INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES TOULOUSE

INNOVATIVE SMART SYSTEMS

Electromagnetic energy harvesting and wireless power transfer

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I/Introduction

This report is produced as part of our final year of study at INSA Toulouse, where we are pursuing a Master's degree in Innovative Smart Systems (ISS). The focus of this practical course is on electromagnetic energy harvesting and wireless power transfer, crucial technologies for enabling energy autonomy in connected devices.

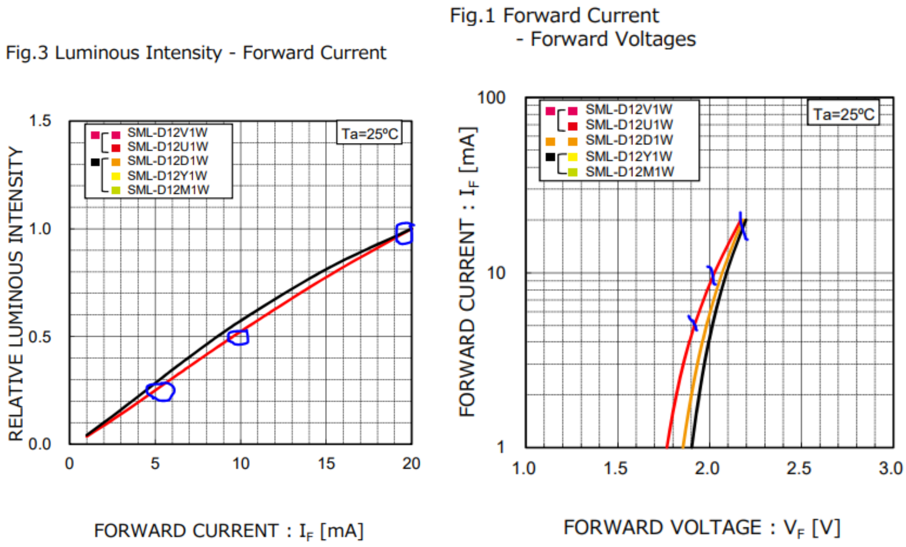
The objective of this study is to investigate the activation of a red LED (SML-D12U1WT8) from Rohm Semiconductor using energy harvested from ambient or specifically generated electromagnetic fields. This process allows us to explore two key approaches to energy management: the "direct consumption" strategy and the "store then use" strategy. The report will analyze the power and energy requirements for the LED, focusing on how to effectively harvest energy and optimize power consumption.

In addition, we will characterize rectifiers operating at different frequencies (868 MHz and 2.45 GHz) to determine optimal efficiency, load, and power conditions. The selection of an appropriate antenna for energy harvesting and wireless power transfer will also be thoroughly discussed. Moreover, the report will evaluate the performance of rectenna systems in both ambient energy harvesting and radiative wireless power transfer scenarios, including calculations of maximum operational distances under regulatory constraints.

II/Study of the load and design

We will determine the DC power required by the LED to operate at its nominal luminosity, as well as the power needed to achieve 50% and 25% of its nominal luminosity.

- 100 % of luminosity :
  20mA x 2.2V = 44 mW
- 50% of luminosity : :
  10mA x 2V = 20 mW
- 25% of luminosity : :
  5mA x 1.9V = 9.5 mW



Figures 1 : Forward current and voltage of our component and similar ones

We will determine the amount of energy required to turn on the LED for 1 second for the different percentage of luminosity using the following formula :

$$Watts = \frac{Joule}{S}$$

- 100% of luminosity : 44 mJ
- 50% of luminosity : 20 mJ
- 25% of luminosity : 9.5 mJ

A LED lit for one second is representative. It's easy to handle, represents communication, and can be used for sensor reading. First, we want to implement the "direct consumption" strategy.
For that goal, we will determine how much power must be provided to the LED to make it work, at which voltages, and what the luminosity of the LED will be.

To obtain the minimum value, we perform the following calculation (1% according to the diagrams):

$$1\,mA \;\times\; 1,78\,V \;=\; 1,78\,mW$$

However, the datasheet is incomplete and does not provide the threshold values for voltage and current. As a result, it is not possible to determine the exact minimum voltage and current. The datasheet is poorly written, with many missing details regarding the consumption limits. We do not know the maximum luminosity of the LED, nor the corresponding voltage and current for this intensity. What we do know is that the maximum power is 54 mW.

Some points we identified in the datasheet:

- The lines are not precise.
- The extreme cases are poorly documented (max mcd, min power, max power, etc.).
- The units differ within the same table (max power next to a typical value).
- There is no explanation provided to justify the absence of extreme data in the figures.

We will determine the configurations of capacitance and activation/deactivation voltage thresholds that can be employed, along with the minimum input DC power required to operate the system in the worst-case scenario.

$$E_{Stockée} = \frac{1}{2} * \ C * V^2$$

Where C is the capacitance and V is the voltage. We will use Vmin, the minimum supply voltage for the LED, and Vmax, the maximum supply voltage.

$$E_{Usable} = \frac{1}{2} \times \ C \ \times (Vmax^2 \ - \ Vmin^2)$$

Vmax will be 5.25V because there is both an activation and deactivation threshold, so we will use Vmin as 2.2V.

$$C \ >= \ (E \times 2) \div \ (Vmax^2 - Vmin^2)$$
$$C \ >= \ (44mJ \ \times 2) \div \ (Vmax^2 - Vmin^2)$$
$$C \ >= \ 3,87mF$$

We will therefore use a capacitance of 6.8 mF. By reducing Vmax to prevent an increase in unused energy, we find that Vmax should be approximately 4.3V, which results in a usable energy of 46 mJ.

$$E_{100\%} \gg \ 20mJ \ = \ \frac{1}{2} * \ 6,8 * 10^{-3}(4,3^2 - 2,2^2)$$
$$E_{50\%} \gg \ 20mJ \ = \ \frac{1}{2} * \ 2,2 * 10^{-3}(4,8^2 - 2,2^2)$$
$$E_{25\%} \gg \ 20mJ \ = \ \frac{1}{2} * \ 1,5 * 10^{-3}(4,2^2 - 2,2^2)$$

We will have to compensate for the energy requirements, so the minimum power supplies will be 413uW, 606uW and 52.5uW.

P in min 100% = 79μW
P in min 50% = 624μW
P in min 25% = 432μW

We will need to compensate for the energy requirements; therefore, we will set the minimum input power to 413 μW, 606 μW, and 52.5 μW.

III/Rectifier characterization

To characterize the antenna of our component, we used Gnu Radio Companion to simulate a real case utilisation. Chosen Raspberry Pi model: SDR 9

Assembly with :
- A constant source
- One UHD USRP Sink
- Two QT GUI ranges for frequency and power

We notice that the power curves are all similar between the groups, the beginning is zero because the threshold voltage of the LED is not reached. At the end we all have saturation. The capacitor is therefore charged.

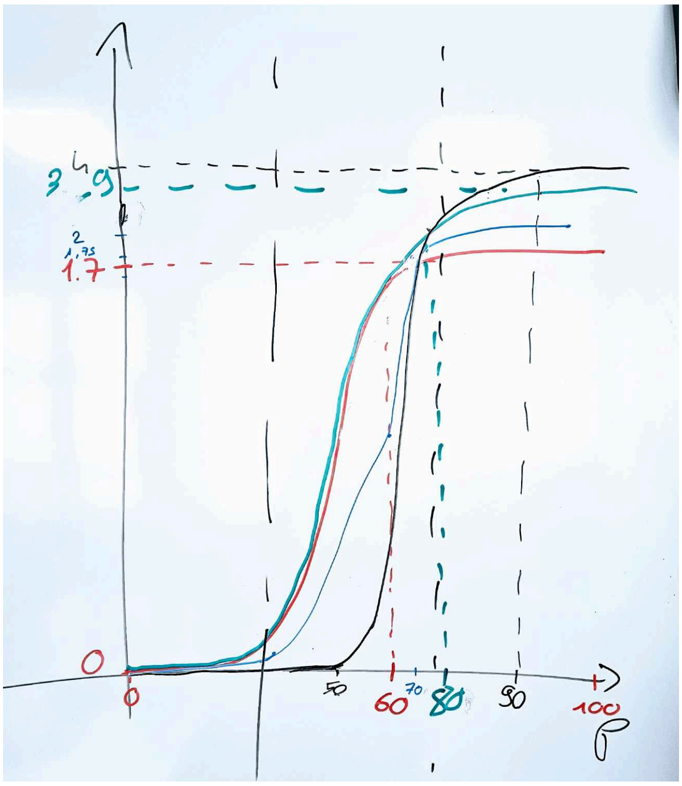


Figure 2 : Curves of the power to voltage threshold for all class groups. Our's is in green

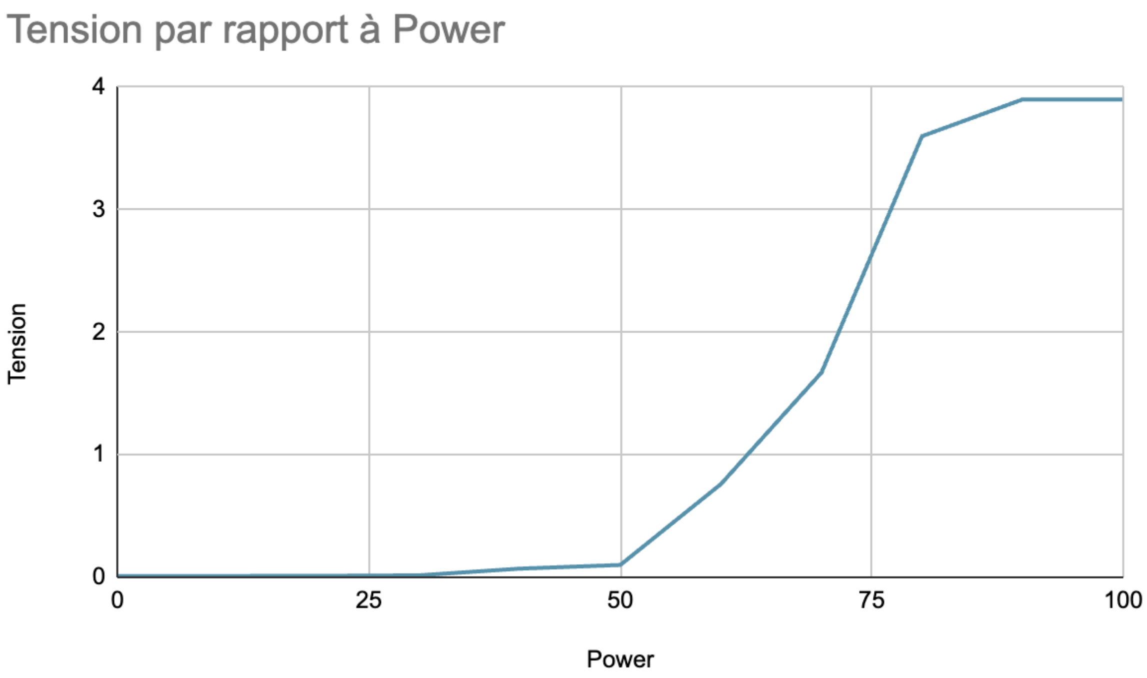


Figure 3 : Curve of our power to voltage ratio
X axis : power percentage / Y axis : Volts

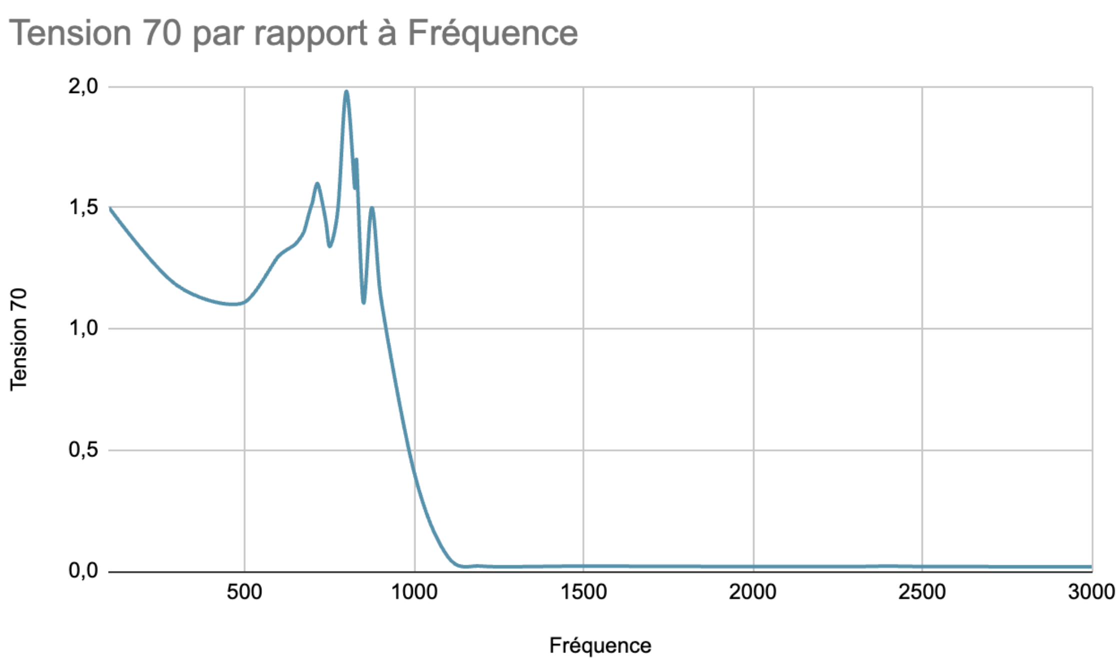


Figure 4 : Curve of our tension to frequency ratio
X axis : Mhz / Y axis : Volts

At low frequencies, we have the PMU as a load, which explains the curve and the efficiency of our graph compared with the green curve of another group that only has the LED as a load.

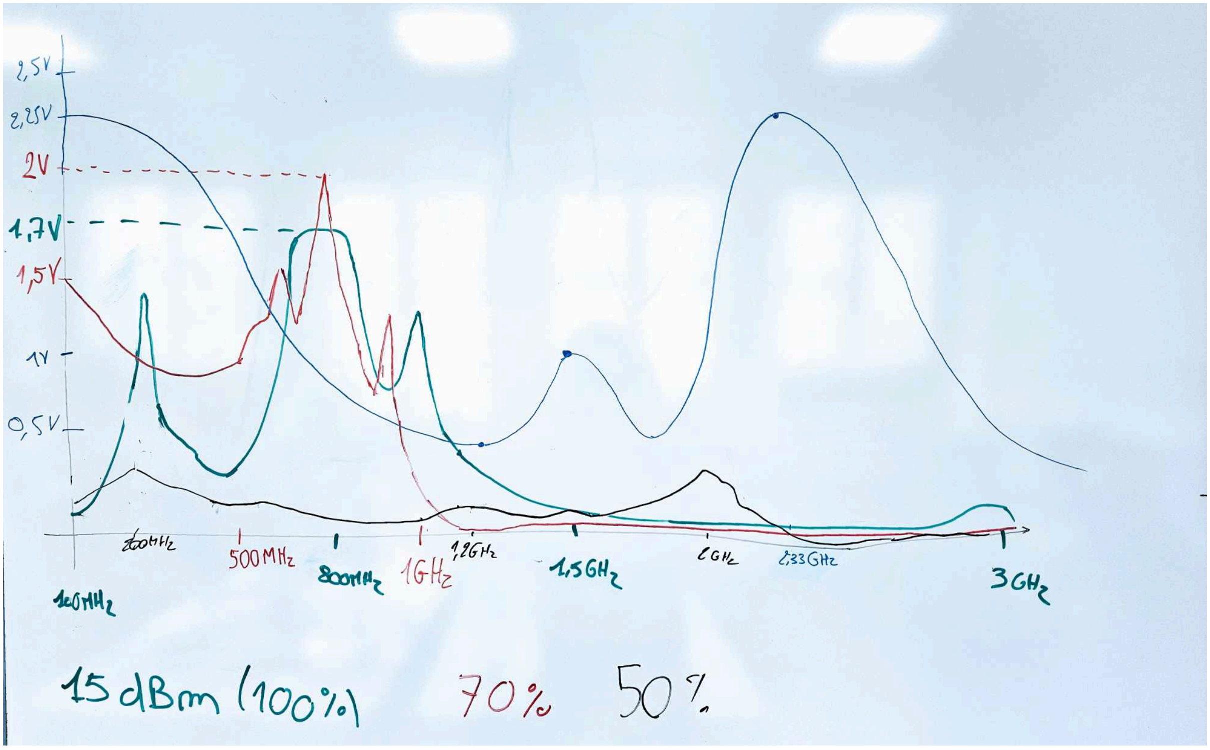


Figure 5 : Curve of our tension to frequency ratio compared to other groups Our's is in red

The difference in frequency can be explained by the precision of the components, which is more or less 10%. Component faults are therefore very visible at high frequencies.

For the black and blue curves, the shape of the curve is the same, but the voltage is different. We are looking at two similar rectifiers. A fault at a high frequency leads to greater differences.
As far as low frequencies are concerned, the difference is also explained by the load, one a PMU and the other an LED.

IV/Antenna choice

Antenna Size vs. Frequency :

The size of an antenna is inversely proportional to its operating frequency. This relationship is given by the equation:

$$L_{Antenna} \gg \frac{\lambda}{2} = \frac{c}{2 \times f}$$

Where:

- L antenna : Length of the antenna
- lambda : Wavelength
- c : Speed of light (3.10^8 m/s)
- f : frequency of opearation

For example:

- at f = 868 MHz , lambda = 0,345 m , so L antenna = 0,172 m
- at f = 2,45 GHz , lambda = 0,122 m , so L antenna = 0,061

Be careful this is only theoretical and can be different in reality in function of hardware characteristics.

Thus, **lower frequency antennas (e.g., 868 MHz)** are physically larger than **higher frequency antennas (e.g., 2.45 GHz)**.

Antenna Types :

Based on the provided information and our experiments, we evaluated that the component given to our class where embedded with two kinds of antennas :

- **Long Antenna (868 MHz)**:
  - **Size**: Larger, optimized for lower frequencies.
  - **Efficiency**: Higher due to larger effective area.
  - **Use Case**: Suitable for long-range transmission, but bulkier.
- **Short Antenna (2.45 GHz)**:
  - **Size**: Smaller, suitable for higher frequencies.
  - **Efficiency**: Slightly lower due to reduced size.
  - **Use Case**: Ideal for compact systems requiring higher frequency operation.

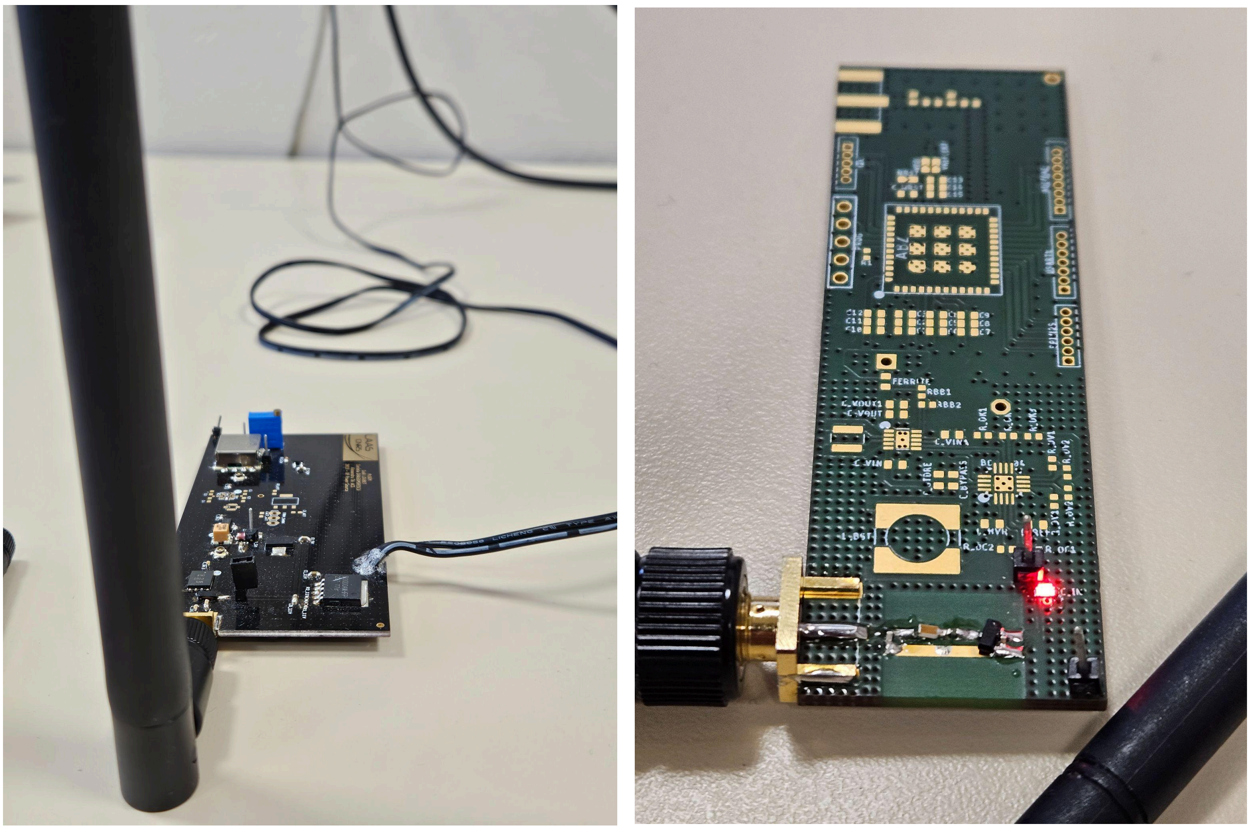
As our group had a spike around 800 Mhz, we have a long antenna embedded.

Energy transfer experimentation :

During the last part of the course, we focused on wireless energy transfer. This part aimed at powering on the LED of our component without having it connected to a wired power supply. To achieve that, we learned about the ability of gathering power from electromagnetic waves sent to an antenna.

Every wave contains energy; this energy is lowered when going through obstacles and/or hitting an antenna or metallic object which will absorb the wave's power. Using this knowledge, we focused on storing enough energy in our component to hit the LED's powering on threshold.

We were introduced to three antennas which we could try with a component to test their energy gathering ability from a source. Here are the source and it's long linear antenna, and the component which we'll try to power on :



Figures 6 : Source on the left and receiver component on the right

And here are the three antennas which we could test the energy transfer with :

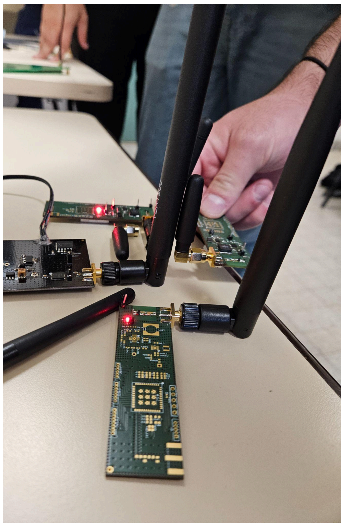


Figure 7 : Linear Antenna

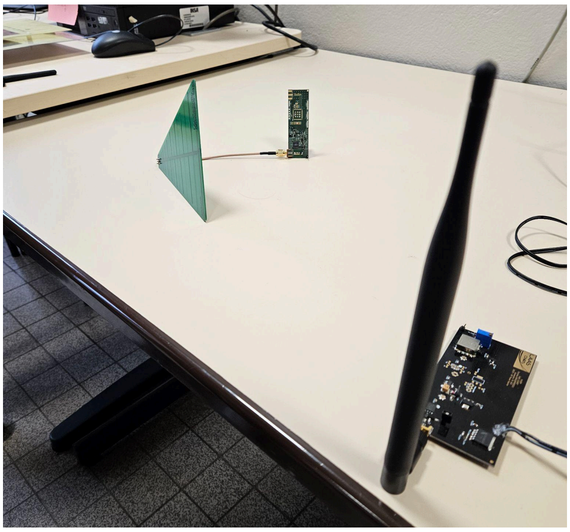
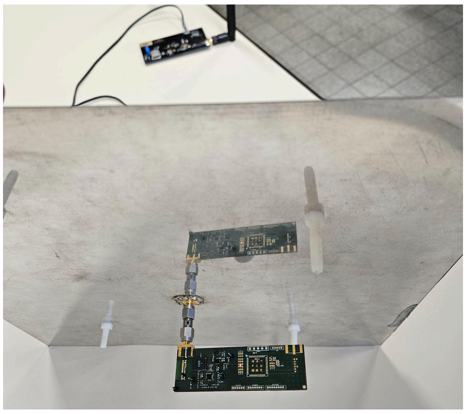


Figure 8 : Yagi Uda Antenna

Figure 9 : Patch Antenna



By connecting to these antennas and testing the transmission, we could gather some information and conclusions about this experiment. Here are our observations :

- We had negligible results with the Yagi Uda antenna whatever the orientation and distance (except at very close range thanks to the electromagnetic field's close range energy of the source.

- The Patch antenna, while allowing for the longer range of operation with its two sided reception surface, had some moderate results. The LED had a hard time getting turned on even at a somewhat close range. Also, we discovered that it was very sensitive at the alignment with the source : tilting it even a little would significantly decrease the efficiency.

- Finally the linear antenna gave us by far the best results at close and moderate range (>=1m). The antenna maintained the LED of the component on during most of the time and it handled the different orientation of the antenna quite well (tilting it had a lower impact than tilting the Patch antenna)

This experiment allowed us to grasp the concept of the energy transfer and the impact of the choice of the antenna, regarding distance and orientation.

V/Radiative Electromagnetic Wireless Power Transfer

The goal of this section is to calculate the theoretical maximum distance between the transmitting antenna and the receiving rectenna for powering an LED with wireless energy transfer. The calculations are based on the provided data and regulatory constraints.

Efficiency

$$\eta_{rectenna} = \frac{P_{DC\_out}}{P_{RF\_in}} = \frac{P_{DC\_out}}{S \cdot A_{eff}}$$

Effective electric field

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

Incident electromagnetic power density

$$\mathrm{S} = \frac{E^2}{120 \cdot \pi} (W \cdot m^{-2})$$

Effective area of the antenna

$$\mathrm{A}_{eff} = G_{RX} \cdot \frac{\lambda^2}{4 \cdot \pi} (m^2)$$

Data and Parameters

- Frequency (f): 868 MHz
- Transmitted Power (P): 33 dBm (2 W)
- Minimum Power for LED (Pmin): 44 mW (for 100% luminosity)
- Transmitting Antenna Gain (G): 9 dBi = 7.94 (linear gain)

Step-by-Step Calculations :

Wavelength (lambda):

The wavelength of the electromagnetic wave is given by:

$$\lambda = \frac{c}{f} = \frac{3.10^{8}}{868.10^{6}} = 0,345\, m$$

Electric Field (E):

The effective electric field at the receiving antenna is calculated as:

$$E = \sqrt{30 \times P \times Gtx} = \sqrt{30 \times 2 \times 7,94} = 21,83\, V/m$$

Power Density (S):

The power density at the receiving antenna is determined by:

$$S = \frac{21,83^{2}}{120 \times \pi} = 1,26\, W/m^{2}$$

Maximum Distance (D):

Assuming the received power equals the LED's minimum power requirement Pmin=44 mW, the theoretical maximum distance is given by:

$$D = \sqrt{\frac{30 \times 2 \times 7,94}{1,26}} = 14\, m$$

The theoretical maximum distance between the transmitting antenna and the receiving rectenna, under ideal conditions, is **14 meters**. This is the distance required to transmit 44 mW of power to fully illuminate the LED.

Proposals for Improving Distance

To extend the maximum distance for energy transfer, the following solutions can be implemented:

1. **Use of High-Gain Antennas**:
   Employing antennas with higher gain increases the efficiency of power transmission, reducing losses in the propagation path.
2. **Reduction of Component Losses**:
   Minimize energy dissipation in the rectenna circuit by using high-quality components with low resistance and high conversion efficiency.
3. **Optimized Rectenna Design**:
   Enhance the rectenna's design to maximize its power harvesting capability, ensuring better alignment and impedance matching.

VII/Conclusion

This project has been an invaluable experience in exploring the potential of **energy harvesting and wireless power transfer** for connected devices. Throughout the course, we gained practical insights into key concepts such as electromagnetic energy harvesting, rectenna optimization, and the theoretical and experimental design of efficient power transfer systems.

We were able to:

- Analyze and calculate the power and energy requirements of a connected device, such as an LED, in both direct consumption and store-and-use strategies.
- Design and test rectifiers operating at different frequencies, identifying optimal conditions for load and power efficiency.
- Study the characteristics of various antennas, understanding their influence on the range and efficiency of power transmission.
- Explore theoretical principles and apply them in real-world scenarios, linking classroom knowledge to hands-on experimentation.

A special thanks to **Mr. Gaël Loubet** for his guidance and support throughout the laboratory sessions. His expertise and availability were crucial in helping us overcome challenges and deepen our understanding of these advanced technologies. The practical sessions not only enriched our technical knowledge but also emphasized the importance of collaboration and innovation in tackling real-world problems.

This course has prepared us to address the growing demand for **energy-autonomous connected devices**, equipping us with the tools and knowledge to contribute meaningfully to the field of smart systems. We leave this project with a strong appreciation for the intricate balance between theoretical design and practical implementation, and we are inspired to continue exploring this exciting domain in the future.