Design of a Rectenna for Energy Harvesting on Wi-Fi at 2.45 GHz

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***Abstract*—This research presents the design of a rectenna to harvest electromagnetic energy from Wi-Fi at 2.45 GHz. Tuning techniques were applied on the dimensions of the elements of the rectenna in order to improve its performance. The antenna and the low pass filter were characterized according to their dimensions. Tuning the antenna, S_{11} magnitude was improved from -9.98 dB on the calculated antenna to -24.12 dB, and the gain was increased in 1 dB. Using the tuned low pass filter, the matching impedance was enhanced with an SWR equal to 1.126. For the rectifier, a single diode and a voltage doubler were evaluated, obtaining a maximum RF to DC conversion efficiency of 31.93% and 45.66% respectively at 20 dBm. The minimum input voltage of the DC-DC boost converter limits the maximum distance between the rectenna and the RF source, to 42 cm for the single diode and to 80 cm for the voltage doubler. It was concluded that the rectenna with doubler configuration offers better output response than the single diode rectifier. The tuning techniques on the design space were effective to enhance the performance of the elements of the rectenna.**

***Index Terms*—Rectennas, Energy Harvesting, Wi-Fi.**

I. Introduction

In recent decades, the use of wireless transmission on communication systems has increased [1]. These systems are distributed on the electromagnetic spectrum according to their technical characteristics and applications, radiating waves around a coverage area [2]. Nowadays, Wi-Fi and mobile telephone applications are the most used wireless services, which are accessible anytime and from almost anywhere [3], so people are in constant interaction with them, even if these are not in use. Therefore, there is an electromagnetic energy that could be recycled through a rectenna or rectifying antenna.

A rectenna is a device that receives electromagnetic waves on frequencies typically higher that 850 MHz, converting them to electrical energy. Thus, this device harvest environmental wireless energy [4]–[6]. The harvested energy can be used to recharge batteries or to feed low power gadgets, e.g. wireless sensors, robots, watches, among others [7]–[10].

The main advantage of rectennas is being sustainable devices because they are able to efficiently harvest energy under appropriate conditions [5]. Additionally, these do not need replacement and the lifetime of the fed gadgets is larger than when conventional sources are utilized.

Nevertheless, the design of rectennas is a complex process. As these devices work on high frequency, their circuit efficiency decreases due to spontaneous resonance and parasitic effects caused by their small sizes, close to the wavelength [6], [11], [12]. To mitigate these effects it is necessary to characterize the behavior of each of its elements and their response as function of their parameters.

The objective of this research is to design a rectenna to harvest electromagnetic energy from Wi-Fi at 2.45 GHz. The rectenna is designed using conventional structures of its elements, and a tuning technique over the variables of its different elements is applied to improve its performance.

This design characterizes the effects of varying the dimensions of the rectenna's elements on its main variables in order to implement an improved tuning process. Furthermore, the designed rectenna is compared with precedent designs with conventional structure [13], [14].

II. Design of the rectenna

The different elements of the designed rectenna are shown in Fig. 1. The antenna is used to receive electromagnetic energy. The low pass filter (LPF) eliminates the harmonics generated by the rectifier and improves the matching impedance with the antenna. The rectifier converts received electromagnetic energy into electrical energy [15]. Also, a DC-DC boost converter is included to increase the voltage level to a functional value for electronic devices.

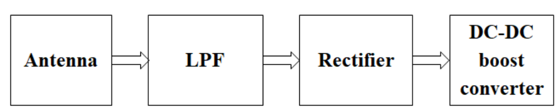

Fig. 1. Block diagram of the designed rectenna.

The rectenna was designed on FR-4 substrate, which has a dielectric constant of ϵ_r=4.4, a dielectric loss tangent (it indicates the lossiness of the medium) $\tan\delta$=0.02 and a thickness equal to 1.6 mm. The dimensions for each component after the tuning process are rounded using a resolution of 1 mm. For the simulation of the antenna and LPF, the software

CST Microwave Studio was employed [16], while the rectifier circuits were simulated with a SPICE software.

A. Design of the Antenna

A printed rectangular microstrip antenna was designed for a frequency of 2.45 GHz. The antenna width (W) and length (L) were calculated with basis on Section 14.2 of [17], and the feeding microstrip width (W_f) and length (L_f) were calculated with basis on Section 11.2 of [18]. These dimensions are shown in Fig. 2 and their values are in Table I. The feeding method is chosen because it eases the control of the matching impedance [19].

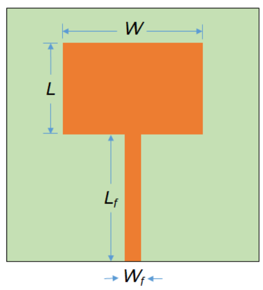

Fig. 2. Dimensions of the antenna.

The calculated antenna was simulated, obtaining the parameters shown in Table I (first column), where S_{11} magnitude, standing wave ratio (SWR), impedance and gain at ϕ=0° were determined at 2.45 GHz. The S_{11} magnitude is -9.98 dB at 2.45 GHz. The bandwidth, where the S_{11} magnitude is less than -10 dB, is 64 MHz. The resonant frequency (f_r), which presents the lowest S_{11} magnitude, is 2.486 GHz.

Therefore, it is necessary to tune the antenna in order to improve its performance for the reception of electromagnetic waves at the design frequency, it is essential to adjust the resonant frequency to 2.45 GHz and to increase the gain. In this work, the design consists in two steps: 1) the design space exploration: characterization of the antenna variables in terms of the design parameters, and 2) the tuning: progressive selection of parameters. The design parameters are the dimensions L, W, L_f and W_f of the antenna and the characteristics are the resonant frequency and the gain.

TABLE I
RESULTS FOR THE ANTENNA.

Parameter	***Calculated Antenna***	***Tuned Antenna***
L (mm)	28.8	28.0
W (mm)	37.3	53.0
L_f (mm)	28.6	30.0
W_f (mm)	3.0	4.0
S_{11} (dB)	-9.98	-24.12
SWR	2.035	1.133
Z (Ω)	102.160-j0.121	50.853-j6.072
G (dBi)	2.38	3.38

Design space exploration: For the characterization, the values of L, W, L_f and W_f were varied with a step of 0.5 mm, 5 mm, 2.5 mm and 0.5 mm, respectively. Each dimension was varied one at the time, while the rest of them remained at their calculated value. The steps of L, W and L_f were obtained after evaluating values that generated a fluctuation higher than 0.01 GHz on the resonant frequency. For the steps of W_f the variations were close to the value calculated for a characteristic impedance equal to 50 Ω [20].

The results of the resonant frequency characterization are shown in Fig. 3. It is noted that when L increases, the resonant frequency decreases in approximately 0.025 GHz for each step. This behavior is similar to the increase of W and L_f, which reduces 0.02 GHz approximately for each step that it is raised. However, when W_f increases, the resonant frequency increases as well, almost 0.001 GHz for each step.

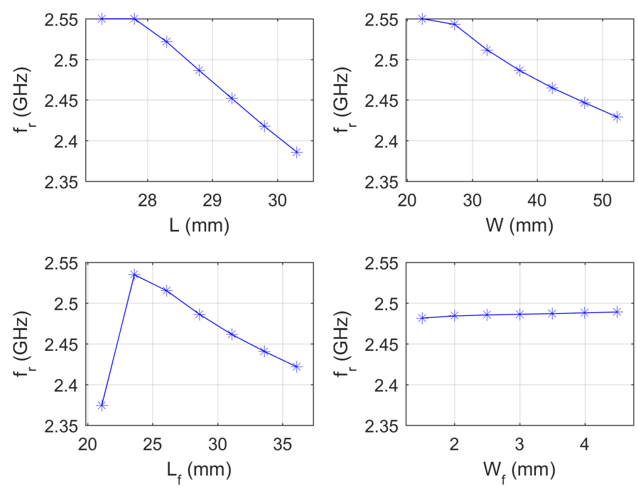

Fig. 3. Characterization of the resonant frequency.

Simulation shows that the gain of the antenna is mostly determined by L and W. The gain increases with W and its maximum value was obtained for L close to 28 mm. These behaviors are shown in Fig. 4 for a frequency of 2.45 GHz.

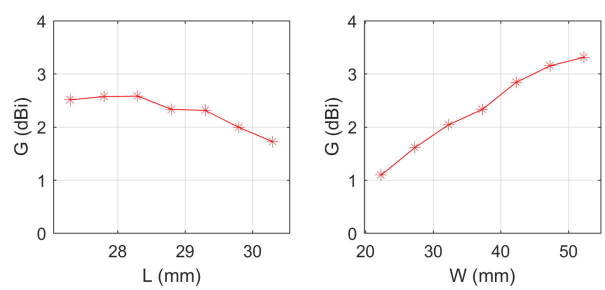

Fig. 4. Characterization of gain.

Tuning: The tuning process consists on a progressive adjustment of the dimensions according to the effect on the resonant frequency and the gain. For that, the dimension W was increased on 15.7 mm, L_f on 1.4 mm and W_f on 1.0 mm, and L was decreased on 0.8 mm, leading to obtain the dimensions shown in Table I (second column).

The antenna with the tuned dimensions was simulated and results are shown in Table I. The frequency with the lowest

S_{11} magnitude was improved to 2.453 GHz and the gain was increased in 1 dB, as shown in Fig. 5 and Fig. 6 respectively. Furthermore, the impedance of the antenna was improved to a value close to 50 Ω, the SWR to 1.133 and the bandwidth to 68 MHz.

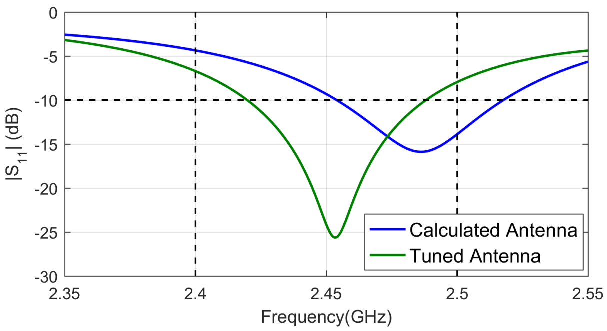

Fig. 5. Simulated S_{11} magnitude of calculated and tuned antenna.

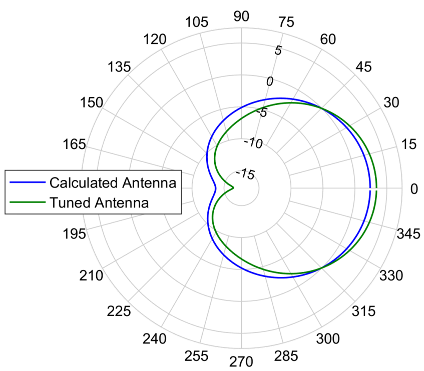

Fig. 6. Simulated gain in H plane of calculated and tuned antenna.

B. Design of the low pass filter

A stepped impedance LPF is designed to eliminate the harmonics generated by the rectifier and to improve the matching impedance. A cutoff frequency of 2.5 GHz and an insertion loss of 20 dB at 4 GHz are considered. The dimensions are calculated with basis on Section 8.6 of [21], where the highest and lowest characteristic impedance were 120 Ω and 20 Ω respectively. It was obtained a five elements filter with three capacitive elements (1, 3 and 5) and two inductive elements (2 and 4). The length of the elements (L_i) are 2.44, 7.50, 7.91, 7.50 and 2.44 mm; with widths (W_i) of 11.11, 0.41, 11.11, 0.41 and 11.11 mm (Fig. 7).

The calculated LPF was simulated, obtaining a cutoff frequency of 2.172 GHz at -3 dB and insertion frequency of 4.056 GHz at -20 dB (Fig. 8). This filter was simulated in combination with the tuned antenna, obtaining the performance shown in Fig. 9, where a high decoupling impedance is detected. Therefore, it was necessary to tune the filter, adjusting the dimensions of its elements.

In this work, the performance of the LPF is characterized according to the size of its capacitive elements while the

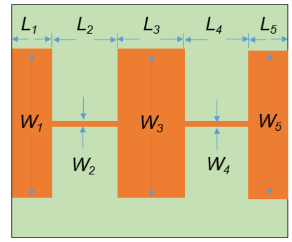

Fig. 7. Dimensions of the LPF.

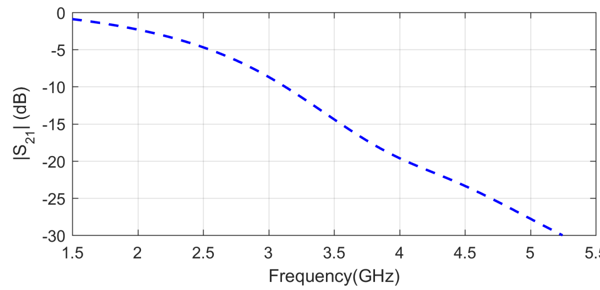

Fig. 8. Simulated S_{21} magnitude of calculated LPF.

dimensions of the inductive elements remained fixed to the calculated values. The simulation results are shown in Fig. 10, where the dimensions of each element, L and W, are shown in rows (1, 3, and 5 respectively). The left axis in blue correspond to the resonant frequency, while the right axis, in red, corresponds to the S_{11} magnitude.

It can be observed that the resonant frequency decreases when dimensions of the elements are increased, except with the length of the 5^{th} element. The S_{11} magnitude increased with the increment of the 3^{rd} element dimensions and decreased with the augment of the 1^{st} and 5^{th} element dimensions in their correspondent ranges (Fig. 10).

In order to improve the matching impedance between the antenna and the filter a tuning process was applied considering the previous characterization. The dimensions of the inductive elements were rounded with the indicated resolution. The length of the tuned elements are 3, 8, 5, 8 and 5 mm; with tuned widths of 10, 1, 12, 1 and 12 mm respectively.

The tuned LPF is simulated, obtaining a cutoff frequency of 2.720 GHz at -3 dB and insertion frequency of 3.792 GHz

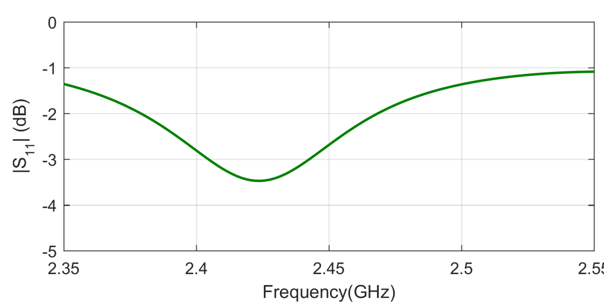

Fig. 9. Simulated S_{11} magnitude of tuned antenna with calculated filter.

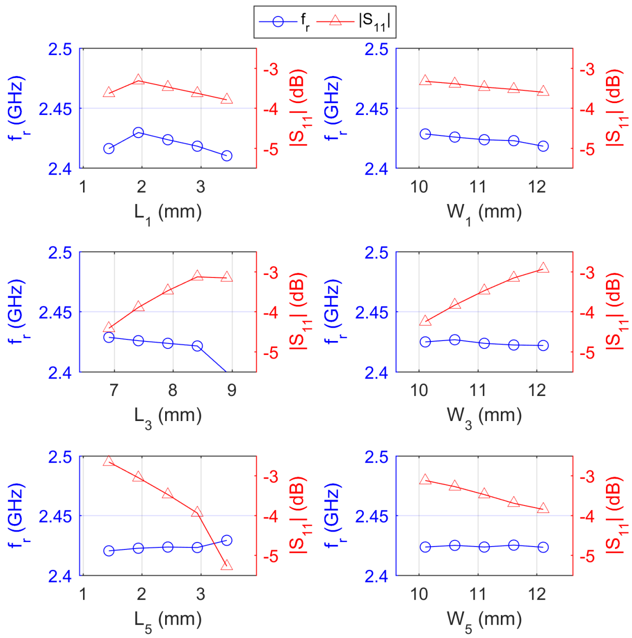

Fig. 10. Characterization of resonant frequency (left axis) and S_{11} magnitude (right axis) of the filter with antenna.

at -20 dB (Fig. 11). With this performance, the LPF has an increment of the attenuation at the insertion frequency and a reduction of the attenuation at the cutoff frequency equal to 3.2 dB. Thus, the high decoupling impedance was eliminated.

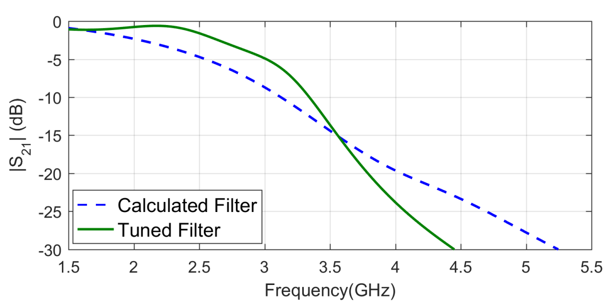

Fig. 11. Simulated S_{21} magnitude of calculated and tuned LPF.

The tuned filter was simulated in combination with the tuned antenna, obtaining the performance shown in Fig. 12. It is observed that the value of S_{11} magnitude at 2.45 GHz improves from -24.12 dB to -24.56 dB, because a better matching impedance was obtained with a SWR value of 1.126 at the design frequency, which represents an improvement from the previous value of 1.133 for the tuned antenna.

C. Design of the rectifier

Two options were evaluated for the rectifier: a single diode and a voltage doubler. The first one has a basic structure of a series mounted diode and the second one has a configuration of a single stage, as shown in Fig. 13. Both rectifiers use the Schottky diode HSMS-2820. Additionally, the length of the transmission line is equal to a quarter of the wavelength [6].

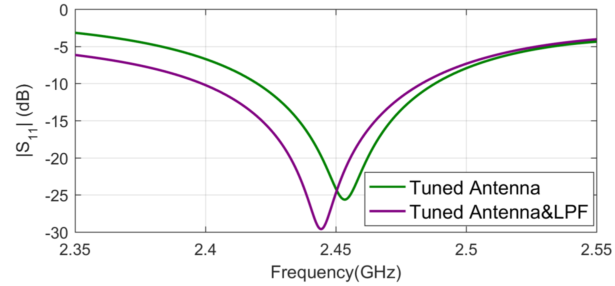

Fig. 12. Simulated S_{11} magnitude of the tuned antenna and the combination of the tuned antenna and filter.

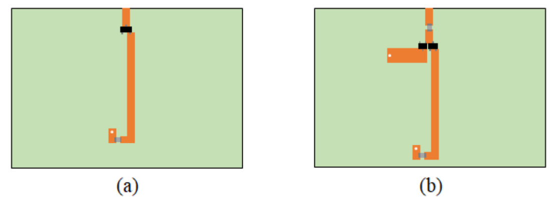

Fig. 13. Rectifier circuit with single diode (a) and voltage doubler (b).

The RF to DC conversion efficiency of the rectifier was calculated with (1), where P_{DC} is the power on the load, V_{rect} is the output voltage on the load, R_{load} is the load resistance and P_{RF} is the input power of rectifying circuit. Both rectifier circuits were simulated to determine the optimal load resistance adjusting R_{load} in steps of 100 Ω from 100 Ω to 1000 Ω.

$$\eta_{RF-DC} = \frac{P_{DC}}{P_{RF}}100\% = \frac{V_{rect}^2}{R_{load}P_{RF}}100\% \tag{1}$$

The rectifier circuits were simulated to obtain the RF to DC conversion efficiency as a function of the load impedance. Fig. 14 shows that the optimal load impedance that maximizes the efficiency is 100 Ω and 300 Ω approximately for rectifier of single diode and voltage doubler respectively. It is observed that for this range of resistance the RF to DC conversion efficiency is higher for the voltage doubler than for the single diode.

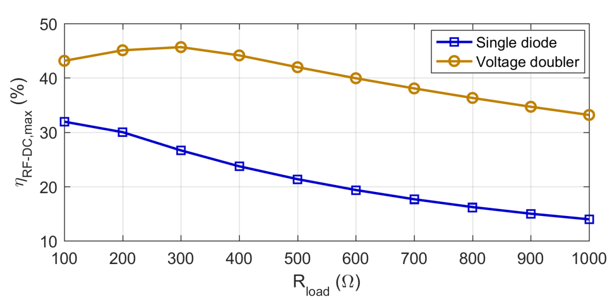

Fig. 14. Simulated conversion efficiency of the rectifiers as function of the load impedance.

The rectifiers with their optimal load resistance were simulated, varying the input power. Fig. 15 shows the conversion efficiency for each rectifier according to the input power. For low power levels, the rectifier with single diode had the best performance. However, the rectifier with voltage doubler was better for values higher than 8 dBm. The obtained maximum efficiency was 31.93% and 45.66% for rectifier with single diode and voltage doubler respectively at 20 dBm.

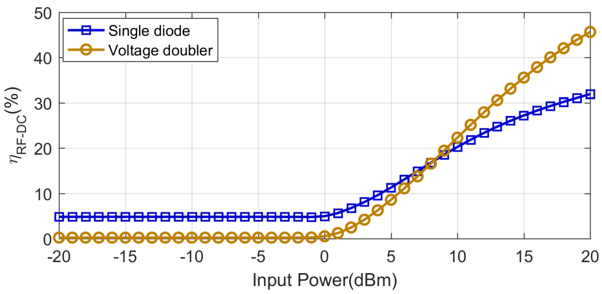

Fig. 15. Simulated conversion efficiency of the single diode rectifier and the voltage doubler.

D. Design of the DC-DC boost converter

The DC-DC boost converter was included, as shown in Fig. 16, this configuration helps to maintain the voltage across the load [22]. The supercapacitor (SC) is connected to the input of the step-up converter to store the harvested energy. The capacitance of the SC was 2.5 F. The selected step-up converter was a MAX1675, which is set up for an output voltage of 3.3 V, has a typical efficiency of 90% and its minimal input voltage is 0.9 V.

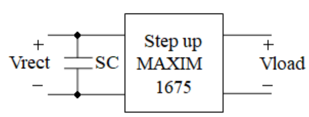

Fig. 16. Scheme of DC-DC boost converter.

III. Performance of the Designed Rectenna

For the evaluation of the designed rectenna, the antenna and LPF with the different rectifiers were simulated. The rectification voltage and the conversion efficiency of the rectenna are determined as functions of the input power and the results are compared with other works. The obtained rectification voltages as a function of the input power of receiving antenna P_{Rx} are shown in Fig. 17. The input power is determined using Friis transmission (2), where λ is the wavelength of operating frequency, G_{Tx} and G_{Rx} are the gain of the transmitting antenna and receiving antenna respectively, P_{Tx} is the transmitting power and r is the distance between the transmitting antenna and the rectenna [17].

$$P_{Rx} = \left(\frac{\lambda}{4\pi r}\right)^2 G_{Tx} G_{Rx} P_{Tx} \tag{2}$$

A scenario with an outdoor Wi-Fi transmission system was considered, where P_{Tx} = 30 dBm [23] and G_{Tx} = 15 dBi [24]. For the reception, the gain of the designed rectenna was used, G_{Rx} = 3.38 dBi with a range of input power between -20 dBm and 20 dBm [25], [26]. The minimum input voltage of the DC-DC boost converter, which is 0.9 V to keep the load voltage on 3.3 V, determines the minimum input power at the antenna to supply power to the load 15.6 dBm for the single diode rectifier and 10.0 dBm for the voltage doubler. Finally, using the Friis equation, the maximum distances between the transmission source and the rectenna are calculated, approximately 42 cm and 80 cm for the rectifier of single diode and voltage doubler, respectively.

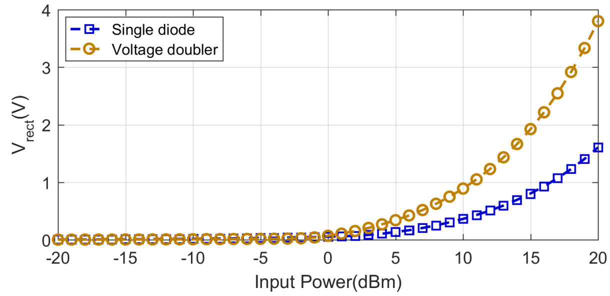

Fig. 17. Simulated rectification voltage of the rectenna with a rectifier of single diode and voltage doubler.

The conversion efficiency of the rectenna was determined with (3), and it is shown in Fig. 18. The rectenna with the single diode rectifier had a maximum conversion efficiency equal to 23.21%, while for the rectenna with voltage doubler it was 43.35%. Both values were obtained with an input power of the receiving antenna equal to 20 dBm.

$$\eta_{end-to-end} = \eta_{DC-DC} \frac{V_{rect}^2}{R_{load} P_{rx}} 100\% \tag{3}$$

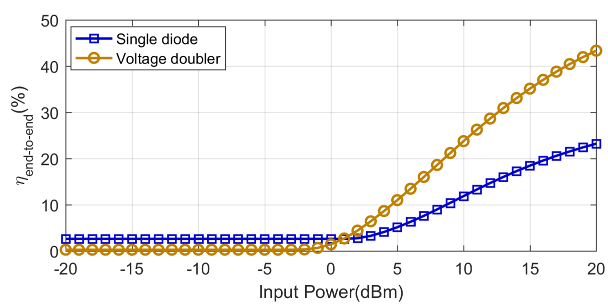

Fig. 18. Simulated conversion efficiency of the rectenna with a rectifier of single diode and voltage doubler.

This rectenna was compared with previous works where a printed rectangular microstrip antenna, an LPF and a rectifier with a single series diode or a voltage doubler with conventional structure were employed, i.e. with no modifications in the layout of the elements. The comparison was made in function of the simulated S_{11} magnitude of the antenna and the simulated efficiency of the rectenna for each type of rectifier, whose values are shown in Table II.

The designed rectenna with a single series diode has performance values lower than [13], but in that research optimization techniques were employed for the design through a simulator with SPICE software. In the rectenna with the voltage doubler, the performance was significantly better than the work of [14], because for the antenna all the design variables were tuned here but in the mentioned research only the length L was tuned.

In this sense, the rectenna with the voltage doubler rectifier had the best conversion efficiency among the designed and compared rectennas, although optimization techniques were not applied for the design. This allows to harvest electromagnetic energy at 2.45 GHz to energize low consumption devices.

TABLE II
COMPARISON WITH OTHER DESIGNS.

Rectenna	$\|S_{11}\|$ ***(dB)***	**Rectifier**	$\eta_{end-to-end}$ **(%)**
This work	-24.120	Single diode	23.21
[13]	-26.915	Single diode	36.92
This work	-24.120	Voltage doubler	43.35
[14]	-12.473	Voltage doubler	7.15

IV. CONCLUSIONS

In this work, a rectenna for energy harvesting on Wi-Fi was designed applying tuning techniques in order to improve the performance of its elements with conventional structures. The effectiveness of these techniques was corroborated obtaining a better S_{11} magnitude and gain for the antenna, matching impedance for the LPF and maximum RF to DC conversion efficiency for both rectifiers.

Considering the simulation results for the designed rectenna, it is concluded that the rectenna with voltage doubler configuration offers a better output response than the single diode rectifier. It permits to utilize the rectenna for a longer distance range with a higher conversion efficiency.

The designed rectenna is suitable as candidate for energy harvesting on Wi-Fi at 2.45 GHz, compared with other rectennas that employ similar structures on their elements. This rectenna can be applied to feed devices with an input voltage of 3.3 V, such as watches, wireless sensor nodes and actuators. Future work will be oriented to the modification of the conventional structure to obtain a better performance of each element and of the whole the rectenna.

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