Innovative Smart System

Energy for Connected Objects

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Introduction and Objectives

In this tutorial, we discovered how to power connected objects using wireless power. Our team believes that this report aims to achieve the following objectives:

- Exploring energy solutions for powering connected objects:
  - Without wires,
  - Without batteries,
  - Using ambient energy harvesting,
  - Employing wireless power transfer, and
  - With the integration of (super)capacitors.
- Understanding good practices for designing low-power wireless connected objects:
  - Hardware considerations (components, routing, etc.),
  - Software optimization (initialization, architecture, etc.), and
  - Electromagnetic compatibility (wireless communication, EMC, etc.).
- Studying state-of-the-art solutions for powering IoT devices.

1

Study of the Load and Design

The system modelling begins with the LED selected for this project, the SML-D12U1WT8 from Rohm Semiconductor. According to its data sheet, its luminous intensity depends on the forward current, with associated forward voltage values.

1.1 Power Requirements of the LED

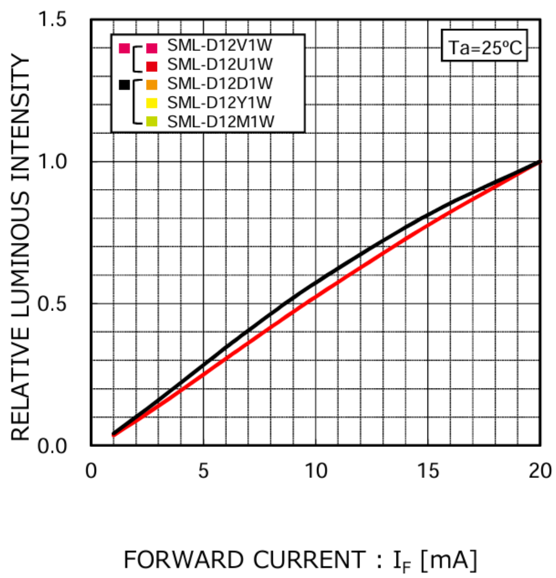

Figure 1.1: Luminous intensity depending the current consumption

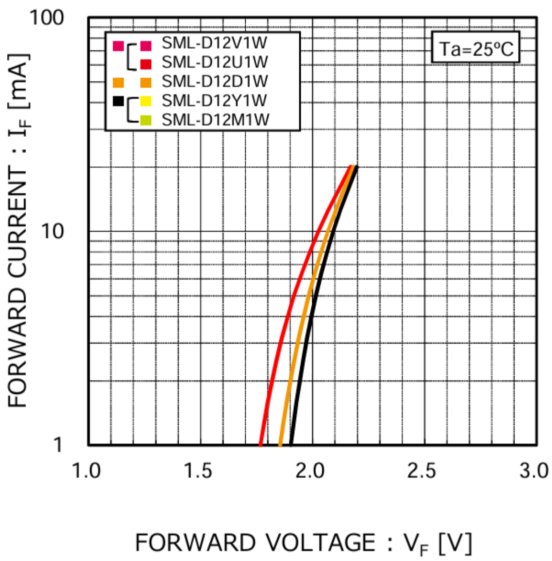

Figure 1.2: Forward current as a function of forward voltage.

Luminosity (%)	Current (mA)	Voltage (V)	Power (mW)
100	20	2.2	44
50	10	2.0	20
25	5	1.9	9.5

Table 1.1: LED power requirements for various luminosity levels.

The variation in voltage depending on the current arises from the resistance of the circuit. Different luminous intensities simulate the behavior of a connected object with visible variation in luminosity (parallel to power consumption).

At this stage of the project, we wondered whether, assuming we could light an LED at this instantaneous power level, it might not be possible to power other components?

1.1.1 Energy Requirements

- **Energy to light the LED for 1 second at 100%:** $44\,\text{mW} \times 1\,\text{s} = 44\,\text{mJ}$

1.1.2 Minimum Power and Voltage Thresholds

- **Minimum power for LED to light (5% luminosity):** $1\,\text{mA} \times 1.75\,\text{V} = 1.75\,\text{mW}$
  It probably still works below this wattage, but the LED has just not been characterised.

- **Maximum power :** Corresponds to the maximum dissipated power $= 54\,\text{mW}$
  We've surpassed 100% (probably a poorly chosen unit, as we can exceed the scale set).

1.1.3 Capacitance and Threshold Configuration

- To light at 100% for 1 second, energy storage of $44\,\text{mJ}$ is required.

- Threshold voltages are determined by maximizing the voltage difference (e.g., $5.5\,\text{V} - 2.2\,\text{V} = 3.3\,\text{V}$) to optimize capacitance choice.

Results:

- At 100%, $C = 6.8\,\text{mF}, V_{\text{max}} = 4.3\,\text{V}$

- At 50%, $C = 2.2\,\text{mF}, V_{\text{max}} = 4.8\,\text{V}$

- At 25%, $C = 1.5\,\text{mF}, V_{\text{max}} = 4.12\,\text{V}$

For system losses, a minimum input power of $16.62\,\mu\text{W}$ is required. For the worst case (100% operation), the consumption is $52.5\,\mu\text{W}$.

Faced with these theoretical consumption figures, we can try to put them into perspective with the consumption of a microcontroller. Let's take the RL78/G13 from Renesas as an example. This is one of the lowest-consumption microcontrollers on the market today.

Power Mode	Current	Power @ VDD = 3V	Description
Active (Normal)	2.3 mA @ 16 MHz	6.9 mW	CPU and peripherals are fully operational, standard mode of operation.
HALT	50 µA	150 µW	CPU is halted, system or specific peripheral clocks remain active.
SNOOZE	40 µA	120 µW	Specific tasks executed by peripherals (e.g., UART, I^2C) without waking the CPU.
STOP	210 nA	630 nW	Deep sleep, SRAM data retention, main oscillator inactive.
OFF	Practically zero	Not mesured	Total shutdown, no activity, minimal power for external wake-up if configured.

Table 1.2: Power Consumption of RL78/G23 in Different Modes

1.2 Energy Storage Configuration

In order to be able to store enough energy to light the LED at 100% for 1 second, we need to choose a capacitor with specific activation and deactivation voltage thresholds.
To switch on the LED for 1 second at 100% we need 44mJ.

$$E_{100\%} = 44mJ = \frac{1}{2}CV^2 = \frac{C(V_{max}^2 - V_{min}^2)}{2} \tag{1.1}$$

Flipping the equation we have:

$$C = \frac{2E}{V_{\text{max}}^2 - V_{\text{min}}^2}$$

where:

- E is the required energy,
- V_{max} is the maximum voltage (5.25 V),
- V_{min} is the minimum voltage (2.2 V).

For $E = 44$mJ, we calculate a minimum capacity of:

$$C \geq \frac{2 \times 44 \times 10^{-3}}{5.25^2 - 2.2^2} = 3.87\,\text{mF}$$

As the capacitance is the most limiting element, we take the nearest available upper value, in this case 6.8 mF.
However, this value is far too oversized, and we can't increase the voltage V_{min}, because we want to keep it as low as possible. So we can only try to determine the minimum

possible value of V_{max}.

$$V_{max} = \sqrt{2 \times \frac{E}{C} + V_{min}^2} = 4,22V$$

We round it off to $4,3$V to be sure of exceeding 100%.

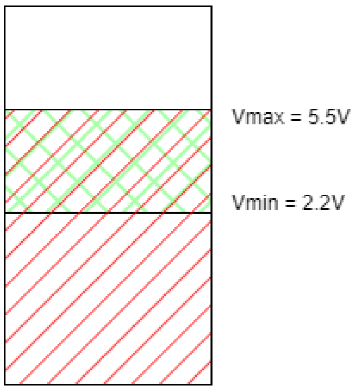

Figure 1.3: Capacitor Schematic

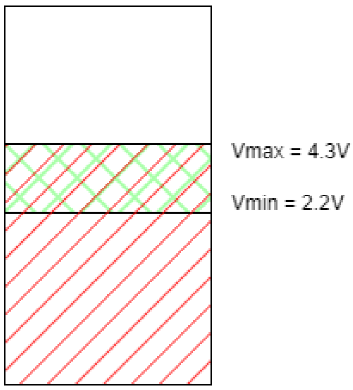

Figure 1.4: Capacitor Schematic

We carry out the same operation for 50% and 25% to obtain the following results results:

- At 50%, the capacitance obtained is $C = 2.2mF$ for a $V_{max} = 4.8V$.
- At 25%, the capacitance obtained is $C = 1.5mF$ for a $V_{max} = 4.12V$.

To operate, we need to compensate for the system losses, so we need at least 16.62 μW to power our system while making up for the losses.
For example, in the worst case, for the capacitor chosen to operate at 100% operation, its consumption is 52.5μW.

2

Rectifier Characterization and Frequency Choice

2.1 Frequency Response

We measured the voltage at the ports of the potentiometer during a frequency sweep, between 800 MHz and 950 MHz and between 2.4 GHz and 2.5 GHz, with a step of 10 MHz, for a resistive load of 1.5 kΩ and an RF input power of -15 dBm. We then tried to find the frequency for which the rectifiers work the more efficiency. Measure their frequency bandwidth.
The measured output voltages across the potentiometer are shown in Figures 2.1 and 2.2.

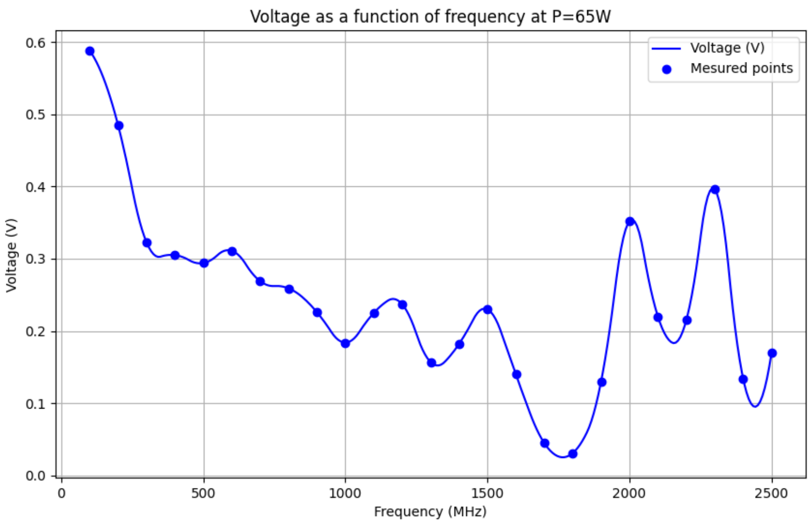

Figure 2.1: Voltage response for the rectifiers during a frequency sweep.

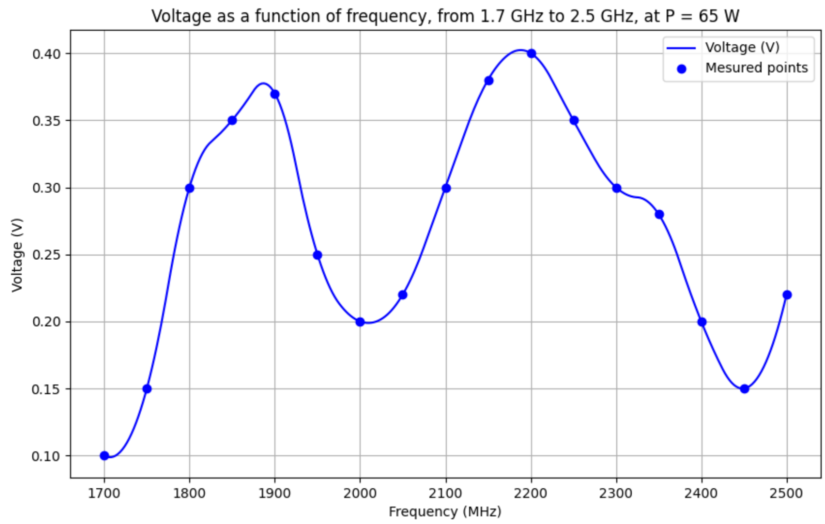

Figure 2.2: Voltage as a function of frequency, from 1.7 GHz to 2.5 GHz, at P = 65 W

In our case, we had a 2,45GHz receiver, but we can see that it is in the low frequencies that it achieved its maximum voltage, at 600 MHz if we take the 500MHz to 950Mhz sweep frequencies.
While around the 2GHz, we observed that it peaked at 2.2 GHz.

When we compare with the rest of the class, which you can see in Figure reffig:ref, we find completely different cases. The behaviour of 868 MHz modules changes significantly around 800 MHz, although the behaviour of each of the groups varies widely.

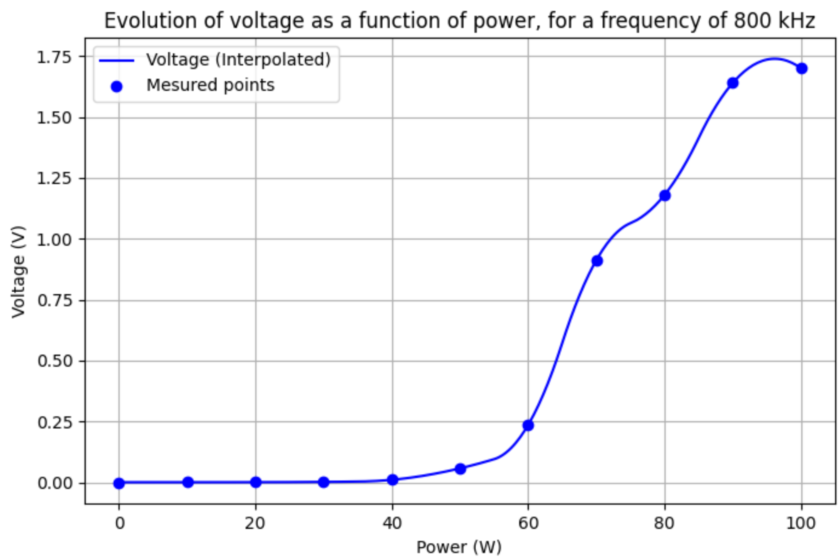

Figure 2.3: Voltage as a function of load resistance for both rectifiers.

4. Minimum RF Input Power for Targeted Loads

The minimum RF input power required to power the targeted load (LED or board) was determined experimentally:

- For the LED, the minimum RF power was -23 dBm for visible light output.
- For the "store-then-use" board, the minimum RF power was -20 dBm to charge the supercapacitor to operational voltage.

These results are consistent with the previously computed efficiencies and minimum DC power requirements.

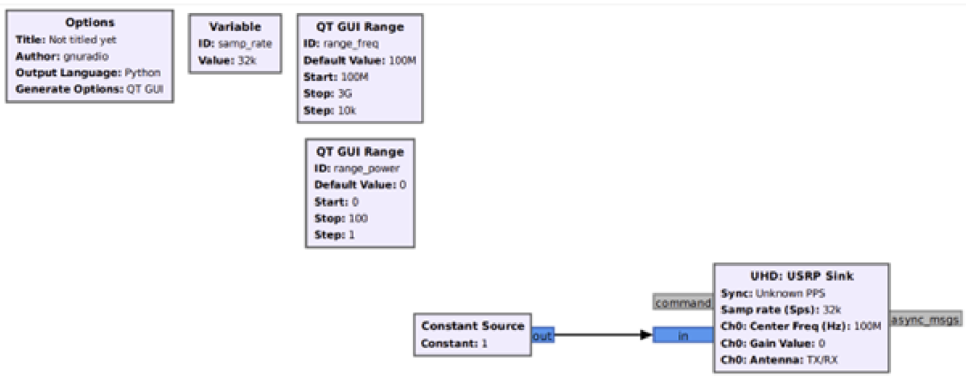

Figure 2.4: GNU radio simulation.

3

Antenna Choice

We know that the choice of antenna is critical in wireless power transmission (WPT) systems. Antennas affect the range, efficiency, and orientation of the power delivery. For this lab, we used patch antennas, for its high gain and directional properties, and whips antennas for their compact size and omnidirectional radiation pattern. This section explores the behavior of these antennas and their implications for WPT.

3.1 Patch Antenna Characteristics

The patch antenna has an operating frequency of 868 MHz and a gain of 9 dBi. Its directional radiation pattern focuses energy, thus enhancing the efficiency of power transfer over a line-of-sight path.

Advantages:

- High gain enhances energy transfer efficiency.
- Suitable for fixed positions with consistent orientation.

Limitations:

- Requires precise alignment with the receiver.
- Performance drops significantly if misaligned or rotated.

3.2 Whip Antenna Characteristics

The whip antenna, used on our test as the receiving side, provides a good compromise between size, radiation pattern, and gain. While its gain is lower than the patch antenna, its omnidirectional pattern allows for energy reception from multiple directions.

Advantages:

- Flexible orientation due to omnidirectional radiation.
- Compact size makes it suitable for IoT devices.

Limitations:

- Lower gain (approximately 2 dBi) compared to the patch antenna.
- Reduced efficiency at long distances.

3.3 Testing Antenna Performance

Using GNU Radio and an Analog Discovery 2, we tested the performance of the patch and whip antennas. The following tests were performed:

1. Directional Sensitivity Test: Rotating the patch antenna by 90° reduced received power to nearly zero, confirming its high directionality.
2. Power Transfer Range Test: At optimal alignment, the LED was visible up to 1 meter from the transmitter.
3. Frequency Response Test: The patch antenna exhibited optimal performance at 870 MHz, with minor degradation at frequencies ±20 MHz.

Figure 3.1: Example of a module lighting a LED at a distance of 30 cm from the transmitter

3.4 Improving Antenna Performance

To enhance the range and efficiency of WPT systems, the following approaches can be considered:

- Using high-gain antennas on both the transmitter and receiver sides,
- Designing antennas that are specifically tuned to the operating frequency,
- Ensuring proper alignment between antennas for maximum power transfer.

4

Ambient energy harvesting

4.1 Insufficient ambient energy

Ambient energy harvesting makes use of electromagnetic waves present in the environment to power connected devices. Sources of such energy include:

- Wi-Fi signals,
- Radio and television broadcasts,
- Cellular networks.

In this TP, if we had had the time, we should have analysed the feasibility of harvesting energy from the environment to power the LED, by using a spectrum analyser. After discussing this with the professor, he told us that we should have observed that the noise level would be too low to power the LED even at its minimum luminosity.

4.2 Alternative Sources of Energy

In the case not being able to import our own energy, the possibility of using other energy sources can be raised, such as for examples :

- The thermal energy, by using the temperature differences, that can be used to generate electricity using thermoelectric generators.
- Vibrations or movements can power piezoelectric generators, allowing the exploitation of mechanical energies.
- The solar energy by employing photovoltaic cells to provide sufficient power in well-lit environments.
- ...

The exploitation of energy sources depends on their form and the environment that constrains them. The use of solar energy is minimal in an area that is shaded while effective in an open and sunny environment. The recovery of cynetic energy in inertive environment is difficult and effective in dynamic environment, thanks to wind, or water for example. The requirement of a sufficient temperature difference for the exploitation of the thermal energy is not available in every application. All this to say that the energy to be used will depend on the environment surrounding the site.

The ability to wirelessly harvest ambient energy in the form of electromagnetic noise, or to position an external generator outside of constrained environments, underlines the strength and flexibility of wireless energy solutions. By tailoring the energy-harvesting strategy to the surrounding environment, innovative solutions can be developed to power connected devices in even the most challenging conditions.

5

Link with our project

Our innovative project called 'Wisper' aims to establish the complete acquisition chain for an intracranial pressure sensor, from the wireless acquisition of data from the intracranial sensor via a patch to the storage of the data on a server, including the power supply and wireless communication between the patch and a decentralized hub. This project is linked to the concepts of this course/task because the patch is intended to be 'autonomous' in terms of energy, in the sense that the patch does not have to incorporate a battery. To achieve this, we have chosen to implement the RuBee protocol, which we have chosen to establish wireless communication between the patch and the hub, and which has a wireless power option on a specific frequency band (65536 Hz).

The motivation for choosing the RuBee protocol was not only based on this power option, which could be used in parallel with other communication protocols, as shown in this TP, but also on its communication at low frequencies, over distances much shorter than the wavelength of the communication carrier frequency, using magnetic dipole antennas, and its anti-collision system.

Conclusion

This lab has presented the possibilities and challenges of WPT for the connected objects. With such considerations regarding the power needed for an LED and optimization of energy storage systems, the basis for energy autonomy has been set. Rectification characterization at 868 MHz and 2.45 GHz reveals a need to adjust the frequency of operation, the load used, and the input power to achieve the maximum possible efficiency while tests involving an antenna have emphasized trade-offs related to gain, directionality, and flexibility.

The ambient energy harvesting study has also brought into focus its limitation as electromagnetic noise in the natural environment is found to be lacking and practically infeasible to be applied in the field for high power requirements. Under these constraints, sources like solar, mechanical or thermal energy became alternative ways.

This work proved the possibility of achieving energy autonomy for IoT systems by integrating wireless power and communication by applying the concept to practical implementation through the "Wisper" project. WPT brings a great promise; however, more improvements on efficiencies, scalability, and hybrid energy solutions are its potential future. The laboratory provided a solid foundation in innovation toward sustainable and autonomously functioning devices.