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A Dual-Band Rectenna for Ambient RF Energy Harvesting in RFID Systems

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Abstract

How to optimize simulation performance parameters such as gain, directivity, losses and bandwidth with a view to energy efficiency? This paper presents a dual-band rectenna based on a slotted patch antenna printed on an FR4 substrate (50 mm × 39 mm × 1.6 mm). This antenna model, whose parameters have been adjusted, is able to respond effectively to the two targeted resonance frequencies $f_1 = 900$ MHz and $f_2 = 2.45$ GHz at low power levels. The aim of this study is to develop a multifunctional antenna that can simultaneously act as an RFID tag and an ambient radio frequency energy recuperator, making its system self-powered. The proposed solution incorporates not only a sketch of an antenna, but also a rectifier circuit and an energy storage system. We have chosen to use a 3.7 V - 600 mAH Lithium Polymer (LIPO) battery for its low self-discharge, light weight and high energy density. The proposed solution is to radiate the antenna on two frequency bands in order to recover the surrounding RF energies. The GSM and Wi-Fi frequencies are a convincing choice, providing a high bandwidth, reflection coefficient and gain for optimum power. The RF/DC conversion circuit is based on a series topology using the SMS7630 Schottky diode, receiving an input power of between 10 dBm and 30 dBm, for load resistors of 2.5 kΩ, 3 kΩ and 3.5 kΩ respectively. Maximum conversion efficiency of 67.24% at 1.77 GHz for a 3 kΩ load resistor. The antenna and rectifier circuit were designed and simulated using Advanced Design System (ADS) 2023 R1 software. This study yielded RF/DC conversion efficiencies of 67.243% and 3.902% respectively for resonant frequencies of 1.77 GHz and 2.7 GHz with an optimum 3 kΩ load.

Keywords

RFID Tag, RF/DC Conversion, Dual-Band Rectenna, Energy Recovery, Patch Antenna

1. Introduction

Recent years have seen the exponential growth of wireless sensors and low-power electronic devices, leading to a number of issues and challenges related to energy autonomy. Ambient energy recovery is emerging as an alternative solution, particularly for ensuring the operation of very low energy consumption systems [1] [2]. Energy harvesting is the method of capturing energy from available sources, such as solar energy, vibration stimulation, pressure gradients and radio frequency (RF) signals, and converting it into direct current [3]. The technique used involves converting the electromagnetic waves produced by GSM and WIFI access points into direct current [4]. The aim of this article is to develop a compact, high-performance antenna and rectifier circuit capable of recovering low-power-density electromagnetic waves and converting them into a DC power source.

However, the power received is generally too low, requiring a highly optimized design capable of efficiently capturing, converting and storing energy [5]-[7]. In this context, rectennas that integrate an antenna and a rectifier circuit are being studied in particular, and several works have proposed multi-band topologies [8] [9], but miniaturization and power supply, dual functionality and conversion efficiency remain open challenges [10]-[12]. Thus, J. O Olowoleni *et al.* have worked on the design and simulation of a new 3-point star patch antenna with the aim of improving energy recovery at 2.4 GHz. The antenna developed is combined with a voltage doubler rectifier circuit incorporating two HSMS2820 Schottky diodes, giving a maximum efficiency of 88.02% with 28 dBm of power [13]. In addition, Pavan Mehta *et al.* presented a dual-band RF/DC converter circuit designed for low-power, high-sensitivity applications, operating in the 2.45 and 5.5 GHz bands. The converter circuit gives a DC output voltage of 48 mV at 2.45 GHz for an input power of -25 dBm and a maximum conversion efficiency of 47% at the 2.45 GHz band [14]. **Table 1** summarizes the performance of these authors' antennas.

Table 1. Comparison of results obtained with previous work.

Reference	Frequency	Antenna type	Schottky diode rectifier circuit	Input power	η maximum
(Shi *et al.*, 2018)	2.4 GHz	Fractal slit patch	HSMS2852	0 dBm	62%
(Vital *et al.*, 2019)	2.45 GHz	Rectangular textile patch	SMS7630	8 dBm	70%
(J. O. Olowoleni *et al.*, 2021) [13]	2.4 GHz	3-point star patch	HSMS2820	28 dBm	88.02%
Pavan Mehta *et al.* [14]	2.4 GHz & 5.5 GHz		SMS7630	25 dBm	47%
This research	1.7 GHz	Rectangular slit patch	SMS7630	10 dBm	67.243%
	2.7 GHz			30 dBm	3.902%

The aim of this research is to model a multifunctional antenna capable of processing information and collecting electromagnetic waves from GSM and WIFI to power itself. It is illustrated by the functional block diagram in Figure 1.

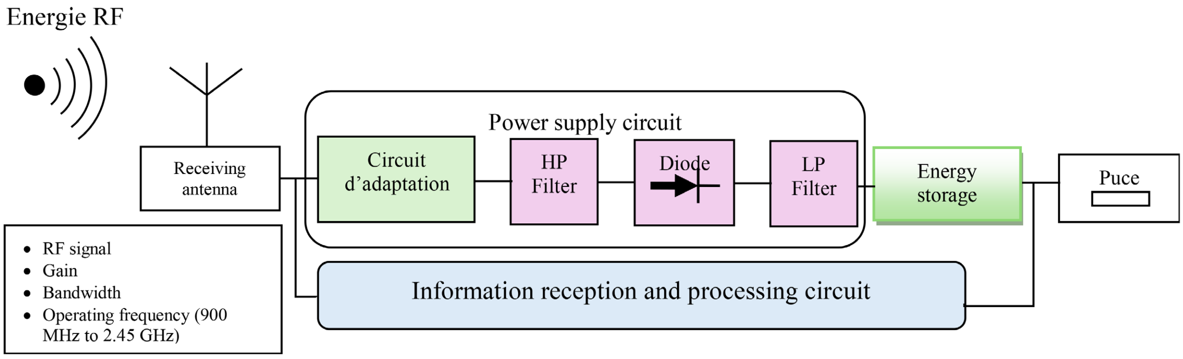


Figure 1. Functional diagram of a radio frequency energy recovery system.

The following section describes the design of the circuit for converting the RF signal received by the antenna at frequencies of 900 MHz and 2.45 GHz into a DC voltage that can be used for low-power applications, and its optimization by means of an impedance matching circuit. The Schottky diode, capacitors and inductors are the main elements of the RF/DC rectifier device.

2. Materials and Methods

2.1. Equipment

In this work, we used a Core i5 computer, 3.0 GHz processor, 8 GB RAM and NVIDIA GEFORCE GTX 950M, the Advanced Design System (ADS) 2023 design software, which is a tool for electronic and electromagnetic simulation of HF circuit systems.

2.2. Method

The design and simulation of both the antenna and the rectifier circuit will be developed in this section. The antenna and rectifier components were developed and evaluated separately and then integrated together into a module for simulation using Advanced Design Systems (ADS) simulation software developed by Keysight Technologies. The block diagram of our circuit is shown in Figure 1.

2.2.1. Antenna Design

RF energy is collected by a rectenna (antenna and rectifier) whose antenna is an essential element in the recovery of ambient electromagnetic waves. We used a rectangular patch antenna fed by a microstrip line, the dimensions of which were calculated on the basis of parameters relating to resonance frequencies, substrate and celerity (see Figure 2). The formulae and dimensions are shown in Table 1. In our case, the frequencies chosen are 900 MHZ and 2.4 GHz.

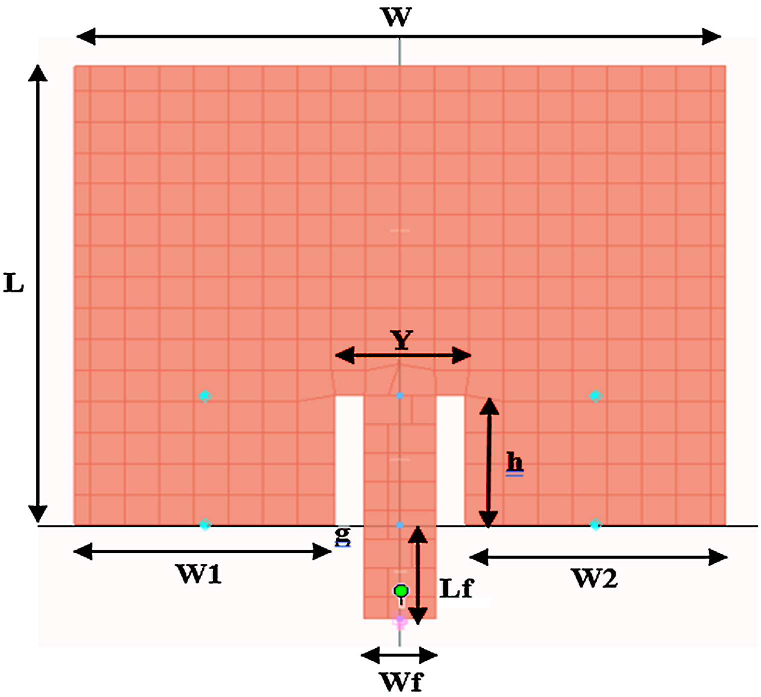


Figure 2. Illustration on ADS of the sized patch antenna.

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\frac{1}{\sqrt{1+12\left(\frac{h}{W}\right)}}\right] \tag{1}$$

$$W = W_1 + Y + W_2 = \frac{c}{2f\sqrt{\varepsilon_r}} \tag{2}$$

$$L = \frac{c}{2f\sqrt{\varepsilon_{eff}}} - 0.824h\left(\frac{\left(\varepsilon_{eff}+0.3\right)\left(\frac{W}{h}+0.264\right)}{\left(\varepsilon_{eff}-0.258\right)\left(\frac{W}{h}+0.8\right)}\right) \tag{3}$$

$$H = 0.822 \times L/2 \tag{4}$$

$$Y = W/5 \tag{5}$$

$$W_1 = W_2 = 2W/5 \tag{6}$$

$$g = \left(Y - W_f\right)/2 \tag{7}$$

These equations have enabled us to calculate the various values of the antenna parameters in Table 2 with the FR4 type substrate chosen.

By taking into account certain parameters of microstrip antennas, it is possible to design an antenna that is better suited to certain applications. For example, the dielectric constant plays a key role in determining the antenna's bandwidth and radiation efficiency, by giving it a wider impedance bandwidth, reducing surface wave excitation and giving it a lower permittivity. The thickness of the substrate has an impact on the bandwidth and the level of coupling. A thicker substrate gives a wider bandwidth.

Table 2. Summary of the values of the parameters used in the design of the antenna under ADS.

Parameters	Values
Substrate material	FR4
Dielectric constant (ε_r)	4.6
Substrate thickness (h)	1.6 mm
Tangential losses	0.02
Conductivity	5.8E7 S/m
Metal thickness	5 µm
Width of microstrip patch (W_f)	50 mm
Length of microstrip patch (L_f)	39 mm
Length of vertical slot (h)	11 mm
Length of supply line (L_f)	8.5 mm
Feed line width (W_f)	5.5 mm
Width ($W_1 = W_2$)	20 mm
Gap width (g)	2.15 mm
Frequencies (f_1 and f_2)	900 MHz and 2.45 GHz

The length of the microstrip patch is related to the resonant frequency of the antenna and the width of the microstrip patch is an important determinant of the resonant resistance of the antenna. A wider microstrip patch gives a lower resistance. The length of the feed line influences the input impedance, the width of the feed line can affect the coupling, the return loss and even the resonant frequency.

The feeding technique plays a key role in improving input impedance matching and enabling efficient antenna operation. Several feeding techniques can be used, including microstrip line feed, insertion feed, coaxial coupling feed, aperture coupling feed and proximity coupling feed [15]. The choice of the microstrip line feed technique in this research is justified by the fact that it gives the antenna a relatively high gain and low return loss, particularly when the FR4 dielectric (relative permittivity of 4.6, substrate thickness of 1.6 mm and tangential loss of 0.02) is used.

Finally, the wavelength (λ) of a signal is indirectly proportional to its frequency (f); we can therefore deduce from the previous equation that the power (Pr) that can be received at a certain distance from the transmitter decreases as the frequency increases, since an increase in frequency leads to a corresponding reduction in wavelength (λ). However, frequencies between 0.5 GHz and 3 GHz are considered to offer a good balance between free-space power attenuation and compact antenna dimensions.

2.2.2. Rectifier Design

Radio frequency signals are available in most telecommunications bands, such as GSM900 (850 - 910 MHz), GSM1800 (1850 - 1900 MHz), UMTS (2150 - 2200 MHz), Wi-Fi/Bluetooth (2.4 - 2.45 GHz), television applications (900 MHz - 2 GHz), ISM (2.1 - 2.6 GHz), WLAN (3.1 - 4.4 GHz), Wi-MAX (5.1 - 5.3 GHz) and Wi-Fi/WLAN (5.1 - 5.8 GHz) are all available and exploitable sources of energy. Radio frequency energy can therefore be captured and converted into the direct current needed to operate low-power devices. In a recovery system, the rectifier plays an important role in converting RF signals into DC. In this field, many rectifier configurations have been studied to assess the performance and conversion efficiency.

The rectifier circuit discussed in this section has a simple structure (see **Figure 3**). The advantage of this structure is that it is compact and efficient for low input power levels. It comprises two SMS7630 Shottky diodes, an inductor, capacitors and a 3 kΩ impedance for a battery voltage of 3V and a current of 1 mAH. The different values of the components chosen for this conversion circuit are shown in **Table 3**.

The conversion efficiency of the circuit is a ratio between the power of the DC current P_{DC} obtained and the power of the radio frequency energy P_{RF} collected. It can also be expressed as a function of the output voltage V_{DC}, the load or output

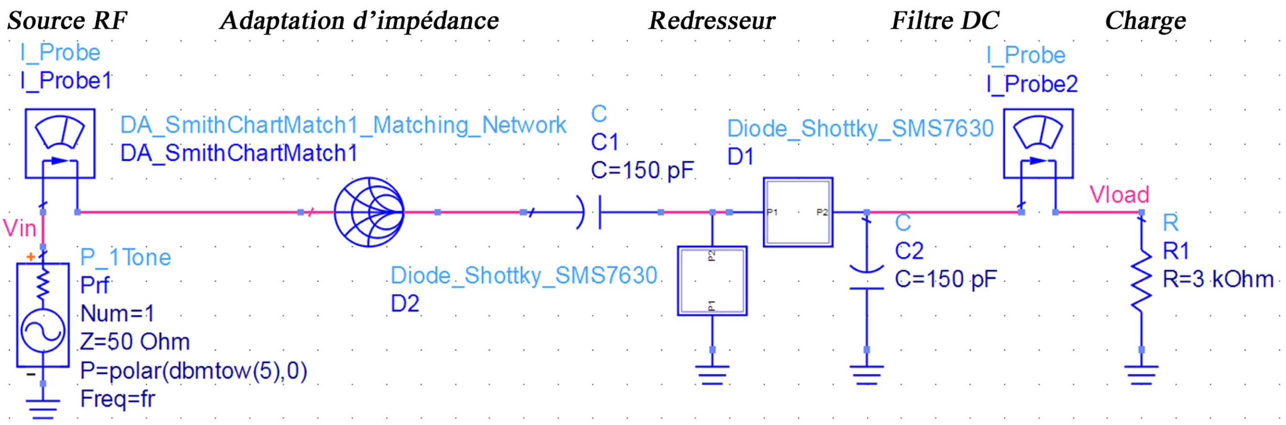


Figure 3. Electrical diagram of the 2.45 GHz RF/DC signal converter.

Table 3. Rectifier circuit component values.

Components	Value
Capacitor C_1, C_2	150 pF
Capacitor C_3	0.25 pF
Inductance L	0.2 nH
Shottky diode D_1, D_2	SMS7630
Inductance R	3 kΩ

impedance R_{load} and the power of the energy collected P_{RF}, given by the following equation [16]:

$$\eta = \frac{P_{DC}}{P_{RF}} \times 100 = \frac{V_{DC}^2}{R_{load} \times P_{RF}} \times 100 \tag{8}$$

As with the antenna design, the FR4 substrate (dielectric constant = 4.6, substrate height = 1.6 mm, thickness = 0.7 mil, tangential losses = 0.02) was used with the same parameters, enabling the rectifier circuit to be optimized using Advanced Design System simulation software (ADS).

Harmonic balance simulation using circuits with several input frequencies, to calculate the amplitude and phase of currents or voltage in a potentially non-linear circuit.

3. Results and Discussions

Various simulations were carried out on the antenna on the one hand, and the rectifier and impedance matching circuit on the other, before integrating them all into a single device in order to determine the conversion efficiency.

3.1. Simulated Antenna Performance

To evaluate the operation of the energy harvesting system with our rectenna, voltage and current measurements are made using the Keysight ADS simulator. **Figure 4** shows the simulation results for the dual-band slot patch antenna. At 900 MHz and 2.4 GHz, the antenna radiates best at 1.77 GHz and 2.7 GHz, with S_{11} = −21.47 dB and −21.73 dB respectively (see **Table 4**). **Figure 5** shows an almost equivalent gain for the two resonant frequencies and a fairly satisfactory directivity.

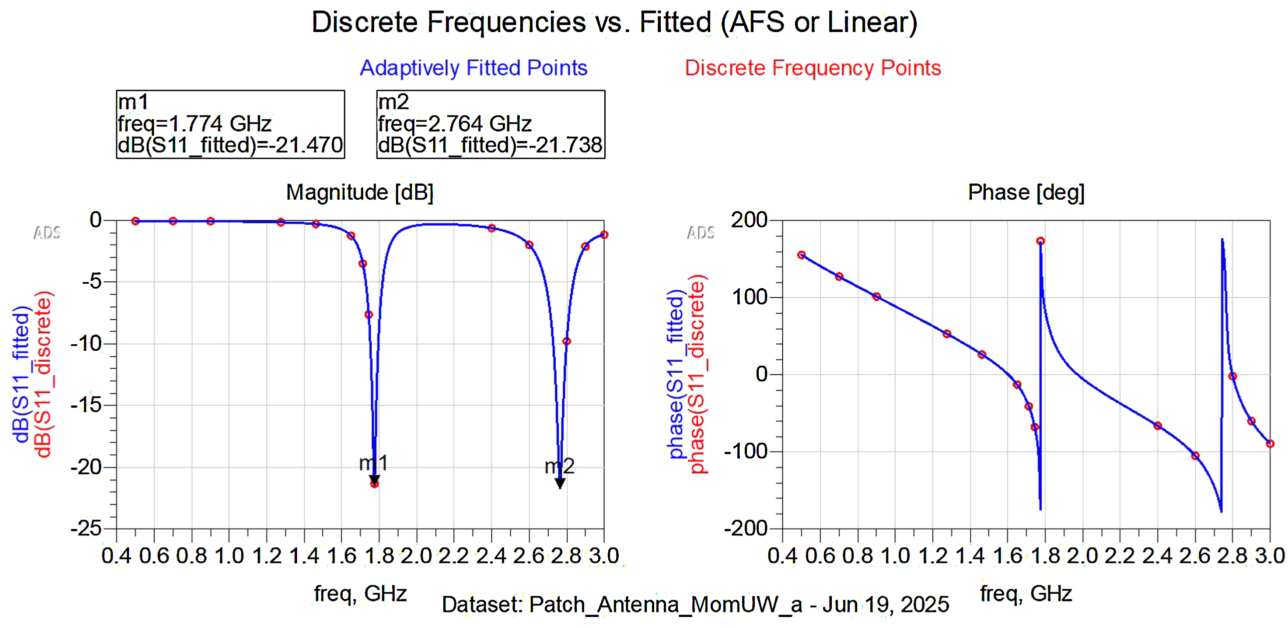


Figure 4. Reflection coefficient for different frequencies.

Table 4. Summary of antenna simulation results.

Parameters	Patch antenna values
Frequency (GHz)	1.85 GHz
Maximum efficiency (%)	75.810
Reflection coefficient S_{11} (dB)	−14.62
Gain (dBi)	3.922 at 1.7 GHz and 3.828 at 2.9 GHz
Directivity (dBi)	6.536 at 1.8 GHz and 8 at 2.4 GHz

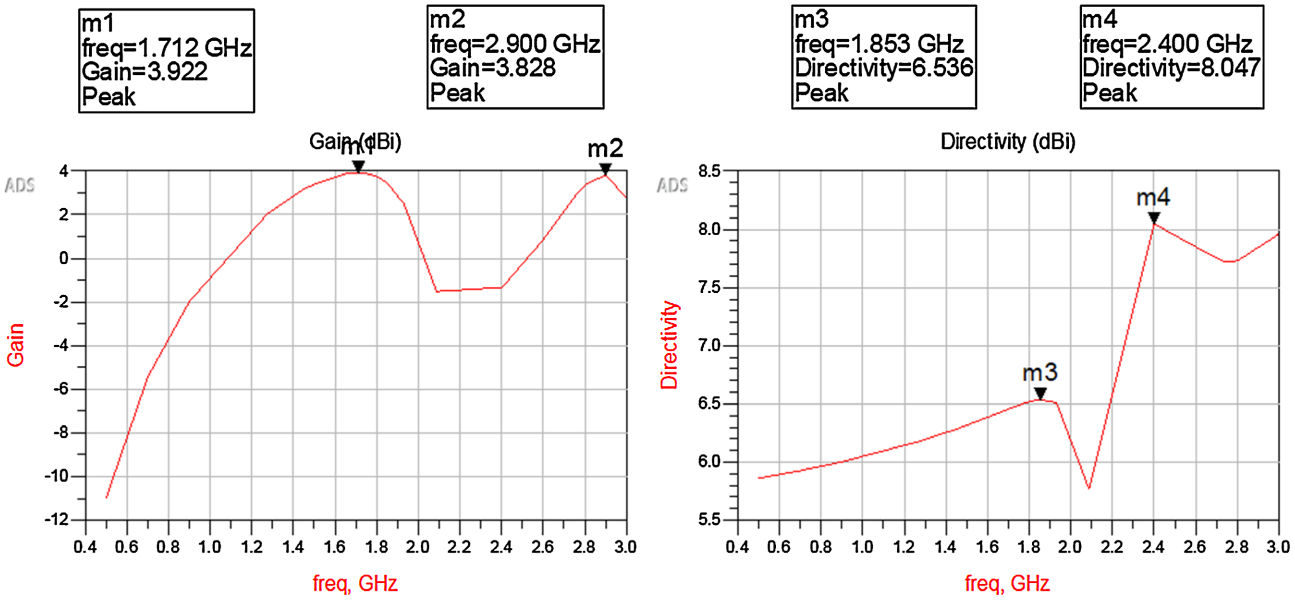
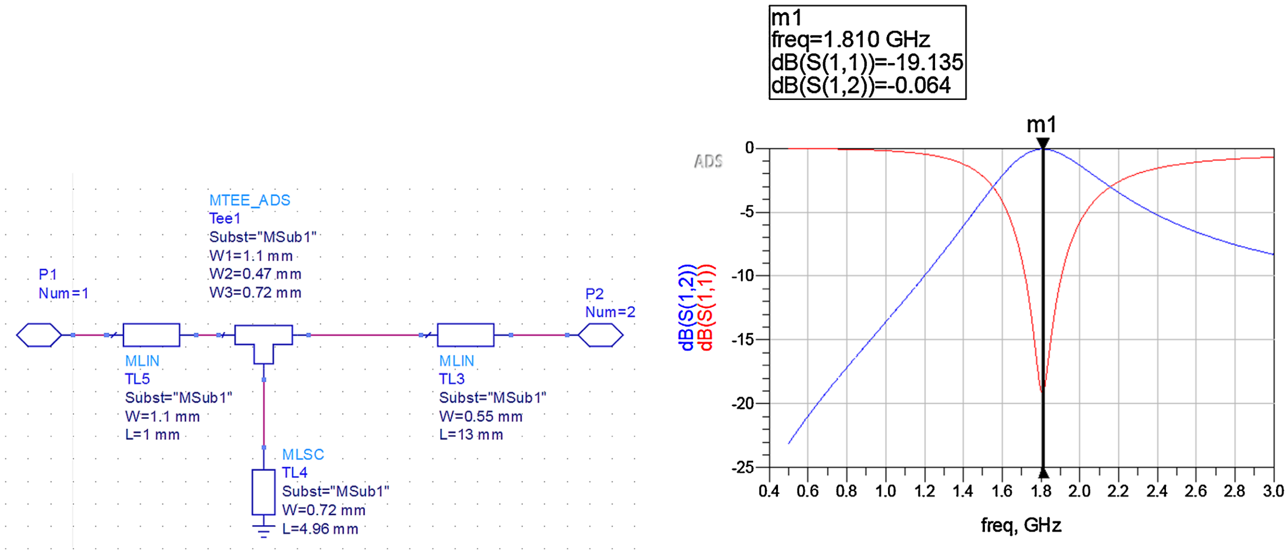


Figure 5. Antenna gain and directivity diagram.

The resonance frequencies obtained during simulations are 1.77 GHz and 2.7 GHz, respectively. This represents a significant shift from the initial frequencies of 900 MHz and 2.45 GHz. This frequency shift is due to the constraints on the length and width of the microstrip patch antenna. To reduce this shift, the dimensions of the antenna would need to be increased, which would defeat the purpose of having an RFID antenna. These values still allow the main use of GSM 1800 frequencies, which are better suited to denser urban areas and offer greater capacity than GSM 900 MHz. 2.4 GHz Wi-Fi has a long-range band, widely used for wireless connections by the public, which is close to the resonance values obtained.

3.2. The Impedance Matching Circuit

This circuit is designed here to improve the efficiency of our rectenna. MLIN (Microstrip Line) components, some of which play a role in matching the input and output impedance to the rectifier circuit, have been chosen for the impedance matching circuit (**Figure 6(a)**). The simulation results (**Figure 6(b)**) show a reflection coefficient of −19.135 dB matched to −0.064 dB at a frequency of 1.8 GHz.



(a) (b)

Figure 6. (a) Impedance matching circuit; (b) Simulation result.

3.3. Simulated Rectifier Performance

By using different values (2 kΩ between 3 kΩ) of load impedances during simulation, it was possible to determine the conversion efficiency η of the rectifier at an input power level of between 10 dBm and 30 dBm. The efficiency value is defined by the following equation [16]:

$$\eta = \frac{P_{DC}}{P_{RF}} \times 100 = \frac{V_{DC}^2}{R_{load} \times P_{RF}} \times 100 \tag{9}$$

The measured conversion efficiency values for the selected range of input power levels are shown in **Figure 7**. The optimum conversion efficiency value of 75.810% is obtained with a 3 kΩ load resistor at a frequency of 1.85 GHz.

In addition, **Figure 8** shows that the conversion efficiency tends to increase

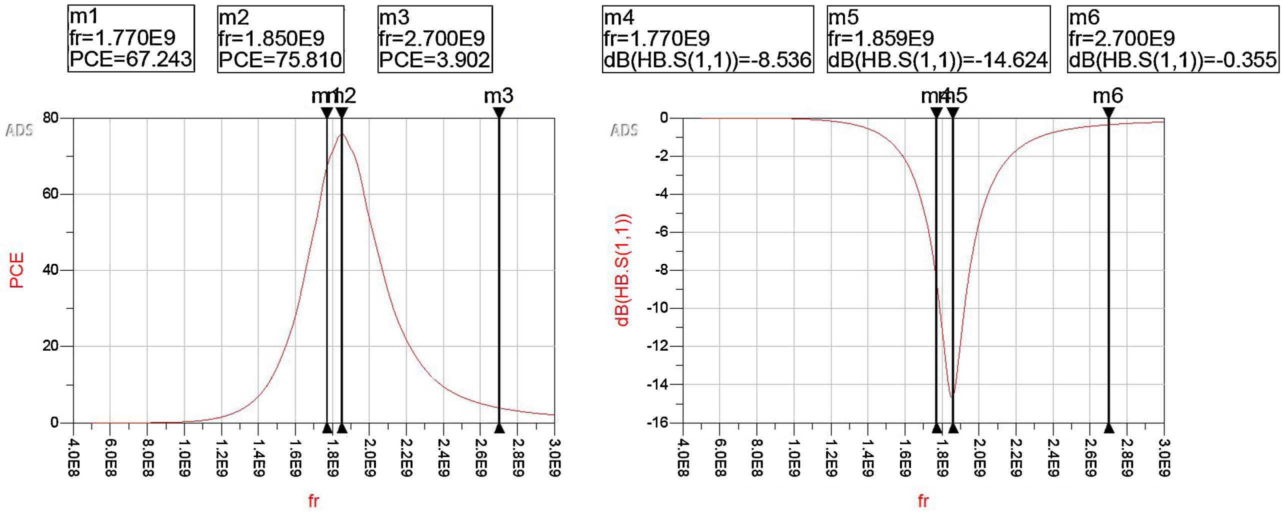


Figure 7. Efficiency measured as a function of power collected for a 3 kΩ load.

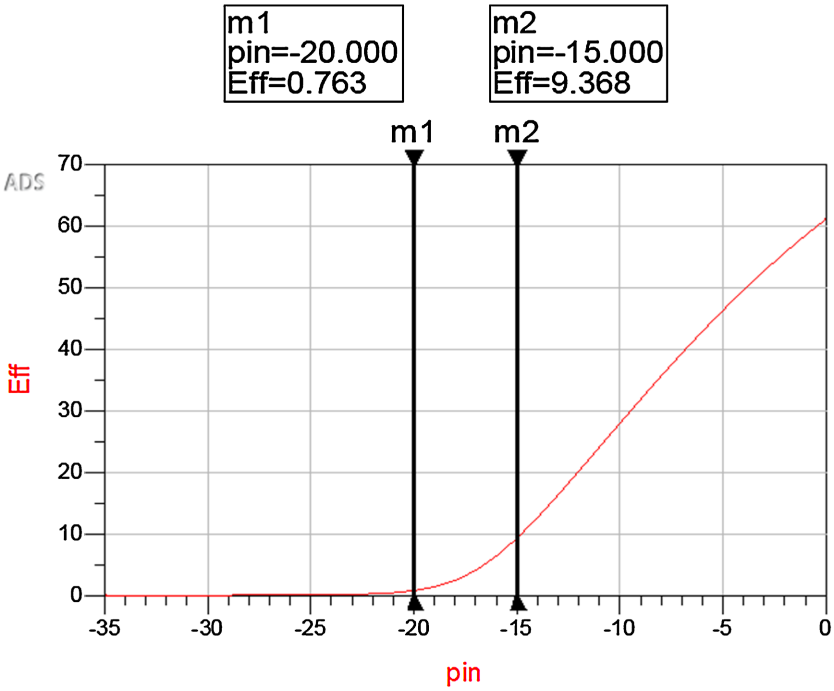


Figure 8. Simulation of conversion efficiency for different collected powers.

from a frequency of 1.2 GHz until it reaches a maximum value at a frequency of 1.85 GHz, then gradually decreases until 2.5 GHz. Thus, the proposed rectifier circuit, for an optimum load impedance value of 3 kΩ, achieves a maximum conversion efficiency of 75.810 for a particular input power level. Finally, the rectifier achieves a reflection coefficient of −15.677dB, which is satisfactory and does not require any improvement in the impedance matching of the circuit.

Conversion efficiency becomes insufficient above a frequency of 2 GHz (less than 50%) for practical applications. At a resonance frequency of 2.7 GHz, it is 3.9%, which does not provide sufficient DC voltage despite the long range of 2.4 GHz Wi-Fi. This requires optimization of the RF/DC conversion circuit in order to take full advantage of dual band.

4. Conclusions

In this work, the approach was to use the dual-band microstrip patch antenna of a semi-passive RFID tag to collect radiofrequency energy. A patch antenna (50 mm × 39 mm × 1.6 mm), an impedance matching circuit and an RF-DC signal converter were designed and simulated. Frequency bands favourable for energy harvesting were chosen in the range 500 MHz to 3 GHz, with a minimum input power of -20 dBm. A microstrip transmission line model was also used in the design of the RF-DC converter. The proposed converter circuit exhibits satisfactory RF-DC conversion efficiency at a frequency of 1.77 GHz, consistent with previous work summarized in Table 1. Consequently, this circuit, which is better suited to GSM energy harvesting, can be used not only to recharge the battery of a semi-passive RFID tag, but also in low-power electronic devices and sensor networks in the Internet of Things.

The simulation results show better performance at the 1800 MHz GSM frequency than at the initially planned 900 MHz frequency. The conversion efficiency at the resonance frequencies of 1.77 GHz and 2.7 GHz are 67.24% and 3.90% respectively. The maximum efficiency value is 75.81% and is obtained at a frequency of 1.85 GHz. As the main operating point of the device is 1.77 GHz, the efficiency will therefore be 67.24%.

The device obtained has limitations for the GSM 900 MHz and WIFI 2.4 GHz frequencies. In fact, the device operates efficiently for the GSM 1800 frequency. Also, the challenge of designing a short and thin patch antenna does not allow for a significant reduction in the resonance frequency. Another solution for future work would be to study the use of materials with a higher substrate permittivity than the FR4 used.

Furthermore, the RF/DC conversion circuit does not offer better efficiency for high frequencies (above 2 GHz), even though it is widely used. Modifying the circuit for optimal conversion at the resonance frequencies obtained would allow full advantage to be taken of the dual band. One solution for future work would be to optimize the impedance matching at these frequencies or to use low-barrier Shottky diodes.

Conflicts of Interest

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

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