Lab : Energy for connected objects

Rémi Goalard - Alexis Payet

Objective of the course :
This following lab is in direct continuity with the harvesting and wireless power transmission lecture. This class have various objectives :

- Knowing the different technologies to store energy
- Having a look on the environment sources we can retrieve energy from, and how
- Discovering the technologies used for wireless power transmission
- Keep in mind the final product we want to design, how to deploy the previous technologies, and is it a feature that makes sense for that device?

Objective of the lab :
In this lab, we want to power a device (i.e a LED) using wireless power transfer. To do so, a couple of antennas are deployed, the first one emitting radiofrequency waves, the second one receiving them. Once the second antenna receives the electromagnetic weaves, a rectifier is used to transform them into DC current. Finally, the DC current can power the LED.
The objective behind this application is to study each component of the architecture, and find their characteristics to assure a good functional of the whole system

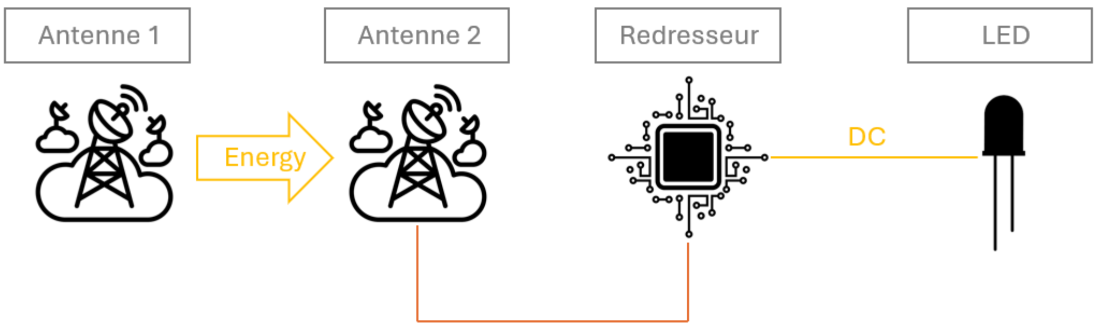


Figure 1 : wireless power transfer lab architecture

Part 1 : Study of the load and design

In the first part, we want to study the characteristics of the powered device, a red LED SML-D12U1WT8 in our case. To do so, we will rely on its related datasheet.

1. **Required power for nominal use case, 50% and 25% intensity**

To determine the necessary power, we need to know the LED current and voltage requirements : P = V*I

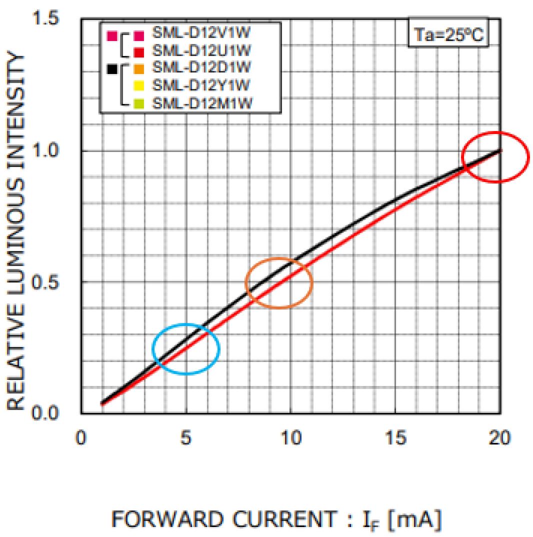
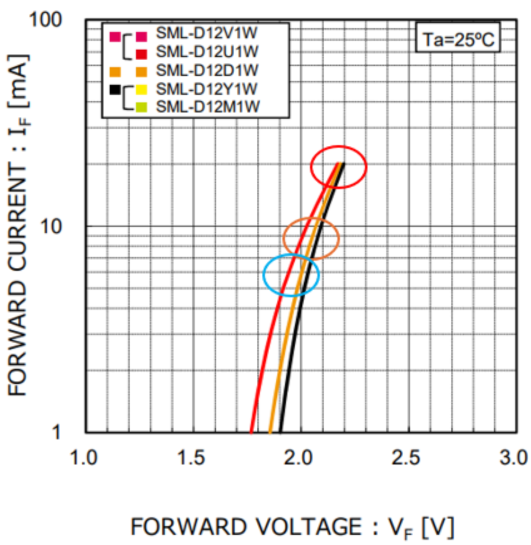


Figure 2 : Intensity depending on input current

Intensity (%)	Input current (mA)
100	20
50	9,5
25	5

Voltage (V)	Input current (mA)
2,2	20
2,1	9,5
1,94	5



Intensity (%)	Power (mW)
100	44
50	20
25	9,7

Figure 3 : forward current depending on input current

2. Required energy to turn on the LED

Considering we want full intensity during 1s, we need a power of P = 44mW during 1 second => E = 44mJ

Looking at the datasheet, we can find the maximum and minimum energy values needed to make the LED work during that time :

- Emin : Vmin = 1.7V / Imin = 1mA => Emin = 1.7mJ
- Emax : Pmax = 54mW (table p1) => Emax = 54mJ
-

Looking at the characteristics, we don't have any information about what happens above a forward voltage of 2V. It means that we could be able to apply a more powerful voltage, but the constructor doesn't give any guarantee about what will happen.

The nominal case energy quantity required is interesting. Indeed, most of IoT components are working using a few xx mA, and usually using 1.8 V sources. Therefore, the LED we want to power is a good representation of the power needed to make IoT devices work.

3. PMU and supercapacitor configuration choice

Reminder : we need E = 44mJ & $E = 0.5*C*V^2$

When using a PMU (power management unit), we can't rely on the full quantity of energy provided, as the component needs some to work. This energy is considered a loss, and is represented by a minimal voltage threshold at the PMU input. As a result, the quantity of energy we want is $E = 0.5*C*(Vmax^2-Vmin^2)$

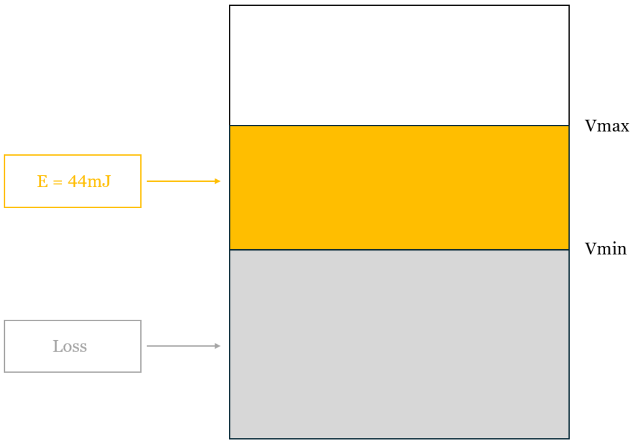


Figure 4 : PMU energy loss

According to the PMU datasheet, its maximum threshold is Vmax = 5.25V while the minimum one is Vmin = 2.2V. Therefore => $C = (2*E)/(Vax^2-Vmin^2) = 4.5mF$.

We don’t have a supercapacitor for the value 4.5mF, so the best one we can take is the 6.8mF. As a consequence, we have E > 44mJ. It gives us two options, reduce Vmax or increase Vmin :

- Increasing Vmin: it would lead to more loss, so this is not a good strategy
- Decreasing Vmax : need less voltage to supply the PMU, is a good idea !
  $Vmax = [(2*E)/C + vmin^2]^{0.5} = 4.4V$

We obtain the components configuration for each luminosity intensity :

Intensity (%)	100	50	25
Energy (mJ)	44	20	9.7
Capacity (mF)	6.8	2.2	1.5
Vmax (V)	4.4	4.9	4.1
Vmin (V)	2.2	2.2	2.2

To power our system, we can either provide all the energy at once or charge it during a certain time. To do so, we should look at the components losses, to see what is the minimum power required to charge the system.
Once again, let’s refer to the datasheet:

- PMU: in the worst case, $P_{pmu} = 16.62uW$
- Supercapacitor : depend on the capacitor, essentially because of their technology !

We use the previous table (and the supercapacitor choice) to find the minimum energy required to power each luminosity intensity during time:

Intensity (%)	100	50	25
Capacity (mF)	6.8	2.2	1.5
Pin = Ppmu + Pc (uW)	69	620	430

Looking at these results, we see 2 counterintuitive behaviors:

- The value Vmax is not always decreasing when the energy needed does.
- The instantaneous power required is not correlated to the intensity desired (P100% < P50%).

Part 2 : Rectifier characterisation

The second part is dedicated to the study and characterisation of the rectifier. This component takes radiofrequency waves as input and transforms them into DC voltage.

1. Rectifier efficiency depending on the frequency

Depending on the components used to create them, each rectifier is designed to be efficient on a specific bandwidth.
We have at our disposal two kinds of rectifiers, one for 868 MHz and one for 2.45 GHz. We use these specific frequencies as they are part of ISM (industrial, scientific, medical) bands, which are free to use.

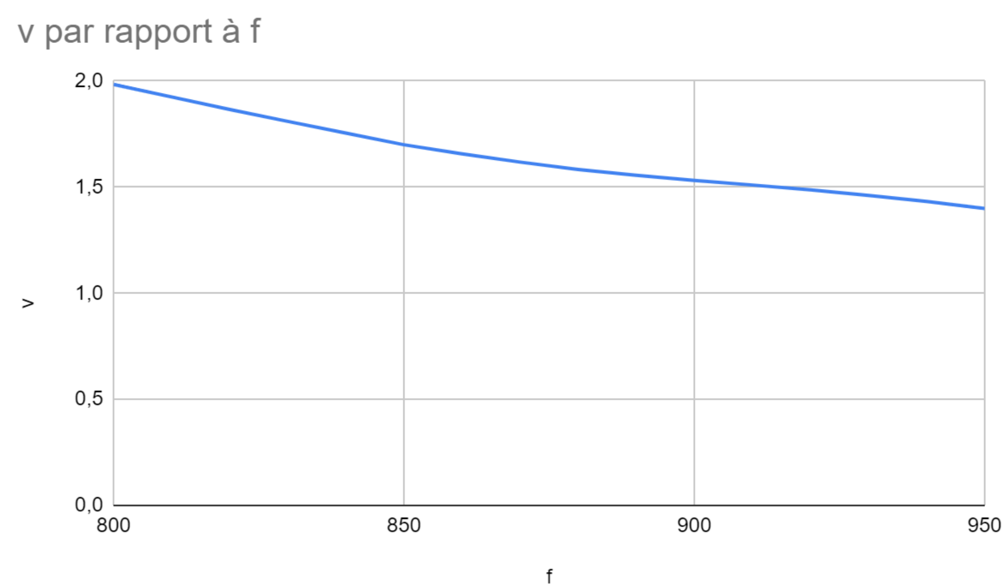
The objective is to measure the efficiency of the rectifier, i.e measure the power transformed from waves to DC current. To do so, we can do an indirect measure, by using P = V*I.
We use a potentiometer resistor configured at 1.5kOhm, GNUradio and a USRP to send waves to the rectifier. At reception, we are able to measure the Voltage via a multimeter, and the current using the resistor value.

First, we want to know if our rectifier is designed to work with frequencies around 868 Mhz or 2.45 GHz. On GNURadio, we use a source, and a 'Sink' block that will represent our USRP, i.e the wave received by the rectifier. We send both frequencies and look at the voltage measured on the rectifier:

- 868 MHz : 0.3V
- 2.45 GHz : 0.02V

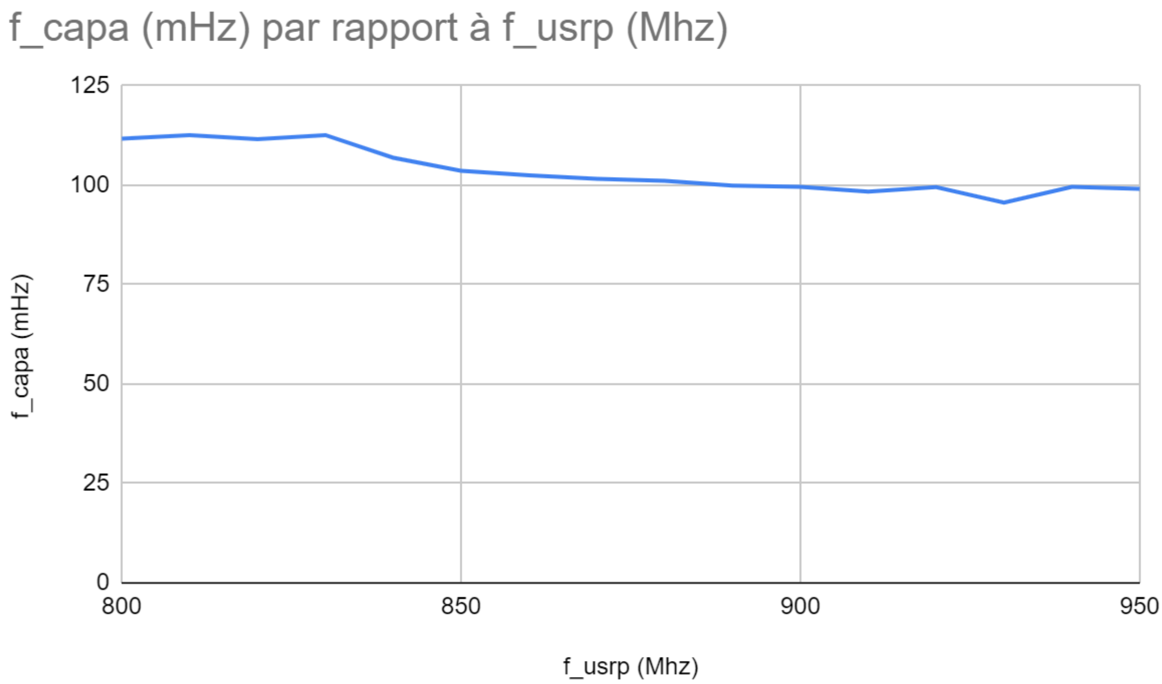
Our rectifier as therefore designed to be used around 868 MHz

Now we know the frequency must be around 868 MHz, we want to find the exact frequency for which the rectifier is optimized. We sweep the value of the frequency between 800 MHz and 950 MHz, and plot it on a graph:



This is not what we expected. We were supposed to clearly see a peak somewhere in the graph, that would be the more efficient frequency. We tried with 3 different cards but still obtained something similar. As they are new ones, and we were the first doing the lab, it is possible a problem happened during their manufacture.

In a third time, we were proposed to use cards from previous years to continue the lab. These cards are a bit different, as they integrate a capacitor, so the LED can be powered with a low power source, and turn ON only when the necessary amount of energy is collected.
Having the same idea in mind, we wanted to characterize the frequency with the best efficiency. This time, we power the LED, sweep the frequency on GNURadio, and measure for each of them the capacitor charge/discharge frequency => shorter period ⇔ more efficient.



This time either, we were not able to identify a clear peak in the frequency bandwidth.

To do the rest of the lab, we use the 868 MHz frequency.

2. **Rectifier efficiency calculation.**

As we decided to use an input frequency f = 868 MHz, we now want to calculate the rectifier's effective efficiency, i.e the ratio between received energy and the one needed to turn ON the LED.

$$\eta = \frac{E_{on}}{E_{in}} = \frac{P_{on} * t_{on}}{P_{in} * t_{in}}$$

- Pon = 20 mW => because we use a 50% luminosity LED.
- t_on = 1s.
- Pin = -15 dBm = 0.032 mW.
- t_in = 9.56s => time to charge the LED from 0% to 100%, measured with an oscilloscope. The intern component of the tool could have an effect on this charge time, but here it is negligible.

$$\eta = 65.37$$

Looks like we created an infinite source of energy !
To do the energy transfer, we configured the GNURadio blocks using the following lookup table:

868 MHz		*2.45 GHz*	
UHD: USRP Sink gain	*Output power (dBm)*	*UHD: USRP Sink gain*	*Output power (dBm)*
73.0	-16	72.3	-16
73.9	-15	73.3	-15
74.8	-14	74.2	-14
75.8	-13	75.2	-13
76.5	-12	76.2	-12
77.5	-11	77.2	-11
78.4	-10	78.2	-10
79.4	-9	79.2	-9
80.2	-8	79.9	-8
81.2	-7	80.9	-7
82.0	-6	81.9	-6
83.0	-5	82.9	-5
83.9	-4	83.8	-4
84.8	-3	84.7	-3
85.9	-2	85.8	-2
86.9	-1	86.8	-1
88.0	0	87.9	0
89.5	+1	89.4	+1

As GNURadio is an evolving framework, this table might not be up to date, and therefore our calculation is wrong.

To be sure to find the true efficiency, we acted as follow :

- Find the USRP max output => 20 dBm
- Used a very high gain on the USRP sink to be sure to saturate the USRP => G = 5000 ⇔ Pin = 20 dBm
- Add a 20 dBm attenuator => Pin = 20 - 20 dBm = 0 dBm
- Measure the time between two LED flash

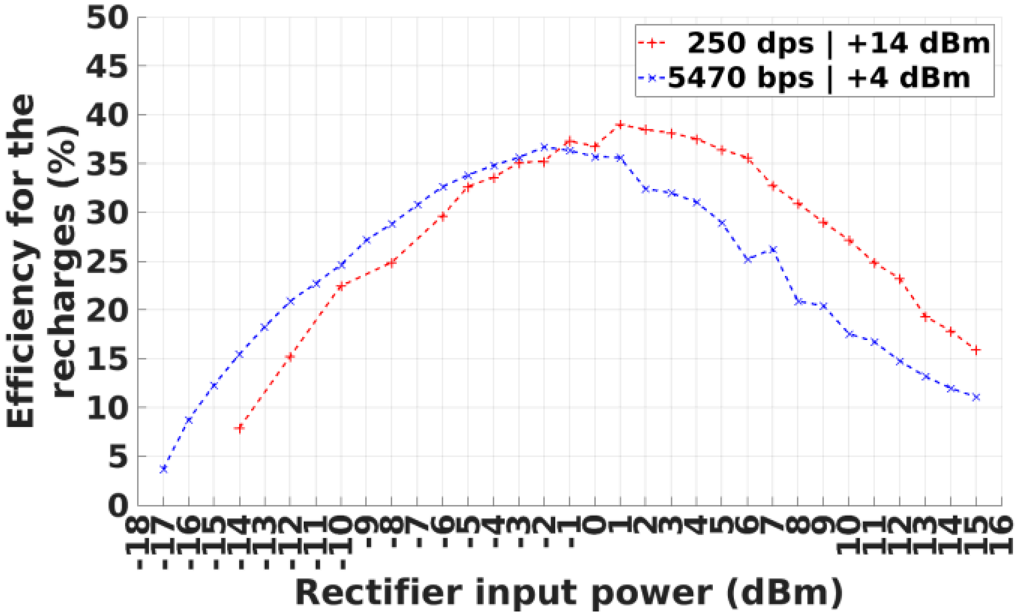
- Do the efficiency calculus again

$$\eta = \frac{E_{on}}{E_{in}} = \frac{P_{on} * t_{on}}{P_{in} * t_{in}}$$

- Pon = 20 mW => because we use a 50% luminosity LED.
- t_on = 1s.
- Pin = 0 dBm = 1 mW.
- t_in = 260s.

$$\eta = 0.077$$

We end up with an efficiency of 7.7%. According to this graph from the lecture, we should be around 30%-40%, so what we found is quite low.



Part 3 : Energy transmission

In the first two parts, we only considered the system between the second antenna and the LED. In this one, we will integrate the energy transmission part, and have a look at ambient energy available

1. Ambient energy harvesting

Does the current environment provide enough collectable energy to power our LED?
To answer this question, we use the spectrum analyzer present in the room. When it is turned on, we only see noise. Furthermore, for the frequency 868 MHz, this noise power is Pnoise = -80 dBm.
As the minimal power input to make the capacitor store energy is -17 dBm, the ambient noise should be 1*10^6 higher to be usable.
In this configuration, we can't consider harvesting that kind of energy, but we still have the opportunity to think about other ones, such as solar energy harvesting !

2. Wireless energy transmission

To complete the system we have to stop using the USRP as a power source, but instead put an antenna somewhere in the room and use another one to receive the energy.

The antenna used has a power up to 1 W, and is coupled with a 3 dBi gain, which corresponds to multiplying the power by two.
We tried various antennas as a receptor, to see the difference between them: transmission range / radiation / gain / polarization ...

We decided to use the flat one, and calculate the theoretical maximal distance from which we could retrieve energy :

$$d = \left[\frac{P_{tx} * G_{tx} * G_{rx} * c^2}{P_{rf} * 16 * \pi^2 * f^2} \right]^{\frac{1}{2}}$$

- Ptx = 1 W.
- Gtx = 3 dBi = 2.
- Grx = 9 dBi = *8 => flat antenna gain.
- Prf= 0.032 mW.

$$d = 19.4m$$