC, etc.) and global (MCU) strategies must be defined for the use of the low-power modes (standby, sleep, deep-sleep) with a trade-off between performances, consumption and wake-up time.
- The code must be optimized, especially by avoiding polling.

Reduce the current in active mode, in standby mode, and in (deep)sleep mode of all the components and their parts

To reduce the instantaneous static consumption / leakage currents:

- The supply voltage must be reduced.
- The unused internal blocks must be disconnected from the supply voltage.
- Unused pin (GPIO) must be pulled-down or pulled-up (input), tied to ground or pushed-pulled (output) but never floating.
- A fine strategy must be adopted for the data storage in SRAM, Flash/EEPROM and FRAM memories (e.g. find a trade-off between consumption, volatility and access time (executing program from RAM consumes less energy, is faster but a copy of the program into RAM is required after start-up or reboot)), etc.)

Reduce the current in active mode, in standby mode, and in (deep)sleep mode of all the components and their parts

To reduce the instantaneous dynamic consumption / leakage currents:

- The operating frequency must be reduced.
- A fine (and complex) strategy must be adopted for the clock management (e.g. find a trade-off between consumption, frequency and stability (external quartz or oscillator improves the stability at the cost of a higher consumption), increase the number of internal clock buses with local prescaler to optimally adjust peripheral frequency, etc.).
- The unused internal digital blocks and peripherals must be disconnected from the clock tree.

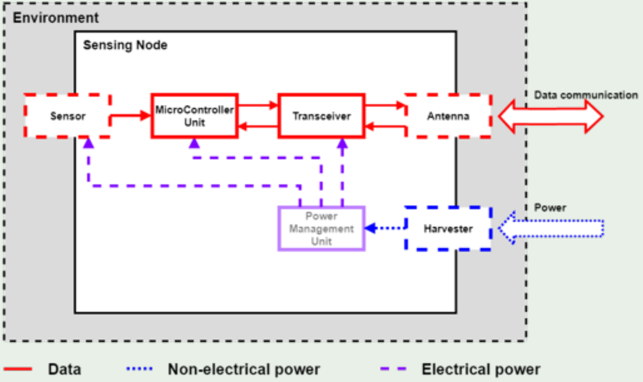
Reduce the peak current during the initialisation and the wake-up

- Start-up and wake-up procedures must be lengthened.
- The wake-up mechanisms must be optimized (based on RTC (periodic), watchdog, or external interruption), and supply by a specific back-up power supply domain.
- A wake-up could reconfigured some peripherals with defaults states.

Strategies of use

Direct consumption

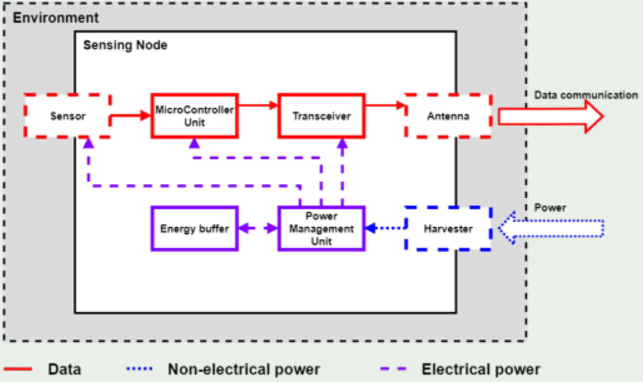
$P_{DC} > P_{LOAD}$ and the power in excess is wasted. Real-time constraints could be met.



Strategies of use

Store the use

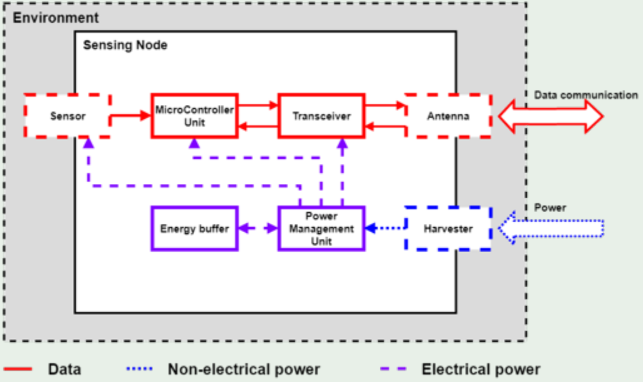
$P_{DC} << P_{LOAD}$ and thus, a discontinuous consumption profile with a very low duty cycle.



Strategies of use

Simultaneous use and store

Usually $P_{DC} > P_{LOAD}$ and the power in excess is stored to compensate the variations of the input power over time.



Energy management

- Power management unit (PMU or PMIC)
  - Activation and deactivation voltage thresholds
  - Protection thresholds
  - Cold start procedure
  - Etc.

  Examples: Texas Instruments bq255xx, e-peas AEM30xx0, etc.

- DC-to-DC converter
  - Low drop-out (LDO)
  - Buck
  - Boost
  - Buck-Boost

Maximum power point tracking (MPPT) hardware or software solutions can be implemented to optimise the input power use.

Energy storage device

For long term use:

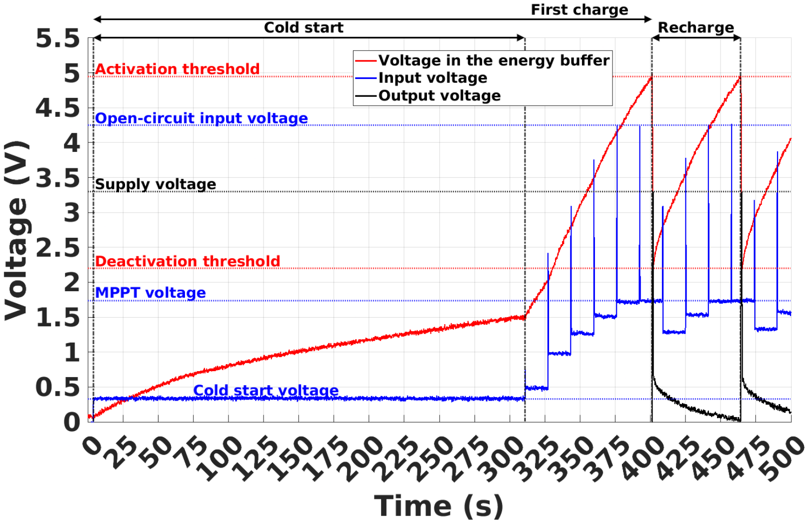
- ✔ Electrochemical batteries.
- ✘ (Super)Capacitors.

with a *store then use* strategy.

Stored energy

$E = \frac{1}{2} \cdot C \cdot (V_{max}^2 - V_{min}^2)$

Energy management



How-to design connected objects?

Input power required

The data part (sensor(s) + MCU + wireless transceiver) defines the amount of energy requires, whilst the losses and needs of the power/energy part (energy storage device (tens of μW) and PMU (ten of μW for hundred of mV) must be compensate.

Input power available

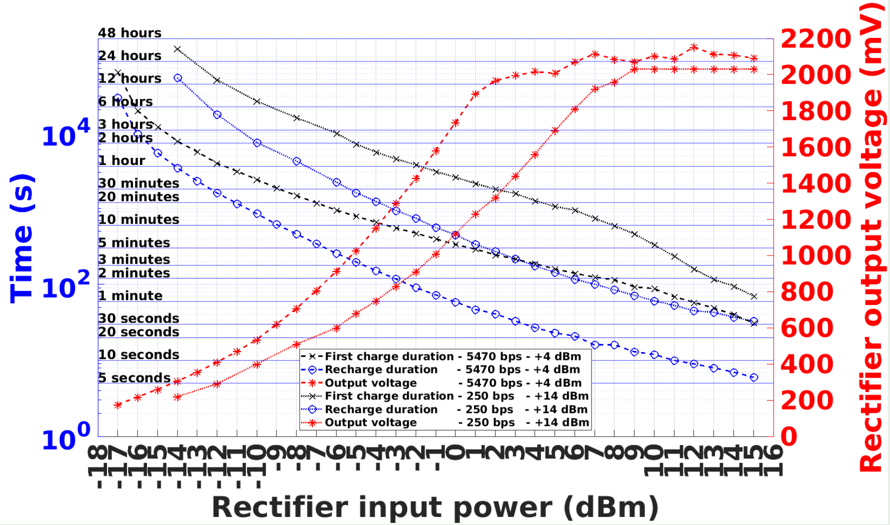
The amount of input power available is a function of: the type of targeted energy, the choice of ambient energy harvesting or wireless power transfer, the efficiency of the harvester, the environment, the application and the strategy, the fluctuations, etc.

How-to design connected objects?

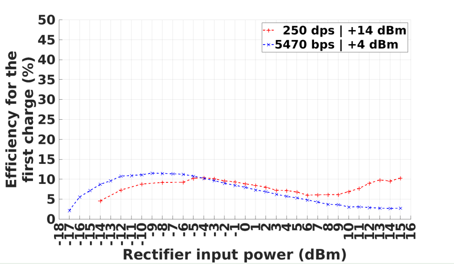
State of the Art of wireless power transfer solutions to power battery-free wireless sensing nodes

- Few complete implementations
- Applications: monitoring (structures, vehicles, rotating machines, environment, etc.)
- Sensors: temperature, relative humidity, angular velocity, acceleration, pressure, strain gauge, resiti-meter, etc.
- Frequency bands: ISM 868 MHz (+33 dBm) or 2.45 GHz (+20 dBm)
- Strategies: *Direct consumption* or *store then use*
- Maximum range of use: less than 1 meter or 11 meters
- Minimum power at the input of a rectifier: -18 dBm or 16 μW

Wireless power transfer characterization: charging time



Wireless power transfer characterization: efficiency



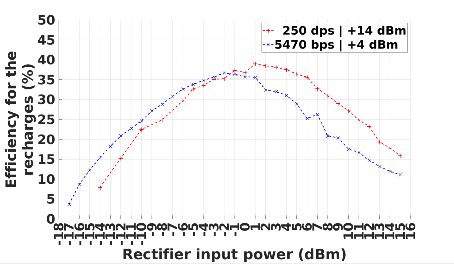


Table of contents

Conclusion

- Energy storage devices for electricity
  - Direct: inductor and capacitor
  - Indirect: electrochemical (fuel cell, thermal cell, primary cell, secondary cell) versus electrostatic (supercapacitor, capacitor)
- Ambient energy harvesting versus wireless power transfer
  - Wasted versus predictable, controllable and constant power
  - Environment and application dependent versus independent
- Ambient energy harvesting and wireless power transfer with electromagnetic waves
  - Tesla's dream!
  - Seems easy to design, but requires a lot of optimizations/considerations
- Design of an energy autonomous low power wireless sensing node
  - It is always a question of finding the best trade-off to meet the requirements...

Perspectives

- Optimization of the harvesters

  Rectennas, antennas, rectifiers, non-linear devices, impedance matching networks, etc. for higher efficiencies

  Concentrator, multiband or broadband solutions, networks/arrays, hydrid solutions, etc. for higher amount of input power

- Optimization of the power management and storage

  Power management units, converters, energy storage devices, etc. with higher efficiencies and lower losses

- Optimization of the power transfer

  Beamforming and frequency diverse arrays for focusing the transmitted power

  Signal waveform with high PAPR (multi-tones, chaotic, APSK, pulses, chirps, etc.) for higher efficiencies

  Eco-friendly and ubiquitous sources

- Optimization of the connected objects

  Hardware and software optimizations, wake-up radio, for lower power consumption

  Miniaturisation, use of flexible substrates, additive techniques and 3D printing, safety and security considerations, etc. for long term deployment

Future?

Towards networks for the simultaneous wireless information and power transfer?