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Design of Rectenna in the Global System for Mobile Communication/Universal Mobile Telecommunication System, Long-Term Evolution and Wireless Fidelity Bands

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Abstract

Our research work in this paper takes a multidisciplinary perspective, combining concepts from electromagnetism, antenna theory, power electronics, and mathematical modeling. By exploring recent advances and contributing to the rise of energy-efficient technologies, this study aspires to play a key role in creating sustainable solutions to meet the growing needs of our connected society. Thus, we set the objective of designing and optimizing Rectenna energy conversion devices (antenna plus rectifier) at very high frequencies such as the 1800 MHz, 2100 MHz and 2500 MHz bands. We designed under Ansys HFSS and ADS, three single-band rectenna operating respectively in the GSM/UMTS, LTE and WI-FI band. The simulation results showed a lower reflection coefficient of −22.12 dB, −17.70 dB and −28.51 dB at 1800 MHZ, 2100 MHz and 2500 MHz band respectively. These results also gave gains of 3.28 dB, 7.11 dB and 5.65 dB respectively at the 1800 MHz, 2100 MHz and 2500 MHz frequency bands and a radiation efficiency greater than 96% in all 3 bands. Finally, after a broad comparison of the materials constituting the substrates, we obtained a rectenna of 60% efficiency which exactly meets the set specifications.

Keywords

Rectenna, Antenna, RF-DC Conversion, Schottky Diode, Efficiency, RF Energy Harvesting

1. Introduction

There are different physical sources in the ambient environment that produce energy in a given form. This energy can be harvested and converted to power electronic devices. Among these sources we have: solar sources [1]-[3], thermal sources [3]-[5], mechanical vibration sources [5]-[7] and radio frequency (RF) sources [8]-[10]. The use of RF sources appears to be a relevant solution for energy recovery aimed at low-consumption electronic devices. This type of recovery from electromagnetic waves is one of the most used and favorable technologies providing continuous power to autonomous devices [11]. It aims to exploit the RF waves of telecommunications which mainly ensure voice and data traffic. This allows another use of the RF resource. At the heart of this quest is the Rectenna, an innovative energy conversion device that combines the principles of antenna and rectification (**Figure 1**) to capture and transform ambient electromagnetic waves into usable electricity. However, despite its revolutionary promise, the effectiveness of Rectenna remains a critical challenge.

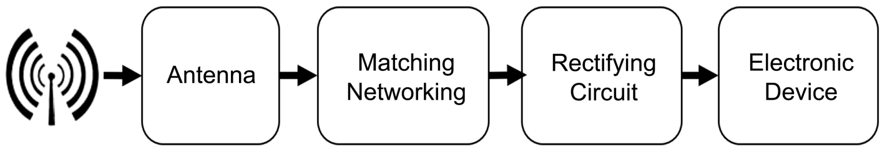


Figure 1. Block diagram of rectenna for ambient RF energy harvesting.

Research into optimizing the power conversion device in a Rectenna is a critical area to maximize energy efficiency, promote battery life of wireless devices, and expand Internet of Things (IoT) applications. This complex issue requires an in-depth understanding of energy conversion principles, factors influencing Rectenna efficiency, and optimization strategies to overcome current limitations [12]-[14].

In this perspective, this study undertakes to explore the fundamental challenges related to energy conversion in Rectennas and to propose innovative solutions to increase their efficiency. With a focus on optimization, we aim to push the current limits of energy efficiency, paving the way for new applications in areas such as long-range wireless communication, autonomous sensor networks, and other emerging technologies.

This article aims to design and improve an energy harvesting device operating in the GSM/UMTS 1800 MHz, LTE 2100 MHz and WIFI 2500 MHZ bands. This device is called Rectenna.

So, to achieve this objective, the remainder of the paper is structured as follows:

- The design and simulation of the antenna with the HFSS tool;
- The design and simulation of the rectifier using the ADS tool;
- Determining the parameters of the adapter between the antenna and the rectifier. This adapter allows optimal transfer of energy between the antenna and the rectifier [15] [16];
- Analysis and discussion of the results of the functioning of the rectenna.

2. Materials and Methods

2.1. Design of the Antenna

The notion of microstrip patch antenna appeared in the 1950s [2]. A microstrip patch antenna is an antenna with printed radiating elements. These antennas are compact (not bulky) and can be placed on any flat or non-flat surfaces. Their geometries are relatively simple. They are inexpensive and mechanically robust. Microstrip patch antennas (**Figure 2**) are made up of three elements: the radiating element, the dielectric substrate and the ground plane. The power line and the patch forming a unit rest on the dielectric substrate. The patch is the conductive or radiating part of the antenna. The dielectric substrate is the insulating part of the antenna. It generally has a rectangular shape. It is characterized mainly by its thickness, its relative permittivity and its loss tangent. Its dimensions must be greater than those of the patch and power line assembly. The dimensions of the substrate influence the performance and resonance frequency of the antenna. The ground plane taken as a potential reference (0 Volt potential) is located below the substrate. However, it can cover the entire surface of the substrate or only part of it. The modification of the ground plane also influences the performance of the antenna [3]-[5].

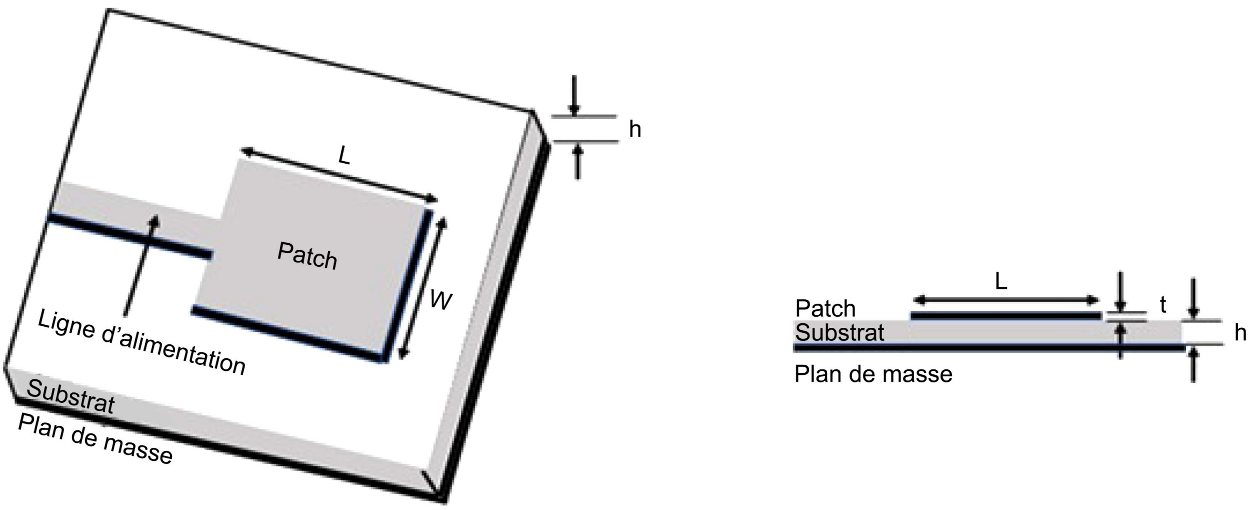


Figure 2. Different parts of a patch antenna.

The design phase of an antenna, using suitable software, is a mandatory step in the interest of saving time and optimizing the structure to the desired parameters. For this, we chose an HFSS version 15.0 electromagnetic simulation tool. It is dedicated to the high frequency simulation of microwave circuits. This is powerful software that allows you to simulate complex structures in three dimensions. It is used in particular to calculate the S parameters, the resonance frequencies as well as the electric and magnetic fields and also the visualization of the 3D radiation diagram.

The design of the antenna in HFSS follows the flowchart in **Figure 3**.

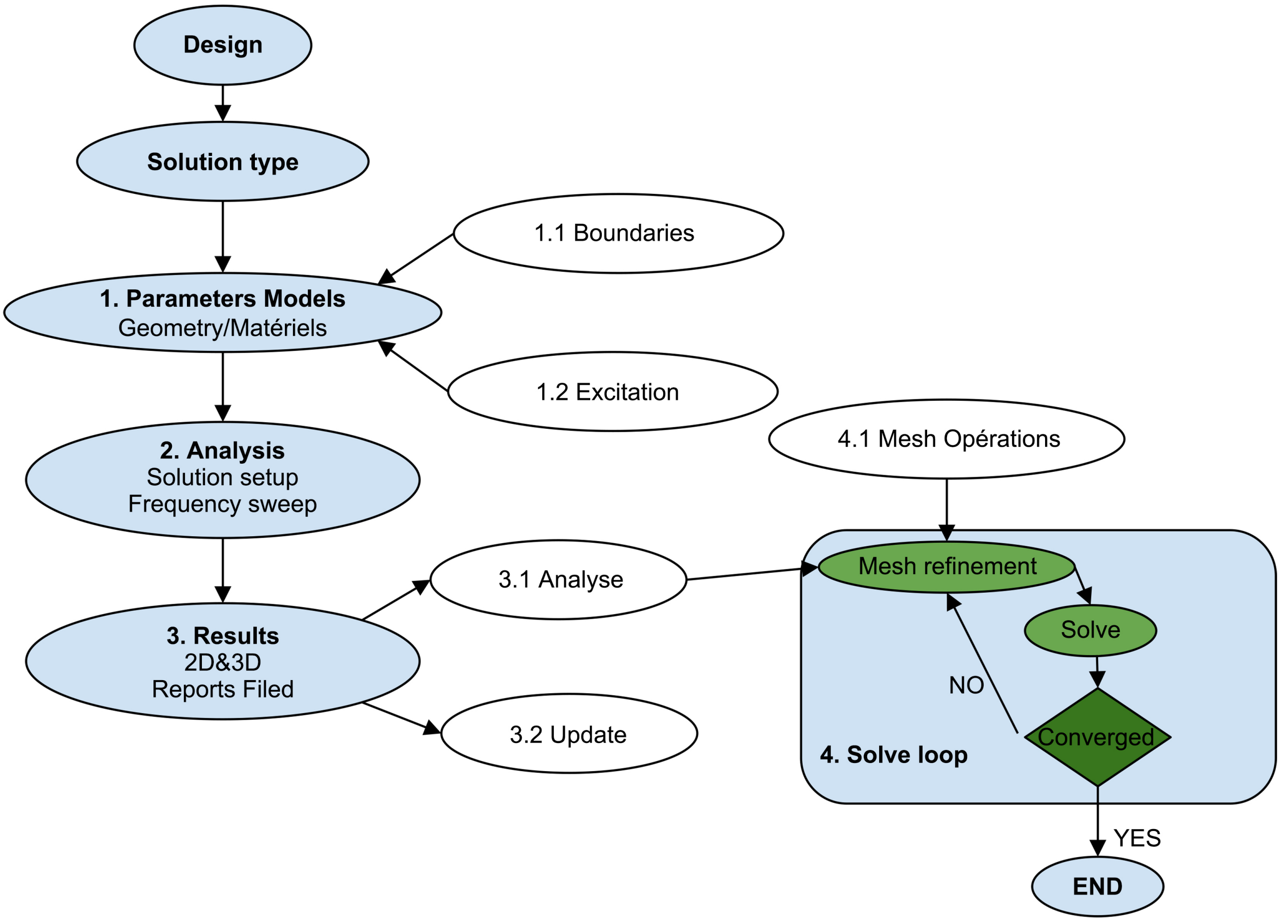


Figure 3. Flowchart of the different steps of an HFSS design of antenna [17].

The practical design procedure of a rectangular patch antenna assumes knowledge of the substrate dielectric constant (εr), resonant frequency (fr), and substrate height (h). The design therefore follows the following steps [14]:

Specification of fr, εr and h.

Determination of the width (W) and length (L) of the patch.

To ensure effective radiation, the practical patch width is calculated according to Equation (1).

$$W = \frac{C}{2 f_r} \sqrt{\frac{2}{\varepsilon_r + 1}} \tag{1}$$

where c is the speed of light.

The length of the antenna L can be described as (Equation (2)):

$$L = \frac{C}{2 f_0 \sqrt{\varepsilon_{reff}}} - 2\Delta L \tag{2}$$

where ε_{reff} is the effective permittivity of the substrate define by (Equation (3)):

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left(1 + 12 \frac{h}{W}\right)^{-\frac{1}{2}} \tag{3}$$

And ΔL is the extension of the patch length defined as follows (Equation (4)):

$$\Delta L = 0.412h \frac{\left(\varepsilon_{reff} + 0.3\right)\left(\frac{W}{h} + 0.264\right)}{\left(\varepsilon_{reff} - 0.258\right)\left(\frac{W}{h} + 0.8\right)} \tag{4}$$

To determine the width Ws and the length Ls of the substrate, we generally use Equations (5) and (6) [17].

$$w_s = W + 6h \tag{5}$$

$$L_s = L + 6h \tag{6}$$

FR-4 (Flame Retardant-4) substrate with relative permittivity 4.4, loss tangent 0.02 and thickness 1.6 mm are chosen to design the antenna structure because this type of substrate is less expensive. The ground and the radiating element are each 0.03 mm thick.

2.2. Design of the Rectifier

An RF/DC conversion circuit and the associated impedance matching stage can be made from localized components and/or partly using distributed elements. Among existing commercial software, the Advanced Design System (ADS) software developed by Keysight Technologies is chosen for the work carried out in this thesis. Indeed, ADS [1] is a reference in the field; it is 2.5D simulation software allowing the design of all types of electrical circuits operating in the RF domain. It has the advantage of integrating specific analysis tools particularly suited to circuits composed of non-linear elements as we will present later. The steps of the rectifier design methodology are shown in **Figure 4**.

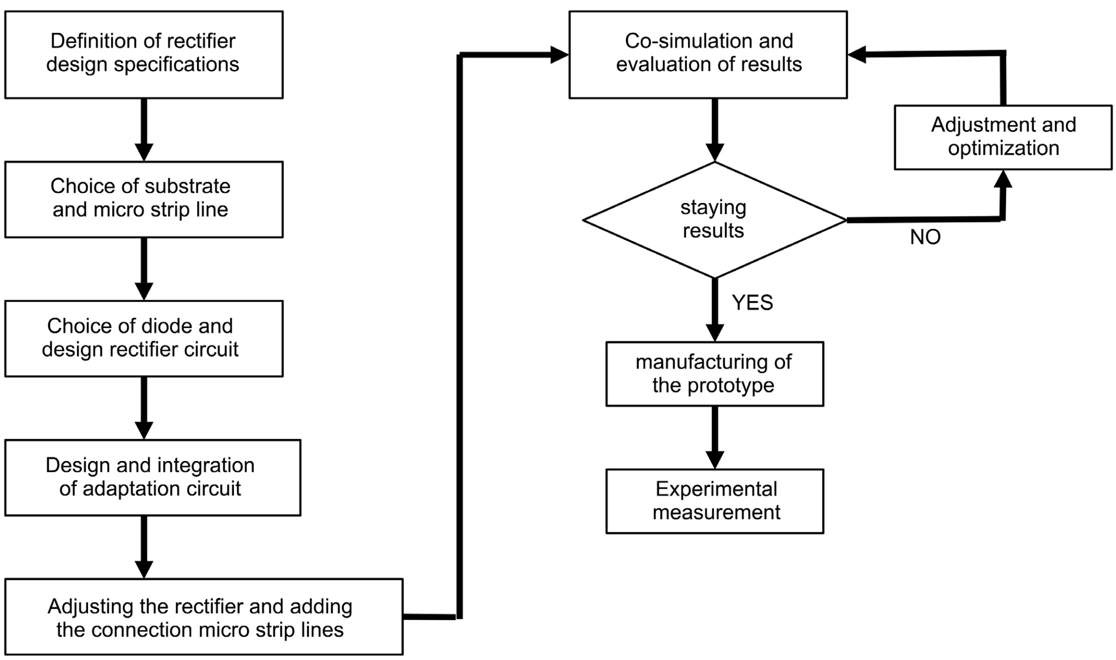


Figure 4. Flowchart of the different steps design of the rectifier [15].

The diode is chosen to realize the rectifier is Sckottky type. This choice is justified by the fact that with the diode-based rectifier we will not need an external power source, therefore, less bulky, easy to make and at low cost. Thus, the sensitivity of our rectifier will be linked to that of the diode. Thus, the Schottky diode HSMS2850 (AVAGO) was selected for use in the circuit recovery because it has high efficiency in high frequencies (**Figure 5**). This is a diode widely used in detection and measurement circuits, with very precise sensitivity.

As shown in **Figure 6**, this diode has a series resistance (RS) of 25 Ω, a threshold voltage of 0.25 V, and a junction capacitance of (Cj) 0.18 pF. It is one of the Schottky diodes with a much lower threshold voltage.

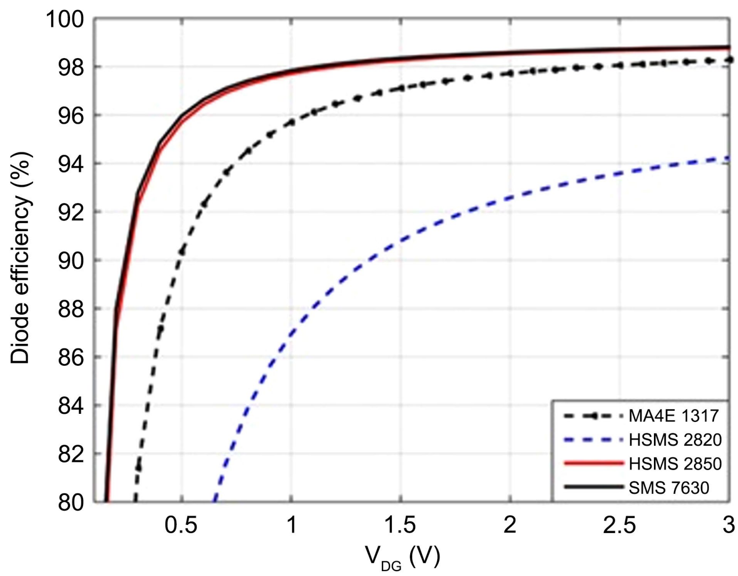


Figure 5. RF-DC conversion efficiency of diodes [14].

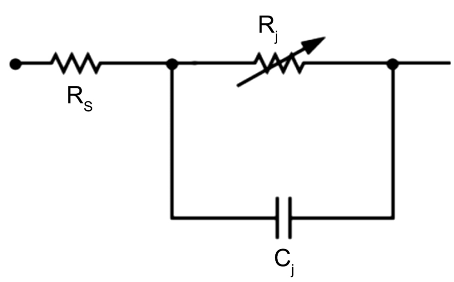


Figure 6. Schottky diode in a little signal [14] [16].

2.3. Calculation Model of the Rectenna Efficiency

RF/DC conversion efficiency is the ratio of the load power to the RF input power collected by the antenna. This efficiency η is given by:

$$\eta(\%) = \frac{P_{out}}{P_{in}} \times 100 = \frac{V_{out}^2}{P_{in} \times Z_{load}} \times 100 \tag{7}$$

where P_{in} and P_{out} are respectively the antenna input power and the power at the load terminals;

V_{out} is the charging voltage;

Z_{load} is the module of the load impedance.

3. Results and Discussions

The antennas and rectifiers to be designed must meet the following performance criteria to ensure optimal power conversion and high efficiency in wireless power transmission applications.

3.1. General Technical Specifications

The designed antennas must comply with the following characteristics:

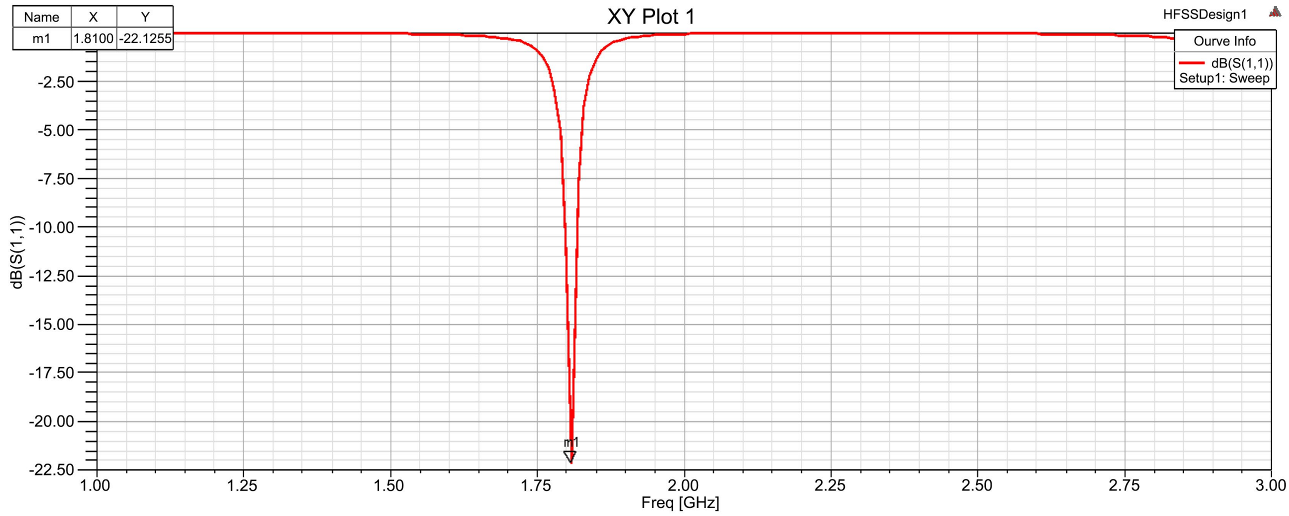
- Operating Frequencies: The antenna must operate effectively in the bands of 1800 MHz, 2100 MHz and 2500 MHz.
- Reflection coefficient: The antenna must have a reflection coefficient (S11) less than −10 dB on each of the specified frequency bands. This ensures good impedance matching and low signal loss.
- Gain: The antenna must have a positive dB gain on each frequency band, ensuring the ability to effectively pick up low power signals.
- Radiation Efficiency: The antenna must have a radiation efficiency greater than 50%. This implies that more than half of the antenna power is radiated efficiently, improving the overall power conversion performance.
- The rectifier to be designed must have the following performance characteristics:
- It must be suitable to operate in the frequency ranges of 1800 MHz, 2100 MHz and 2500 MHz.
- The diode used must be Schottky type, suitable for energy harvesting under low power conditions (from −30 dBm to 0 dBm).
- It must display a satisfactory conversion efficiency, i.e. greater than 50%.
- It must have a reflection coefficient less than −10 dB.
- The output voltage must be continuous.

3.2. Equations

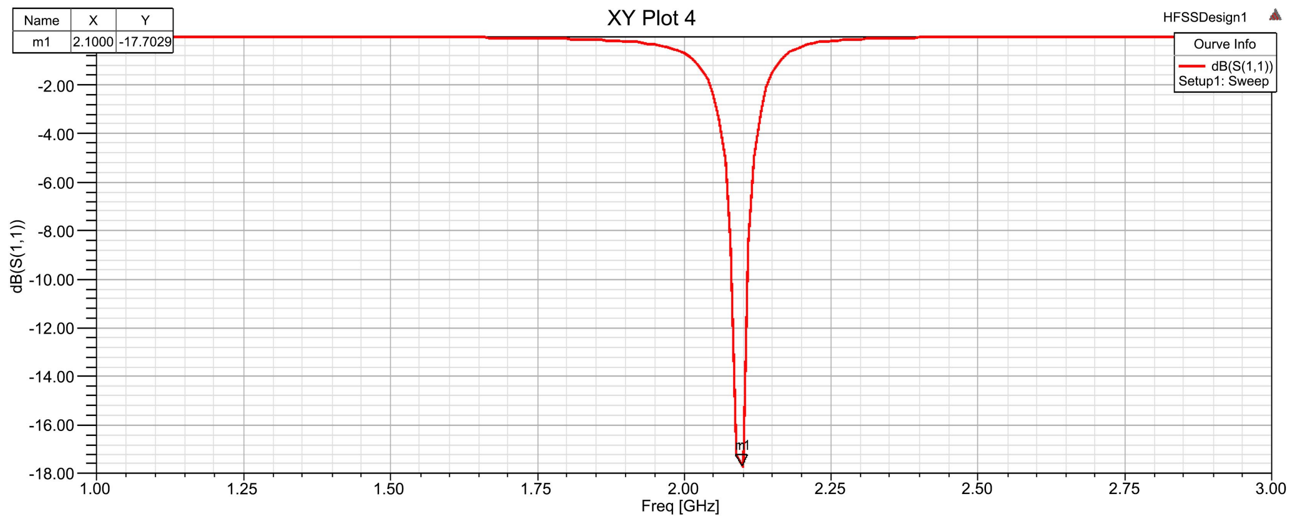
3.2.1. Antennas

Table 1 shows the geometric dimensions of the different parts of the antennas designed and radiating at the frequency 1800 MHz, 2100 MHz and 2500 MHz respectively. The substrate used for the three antennas is Rogers RT/duroid 5880 and relative permittivity $\varepsilon r = 2.2$ whose thickness is 1.6 mm. The power line has a width of Wf and a length of Lf.

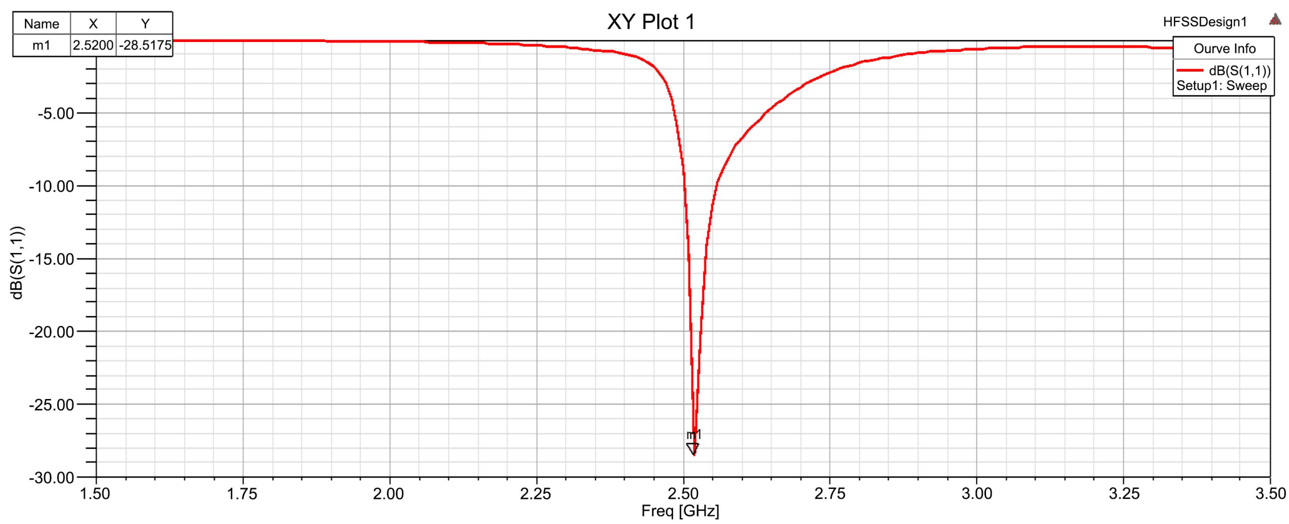
Figure 7(a), Figure 7(b) and Figure 7(c) illustrate the evolution of the reflection coefficient S11 (respectively in (1800 MHz), (2100 MHz) and (2500 MHz). It shows an S11 of −22.12 dB at the frequency 1800 MHz of −17.70 dB at the frequency 2100 MHz and −28.50 dB at the frequency 2500 MHz. This indicates that the three (3) antennas are well matched and operate effectively in the chosen frequency bands.



(a)



(b)



(c)

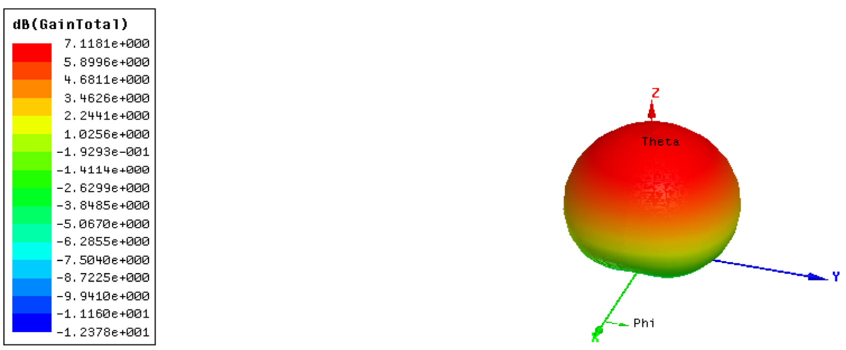
Figure 7. S11 reflection coefficient in (a) 1800 MHz, (b) 2100 MHz, (c) 2400 MHz.

Table 1. Dimensions of antennas in mm.

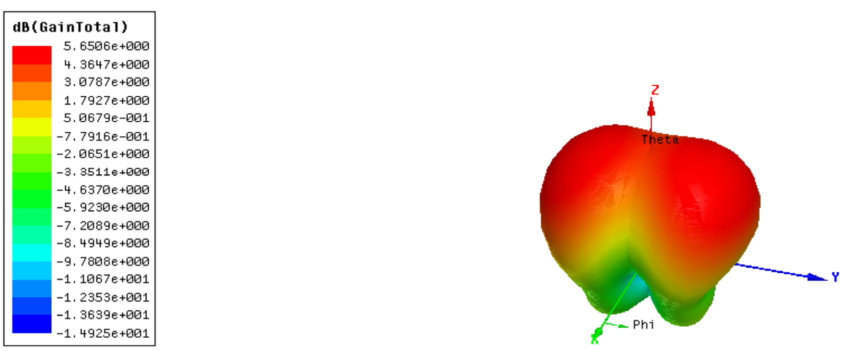
	W_s	L_S	W	L	h	(L_f, W_f)
1800 MHz	73.6	63.6	64	54	1.6	(39.05, 5.2)
2100 MHz	105	100	56	47	1.6	(22.24, 5.2)
2500 MHz	105	100	80	36	1.6	(40.05, 5.2)

Figure 8(a), Figure 8(b) and Figure 8(c) illustrate the evolution of the radiation gain (respectively in (1800 MHz), (2100 MHz) and (2500 MHz). It presents a gain of 3.26 dB, a gain of 7.1 dB and a gain of 5.1 dB respectively at the frequency 1800 MHz, 2100 MHz and 2500 MHz.

(a)



(b)

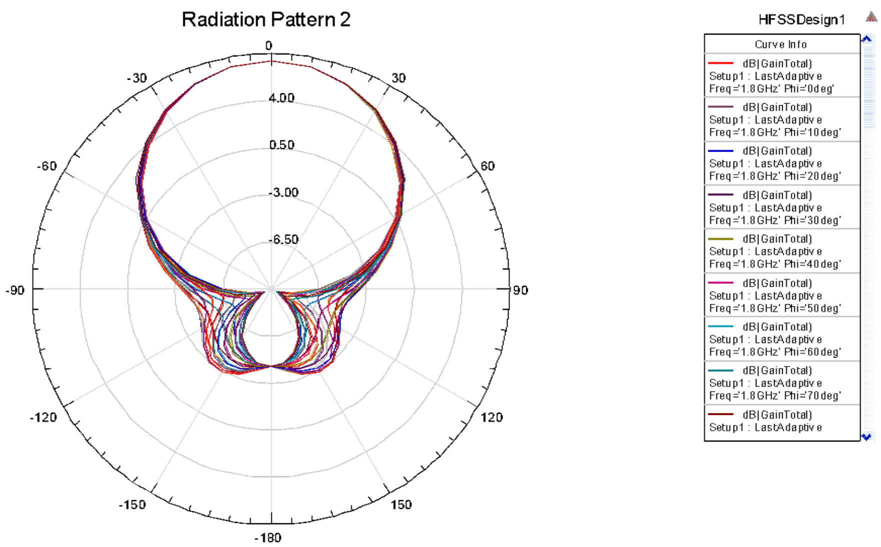


(c)

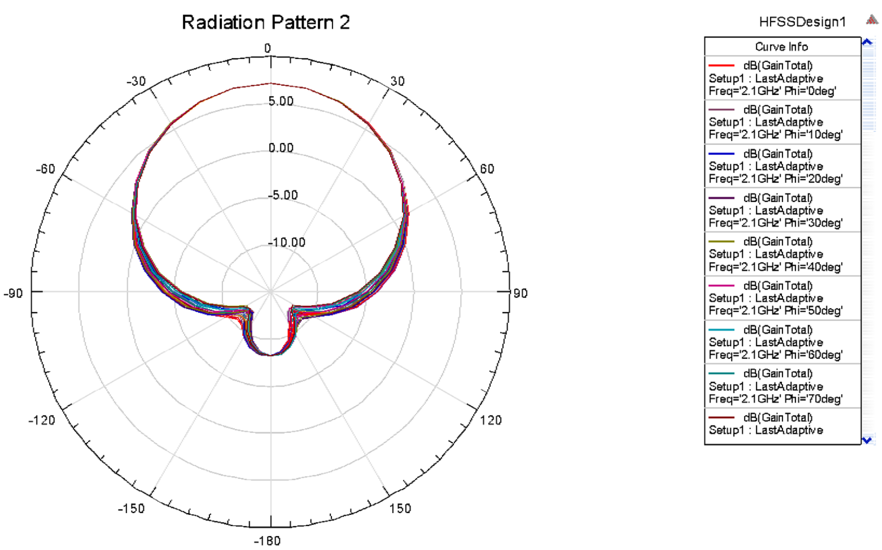
Figure 8. Antennas gain (a) 1800 MHz, (b) 2100 MHz, (c) 2400 MHz.

The 2D radiation pattern is a graphical representation of how an antenna emits or receives electromagnetic waves in space depending on the viewing angle relative to the antenna axis, in a given plane. The following figure illustrates the curve which shows the representation of the angle φ is equal to 0 degrees and 360 degrees in a directional radiation diagram (**Figure 9**). The evolution of this radiation pattern of the designed rectangular patch antennas shows directional radiation, indicating directional radiation in the H (horizontal) plane. This directivity makes it possible to concentrate the energy emitted in specific directions, thus optimizing the transmission and reception of signals in these directions. In the elevation plane (E), the radiation presents a vertical main lobe, confirming the effectiveness of the antenna for point-to-point communications.

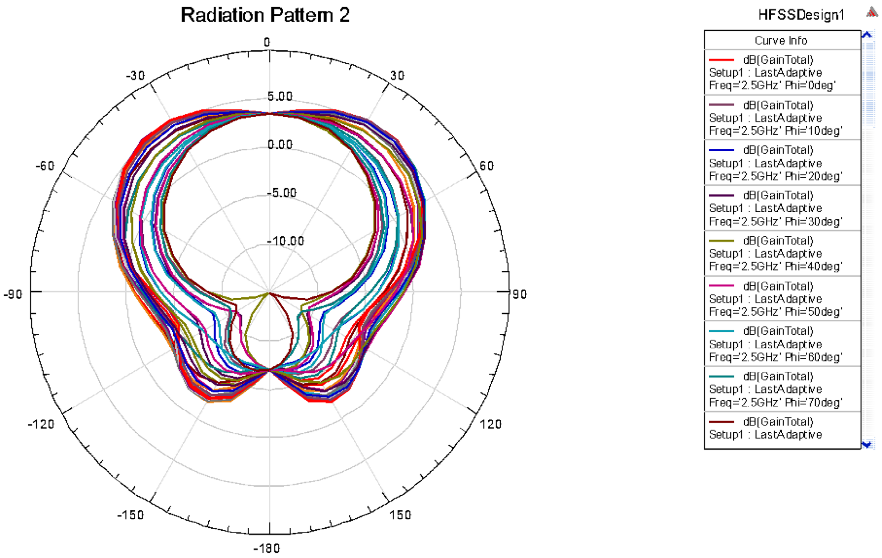
These three (3) patch antennas have conversion efficiencies of 96.7%, 98% and 97% respectively.



(a)



(b)



(c)

Figure 9. Radiation pattern in (a) 1800 MHz, (b) 2100 MHz, (c) 2400 MHz.

3.2.2. Adaptation System and Rectifier

Designing the rectifier circuit to optimize energy conversion in a rectenna is essential to ensure maximum efficiency in energy harvesting from RF signals. Our circuit, consisting of an AC source at PORT1 and a matching circuit including a capacitor, an inductor and an HSMS2850 Schottky diode, represents a typical approach for the rectification of RF signals.

Adding the filter capacitor in parallel to the load helps smooth out the rectified voltage and provides a more stable DC output to the load. This ensures better use of the energy captured by the rectenna.

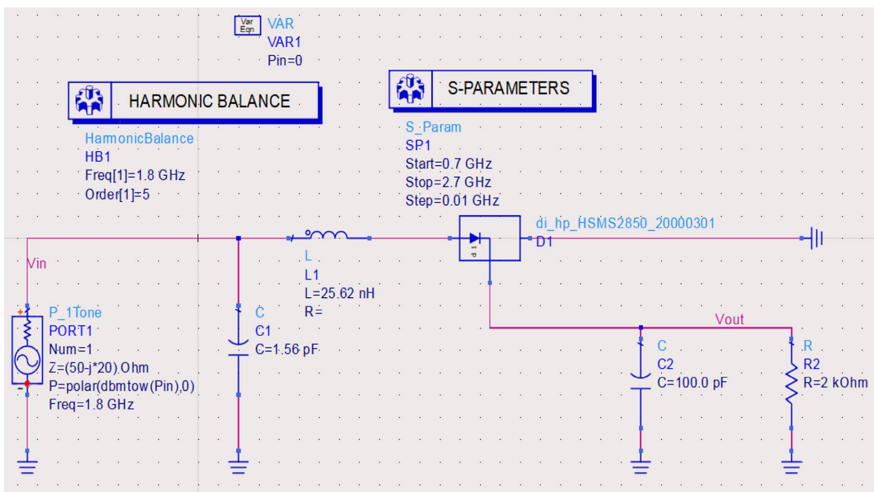


Figure 10. Circuit rectenna in ADS for band 1800 MHz.

The simulations were carried out using Advanced Design System (ADS) software. To adapt the input impedance of the rectifier and the other part of the circuit we used the ADS Smith chart tool. So, for the bandwidth 1800 MHz, we find the values of L and C (**Figure 10**) [15] [16], which are respectively 25.62 nH and 1.56 pF. While at the bandwidth 1800 MHz, and 2500 MHz we find 18.81 nH and 1.21 pF, and 13.36 nH and 1.55 pF, respectively.

We found for the three (3) frequency bands reflection coefficients close to those found with the antennas. These results demonstrate a good adaptation of the energy source and the rest of the circuit.

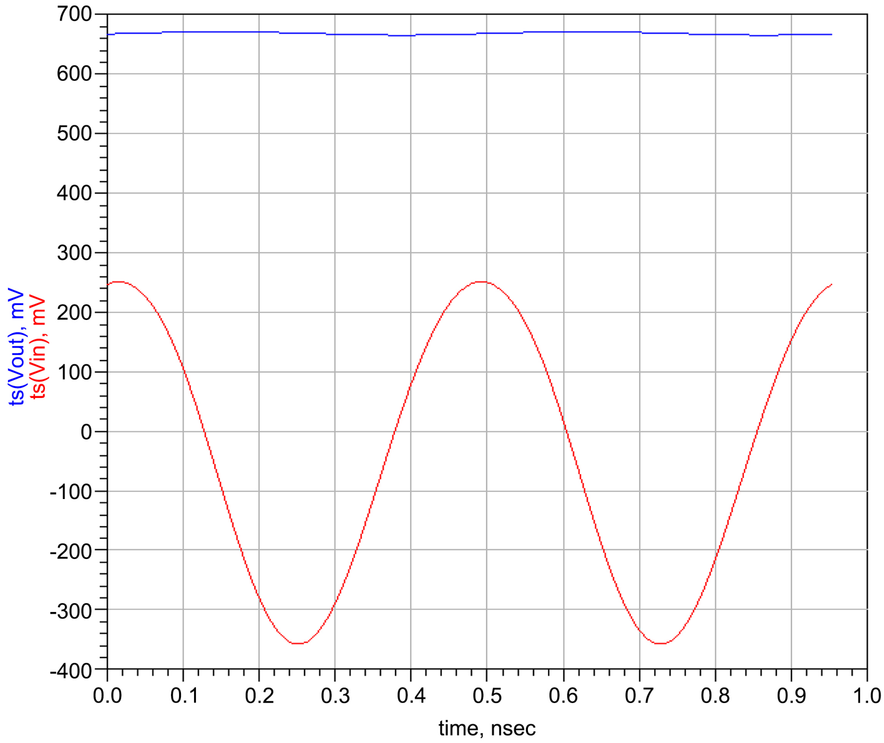


Figure 11. Output voltage of the rectifier (1800 MHz).

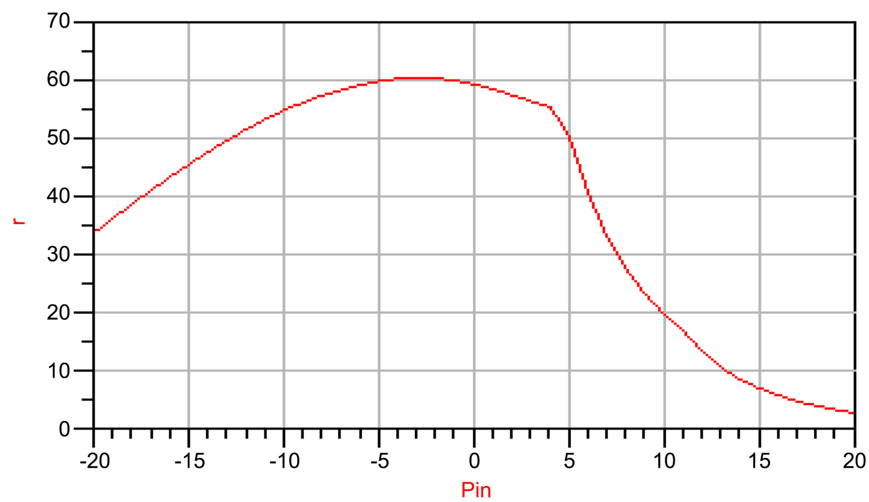


Figure 12. RF-to-DC conversion efficiency versus input power (dBm) when the load resistance is equal to 2 kΩ.

Figure 11 illustrates the RF generator input voltage (1800 MHz) and output voltage across the load. The evolution of this voltage is also of the same form for the 2100 MHz and 2500 MHz RF generators. Thus, the output voltage of the matched rectifier is 670 mV at the frequency of 1.8 GHz, 870 mV at the frequency of 2.1 GHz and 760 mV at the frequency of 2.5 GHz.

Evaluating and optimizing conversion efficiency is essential for designing efficient and economical energy systems. **Figure 12** shows the efficiency as a function of the input and output power at the load terminals for frequency 1.8 GHz. We have a similar evolution for the 2.1 GHz and 2.5 GHz frequencies. Thus, we obtained satisfactory conversion efficiency, reaching 60% for the 1.8 GHz frequency, 55% for the 2.1 GHz frequency and 62% for the 2.5 GHz frequency.

4. Conclusions

This article presents three single-band rectenna operating at frequencies of 1.8 GHz, 2.1 GHz and 2.4 GHz respectively. A detailed study of the design stages using simulation is carried out. In our study, we focused on component selection, antenna and converter circuit design, and performance analysis.

The performance achieved with the designed antennas was in line with the expectations defined in the specifications, demonstrating the effectiveness of our design approach. The use of a rectifier with a diode in series was identified as the most appropriate for low-power applications, providing a satisfactory conversion efficiency of over 60%.

Consequently, the proposed solution looks very promising for powering all types of low-power loads by exploiting the ambient RF waves of the GSM/LTE and WIFI radio standards for indoor and outdoor applications.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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