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# Design of a 5 GHz Circular Rectenna for Efficient RF Energy Harvesting in IoT Applications

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## ABSTRACT

The growing dependence on wireless technologies in urban areas highlights an important challenge concerning how to ensure reliable and sustainable power for sensor devices. Traditional power solutions, such as batteries or wired connections have many limitations such as the finite lifespan of batteries and the requirement of regular maintenance. An effective alternative for regular power sources is radio frequency (RF) energy harvesting, which improves service efficiency as it extends the lifetime of sensor nodes integrated into urban areas. Electromagnetic energy can be captured and transformed into effective direct current (DC) voltage using a radio frequency (RF) energy harvesting device. This paper presents a compact rectenna for RF energy harvesting at the Wi-Fi 5 GHz band, which covers the IEEE 802.11j band. Firstly, a circular antenna surrounded by a circular patch with a whole ground plane is proposed, followed by a transmission line impedance matching for the rectenna design. Additionally, a high-efficiency rectifier is designed using Rogers4003C substrate with a thickness of 1.524 mm, connected to the antenna to create a small rectenna. Simulation results show that an output DC voltage of 1.12 V is achieved at a 3 kΩ resistor for 0 dBm input power at 5 GHz. The experimental results showed a slight difference, with a 0.9 V DC output voltage at 0 dBm input power. The rectenna was able to reach a maximum efficiency of 30.5% at an input power of 5 dBm. The proposed rectenna is viable for several energy-harvesting applications, compact, and easy to build.

**Keywords**: Energy Harvesting, IoT, Microstrip Patch Antenna, Rectenna, Matching Network, Rogers 4003C

## 1 INTRODUCTION

RF energy harvesting is a technology used to collect or harvest small amounts of energy from radio frequencies that exist in the device's nearby environment. Energy harvesters gather small quantities of energy from their local surroundings, as opposed to large-scale solar and wind installations that produce massive amounts of energy [1]. Various radio wave frequencies are used in military communications, mobile phones, FM and AM radio broadcasts, television, and other communications applications. These RF waves are accessible in rural and urban environments, both indoors and outdoors [2]. These waves can be captured and converted into electricity. Recently, there has also been a focus on large-scale energy generation and transmission systems that convert microwaves into direct electrical current using rectifying antennas, commonly referred to as rectennas [3]. The Internet of Things (IoT) market is expected to grow significantly, as the number of IoT sensors might reach billions of devices in years. If these sensors and edge devices are powered by batteries, this would lead to several issues. These sensors may be installed in difficult-to-reach locations, changing the batteries could be challenging [4]. In addition, adopters will see battery replacement as a major drawback and a costly long-term limitation [5]. This bottleneck can be resolved by RF energy harvesting, particularly in locations that lack proximity to a power supply and are extremely isolated. It also negates the necessity of management based on manpower. Additionally, it claims to lower carbon emissions and be more environmentally sustainable [6].

Applying energy harvesting correctly will eliminate the need for power cables, battery changes, charging, fuel tank filling, and other similar tasks [7]. Technology will eventually become completely wireless and unaffected by external influences. This is especially helpful for devices that are placed in hard-to-reach locations. Long-term operation is possible without requiring any maintenance [8]. Furthermore, many IoT and Machine-to-Machine (M2M) devices are currently in use, and this number is expected to grow rapidly in the future. It will become increasingly difficult to periodically replace the batteries or connect each device to a power source [9]. RF energy harvesting can deal with those requirements [10].

Most recent papers focused on the Wi-Fi band, the 5 GHz band is one of two principal frequency bands utilized by current Wi-Fi networks, alongside the 2.4 GHz band. The frequency range that Wi-Fi networks use in the 5 GHz band, particularly for Wi-Fi protocols such as 802.11n, 802.11ac, 802.11ax, and 802.11j, is referred to as the Wi-Fi 5 GHz bandwidth. The IEEE 802.11j standard is a member of the IEEE 802.11 family and was created specifically to handle Wi-Fi communication in Japan, especially in the 4.9 GHz to 5.0 GHz band [11].

IEEE 802.11j supports wireless local area network (WLAN) compliant communications for mobile, indoor, and outdoor applications. The introduction of IEEE 802.11j has been a major factor in supporting the integration of cutting-edge wireless technologies and increasing worldwide interoperability. The IEEE 802.11j standard includes features like Dynamic Frequency Selection (DFS) and Transmit Power Control (TPC) to accomplish this harmonization and enable effective wireless communication. When radar systems are close in range, DFS automatically detects their presence and switches to an available frequency to prevent interference with radar systems that share the same frequency bands. TPC makes it possible to control the transmit power levels to generally enhance wireless network performance and reduce the risk of interference with other communication systems [12,13].

This enables enhanced efficiency, wider wireless connectivity, and more effective use of the existing frequency spectrum. As a result of these features, 802.11j is very useful in Japan for applications including healthcare, public safety, broadband wireless access, and the Internet of Things (IoT) [14,15].

## 2 LITERATURE REVIEW

This system's fundamental components include the receiving antenna, impedance matching network, rectifier, and load. A microstrip Wi-Fi antenna design is presented in [16] featuring a broad bandwidth of 600 MHz, dual-band operation at 2.4 GHz and 5 GHz, and maximum gains of 2.303 dBi and 1.918 dBi, respectively. Ref. [17] presents a simulated conventional cavity-backed slot antenna (CBSA) with a peak efficiency of 25%. In separate studies that analyze the overall system as presented in [18], the proposed rectenna comprises a planar polarization reconfigurable broadband monopole antenna integrated with a varactor-tuned rectifying circuit. The antenna is integrated on a partially grounded R04003C substrate, and the measured efficiency of the rectenna ranges from 22.7% to 31.9%. A high-gain antenna is required to maximize the RF ambient energy delivered to the rectifying circuit. A high-gain dual-band rectenna designed to operate in the 3.5GHz and the 5.8GHz frequency bands is proposed in [19]. The findings show a high gain of 10.2 dBi for the first band and 8.92 dBi for the second band. However, at 5.8 GHz, with an output voltage of 656.88 mV and a low input power of 0 dBm, the achieved conversion efficiency is 29%. In [20], the RF energy harvesting overall system is fabricated on the same substrate, which led to a low power density condition of 0.016 $W/m^2$, resulting in the documented conversion efficiencies of 36.4% and 6.2% at 2.48 and 5.96 GHz, respectively. At 2.48 and 5.96 GHz, significant gains of 12.2 and 13.8 dBi have been attained. In [21], only the fabrication of the rectifier is discussed, with an RF signal source used instead of an antenna to measure output voltage and efficiency. Ref. [22] presents an FR4 substrate with an antenna fabricated on its top layer and a rectifier on its back layer. The efficiency of the rectifier at 5.5 GHz, which only approaches 8% in simulation and roughly 5% in measurement for 0 dBm, highlights a key drawback of using FR4.

The authors in [23] proposed an antenna linked to a dual-band system to harvest radio frequency energy at 2.45 and 5 GHz. The system achieves an efficiency of 12.26% at 0 dBm input power and reaches a maximum of 49.90% at 21.30 dBm input power. At 5 GHz, the achieved output DC voltage is 0.236 V with a 0 dBm input power and a resistor load of 1.1 kΩ. The study in [24] suggests using the slots-loaded ground plane and a dielectric rectangular resonator (DR) in the rectangular dielectric resonator antenna (RDRA). The maximum output voltage offered by the rectenna system is 1.31 V and 1.16 V at 3.5 and 5.8 GHz frequencies, respectively. The measured power conversion efficiencies (PCE) for 0 dBm input power at 3.5 and 5.8 GHz are 47% and 34%, respectively, which falls within the acceptable range for RF energy harvesting in typical ambient conditions. Ref. [25] proposes power conversion using a series diode architecture with an HSMS-2860 Schottky diode. The rectifier under test is fed by the RF signal generator, and the output voltage across the load is measured using a digital meter. The measured PCE at 3.5 GHz and 5.8 GHz, respectively, are 51.8% and 39.73% at 0 dBm input power.

# 3 SYSTEM MODEL

In this work, the design and the fabrication of a proposed microstrip patch rectenna are presented. The resonant frequency of this rectenna is 5 GHz. The proposed antenna is designed to work in conjunction with a rectifying circuit to collect RF energy. This study demonstrates high gain, adequate efficiency, and elevated voltage levels. Additionally, a unique matching network is created to guarantee that the rectifier receives maximum power transfer. Then, the antenna, matching network, and rectifying circuit combination are fabricated. The realized rectifier has the advantages of being small, inexpensive, and offering a greater output voltage. It was designed with low input power situations in mind. The Schottky diode SMS7630-005LF is used in a standard voltage doubler to create the intended rectifier.

The rest of this paper is organized as follows: Section 4 introduces the design process, the antenna's geometric description, the suggested rectifier's topology and design, along with specifics on the impedance matching method and the simulation work. Section 5 presents a detailed explanation of the manufacturing, the parametric analysis measurement of the suggested antenna, and the overall system. In Section 6, the conclusion is drawn, followed by the references.

# 4 DESIGN OF THE PROPOSED RECTENNA

## 4.1 Design of Receiving Antenna

A microstrip circular patch triple-band antenna geometry is designed and simulated using CST Microwave Studio. The substrate is printed with an outer circular patch of radius $R_p$ and centered with an inner circle of radius R, a length of $L_f$ and a width of $W_f$ microstrip line. The microstrip line is fed into the center circle and connected with an SMA connector. A ground plane with the length of $L_g$ and breadth of $W_g$ is positioned on the back side of the substrate material to increase the bandwidth of the impedance.

A design process that results in workable circular microstrip antenna designs is described to create the triple microstrip patch circular-shaped antenna. Using the effective radius F, the circular patch radius R is found as shown in (1) & (2):

$$F = \frac{8.791\text{x}10^9}{f_r\sqrt{\varepsilon_r}} \quad (1)$$

$$R = \frac{F}{\left\{1+\frac{2h}{\pi\varepsilon_r F}\left[\ln\left(\frac{\pi F}{2h}\right)+1.7726\right]\right\}^{1/2}} \quad (2)$$

where $\varepsilon_r$ is the substrate relative permittivity, $h$ is substrate height, and $f_r$ is the resonant frequency.

The fundamental antenna parameters, such as return loss ($S_{11}$), bandwidth, resonant frequency, surface current, and antenna gain are optimized through multi-objective genetic algorithms (GA). The antenna's design achieved three frequencies of resonance: 5 GHz, 7.6 GHz, and 9 GHz. The proposed antenna is primarily based on the circular patch antenna. The substrate layer of the antenna is a Rogers 4003C substrate, with a thickness of 1.524 mm, $\varepsilon_r$ = 3.38, and tan $\delta$= 0.025. The ground and patch layers of the antenna are coated with 0.035 mm thick copper (Cu) material, further supplied via a 50-ohm microstrip feeding line. Figure 1 depicts the proposed antenna's initiator shape and the design specifications. The figure illustrates the antenna's geometrical architecture. The antenna's frontal geometric architecture is depicted in Figure 1(a); and the back view is depicted in (b). The middle circle's radius is denoted by R.

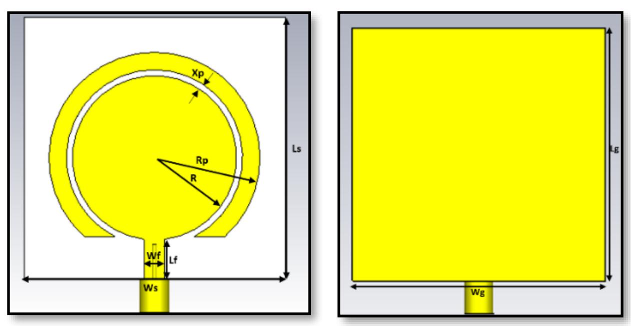



**Figure 1: Proposed dual-band patch antenna; a) front view b) back view**

To get the triple-band response, the parasitic unit with a radius of $R_p$ shown in Fig. 1 (a) is engraved on the patch. Then, multi-objective genetic algorithms (GA) are used to optimize the suggested antenna. GA was created to enhance the parasitic patch, allowing the antenna to operate at 5, 7.6, and 9 GHz while showing the highest achieved gain at triple bands. The optimization process is described in [26,27].

Table 1 provides the antenna's geometric parameters the antenna's dimensions are 60 × 60 × 1.594 $mm^3$ in total.

**Table 1. Antenna's geometric parameters**

| Parameter | Dimension (mm) |
|---|---|
| $L_s$ | 60 |
| $W_s$ | 60 |
| $L_g$ | 60 |
| $W_g$ | 60 |
| $L_f$ | 9.6 |
| $W_f$ | 4.7 |
| R | 18.8 |
| $R_p$ | 24.3 |
| $X_p$ | 1.4 |

Figure 2 demonstrates the simulation results of the proposed antenna's reflection coefficients at different frequency levels. The antenna's return loss is -42.46 dB at 5 GHz, -19.5 dB at 7.6 GHz, and -30.26 dB at 9 GHz.

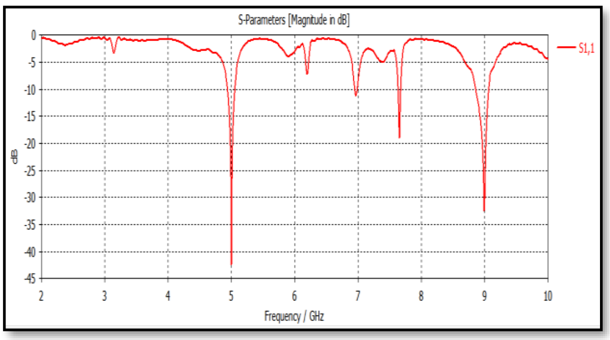



**Figure 2: Simulation results of S-parameter $S_{11}$ for the dual-band antenna**

The simulation results' point required to determine the bandwidth of the three frequency bands are shown in Figure 3. The bandwidth for the 5 GHz frequency is 110.3 MHz, and for the 7.6 GHz frequency is 40 MHz, while for the 9 GHz frequency is approximately 202.2 MHz.

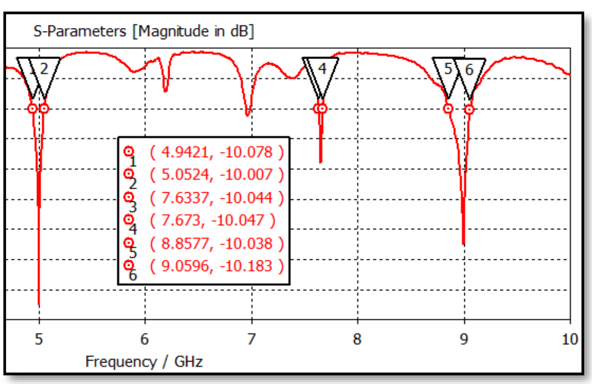



**Figure 3: Bandwidth for the frequencies 5, 7.6 and 9 GHz**

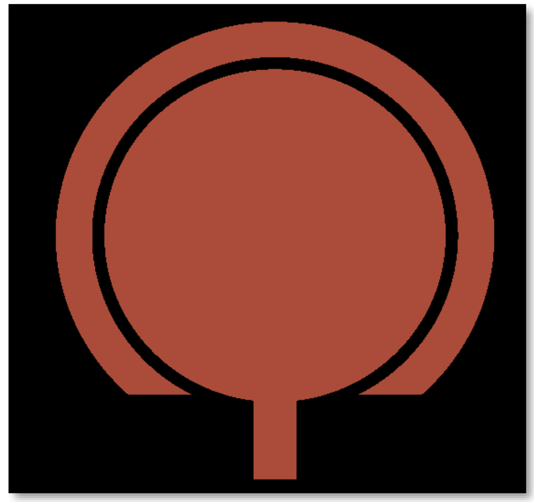


**Figure 4: Proposed dual-band antenna on ADS Layout**

The layout of the intended triple-band antenna is represented in Figure 4 and modeled with ADS Layout. The S-parameter is compared using the antenna's CST model to validate the antenna layout model in the ADS, as shown in Figure 5.

The simulation outcomes of the CST antenna model agree well with the ADS antenna layout model results.

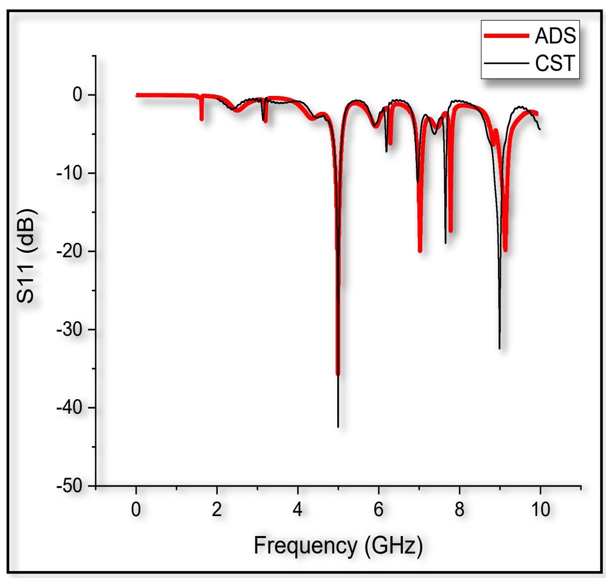



**Figure 5: Comparison of the S11 plots antenna designed on CST and ADS Layout.**

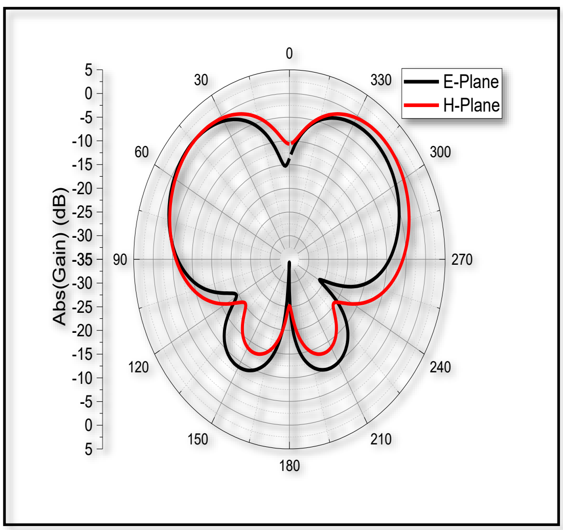
Figure 6 shows the polar far-field radiation pattern at the H-Plane and E-Plane for the antenna tor the triple frequencies 5 GHz, 7.6 GHz, and 9 GHz. Figure 7 displays the surface current distributions of the designed antenna at 5 GHz.

The achieved gains are 4.9 dBi at 5 GHz, 4 dBi at 7.6 GHz, and 8.5 dBi at 9 GHz, as shown in Figure 8. Figure 9 shows the simulated voltage standing wave ratio (VSWR). VSWR values are 1.19 at 5 GHz, 1.25 at 7.6 GHz, and 1.08 at 9 GHz.

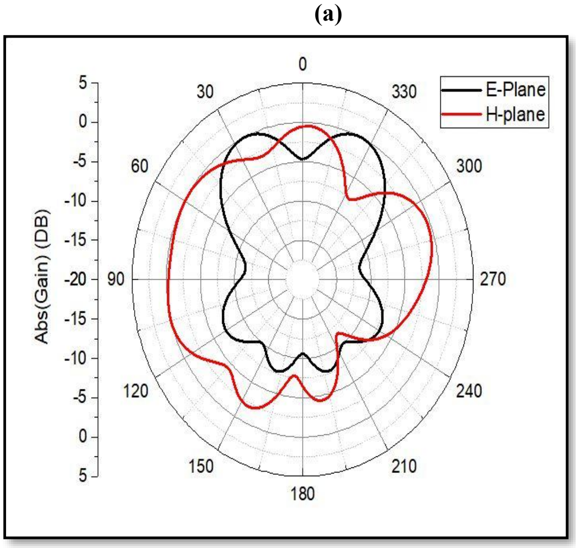
In ref. [11] the simulated antenna gain is 3.31 dBi, with maximum efficiency of 77.12%. This antenna in [13], is designed to function in five frequency bands, at the band from (4.4 -5 GHz) the efficiency will reach 60%, with weak gain of 1.0 dBi.

The authors in [15], fabricated a multiband planar antenna on FR4 substrate for a frequency range from 1.5 GHz to 6 GHz, and achieved an average gain of 2.0 dBi over the entire range.

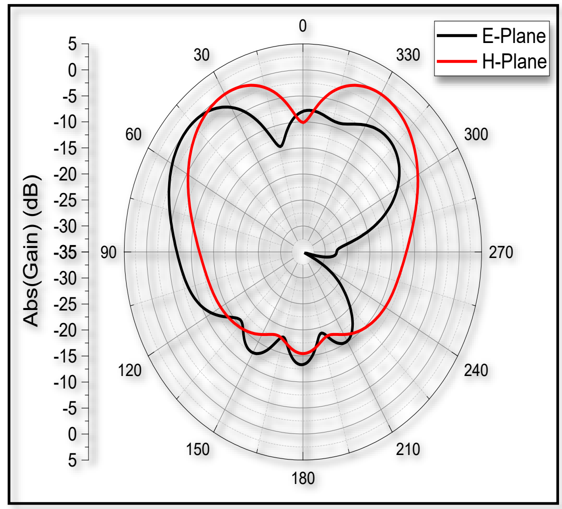
The proposed antenna of this paper has achieved better gain and efficiency.




(a)




(b)




(c)

**Figure 6: Antenna's Polar Far-Field Radiation Pattern; a) H- Plane and E- Plane at 5 GHz, b) H- Plane and E- Plane at 7.6 GHz, c) H- Plane and E- Plane at 9 GHz.**

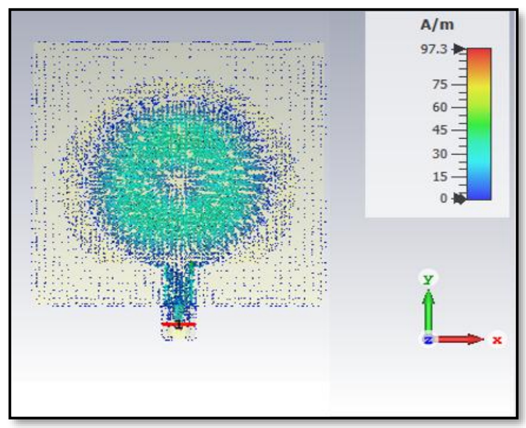



**Figure 7: Surface current distribution diagrams of the designed antenna at 5 GHz.**

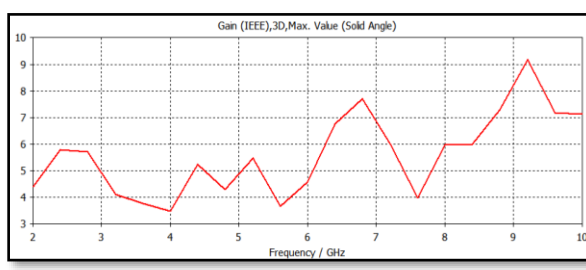



**Figure 8: Frequency versus Gain.**

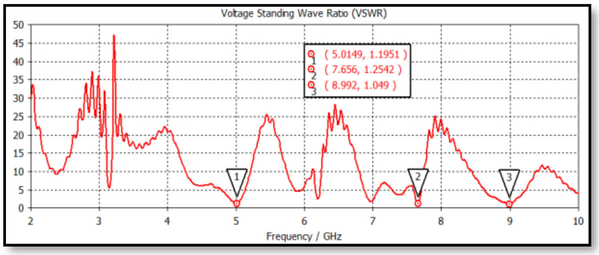



**Figure 9: Simulated VSWR of the two resonance frequencies**

### 4.2 Impedance Matching Circuit Design

The rectifying network is more significant in rectenna design since it determines the efficiency with which RF signals are transformed into DC signals. In the suggested design, the rectifier circuit is a voltage doubler circuit to achieve a good balance between circuit complexity and rectifier efficiency at low input power. Figure 10 shows the proposed rectifier circuit (RC) with an impedance-matching network (IMN). Keysight ADS software is used to simulate the RC with the IMN, and co-simulator harmonic balance is utilized to investigate the RC's properties. The RF source and the rectifier are connected by a straightforward transmission line impedance matching network that operates as a cross-junction integrated into an open-circuited stub (OCS). This improves conversion efficiency by transferring the maximum amount of power from the RF source output to the rectifier input and also by lowering the number of components needed for the circuit, which allows the device to be smaller. In order to match the 1.4-j30.1 rectifier impedance at 5 GHz with the RF source impedance of 50.16 -j 1.64, the IMN is made up of a parallel-series combination of two transmission lines. In the ADS at 5 GHz, the impedance matching network is optimized through the usage of the Smith Chart matching strategy.

### 4.3 Rectifier Design

The primary energy received by the previously constructed triple-band microstrip circular antenna is the radio frequency energy, which must be converted to a DC power supply via a rectifier circuit. [28]. To achieve this, the circuit for a high-efficiency voltage-doubler rectifier is used as shown in Figure 10. The rectifier's design is implemented to attain a balance between the circuit's complexity and the rectifier's low input power performance. A two-branch matching circuit matches the input to the antenna. The rectifier diode's breakdown voltage of 3.8 V and a low forward bias voltage of 180 mV make Schottky barrier diodes SMS7630-005LF suitable for usage. A low-pass filter with a 100-pF capacitor is used to make sure that only the DC current can reach the load. To achieve the highest RF-DC conversion efficiency at a 0 dBm input power level, the circuit parameters are tuned. An Advanced Design System (ADS) is used in the design process. The RF-to-DC-transformation efficiency and the DC voltage at the output are analyzed by changing the input RF power from -30 dBm to 30 dBm. Through a sector branch, the output reduces high-order harmonics to increase the efficiency of rectification. The main purpose of capacitance $C_1$ is to minimize energy loss by preventing the DC component created during the rectification from returning to the circular receiving antenna. Capacitance $C_2$ store the energy in addition to a being a filter capacitor [29].

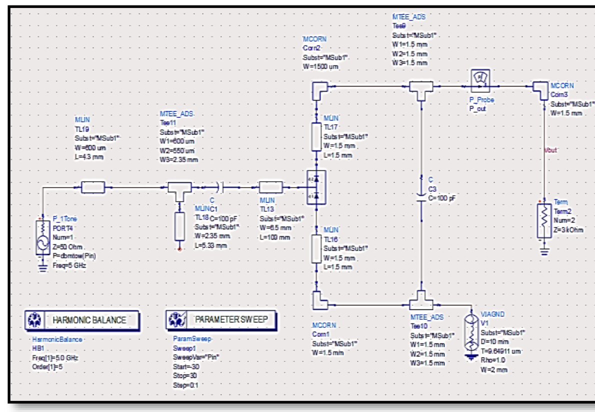



**Figure 10: Schematic of the proposed voltage doubler rectifier circuit and the impedance matching network.**

The RC voltage doubler network is made up of a bypass capacitor ($C_1$ = 100 pF), two rectifying Schottky diodes, a shunt capacitor ($C_2$ = 100 pF), and a suitable load resistance ($R_L$ = 3 kΩ). A tiny built-in voltage diode can provide higher rectifying efficiency. The efficiency of the doubler network is significantly lower when the RC is directly connected to the RF source than when it is connected to the RF source through IMN. This comes from an inefficient transfer of power between the rectifier input and the RF source output. To evaluate its performance, the suggested rectifier is built on a Rogers 4003C substrate with a 1.524 mm thick.

The rectifier's simulated reflection coefficients at a 0 dBm input power level are shown in Figure 11. Certainly, the rectifier functions properly with appropriate impedance matching at a frequency of 5 GHz.

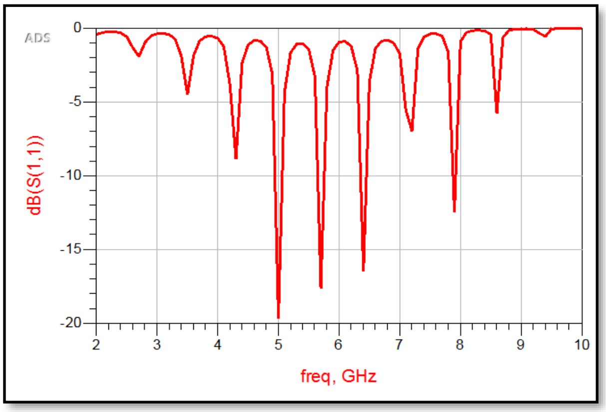



**Figure 11: Simulated rectifier's reflection coefficient at Pin of 0 dBm.**

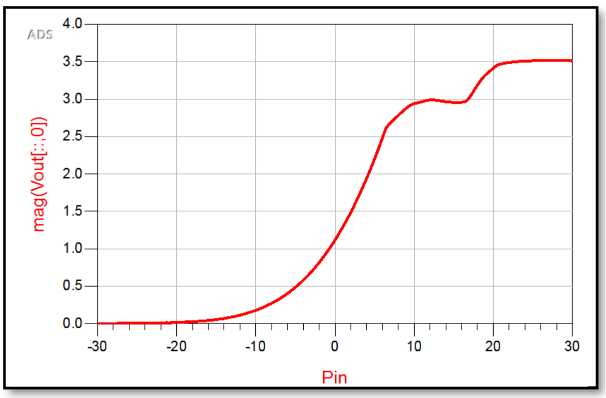



**Figure 12: Simulated results of the rectifier circuit at 5 GHz with 3 kΩ.**

Figure 12 shows the simulated output voltage at 5 GHz with a 3 kΩ resistor; a DC output voltage of 1.12 V is achieved at 0 dBm power input (Pin). The maximum output voltage of 3.5 V is obtained at 27 dBm. Figure 13 shows the rectifier's RF-to-DC conversion efficiency towards frequency at 0 dBm input power. It can be calculated as follows:

$$\eta\,(\%) = \frac{P_{out}}{P_{in}} \times 100 = \frac{V_{DC}^2/R_L}{P_{in}} \times 100 \qquad (3)$$

where $P_{in}$ the RF power at the input of the rectifier, $V_{DC}^2/R_L$ is the DC power delivered to the load, and $R_L$ is the load resistance. The rectifier's efficiency at 0 dBm is 41% at 5 GHz as shown. At 6 dBm and 30 dBm input power, respectively, a peak efficiency of 51.78% and an output DC voltage of 3.52 V are reached. It is possible to reach above 50% efficiency between 4 dBm and 6.6 dBm.

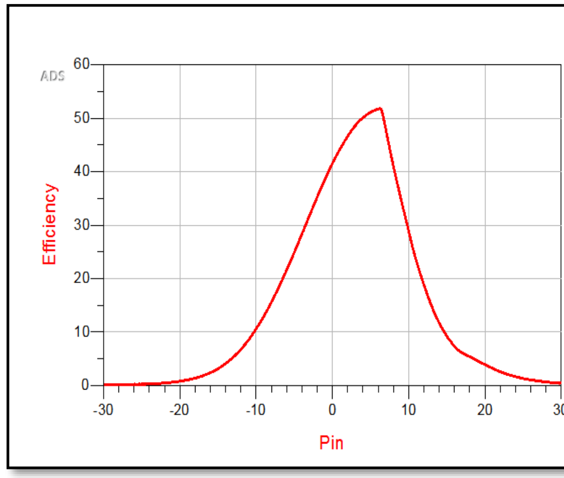



**Figure 13: Input power versus simulated conversion efficiency at 5GHz.**

## 5 FABRICATION

### 5.1 Receiving Antenna Design

The fabricated microstrip patch antenna is shown in Figure 14. The geometrical dimensions are provided in Table 1. Figure 14 depicts the image of the manufactured antenna, where (a) is the top view and (b) is the bottom view with full ground.

**(a)** **(b)**

**Figure 14: The fabricated triple-band microstrip patch antenna: (a)top view (b)back view**

The manufactured prototype design's reflection coefficient performance is evaluated experimentally using a vector network analyzer (VNA). Figure 15 shows the fabricated antenna planes' measured reflection of the coefficient.

The predicted and measured reflection coefficient results of the suggested antenna are compared in Figure 16. It is noticeable that there is good agreement between the measurement and simulation results. Both performances reach a respectable consensus. Consequently, the suggested antenna performs well in all bands when operating at the frequencies of 5, 7.6, and 9 GHz.

**Figure 15: Analyzer connected with the prototype dual-band antenna**

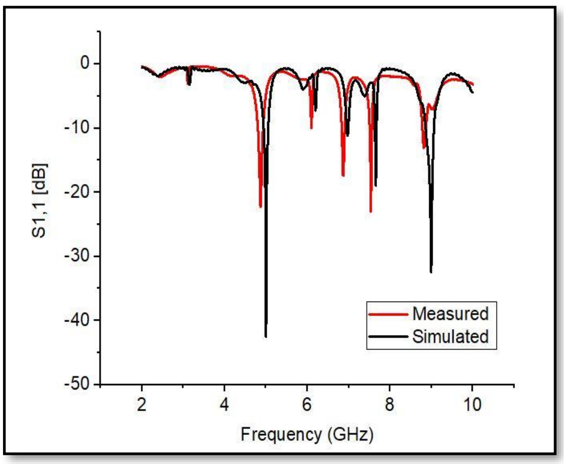



**Figure 16: Comparison between simulated and measured reflection coefficient vs frequency.**

### 5.2 Rectenna Design

For better results in voltage and efficiency, the antenna, impedance matching network, and voltage doubler rectifier are designed as one part on the same circuit to reduce losses. The overall radio frequency energy harvesting system is illustrated in Figure 17, where the power source generator is connected to the horn antenna as a transmitter, the proposed antenna, matching network, and the rectifying part's circuit are also shown. The rectenna is designed with the fewest possible components, minimizing each component's associated losses.

It is expected to place the rectenna in a rich scattering indoor environment.

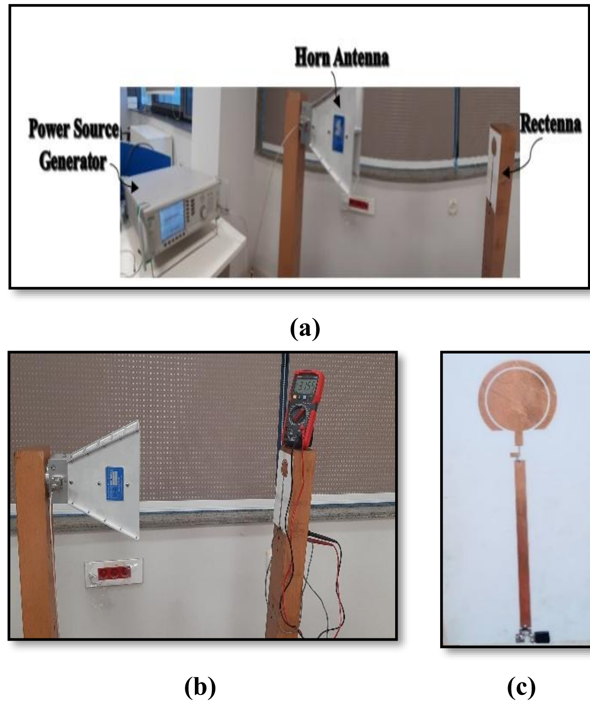



**Figure 17: a) Experimental setup on measuring rectenna performance, b) showing maximum voltage at input power 30dBm, c) proposed rectenna.**

Using the Anritsu MG3697C as a signal generator and a standard horn antenna as a transmitting antenna at a distance of 35 cm (far-field condition) from the proposed rectenna, we calculated the output DC voltage and the efficiency of the rectenna by measuring the output DC voltage using equation (3), as displayed in Figures 18 and 19. At a power input of 0 dBm, the DC Vout is 0.9 V, and efficiency reaches up to 25.7%. Achieving maximum efficiency at 5 dBm input power of 30.5%, and a maximum voltage of 3.1 V at an input power of 30 dBm.

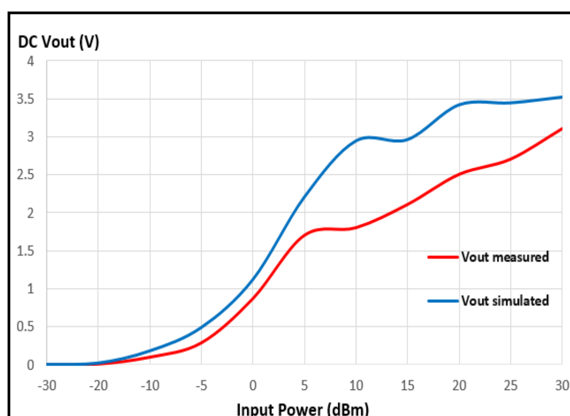



**Figure 18: Comparison of the measured and simulated DC output voltages at various input power levels with a 3 kΩ resistor load.**

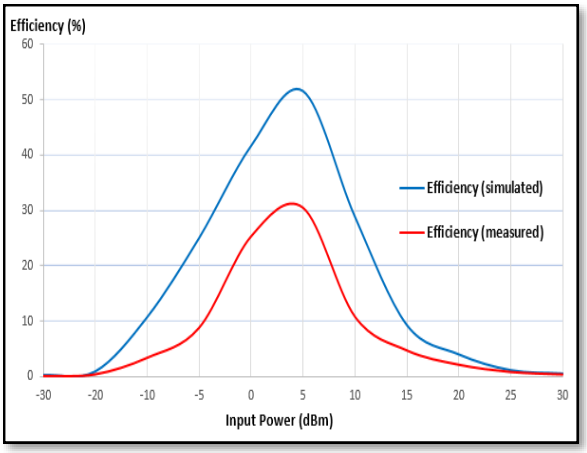



**Figure 19: Comparison of measured and simulated efficiency with a 3kΩ resistor load at various input powers.**

There is a small difference between the simulation and the measurement results. In general, this difference does not exceed 20% of the difference between the simulated and observed efficiency. This can be explained by circuit losses that were not taken into consideration when estimating efficiency. For example, parasitics in devices that can significantly reduce efficiency. The resistance of the diode junction *Rs* may be able to reduce the diode's efficiency since the current across it will cause the semiconductor junction to lose power [30-31]. The circuit performance is also significantly degraded at high frequencies by the junction capacitance *Cj* and the parasitic inductance. Moreover, the efficiency of the energy harvester may be significantly impacted by conventional losses in the transmission lines and substrate SMA connector. Rectenna's performance concerning load resistance has been improved for optimal conversion efficiency.

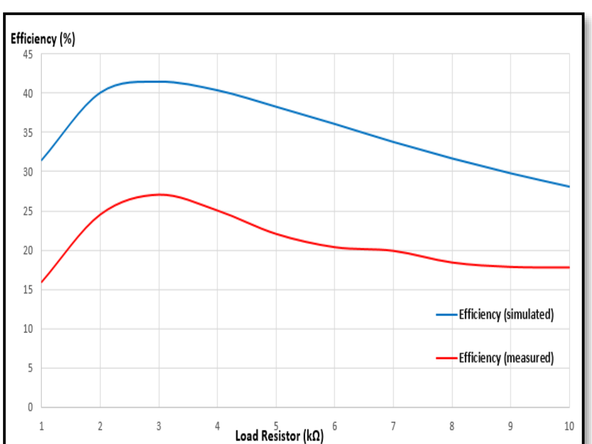



**Figure 20: Variations in measured and simulated efficiency compared with the load terminal at 0 dBm input power.**

The efficiency variation as a function of load resistance is displayed in Figure 20. The efficiency rises with load for an initial 1 mW input power and falls for larger values above 3 kΩ.

Furthermore, at 5 GHz, the average simulated efficiency is greater than 40% with a variable load of 2 kΩ to 4 kΩ. Additionally, the average measured efficiency for a range of loads from 2 kΩ to 4 kΩ is above 25%. Rectenna is discovered to be able to efficiently handle a load of approximately 3 kΩ for the input signal at a frequency of 5 GHz.

Subsequently, the PCE performance is examined over various frequency bands with an input power of 10 dBm and a 3 kΩ load resistance. The corresponding results are displayed in Figure 21. Good results are obtained at the resonant frequency band by the rectenna.

The suggested rectenna shows higher, consistent conversion efficiency when compared to rectennas using traditional broadband matching networks.

Table 2 presents a comparison of the suggested rectenna with comparable works on energy harvesting. It is evident that the suggested rectenna can absorb more RF energy because it has a high output voltage and efficiency in the resonance band.

The main drawback of IEEE 802.11j is its restricted applicability in certain geographic regions, often due to regulatory constraints and interference in the 4.9–5.0 GHz band. To overcome this in future work, the proposed rectenna will be modified to utilize additional Wi-Fi frequency bands.

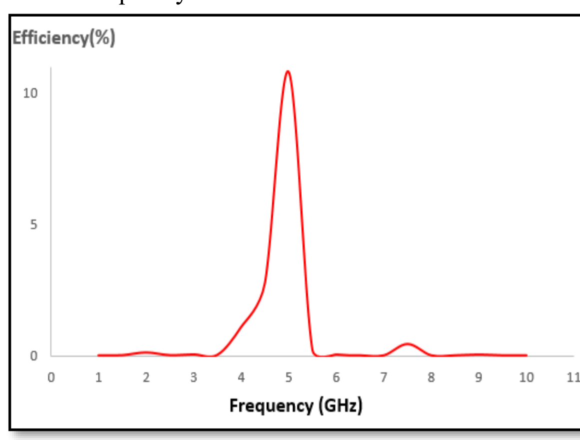



**Figure 21: Efficiency vs frequency at an input power level of 10 dBm.**

By implementing optimization algorithms similar to those in references [32, 33], the rectenna will achieve expanded bandwidth, thereby improving its performance by enhancing data throughput and signal reliability.

This modification will also increase its versatility, enabling it to operate efficiently across a wider range of Wi-Fi standards.

Table 2. Comparing the proposed rectenna's performance to that of the existing rectenna circuits

| Reference | Rectenna Size ($mm^2$) | Frequency (GHz) | Rectenna substrate | Rectifier Diode Type | Input Power (dBm) | PCE (%) | Output DC Voltage |
|---|---|---|---|---|---|---|---|
| [17] | 160×100 | 5.1-5.8<br>5.8-6.0 | Rogers 4003C | HSMS2860 | 16.5 | 24-32%<br>24-28% | 1.41 V |
| [18] | 105×80 | 5.8GHz | Rogers 5880 | SMS7630 | 0 | 29% | 656.88 mV |
| [20] | 100×60 | 1.83<br>4.37<br>5.53 | Rogers | SMS7630-079LF | 0 | 11.36 %<br>15.96 %<br>2.27% | 0.952 V<br>0.846 V<br>0.475 V |
| [21] | 180×60 | 2.4<br>5.5 | Teflon (PTFE) | HSMS 2852 | 0 | 36%<br>5% | - |
| [22] | 80×80 | 2.4<br>5 | FR4 | HSMS286B | 0 | 15.50%<br>12.26% | 0.167 V<br>0.236 V |
| [34] | 60 × 72.5 | 2.45<br>4.9 | Taconic TLC-32 | HSMS-2822 | 28 | <50% | - |
| [35] | 90 × 80 | 1.8, 2.1, 2.8<br>3.5, 4.9, 5.8 | F4B | SMS7630 | -10 | 21 % @ 4.9 GHz | 0.26 V |
| This work | 170×60 | 5 | Rogers 4003C | SMS7630-005 | 0 | 26% | 0.9 V |

## 6 CONCLUSION

This paper presents a rectenna with low power consumption to effectively gather electromagnetic radiation. A circular microstrip slotted antenna serves as the receiving element for the Wi-Fi 5GHz antenna. The receiving antenna and the rectifier circuit is built on Rogers 4003C substrate material and uses an SMS7630-005LF Schottky diode.

The antenna achieved acceptable impedance matching through a transmission line matching network, thereby improving energy conversion efficiency. Simulation and test results demonstrated that the designed rectenna achieves high rectification efficiency in the 5 GHz band, with a maximum measured efficiency of 30.5% at an input power of 5 dBm. At an input power of 0 dBm, the DC output voltage (Vout) is 0.9 V, and efficiency reaches up to 25.7%, making it a good candidate for low-power, self-sustaining Internet of Things devices.

For future work, the matching network and rectifier circuit will be adjusted to achieve rectification for all three received bands. This will result in a wider bandwidth, higher DC output voltage, and better conversion efficiency. Additionally, further modifications will be made to the proposed design to incorporate the other Wi-Fi frequency bands by using different optimization algorithms.

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