Scientific Research Publishing

Energy and Power Engineering, 2025, 17(1), 1-12
https://www.scirp.org/journal/epe
ISSN Online: 1947-3818
ISSN Print: 1949-243X

Design of Dipoles for the RF Energy Harvesting System Dedicated to GSM Applications

Abdoul Karim Mbodji, Mohamed El Moctar, Malang Kambaye, Ousmane Dieme

Department of Physics Applied of UFR-SAT, University Gaston Berger, Saint-Louis, Senegal
Email: akmbodji@gmail.com, moktar412233@gmail.com, malangkambaye2016@gmail.com, ousmanedieme0401@gmail.com

How to cite this paper: Mbodji, A.K., El Moctar, M., Kambaye, M., & Dieme, O. (2025) Design of Dipoles for the RF Energy Harvesting System Dedicated to GSM Applications. *Energy and Power Engineering*, **17**, 1-12.
https://doi.org/10.4236/epe.2025.171001

Received: September 23, 2024
Accepted: January 7, 2025
Published: January 10, 2025

Abstract

Nowadays, we are witnessing an era marked by the autonomy of wireless devices and sensor networks without the aid of batteries. RF energy harvesting therefore becomes a promising alternative for battery dependence. This work presents the design of an RF energy harvesting system consisting mainly of a rectenna (antenna and rectification circuit) and an adaptation circuit. First of all, we designed two dipole type antennas. One operates in the GSM 900 MHz band and the other in the GSM 1800 MHz band. The performances of the proposed antennas are provided by the ANSYS HFSS software. Secondly, we proposed two rectification circuits in order to obtain conversion efficiencies at 0 dBm of 64% for the system operating at the frequency of 900 MHz and 37% for the system at the frequency of 1800 MHz RF-DC. The rectifiers used are based on Schottky diodes. For maximum transfer of power between the antenna and the rectification circuit, L-type matching circuits have been proposed. This rectifier offers DC voltage values of 806 mV for the circuit at the frequency of 900 MHz and 616 mV for the circuit at the frequency of 1800 MHz. The adaptation circuits are obtained by carrying out simulations on the ADS (Advanced Design System) software.

Keywords

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

1. Introduction

For several decades, wireless communicating objects have experienced unprecedented development and are part of our everyday lives [1]. Added to this is the Internet of Things (IoT) technology, which makes it possible to connect machines and sensors with the aim of integrating them into our information network [2].

Faced with this rapid development of connected objects, the energy autonomy of sensors is a major issue. The importance of this energy need continues to increase from year to year.

To overcome this challenge, energy harvesting from existing sources in the ambient environment, more particularly electromagnetic energy harvesting, appears to be a promising and effective technology. It uses radio frequency (RF) telecommunications waves that are already available in the ambient environment. It is also a way to improve the efficiency of using the electromagnetic waves emitted for other applications [2]-[6].

RF energy recovery, based on the transfer of electromagnetic energy between two distant points and without the aid of physical support, involves two stages: electrical energy is converted into RF energy and transmitted by a transmitting antenna; at reception, a rectenna, which is the contraction of the word antenna and rectifier, converts the ambient electromagnetic wave into an RF signal thanks to the antenna then with the help of the rectification circuit, converts the alternating signal into continuous. This is RF-DC conversion. An impedance matching circuit is placed between the antenna and the rectifier. This circuit allows maximum transfer of the power received by the antenna. At the output of the RF-DC converter, a storage device (capacitor, battery, etc.) stores the recovered RF energy in DC form and at the desired voltage to return it to the load. The load can be represented by a simple resistor whose value depends on the input impedance of a circuit to be powered (sensor or microcontroller, for example). The objective of our work is to design, using HFSS software, two antennas operating respectively in the GSM 900 MHz and GSM 1800 MHz bands. The rectifier for each antenna is then designed to collect the maximum power.

2. Material and Methods

2.1. Design of the Antennas

Most RF energy harvesting systems have the synoptic diagram shown in **Figure 1**. 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 purpose, the electromagnetic simulation tool HFSS version 13.0 was chosen. 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

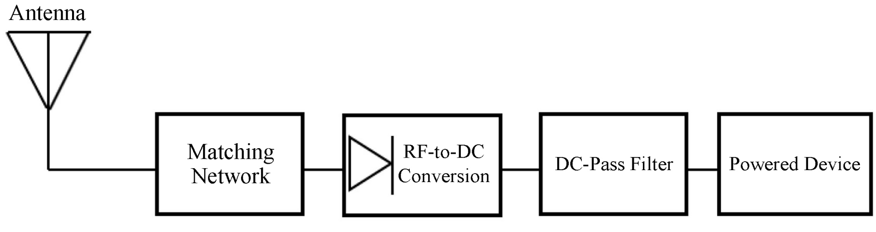

Figure 1. Block diagram of rectenna for ambient RF energy harvesting [6].

frequencies as well as the electric and magnetic fields and also the visualization of the 3D radiation diagram.

In this paper, two dipole antennas will be designed. One operates in the GSM 900 band (890 MHz - 960 MHz) and the other in the GSM1800 band (1710 MHz - 1880 MHz). The length (l) in meters (m) of an antenna is given by Equation (1) [7]:

$$l = \frac{c}{2\sqrt{E_r} f} * 0.9 \tag{1}$$

With $E_r = 1$ being the relative permittivity of dielectric of the ambient medium assimilated to air. The factor 0.9 reflects the fact that the RF energy will propagate across the antenna at approximately 90% of its normal speed. The frequency (f) is either 900 MHz or 1800 MHz. The dipole has a geometric shape similar to a cylindrical one of length (l) and radius R given by Equation (2).

$$R = \frac{l}{60} \tag{2}$$

Thus, the length and radius of the dipole are respectively 15 cm and 0.25 for the frequency 900 MHz and 7.5 cm and 0.125 cm for a frequency of 1800 MHz.

High Frequency Structure Simulator (HFSS) is simulation software that calculates the electromagnetic behavior of a structure.

To do this, HFSS uses partial differential equations. There are three main methods: the finite element method, the finite difference method and the method of moments. The principle of these methods is to discretize the space using a mesh specific to the method and to solve the equations. The software presented here uses the finite element method to solve the Maxwell equations.

The geometry of the model studied under HFSS (**Figure 2**) is automatically divided into a large number of tetrahedre on which the mathematical calculation

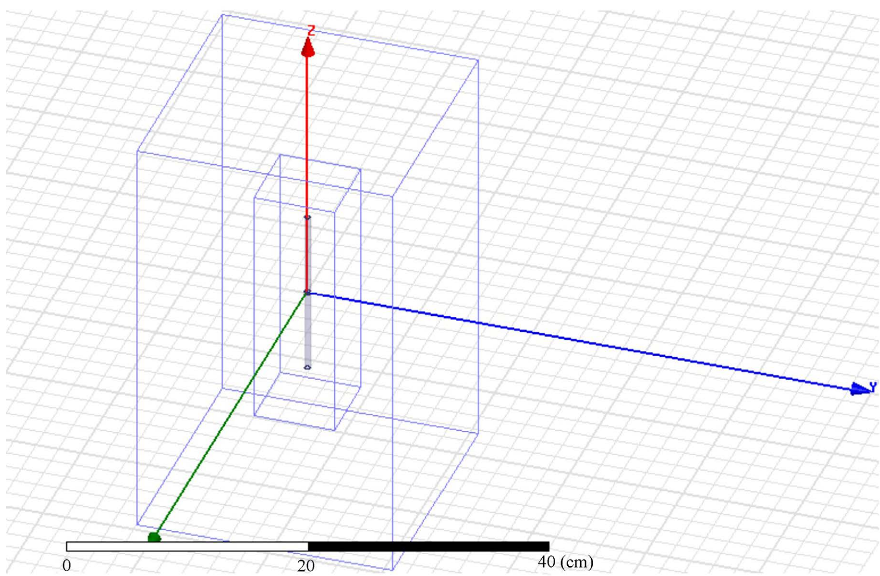

Figure 2. Structure of the dipole antenna.

will be more feasible. The value of a field vector (E or H) at a point inside a tetrahedron is calculated by interpolating the values of the fields in the vertices of the tetrahedron. Thus, by representing the field values in this way, HFSS calculates the fields separately in each element by setting convergence criteria, which corresponds to the maximum uncertainty between at least two successive iterations to be validated as representative of reality. This uncertainty is calculated as the percentage between two successive solutions, and if the ratio between these two solutions is greater than the convergence criterion, the iterations must continue, otherwise the solution is said to be stable and the calculation stops.

2.2. Design of Rectifiers

A rectifier is a system for converting alternating electrical energy into direct electrical energy. At low frequencies, this DC AC converter is made up of two blocks: the input stage corresponds to the rectification part provided by the diodes, the filtering part is provided by a low pass filter (bypass capacitor). At high frequency, it is necessary to add an input circuit (**Figure 3**), in order to ensure the adaptation of the impedance presented by the rectifier to the RF source, therefore minimizing reflection losses, and thus block the passage of harmonics likely to be generated by the diodes at high powers.

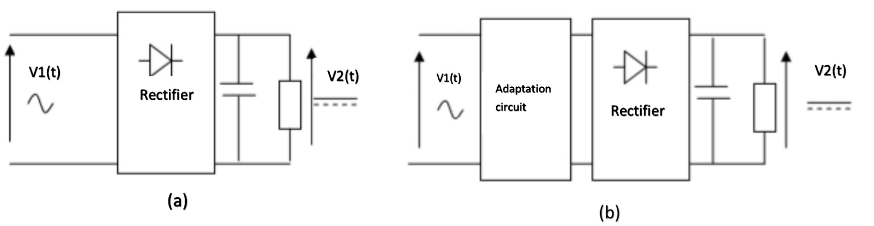

Figure 3. Rectifier design (a) low frequencies (b) high frequencies [7] [8].

The diode chosen to realize the rectifier is Schottky type. This choice is justified by the fact that with the diode rectifier, an external power source will be used, which is therefore less bulky, easy to manufacture and inexpensive. 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 circuit recovery because it has high efficiency in high frequencies (**Figure 4**). This is a diode widely used in detection and measurement circuits, with very precise sensitivity.

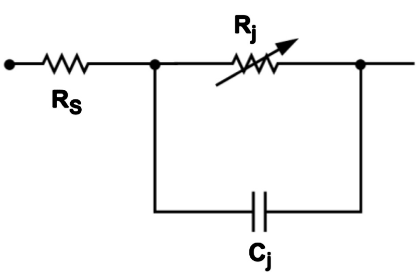

Figure 4. RF-DC conversion efficiency of diodes [8].

As shown in the **Figure 5**, Rj junction resistor can be express by following relation [7] [8]:

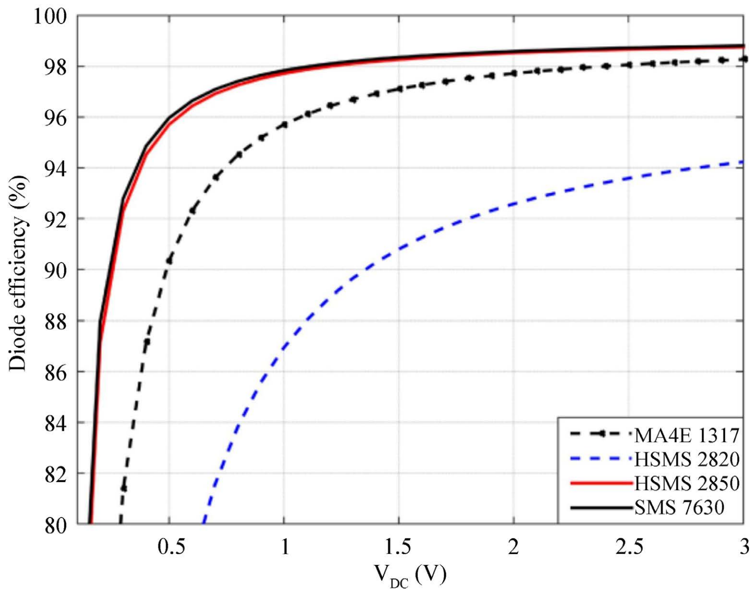

Figure 5. Schottky diode in a little signal [7] [8].

$$R_j = \frac{nkT}{q\left(I_s + I_b\right)} \tag{3}$$

with:

n: Ideality factor;

k = 1.38 10 - 23 J/$^\circ K$, Boltzmann constant;

T: Junction temperature in $^\circ K$;

q = 1.6 10 - 19, electron electrical load;

I_S: Saturation current;

I_b: Polarization current.

2.3. Calculation Model of the Rectenna Efficiency

The conversion efficiency is related to the load, the signal frequency and the internals of the diode Schottky [7] [8]. In general, the saturation current Is is very low and if the bias current Ib is zero, according to Equation (3), the junction resistance R_j becomes high. Which thus causes a drop in the rectified voltage expressed according to Equation (4) [7]-[12].

$$V_{out} = V_{DC}\frac{R_L}{R_L + R_j} \tag{4}$$

with:

V_{out} : Rectified voltage across the load;

V_{DC} : Voltage across the Schottky barrier;

R_L : Load resistor.

The conversion efficiency RF/DC is given by Equation (5) [6]:

$$\eta = \frac{P_{DC}}{P_{RF}} = \frac{1}{1 + A + B + C} \tag{5}$$

with:

$$A = \frac{R_L}{\pi R_s}\left(1 + \frac{V_j}{V_{out}}\right)^2 \left[\varphi\left(1 + \frac{1}{2\varphi}\right) - 1.5 \tan\tan(\varphi)\right]$$

$$B = \frac{R_s R_j C_j^2 \omega^2}{2\pi}\left(1 + \frac{V_j}{V_{out}}\right)\left[\frac{\pi - \varphi}{(\varphi)} + \tan\tan(\varphi)\right]$$

$$C = \frac{R_L}{\pi R_s}\left(1 + \frac{V_j}{V_{out}}\right)\frac{V_j}{V_{out}}\left[\tan\tan(\varphi) - \varphi\right]$$

$$\tan\tan(\varphi) - \varphi = \frac{\pi R_s}{R_L\left(1 + \frac{V_j}{V_{out}}\right)}$$

$$C_j = C_{j0} \cdot \sqrt{\frac{V_j}{V_j + V_{out}}}$$

ω : Pulsation égal to $2\pi f$ (f is the frequency);

C_{j0} : Junction capacity in 0 Volt;

φ : Phase shift during which the diode is conducting.

The conversion efficiency η, at the rectifier terminals is obtained also by Equation (6):

$$\eta = \frac{{V_{out}}^2}{P_{in} x R_L} \tag{4}$$

where V_{out} (in Volt) is the voltage on the resistor, and Pin the input power (in Watt) of the receiving antenna.

3. Results and Discussion

3.1. Antennas

Figure 6(a)-(b) shows the variations of the reflection coefficient as a function of frequency for each antenna design step. The reflection coefficients are −16.76 dB and −15.70 dB respectively at the frequency 899.3 MHz and 1744.8 MHz.

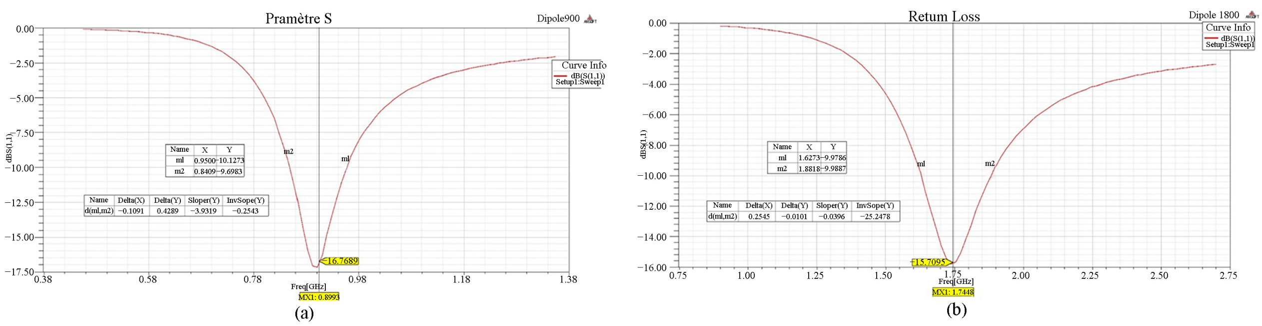

Figure 6. Dipole reflection coefficient 900 MHz (a) and 1800 MHz (b).

These 2 coefficients are satisfactory because they are less than the value 10 dB which is the reference reflection coefficient [9]-[15].

These two figures allow us to see a bandwidth of 100 MHz around the frequency 900 MHz and a bandwidth of 250 MHz around the frequency 1800 MHz. This band corresponds to the frequency range where the best performance of the antenna is observed in terms of impedance matching, radiated power, gain, or radiation efficiency. The higher the bandwidth of a receiving antenna, the more electromagnetic radiation it is capable of capturing. So, with the 1800 MHz dipole will allow the capture of many more frequencies.

Figure 7 and Figure 8 show the dipole radiation pattern respectively at the frequency 900 MHz and 1800 MHz. They allow us to notice that a diagram pattern is directional in the E-plan and omnidirectional in the H-plan.

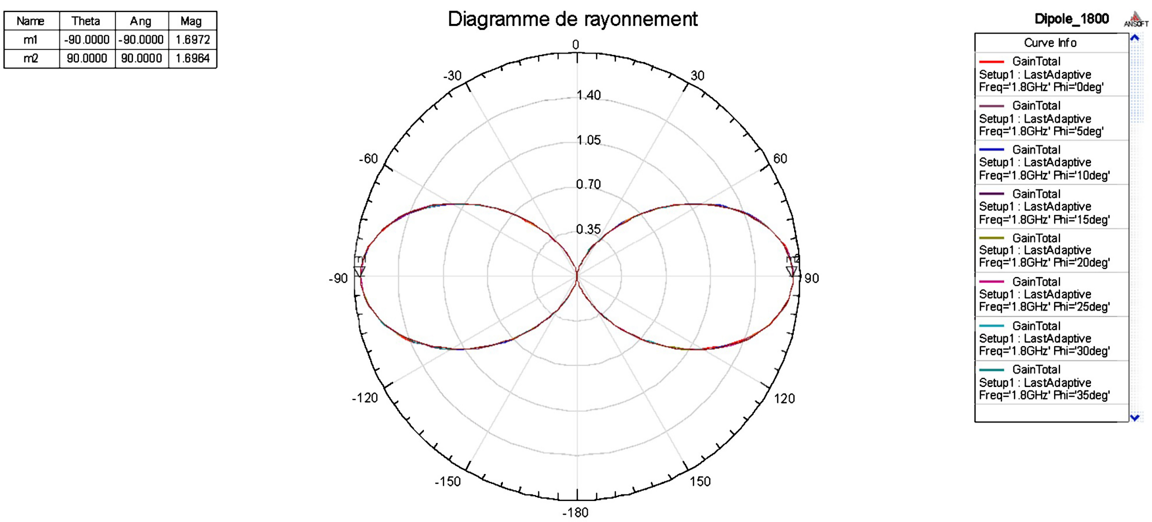

Figure 7. Radiation pattern of the 900 MHz dipole.

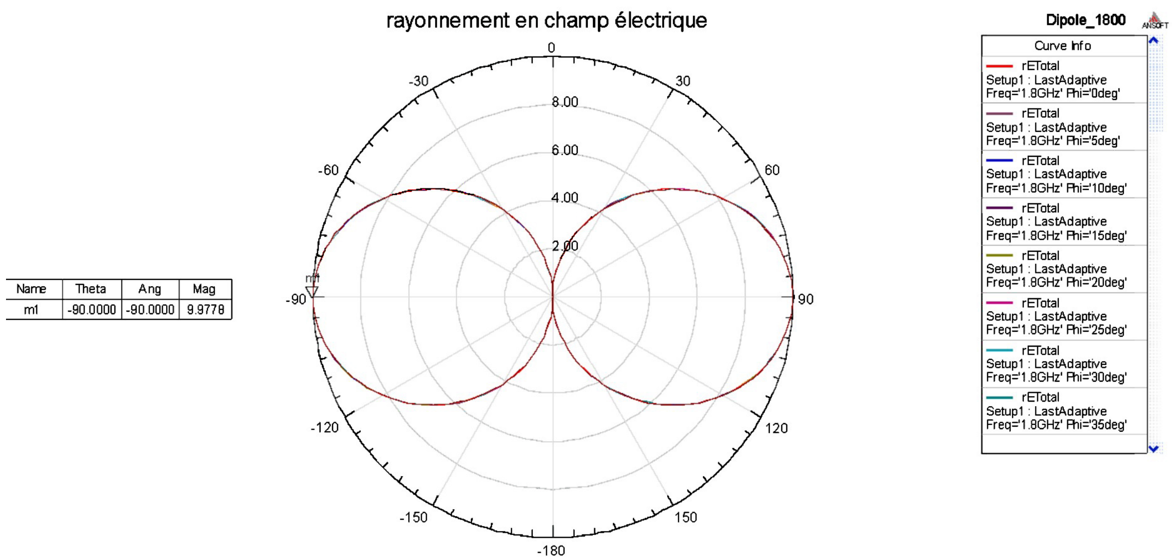

Figure 8. Radiation pattern of the 1800 MHz dipole.

Figure 9(a)-(b) shows the antenna gain at both frequency bands. It is 1.72 dB and 1.69 dB at 900 MHz and 1800 GHz respectively.

3.2. Rectifier

The simulations were carried out using Advanced Design System (ADS) software. To adapt the input impedance of the rectifier and other parts of the circuit, the ADS smith chart design tool will be used. At 900 MHz bandwidth, the values for L and C [15]-[17] are 50.78 nH and 0.29 pF respectively (Figure 10, Figure 11). At 1800 MHz bandwidth, these values become 25.42 nH and 2.49 pF respectively (Figure 12, Figure 13).

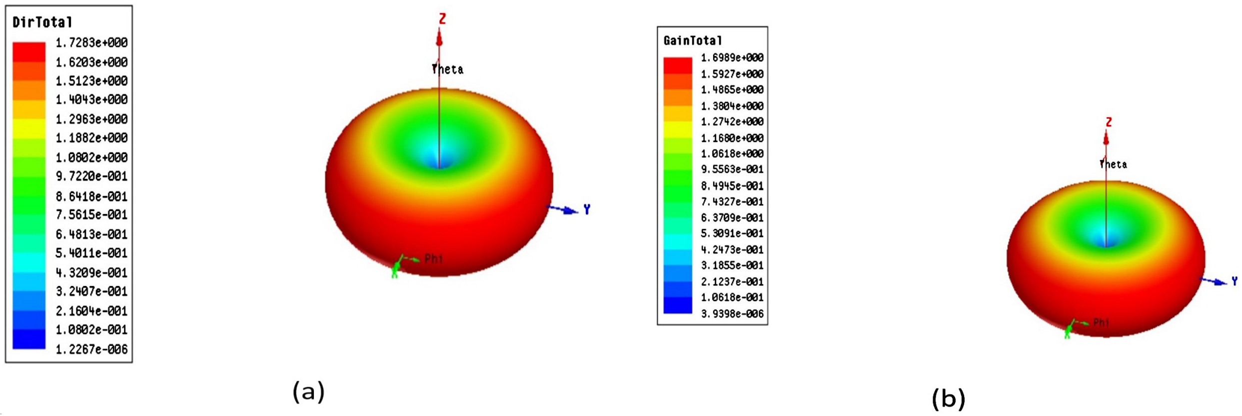

Figure 9. Total dipole gains 900 MHz (a) and 1800 MHz (b).

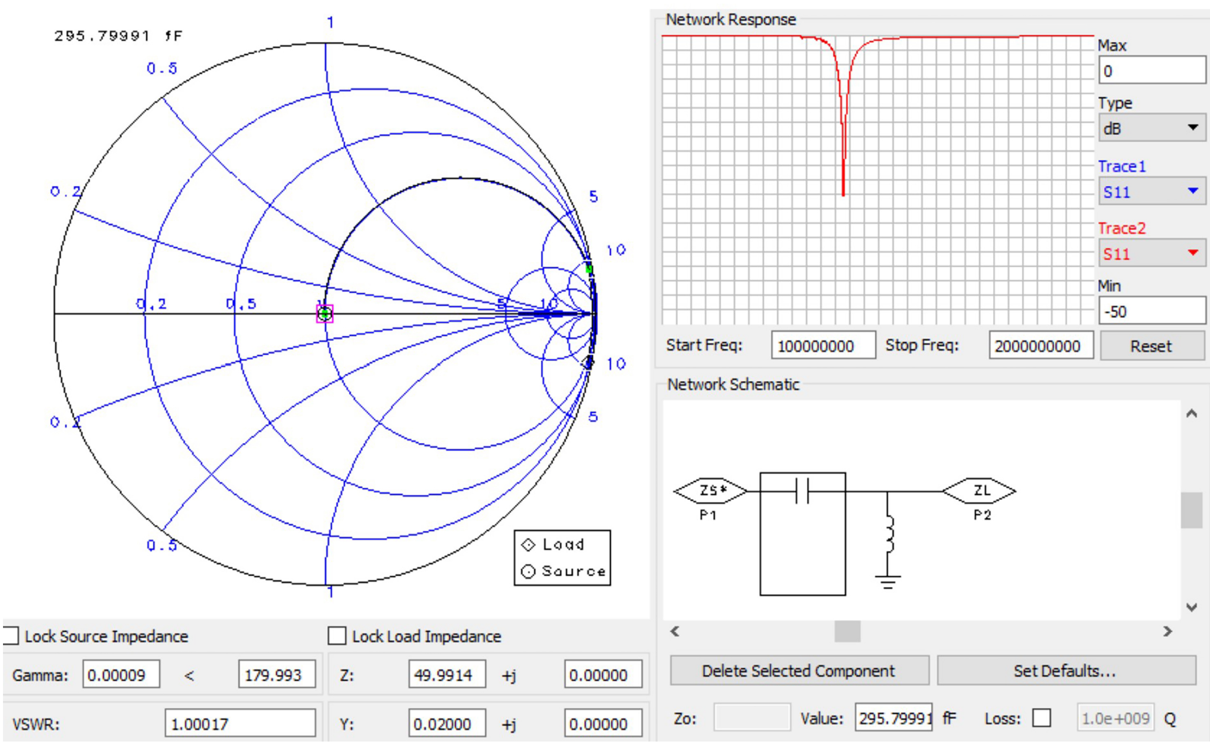

Figure 10. Design of the adaption circuit for frequency 900 MHz.

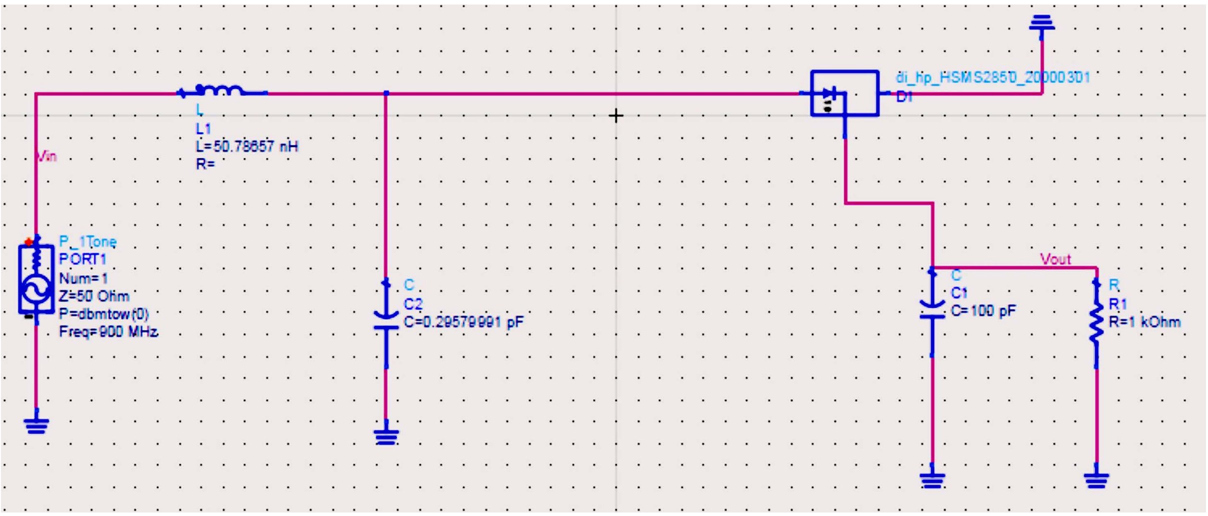

Figure 11. Circuit rectenna in ADS for band 900 MHz.

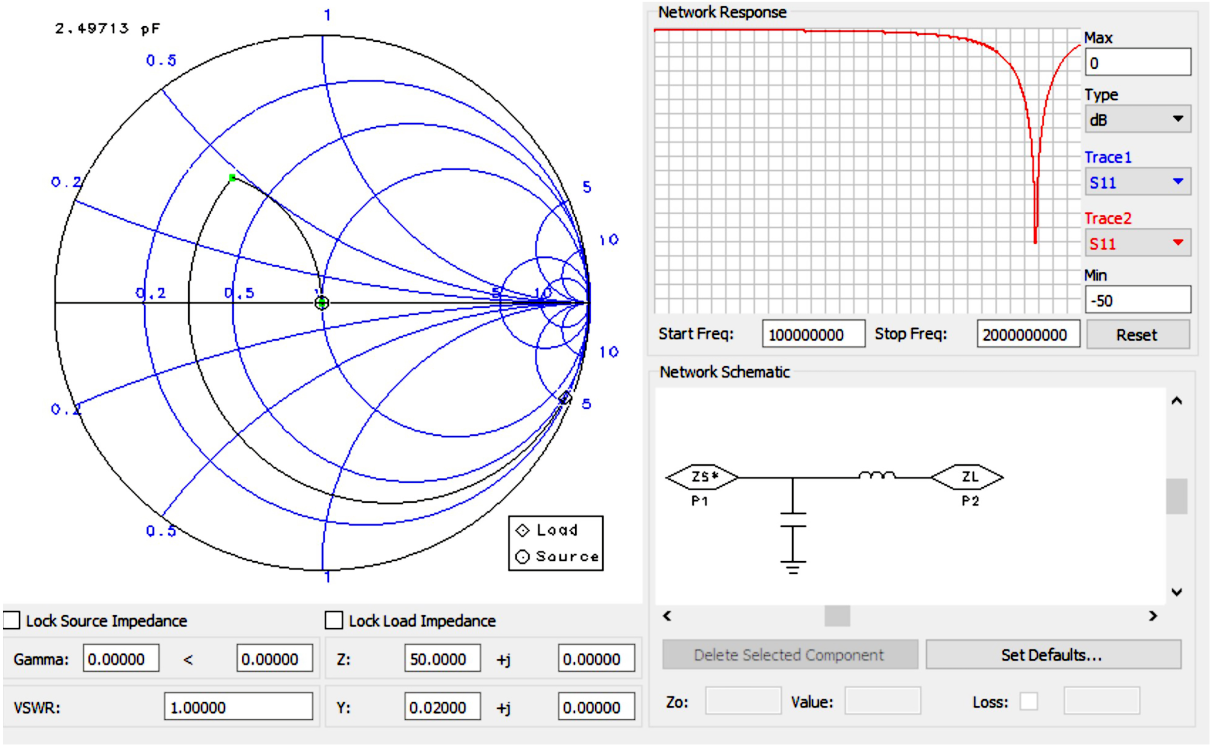

Figure 12. Design of the adaption circuit for frequency 1800 MHz.

The results show that the rectifier used is well adapted to the 900 MHz frequency, producing an output voltage of 806 mV for an input voltage of 330 mV (Figure 14(a)). At the frequency of 1800 MHz the system is also good and it provides an output voltage of 616 mV for an input voltage of 268 mV (Figure 14(b)).

After calculating the efficiency of the overall circuit, i.e. the rectenna, a value of 64% with 0 dB input power and 806 mV output voltage at 900 MHz bandwidth were found. On the other hand, at the 1800 MHz bandwidth an efficiency of 34% was obtained.

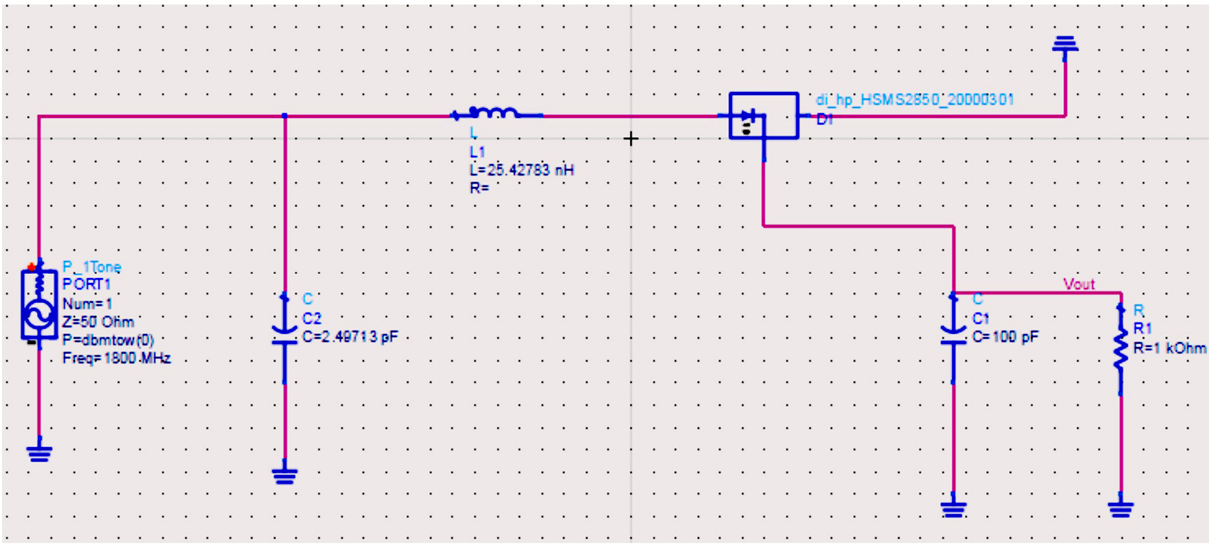

Figure 13. Circuit rectenna in ADS for band 1800 MHz.

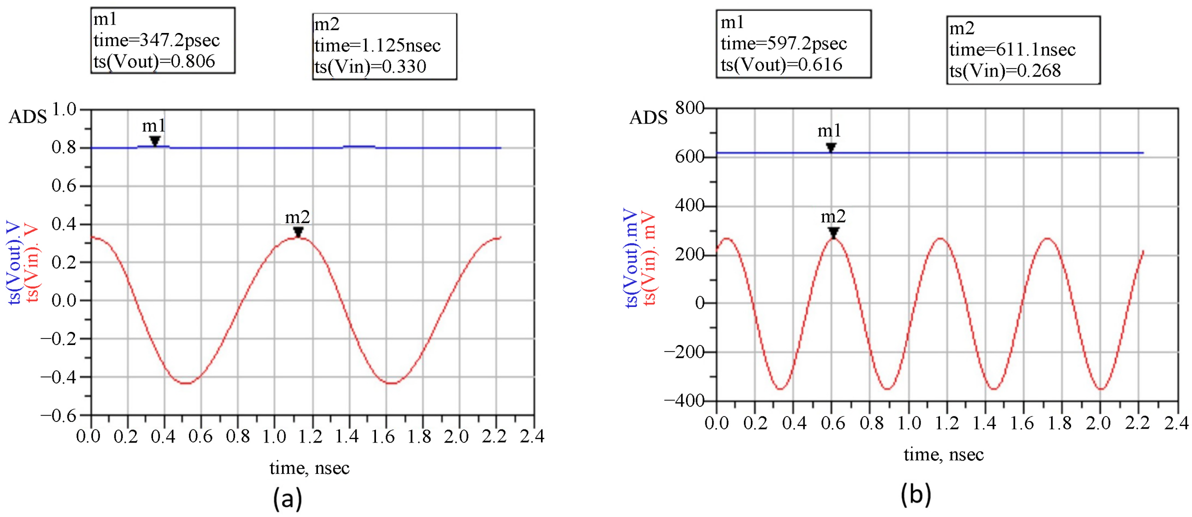

Figure 14. Output voltage of the rectifier 900 MHz (a) and 1800 MHz (b).

In summary, as shown in Table 1, the dipole radiating on frequency 900 has better technical characteristics than that radiating on frequency 1800 MHz. On the other hand, the latter is less bulky and is more suitable for IoT applications.

Table 1. Summary of the results obtained from the 2 dipoles.

	Length of the dipole	Radius of the dipole	Reflexion coefficient S11	Radiation pattern	Total gain	Input voltage of the rectifier	Output voltage of the rectifier
900 MHz	15 cm	0.25 cm	−16.76 dB	Directional in the E-plan	1.72 dB	330 mV	806 mV
1800 MHz	7.5 cm	0.125 cm	−15.70 dB	Directional in the E-plan	1.69 dB	268 mV	616 mV

4. Conclusions

The Rectenna has attracted much attention for recycling the ambient energy emitted by the telecommunication systems. Consequently, the work presented in this paper is part of the development aspect of new Rectennas for the collection of RF energy for a low input power density.

The design and production of the rectennas presented in this paper takes into account constraints such as the limitation of size, low cost, the level of performance for low power levels, and robustness to the impedance of the loads considered.

This work presented the design of an RF energy harvesting system mainly consisting of a rectenna (antenna and rectifier circuit) and a matching circuit. Firstly, two dipole antennas were designed. One operates in the GSM 900 MHz band, the other in the GSM 1800 MHz band. The performance of the proposed antennas is provided by ANSYS HFSS software. In the second step, two rectifier circuits have been proposed for efficient RF-DC conversion. The rectifiers used are Schottky diode based. For maximum power transfer between the antenna and the rectifier circuit, L-type matching circuits have been proposed. The adaptation circuits are obtained by carrying out simulations on the ADS software.

Using a single Schottky diode rectifier, power conversion efficiency is simulated at 64% with 0 dB input power and 806 mV output voltage at 900 MHz bandwidth. For the antenna oscillating on 1800 MHz, the power conversion efficiency is 34%. Both antennas are directional, with directivity gains in excess of 1.6 dB.

Conflicts of Interest

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

References

[1] Okba, A., Charlot, S., Calmon, P., Takacs, A. and Aubert, H. (2016) Multiband Rectenna for Microwave Applications. 2016 *IEEE Wireless Power Transfer Conference* (*WPTC*), Aveiro, 5-6 May 2016, 1-4. https://doi.org/10.1109/wpt.2016.7498799

[2] Alippi, C. and Galperti, C. (2008) An Adaptive System for Optimal Solar Energy Harvesting in Wireless Sensor Network Nodes. *IEEE Transactions on Circuits and Systems I*: *Regular Papers*, **55**, 1742-1750. https://doi.org/10.1109/tcsi.2008.922023

[3] Beeby, S.P., Tudor, M.J. and White, N.M. (2006) Energy Harvesting Vibration Sources for Microsystems Applications. *Measurement Science and Technology*, **17**, R175-R195. https://doi.org/10.1088/0957-0233/17/12/r01

[4] Stark, I. (2006) Invited Talk: Thermal Energy Harvesting with Thermo Life. *International Workshop on Wearable and Implantable Body Sensor Networks* (*BSN*'06), Cambridge, 3-5 April 2006, 19-22. https://doi.org/10.1109/bsn.2006.37

[5] Nechibvute, A., Chawanda, A. and Luhanga, P. (2012) Piezoelectric Energy Harvesting Devices: An Alternative Energy Source for Wireless Sensors. *Smart Materials Research*, **2012**, Article ID: 853481. https://doi.org/10.1155/2012/853481

[6] Agrawal, S., Gupta, R.D., Parihar, M.S. and Kondekar, P.N. (2017) A Wideband High Gain Dielectric Resonator Antenna for RF Energy Harvesting Application. *AEU—International Journal of Electronics and Communications*, **78**, 24-31. https://doi.org/10.1016/j.aeue.2017.05.018

[7] Assogba, O., Mbodji, A.K., Bréard, A., Diallo, A.K. and Duroc, Y. (2022) Tri-Band Rectenna Dedicated to UHF RFID, GSM-1800 and UMTS-2100 Frequency Bands. *Sensors*, **22**, Article 3565. https://doi.org/10.3390/s22093565

[8] Assogba, O., Karim Mbodji, A., Diagne, S. and Karim Diallo, A. (2021) Design of a Rectenna in 2.45 GHz Band Frequency for Energy Harvesting. *Energy and Power Engineering*, **13**, 333-342. https://doi.org/10.4236/epe.2021.139023

[9] Assogba, O., Mbodji, A.K. and Karim Diallo, A. (2020) Efficiency in RF Energy Harvesting Systems: A Comprehensive Review. 2020 *IEEE International Conf on Natural and Engineering Sciences for Sahel's Sustainable Development—Impact of Big Data Application on Society and Environment* (*IBASE-BF*), Ouagadougou, 4-6 February 2020, 1-10. https://doi.org/10.1109/ibase-bf48578.2020.9069597

[10] Assogba, O., Mbodji, A.K., Karim Diallo, A. and Diagne, S. (2020) A Novel Compact Multiband Antenna on Fractal Geometry for Ambient RF Energy Harvesting in the LTE/GSM, UMTS and WIFI Bands. 2020 *IEEE International Conf on Natural and Engineering Sciences for Sahel's Sustainable Development—Impact of Big Data Application on Society and Environment* (*IBASE-BF*), Ouagadougou, 4-6 February 2020, 1-6. https://doi.org/10.1109/ibase-bf48578.2020.9069591

[11] Divakaran, S.K., Krishna, D.D. and Nasimuddin, (2018) RF Energy Harvesting Systems: An Overview and Design Issues. *International Journal of RF and Microwave Computer-Aided Engineering*, **29**, e21633. https://doi.org/10.1002/mmce.21633

[12] Singh, N., Kanaujia, B.K., Beg, M.T., Mainuddin,, Kumar, S., Choi, H.C., *et al.* (2019) Low Profile Multiband Rectenna for Efficient Energy Harvesting at Microwave Frequencies. *International Journal of Electronics*, **106**, 2057-2071. https://doi.org/10.1080/00207217.2019.1636302

[13] Luo, Y., Pu, L., Wang, G. and Zhao, Y. (2019) RF Energy Harvesting Wireless Communications: RF Environment, Device Hardware and Practical Issues. *Sensors*, **19**, Article 3010. https://doi.org/10.3390/s19133010

[14] Shi, Y., Jing, J., Fan, Y., Yang, L., Li, Y. and Wang, M. (2018) A Novel Compact Broadband Rectenna for Ambient RF Energy Harvesting. *AEU—International Journal of Electronics and Communications*, **95**, 264-270. https://doi.org/10.1016/j.aeue.2018.08.035

[15] Harsha Vardhan, B.S., Prasad, R.J.C. and Natarajamani, S. (2019) Design of Rectifier at ISM Band for RF Energy Harvesting of Low Powers. *International Conference on Communication and Signal Processing*, Chennai, 4-6 April 2019, 282-285. https://doi.org/10.1109/ICCSP.2019.8697979

[16] Sun, H. and Geyi, W. (2017) A New Rectenna Using Beamwidth-Enhanced Antenna Array for RF Power Harvesting Applications. *IEEE Antennas and Wireless Propagation Letters*, **16**, 1451-1454. https://doi.org/10.1109/lawp.2016.2642124

[17] Lu, P., Yang, X., Li, J. and Wang, B. (2016) Polarization Reconfigurable Broadband Rectenna with Tunable Matching Network for Microwave Power Transmission. *IEEE Transactions on Antennas and Propagation*, **64**, 1136-1141. https://doi.org/10.1109/tap.2016.2518198