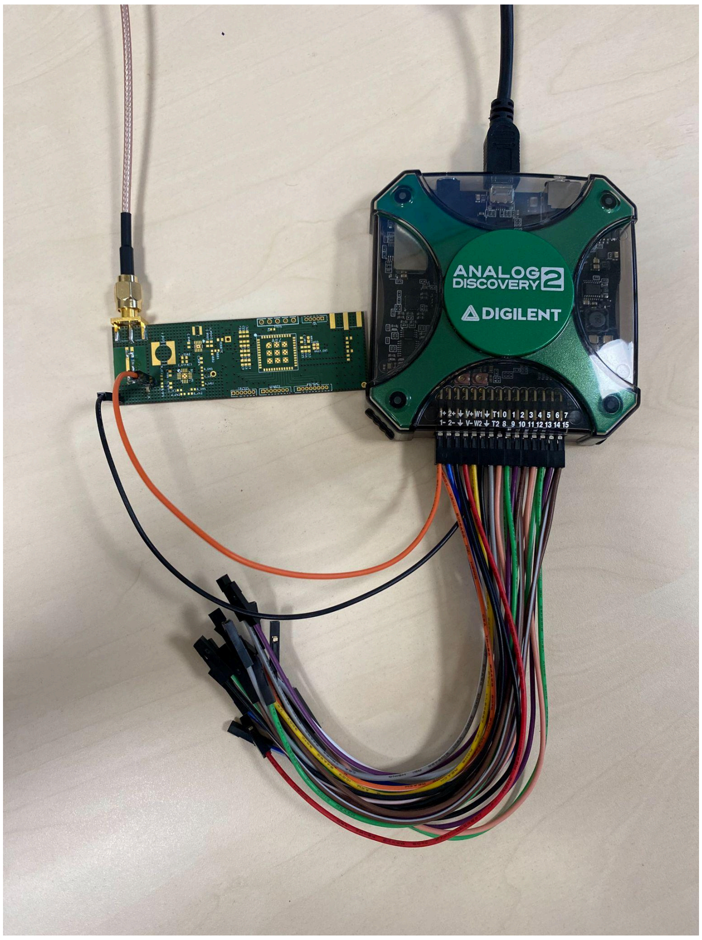
Energy for connected objects



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Summary

Introduction

Wireless sensor networks (WSNs) play an important role in various applications, such as Internet of Things (IoT), industrial and environmental fields and smart systems. These networks are often deployed in large quantities and must operate over extended periods without frequent maintenance to ensure long-term autonomy.

To meet these needs, various methods for powering connected sensors have been explored, each with its advantages and limitations. These methods include traditional battery use, ambient energy harvesting, and wireless power transfer. Different technologies, such as light, thermal, mechanical, and electromagnetic energy harvesting, offer solutions for powering these devices. However, each approach presents trade-offs in terms of efficiency, cost, and applicability.

This lab report investigates the energy harvesting and wireless power transmission techniques used to sustainably power connected devices. We focused on understanding the energy demands of a small red light and explored methods for direct energy use, storage solutions, and the conversion of electromagnetic energy. The objective was to experiment with innovative technologies to enhance the efficiency and autonomy of self-powered devices.

I. Study of the load and design

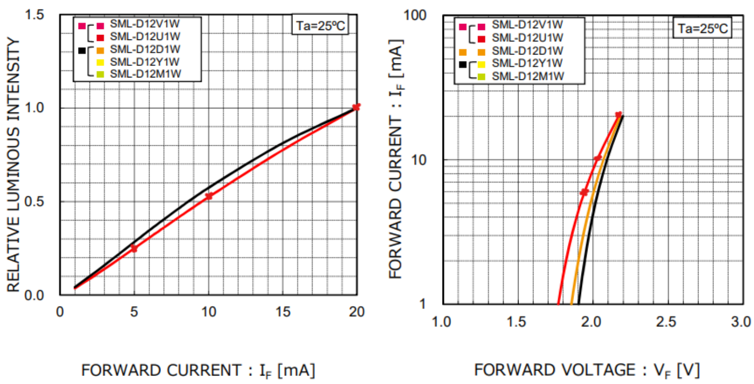
In this section, we will discuss four key points related to the study of the LED SML-D12U1WT8, its power requirements, energy consumption, and how to effectively store and manage energy for connected devices. These points include the DC power needed by the LED, the energy required for its operation, the power required to activate the LED, and the configurations of capacitance and voltage thresholds that impact the system's performance.

The DC power required by this LED varies depending on its operating conditions. Under nominal usage, with a voltage of 2.2V and a current of 20mA, the power consumption is calculated to be 44mW (P = U.I), which represents the typical operating condition.

When the LED operates at 50% of its nominal use, with a reduced voltage of 2V and a current of 10mA, the power drops to 20mW.

At 25% of nominal use, with a further decrease to 1.9V and 5mA, the power consumption is even lower, at 9.5mW.

These variations in power consumption demonstrate how adjusting the voltage and current directly affects the energy requirements of the LED for optimizing energy efficiency in connected devices.



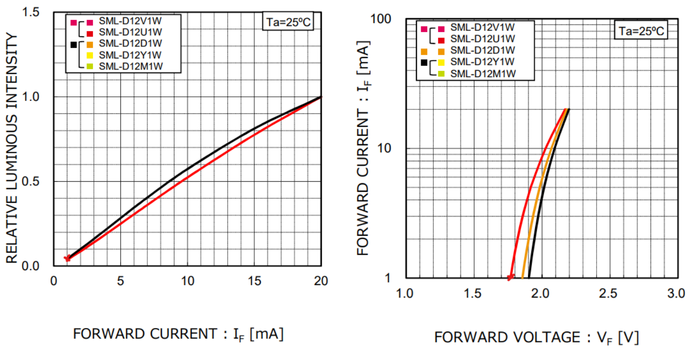
The energy required to light the LED for 1 second depends on the power consumption in each operating state. At 100% of its nominal power, the LED consumes 54mW, leading to an energy requirement of 54mJ for 1 second.

When operating at 50% power, the energy required is 27mJ, and at 25% power, the energy required is 13.5mJ.

These calculations highlight how reducing the LED’s power consumption directly reduces the energy needed for a given period of operation. This strategy of direct energy consumption is advantageous in terms of simplicity and efficiency, but it can be limited by the available power supply and the potential for energy loss, which affects the system's overall performance.

The minimum power required to activate the LED can be calculated based on the minimum current (Imin = 1mA) and voltage (Vmin = 1.75V). In this case, the minimum power required is 1.75mW (Pmin = Imin.Vmin). At this minimum power level, the luminosity of the LED is less than 5%, indicating that the LED is not performing optimally at such low power levels.

PMU and DC-DC converters regulate the power supplied to the LED and allow energy conversion. The PMU ensures that the voltage and current remain within optimal ranges for the LED to operate efficiently. However, losses are inevitable in any power conversion process. These losses arise from inefficiencies in the rectifiers, the conversion process, and energy storage systems. To minimize these losses, careful selection of components and optimization of the PMU settings are essential.



We also wanted to store the minimum unused energy. For this, we choosed a low capacitor/voltage: the power management unit (PMU) associated with a DC-DC converter requires power within specific voltage ranges to operate properly (between 2.2 and 5.25 V).

The available supercapacitors come in different capacitance values: 100 µF, 220 µF, 1.5 mF, 2.2 mF, 6.8 mF, 10 mF and 22 mF. Each of these capacities has associated losses that influence the system efficiency.

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

$E_{usable} = \frac{1}{2} C \left(V_{max}{}^2 - V_{min}{}^2\right)$

$E_{stock\text{-}no\text{-}usable} = \frac{1}{2} C V_{min}{}^2$

So : $C = \frac{2E}{Vmax^2}$ = 3,87mF

To store 44mJ, we have to choose a supercapacitor of 6,8mF, 10mF or 22mF.

For $E_{100\%}$ = 44mJ :

With : C = 6,8mF

We have : $E = \frac{1}{2} * 6{,}8 * 10^{-3} (4{,}3^2 - 2{,}2^2)$ = 44mJ

The minimum input DC power required :

$P_{IN\ min}$= 79 µW

For $E_{50\%}$= 20mJ :

With : C = 2,2mF

We have : E = $\frac{1}{2}$ * 2,2 * 10^{-3} $(4,8^2 - 2,2^2)$ = 20mJ

The minimum input DC power required :

$P_{IN\ min}$= 629 µW

For $E_{25\%}$= 9,5mJ :

With : C = 1,5mF

We have : E = $\frac{1}{2}$ * 1,5 * 10^{-3} $(4,2^2 - 2,2^2)$ = 9,5mJ

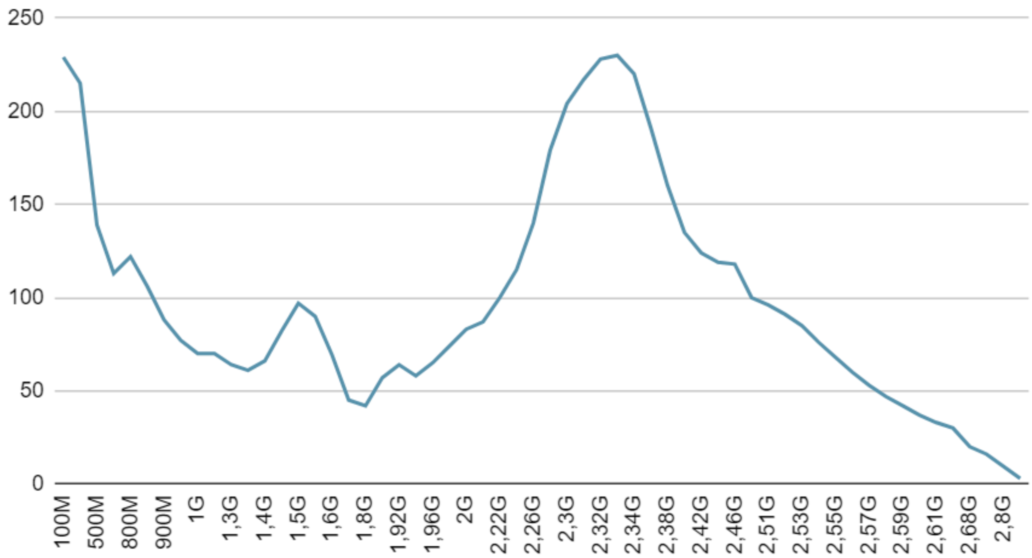
The minimum input DC power required :

$P_{IN\ min}$= 432 µW

The strategy of storing energy and then consuming it offers several advantages. By using supercapacitors, we can store energy during periods of low consumption or when excess energy is available, then draw on it when needed. This reduces the dependence on continuous energy supply and helps optimize the efficiency of the system. However, there are limitations to this approach, such as the potential losses during the charging and discharging cycles of the supercapacitors. These losses can decrease overall system efficiency and performance.

II. Rectifier characterisation

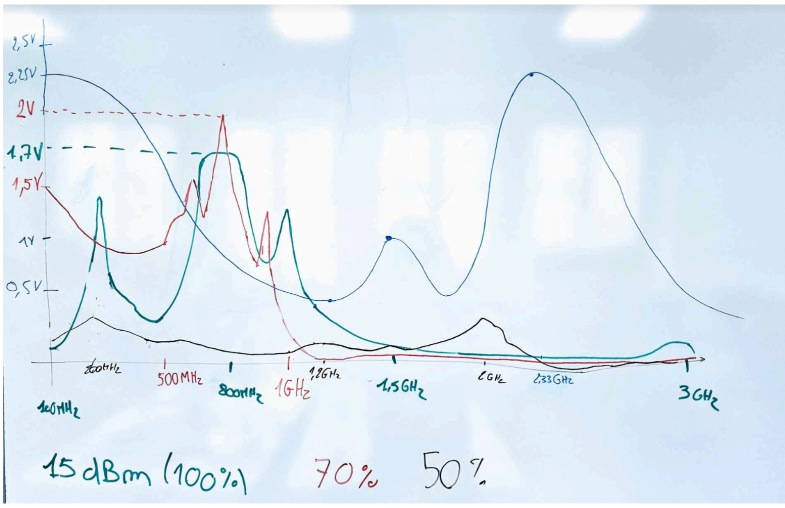
In this section, we first aimed to figure out if our rectifier performed better at 868 MHz or 2,45 GHz. Its objective is to convert the radiofrequency power (at a specific frequency) in direct current power. By using a USRP device, we tested the rectifier at both frequencies and discovered it performs optimally at 2,45 GHz. Next, we varied the frequency between 800 MHz and 900 MHz, between 2.4 GHz and 2.5 GHz to measure how the voltage across the potentiometer changed with these adjustments.



Voltage at the ports of the potentiometer during a frequency sweep

We can conclude from the curve that the optimal frequency of our system is around 2,33 GHz. At this frequency, the LED achieves its brightest luminosity, indicating that the system is operating more efficiently.

If we now look at the curves of our colleagues and compare the charges:



Red VS Green curve:

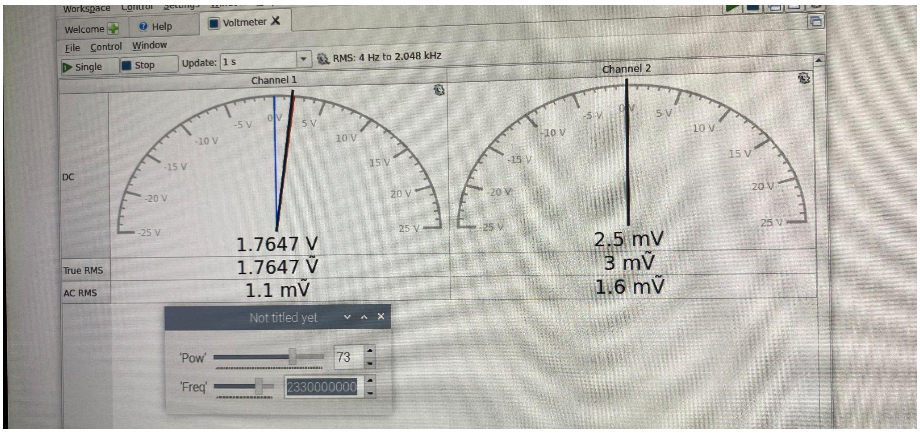
- Observation: The green curve corresponds to a configuration where only the LED is connected as a load, while the red curve represents a configuration where the PMU is in charge.
- Results:
    - Green curve: A voltage peak of 1.7V is observed at 800 MHz.
    - Red curve: The PMU system adapts better to the load, with a peak of 2V at 800 MHz.
- Interpretation:
    - The PMU allows for better voltage stabilization by optimizing the input, which explains the higher peak for the red curve.
    - While the green curve, with a single LED, shows less ability to reach high voltages, which is expected without advanced power management.

Black VS Blue curve:

- Observation: The black and blue curves have a similar overall shape, but a significant difference in output power and voltage.
- Results:
    - Blue curve (LED): The voltage peak reaches 2.25V at 2.3 GHz, which demonstrates better efficiency for this frequency.
    - Black curve (PMU): We observe a voltage peak of 0.25V at 2.3 GHz, much lower than that of the blue curve.
- Interpretation:
    - The blue curve, representing a configuration optimized for 2.45 GHz with a single LED, shows maximum efficiency for this frequency band, with a much higher peak voltage.

- In contrast, the black curve, where the PMU system is associated with a supercapacitor, presents a much lower voltage at the same frequency, which shows that energy management via the PMU and the supercapacitor causes a drop in performance in this frequency band.

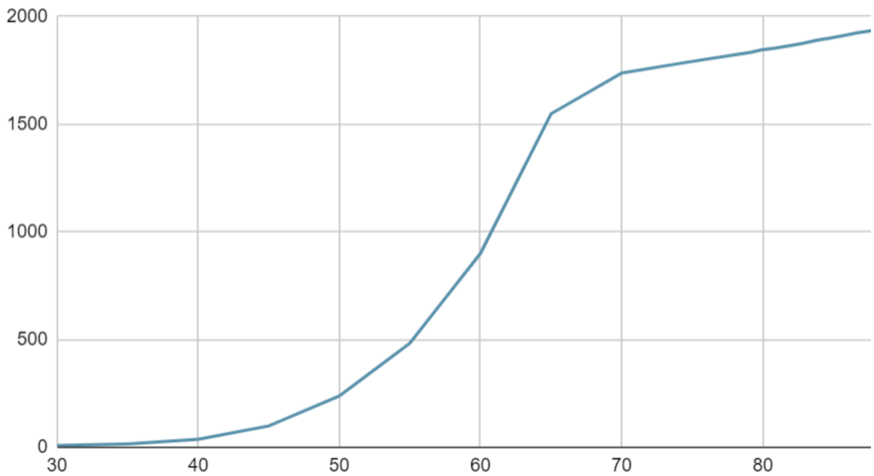
For our optimal frequency of 2,33 GHz and an RF input power of -15 dBm, we measured the voltage at the ports of the potentiometer during a load sweep : U = 1,764 V.



Voltage for 2,33 GHz of frequency and -15dBm of RF input power

The voltage for a frequency of 2,45 GHz is U = 1,769 V and for a frequency of 868 MHz is 1,746 V.

We measured also the voltage at the ports of the potentiometer during a RF power sweep (between -20 dBm and 0 dBm, with a step of 1 dBm) for the optimal frequency found previously and the optimal load :



Voltage at the ports of the potentiometer during a RF power sweep

We can analyze this curve in three parts:

- First phase ⇒ Threshold voltage not reached: In this phase, the power supplied to the LED is insufficient to reach its threshold voltage. The voltage increases gradually, but the LED does not light up yet.
- Second phase ⇒ Gradual saturation of the LED: When the power reaches the threshold value, the LED begins to light up. During this phase, the voltage continues to increase rapidly with the increase in power, and the brightness of the LED increases proportionally.
- Third phase ⇒ Full saturation of the LED: Once the LED reaches its full brightness, the voltage stabilizes. Beyond this point, even if the power continues to increase, the voltage remains constant and the LED can no longer increase in brightness.

Our tests confirm the effectiveness of the rectifier at 2.45 GHz and highlight the importance of selecting the optimal frequency for energy harvesting. By adjusting the frequency and monitoring the voltage changes, we determined that 2.33 GHz is the ideal frequency for our setup. Additionally, the use of the PMU helped stabilize voltage and improve performance in comparison to a simple LED-only configuration.

The LED's response to varying RF power levels demonstrates the need for a minimum input power to achieve sufficient brightness. The curves clearly illustrate the LED's behavior across different phases. The results also highlight how the choice of power management system, as well as frequency and power input, significantly impacts the efficiency of the system.

III. Antenna choice

We had to choose the most appropriate antenna for our application. In this part, we examine two antenna types (patch antennas and whip antennas) to compare their characteristics by identifying their advantages and limitations for our utilization case.

1) Patch Antenna

A patch antenna iis generally designed as a rectangular or circular metal patch on a dielectric substrate. Its compact size and planar structure make it a widely used choice in various applications.

- Advantages:
  - Compact and lightweight : Ideal for space-constrained.
  - High gain : Enhances energy transfer efficiency
  - Fixed Positioning : Best suited for installations with predefined orientations

- Limitations
  - Alignment Sensitivity : Efficient energy transfer requires precise alignment with the receiver.

For the radiation pattern, directional antennas are ideal for fixed objects when the source direction is known

2) Whip Antenna

The whip antenna is simple, it radiates and receives electromagnetic waves efficiently. Its simplicity makes it a good choice for our application, when energy reception from multiple directions is a requirement.

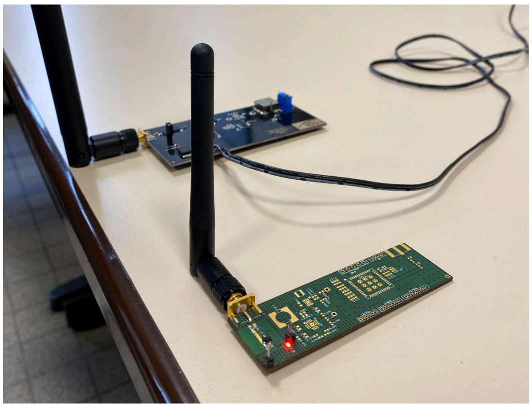
- Advantages:
    - Omnidirectional Reception : Capture signals from all directions.
    - Broadband Capability : Wide range of frequencies.
    - Simple Structure : Easy to design and integrate into systems.

- Limitations
    - Low Gain : Compared to patch antennas, whip antennas offer lower gain.
    - Distance Efficiency : Performance less efficient over long distance.

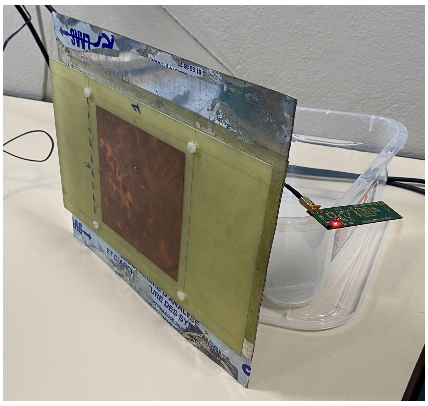
Omnidirectional antennas are better suited for scenarios where the object's position and source direction are unpredictable.

If the source's polarization is known, the antenna's polarization should be aligned accordingly; otherwise, circular polarization is recommended, as it guarantees capturing at least half of the energy regardless of the source's polarization.

Through our tests, we observed that the little antenna had a good intensity for a distance of 3 meters and the large antenna had it for a distance of 5 meters. Also, the large antenna is ideal for flat surfaces (e.g., temperature sensors on walls, switches), but not suitable for non-flat surfaces (e.g., a mouse or similar objects).



Testing the little antenna



Testing the large antenna

The most suitable antenna for our use case, specifically to power a LED, is a whip antenna, as it effectively concentrates energy from a known source direction, maximizing the efficiency of energy harvesting over a fixed distance.

IV. Ambient electromagnetic energy harvesting

Ambient energy harvesting involves capturing electromagnetic waves present in the environment to power connected devices. These sources include radio, Wifi, Bluetooth, cellular network, magnetic broadcast…

There are other possibilities to power our system in case we are not able to use the sources above, other solution can be considered:

- Acoustic Energy: Using sound vibration to generate electricity.
- Wind Energy: Small wind turbines
- Solar Energy: Based on the photovoltaic effect, which converts both solar and artificial lights into direct-current electricity.
- Thermal Energy: Energy due to a variation or a gradient of temperature.
- Kinetic Energy: Energy due to the movement of material particles such as vibrations, displacements, fluid flows and pressures (or forces).

There are a wide range of energy harvesting methods to power connected devices. While ambient electromagnetic energy can be an interesting resource, there are alternative solutions when these sources are insufficient or unavailable. Producing energy through alternative means of capturing and converting energy from the environment could be a strategy to develop a reliable power supply for devices.

V. Radiative electromagnetic wireless power transfer

The wireless power transfer is defined as a 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.

In this section, we evaluated the maximum distance that can be reached between a power source and the rectenna for two targeted frequencies: 868 MHz and 2.45 GHz.

To estimate the maximum distance between the power source and the rectenna, we used the formula:

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

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

We found that the distance is :

$$d = \sqrt{\frac{P_{\text{tx}} \cdot G_{\text{tx}} \cdot G_{\text{rx}} \cdot c^2}{\text{PRF}_{\text{in}} \cdot 16 \cdot \pi^2 \cdot f^2}}$$

For f = 868 MHz :

We calculated the wavelength : λ=c/f = 0.3456 m

So : d = $\sqrt{\frac{1 \times 10 \times 10 \times 0.2456}{100u \times 16\Pi^{2}}}$ = 2,75 m

For f = 2.45 GHz :

We have : λ=c/f = 0,1224 m

So : d = $\sqrt{\frac{1 \times 10 \times 10 \times 0.1224}{100u \times 16\Pi^{2}}}$ = 0,97 m

The results we obtained confirm that higher is the frequency, shorter will be the distance, due to the higher attenuation. So 2.45 GHz provides a shorter distance than 868 MHz and efficiency of transfer is also impacted by factors such as antenna gain.

To increase this range and efficiency, we can put in place some ways to enhance a better antenna qualification. The choice 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)

The wireless sensor networks powered by wireless power transfer open up many possibilities for applications and deployment :

- Environmental Monitoring: Wireless sensors to measure data such as air quality, temperature, humidity..
- Smart City Application: Sensors can be deployed to collect data to improve infrastructure, for example traffic information, semaphores, parking places.
- Hospital Monitoring: To monitor patient vitals like heart rate, blood pressure, fall detection.. In healthcare facilities, WPT systems could provide power to sensors embedded in patient beds or wearable devices, ensuring that they remain operational without the need for regular recharging. WPT units could be embedded in ceilings or walls for seamless and continuous power delivery

Deployment strategies can include integrating existing infrastructures, such as utilizing already installed base stations or transmitters to power the sensors. Additionally, strategically placing transmitters, for example, on rooftops, ensures optimal coverage for sensors spread across a wide area, maximizing the system's efficiency.

Conclusion

This lab focused on the feasibility of using wireless power transfer to power connected devices. We identified the optimal frequency for our rectifier, explored the power requirements of an LED, and assessed different antenna types for various applications. The findings highlight the potential for developing efficient, self-powered wireless sensor networks (WSNs). This approach can significantly enhance energy management and operational capabilities in diverse fields, including healthcare, smart homes, and industrial applications.

Through the experimentation and analysis conducted in this lab, we not only strengthened our theoretical knowledge but also developed practical expertise in selecting the right components and strategies for specific applications. This knowledge is essential for advancing the design of self-powered systems and optimizing energy usage in wireless sensor networks.

In conclusion, the lab provided a comprehensive overview of the challenges and opportunities in wireless power transfer. The practical approach to solving real-world energy challenges will be beneficial for future projects, especially in the fields of connected devices and IoT applications. The experience gained through this work offers a solid foundation for further exploration and development in energy management and sustainable technology.