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Energy for connected objects

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1 Introduction

In an increasingly connected world, Wireless Sensor Networks (WSN) play a crucial role in various fields such as smart cities, Industry 4.0, and healthcare systems. However, their large-scale and long-term deployment relies heavily on their ability to be energy autonomous. Energy autonomy is critical to reducing dependence on batteries, which require frequent replacements and have a significant environmental impact. Several methods for powering connected sensors have been developed, each with its own advantages and limitations. Batteries, while widely used, are constrained by their limited lifespan and require regular maintenance. Ambient energy harvesting offers a promising alternative by utilizing renewable sources such as light through photovoltaic devices, heat via thermoelectric effects, mechanical vibrations through piezoelectric effects, and electromagnetic waves via RF energy harvesting technologies. However, these solutions are highly dependent on the availability and intensity of ambient energy sources. Wireless Power Transfer (WPT) provides a method for delivering energy remotely using electromagnetic waves, but this approach presents challenges in terms of energy efficiency and range. This practical work is part of the exploration and evaluation of power solutions for connected sensors. Its objective is to study the energy requirements of a connected LED and optimize its power supply by combining ambient energy harvesting and wireless power transfer strategies. The experiments also include the characterization of rectifiers to maximize RF energy conversion and the selection and evaluation of suitable antennas. This report details the design and experimental phases, the results obtained, and the prospects for developing energy-autonomous IoT systems. These efforts pave the way for innovative applications in autonomous sensor networks and environments requiring sustainable and efficient power solutions.

2 Study of the Load and Design

In this project, the study of the load is essential to determine energy requirements and adapt energy management strategies effectively. The objective was to power a red LED (SML-D12U1WT8 from Rohm Semiconductor) using either ambient or specifically generated energy sources. The analysis focuses on the characteristics of the load, power strategies, associated losses, and methods to minimize these losses.

The choice of the SML-D12U1WT8 LED was based on its low energy consumption and adaptability under different operating conditions. Under nominal usage, the LED consumes 44 mW (at 20 mA and 2.2 V). For reduced brightness levels, the energy consumption drops significantly to 18 mW at 50% brightness and 9.5 mW at 25%, illustrating a direct relationship between brightness and energy consumption. This makes the LED ideal for optimized energy management in low-power applications.

One strategy explored was direct consumption, where the LED is powered directly from the available energy source. This method eliminates intermediate stages that could cause energy losses but requires the source to continuously supply sufficient power for nominal operation. For instance, at minimal operation (1 mA, 1.75 V), the power needed is 1.75 mW, which increases to 54 mW at full brightness (20 mA). While this approach simplifies implementation, it is less adaptable to fluctuations in the energy source.

To address the limitations of direct consumption, power management units (PMUs) and DC-DC converters were employed. These components regulate and adapt the voltage supplied by the energy source, ensuring stable load operation. A PMU combined with a buck-boost converter (TPS63031) allows the system to function optimally even with fluctuating energy sources. For example, the PMU requires only 16.62 μW during a cold start and 14.725 μW under normal operating conditions, reducing energy losses and improving overall efficiency.

Energy losses in the system primarily stem from three sources: dissipation in PMUs and DC-DC converters due to internal resistance and voltage conversion, leakage losses in supercapacitors (e.g., a 6.8 mF capacitor with maximum losses of 52.5 μW), and radiation and conduction losses in antennas or rectennas. These losses can be minimized by using low-loss components, optimizing voltages and currents, and reducing thermal dissipation.

An alternative energy storage strategy involves capturing harvested energy in supercapacitors before use. This method allows energy accumulation even with intermittent sources, though it introduces additional losses related to the capacitor's capacity and discharge. For instance, a 6.8 mF supercapacitor operating between 4.4 V and 2.2 V can store enough energy to power the LED for multiple cycles.

Ultimately, direct consumption is best suited for stable energy sources, whereas energy storage strategies are more effective in environments with fluctuating ambient energy. The choice of strategy depends on the specific conditions and constraints of the target application.

3 Rectifier Characterisation

The objective of this section is to study the performance of doubler rectifiers operating at frequencies of 868 MHz and 2.45 GHz using a USRP and GNURadio. The analysis includes a detailed characterization based on frequency, load, and RF power sweeps, as well as an evaluation of the overall efficiency of the rectifiers.

First, a frequency sweep was conducted to determine the range where the rectifiers operate optimally. This sweep was performed between 800 MHz and 950 MHz, and between 2.4 GHz and 2.5 GHz, with a step size of 10 MHz. The voltage measured across the potentiometer terminals revealed that the system's optimal frequency is approximately 820 MHz. At this frequency, the associated LED reaches its maximum brightness, indicating optimal energy efficiency (see Figure 1).

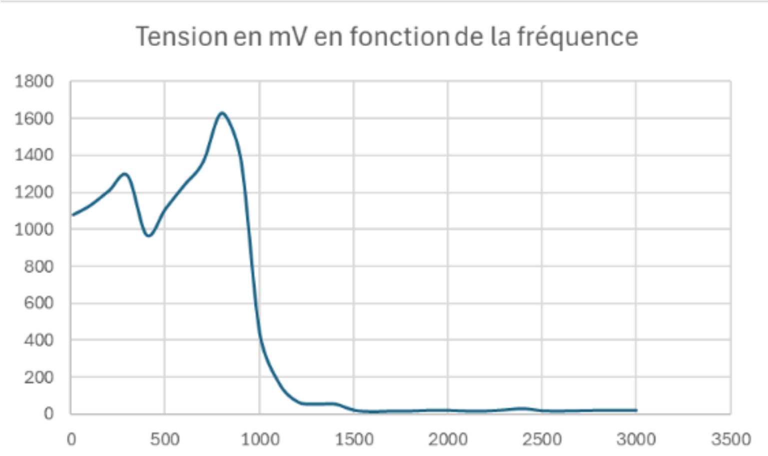

Figure 1: Performance Characterization of Doubler Rectifiers Across Frequency Sweep

Furthermore, an analysis of the voltage curve as a function of applied power revealed a nonlinear behavior. Between 0% and 50% power, the voltage increase was modest, reaching approximately 89 mV. From 60% onward, a marked increase was observed, peaking at 1700 mV at 70% applied power (see Figure 2).

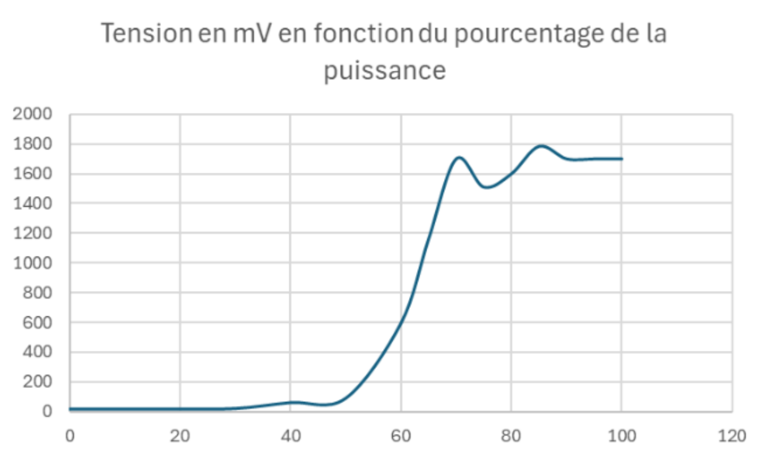

Figure 2: Voltage response as a function of applied power percentage, showing nonlinear behavior and a sharp increase from 60% power onward.

This threshold of 70% represents the most efficient operating range for maximizing voltage, beyond which the voltage stabilizes with slight fluctuations.

An RF power sweep was also conducted, ranging from -20 dBm to 0 dBm in 1 dBm increments, at the optimal frequency and load identified earlier. The goal was to determine the RF power level required to achieve maximum rectifier efficiency. The rectifier efficiency was calculated using the following equation:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{U \cdot I}{P_{in}} = \frac{R \cdot I^2}{P_{in}}$$

These measurements identified the optimal operating conditions for the energy harvesting and wireless power transfer system.

Finally, an evaluation was conducted to determine the minimum RF power required to ensure proper functioning of the target loads, such as the LED or the circuit board. These results were compared with the previously calculated minimum DC input power to validate data consistency. For the "store then use" strategy, the recharge time was characterized as a function of RF input power, ranging from +15 dBm to the minimum measured value. These results highlighted the relationship between RF power levels and the time required for efficient system recharge.

This thorough study of the rectifiers is a crucial step in the design and optimization of energy harvesting and wireless power transfer systems for connected devices.

4 Antenna choice

When selecting the antenna for this project, several technical aspects were considered. First, the wavelength of the transmitted signal plays a central role, as most antennas are designed to be equivalent to half the wavelength. Regarding the radiation pattern, directional antennas are preferred when the object is stationary, and the direction of the source is known. However, for scenarios where the position and direction of the source may vary, omnidirectional antennas are more suitable.

If the source's polarization is known, it should match the antenna's polarization to maximize energy transfer. Otherwise, circular polarization ensures at least 50% energy capture, regardless of the source's polarization.

Our tests revealed that ambient energy harvesting was challenging with our antennas due to the low available power. However, in specific environments, such as a closed room, it is possible to collect luminous energy. For instance, the black antenna shown in the image below provided significant intensity for 3 seconds at a distance of up to 12 meters. As the distance increased, the time required to activate the system also increased. We observed that using two large antennas simultaneously could enhance the operational range.

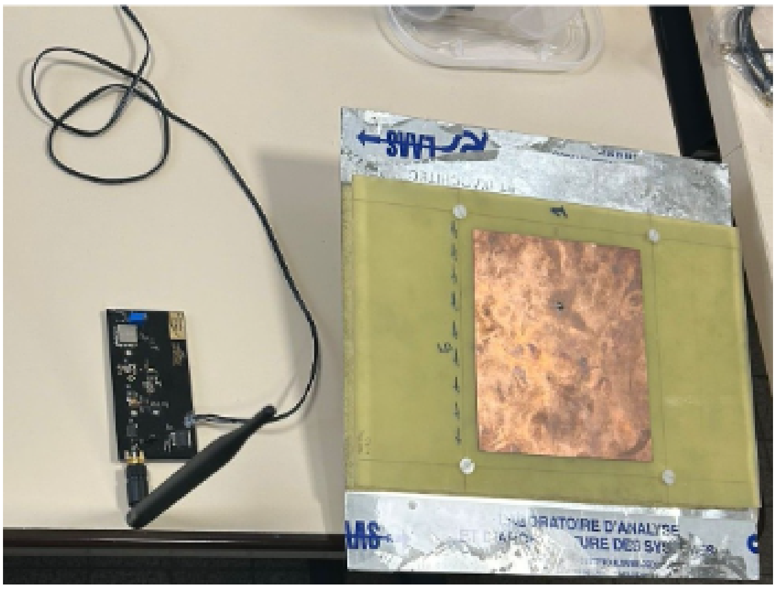

Figure 3: Experimental setup showing the black antenna used for energy harvesting and the associated copper plate.

5 Calculation of Maximum Wireless Energy Transfer Distance

The following steps outline the calculation to determine the maximum distance for wireless energy transfer using the provided formulas.

Initial Data

- **Transmission power (P_{TX})**: 27 dBm (converted to Watts: $0.501\,W$).
- **Minimum received power (PRF_{in})**: -30 dBm (converted to Watts: $1 \times 10^{-6}\,W$).
- **Transmitter antenna gain (G_{TX})**: 9 dBi (converted to linear gain: 7.94).
- **Receiver antenna gain (G_{RX})**: 9 dBi (converted to linear gain: 7.94).
- **Frequency (f)**: $2.45\,GHz$ ($2.45 \times 10^9\,Hz$).
- **Speed of light (c)**: $3 \times 10^8\,m/s$.

The wavelength (λ) is calculated as:

$$\lambda = \frac{c}{f}$$

Substituting the values:

$$\lambda = \frac{3 \times 10^8}{2.45 \times 10^9} = 0.122\,m$$

Using the formula for d:

$$d = \sqrt{\frac{P_{TX} \cdot G_{TX} \cdot G_{RX} \cdot c^2}{PRF_{in} \cdot 16 \cdot \pi^2 \cdot f^2}}$$

Substituting the values:

$$d = \sqrt{\frac{0.501 \cdot 7.94 \cdot 7.94 \cdot (3 \times 10^8)^2}{1 \times 10^{-6} \cdot 16 \cdot \pi^2 \cdot (2.45 \times 10^9)^2}}$$

After performing the calculation:

$$d \approx 94.8\,m$$

6 Link with the Innovative Project

As part of our innovative project, we developed a vehicle access system that utilizes Ultra-Wideband (UWB) technology. This system is based on high-precision localization algorithms and bidirectional communication, which require a reliable and sustainable energy supply. Ensuring this reliability is particularly challenging in an environment subject to constraints such as vibrations, temperature variations, and electromagnetic interference.

The exploration of energy solutions for this project was greatly informed by the study on electromagnetic energy harvesting and wireless energy transfer. Insights from this study helped identify several strategies tailored to our project's requirements, including the use of ambient energy sources and advanced energy management technologies. To address the constraints, we proposed a hybrid energy architecture that combines several complementary components.

First, the main vehicle battery acts as a stable primary energy source, supplying power through a DC-DC converter that meets the energy needs of the UWB system. This is augmented by ambient energy harvesting, where high-efficiency antennas capture ambient RF signals, ensuring a low-power standby mode and recharging supercapacitors when possible. In addition, flexible solar panels integrated into the vehicle's design provide supplementary energy, especially in outdoor environments. To further enhance energy autonomy, a supercapacitor is used as an energy buffer, meeting the peak power demands required for UWB pulses, while a secondary battery maintains system operations in standby mode.

Efficient energy management is critical to the success of this architecture. A power management unit (PMU) plays a central role by regulating the various energy sources, optimizing transitions between them, and minimizing energy losses. It also provides overvoltage protection and ensures a stable power supply for critical components, enhancing overall system reliability.

To optimize the performance of the UWB system itself, several improvements were implemented to reduce energy consumption. For instance, UWB anchors enter standby mode when they are not in active use, conserving energy. The transmission power of UWB pulses is dynamically adjusted based on real-time requirements, ensuring that only the necessary amount of power is used. Furthermore, the signal processing algorithms have been optimized to reduce computational load, which directly minimizes the system's energy demands.

By integrating these strategies, the vehicle access system achieves a high level of energy autonomy while reducing dependence on the main vehicle battery. This innovative approach not only addresses energy efficiency and reliability but also aligns with the broader goals of sustainability in the automotive sector. Through careful design and optimization, the system demonstrates the feasibility of combining advanced UWB technology with state-of-the-art energy management techniques.

7 Conclusion

This report highlights the experimental work conducted to explore energy solutions for connected objects, focusing on energy harvesting and wireless power transfer systems. Key manipulations included analyzing a red LED's energy requirements, rectifier characterization, and antenna evaluation. Results identified optimal rectifier performance at 868 MHz and 2.45 GHz through frequency, load, and RF power sweeps. Additionally, maximum wireless energy transfer distance calculations provided insights into the range and efficiency of such systems.

This work enhanced understanding of energy harvesting principles, rectifier optimization, and antenna selection, while developing skills in tools like USRP and GNURadio. The hands-on experiments bridged theory and application, fostering the ability to design and evaluate energy-efficient systems for real-world scenarios.

Despite challenges such as precise calibration requirements, this practical work offered valuable insights into energy solutions for connected devices, laying a solid foundation for innovations in autonomous IoT networks and energy-efficient technologies.

8 Annexes

The following reference was used for data related to the SML-D12x1 series LED:
ROHM Semiconductor. *SML-D12x1 Series LED Datasheet*. Available online: https://fscdn.rohm.com/en/products/databook/datasheet/opto/led/chip_mono/sml-d12x1-e.pdf.