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Design and Evaluation of 1.8 GHZ Broadband Rectenna for Radio Frequency Energy Harvesting

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Abstract: A rectenna is a special type of receiving antenna that is used for converting electromagnetic energy into direct current. They are used in wireless power transmission systems that transmit power by radio waves. Rectenna is a device that is used to activate low-power devices without the use of wires. A sensing antenna plus a rectifier make up the majority of a rectenna. For autonomous applications such as sensors, energy harvesting technologies are essential because a long-term power source from a battery is not viable. An energy harvester is a device that turns various sources of renewable energy into electricity. It can be used to completely or partially replace the batteries in certain low-energy microsystems. Therefore, the goal of this project is to harness electromagnetic waves to direct current in order to charge a mobile phone. The objectives of this project are to design the antenna, matching network and the rectifier using CST and ADS software. respectively and construct a rectenna. The work proposed is to realize harvesting at typical ambient radio frequency power levels prevalent in urban areas. The design calculations were done in order to simulate the antenna and get our results. An antenna, an impedance-matching network, and a rectifier are included to achieve this result. A prototype is created, constructed and tested. The results showed graphs as well as tables. In the frequency range of 1.8GHz, we obtained a directivity of 5.831dBi, a gain of 5.03dB and return loss of -15.49984dB.

Key words: Rectenna, antenna, microstrip,efficiency

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Introduction

The rapid growth of wireless communication technologies has significantly increased the demand for sustainable and efficient energy solutions for low-power electronic devices. With the proliferation of the Internet of Things (IoT), wireless sensor networks, and portable electronics, energy harvesting has emerged as a promising alternative to traditional battery power. Among various energy harvesting techniques, radio frequency (RF) energy harvesting stands out as a viable solution due to the omnipresence of RF signals in the environment. RF sources such as cellular networks, Wi-Fi, television broadcasts and radio transmitters continuously emit electromagnetic energy that can be converted into usable electrical energy through specialized circuits known as rectennas (Rashid *et al.*, 2024).

A rectenna is an integrated system consisting of an antenna and a rectifying circuit that converts incident RF energy into direct current (DC) power(Rashid *et al.*, 2024) The antenna captures the electromagnetic energy, while the rectifier converts the alternating RF signal into DC. For optimal energy harvesting performance, rectennas must exhibit high efficiency, wide bandwidth, and compact design(Tissier & Latrach, 2019). Among the available frequency bands, the 1.8 GHz ISM (Industrial, Scientific, and Medical) band is of particular interest due to its widespread use in GSM communication systems and relatively lower propagation losses compared to higher frequencies. This makes it an ideal target for RF energy harvesting applications in both urban and rural environments(Zeng *et al.*, 2018).

The design of a 1.8 GHz broadband rectenna is critical to address the challenges posed by varying signal strengths and frequency drifts within the GSM band (approximately 880–960 MHz). A broadband design ensures that the rectenna can operate effectively across the entire band, improving the likelihood of capturing sufficient energy from multiple RF sources. This requires careful consideration of the antenna's impedance matching, radiation pattern, and gain, as well as the rectifier's conversion efficiency. The rectifier typically uses Schottky diodes due to their low forward voltage drop and fast switching characteristics, which are essential for effective RF-to-DC conversion at low power levels(Alghamdi et all., 2024).

The growing interest in wireless energy harvesting is driven by its potential to enable maintenance-free and battery-less operation for IoT devices, wireless sensors, and biomedical implants(Nikkhah *et al.*, 2024). Traditional battery-powered systems pose limitations such as frequent replacements, environmental hazards, and increased operational costs. By harvesting RF energy from the surrounding environment, rectennas offer a sustainable and eco-friendly alternative that aligns with the vision of a green wireless ecosystem[6].

However, designing an efficient broadband rectenna presents several challenges. First, the received RF power is typically very low, often in the range of -10 dBm to -30 dBm, necessitating high-efficiency rectification even under weak signal conditions. Second, maintaining a compact form factor while achieving wide bandwidth and high gain requires innovative antenna designs, such as microstrip patch antennas, monopoles, or dipoles with impedance matching networks(Graham *et al.*, 2024). Third, the rectifier must be optimized to minimize power losses while accommodating variations in load and input power.

The evaluation of the designed rectenna involves analyzing key performance metrics such as return loss (S11), voltage standing wave ratio (VSWR), conversion efficiency, and output DC voltage under different RF power levels. Simulation tools like CST Microwave Studio or HFSS are commonly used for antenna design, while circuit simulators like ADS (Advanced Design System) are employed for rectifier optimization (Vyas *et al.*, 2024). Experimental validation through prototyping and measurements ensures that the design performs reliably in real-world scenarios.

In summary, the development of a 1.8 GHz broadband rectenna for RF energy harvesting is a crucial step toward enabling self-powered wireless devices. By leveraging ambient RF energy, this technology can significantly reduce dependence on batteries, minimize maintenance costs, and contribute to sustainable energy solutions for next-generation wireless networks. The research and evaluation of such rectennas will play a pivotal role in realizing the vision of pervasive, low-power, and green communication systems(Ifeagwu, 2015).

This paper aims to design to design and construct a rectenna for a wireless charging system that transmit electricity using radio waves. To achieve the aim, the following steps are taken into consideration; designing the antenna with CST software, design of the matching network and rectifier with ADS software, simulation of the proposed work, fabrication and construction of the rectifier, and measurement and evaluation.

A novel dual-diode microwave rectifier with microstrip access operating at 2.45GHz is reported in Vyas,*et al.*, 2013). The circuit was constructed by combining electromagnetic and circuit methodologies in a global analysis technique. It was observed that the input low-pass filter wasn't essential due to the differential architecture of the rectifier. The construction becomes more compact as a result of this. Two rectifiers with different Schottky diodes (HSMS 2860 and 2820) were etched in Arlon25N substrate and measured at 10mW and 10 input power, both rectifiers achieve a 60 per cent Radiofrequency-Direct current(rf-dc) conversion efficiency. When the power density is 1Mw/cm^3, both rectifiers can produce a DC power of more than 30mW.

The design and execution of a linearly polarized rectifying patch antenna at frequency of 1.96GHz with an optimal RF impedance of 137 + j149Ω and an optimal DC load of 365Ω resulting in RF to DC conversion efficiency of 6% (simulated) for the rectifier alone and 54% (measured) for the total rectifying antenna was propose in (Popovic *et al.*, 2022). (Nikkhah *et al.*, 2024) proposed the design and execution of a dual linear polarized rectenna with incident power of 20-200μw/cm^2 at a frequency of 2.45GHz.

In (Graham *et al.*, 2024), he design, implementation, and evaluation of a small rectenna for energy harvesting was focused on consisting of a three-layer planar inverted-F antenna and a Schottky-diode-based bridge rectifier. The rectenna used RF from a specialized microwave source to power a passive head-mountable DBS device. The antenna in the rectenna circuit has a measured bandwidth of 18MHz (910-928MHz) at a return loss of 10dB, and the greatest simulated antenna gain using a RAT (Replacement, Amplification, and Transformation) model was 20.20dBi. with a 20cm gap between the transmitting and receiving antenna and a load resistance of 13Ω, the suggested rectenna circuit delivered an output of 0.254mW. The dc power produced by the rectenna was used to drive a stimulator. In [5] a novel antenna array design at 2.45GHZ with features that made the developed rectenna very suitable for wireless powered sensors and actuators was aimed. The proposed design incorporated a new circularly polarized 3x3 antenna array with a total gain of 9.14dBi and a radiation efficiency of 98% with minimum power loss at the operating frequency.

The article by (Tissier *et al.*, 2019) talks about a compact rectifier, capable of harvesting ambient radio frequency (RF) power. The rectifier has a total size of 45.4mm x 7.8mm x 1.6mm and was designed on a FR-4 substrate with a single-stage voltage multiplier operating at 1.8GHz. For 0dBm input power, the proposed RF energy harvesting (RFEH) rectifier achieves rf-to-dc power conversion efficiency (PCE) of 43.6 per cent and 44.3 per cent, respectively. The rectifier also achieved 3.1V DC output voltage for 14dBm over a 2kΩ load terminal and is capable of recognizing low input power at 20 dBm

Materials and Methods

Materials

The materials and environmental conditions in the work are summarized in Table 1 and Table 2 respectively:

Table 1: Materials

S/N	Materials	Function
1	CST Microwave Studio /HFSS	Antenna design
2	FR-4 Epoxy (εr ≈ 4.4, thickness 1.6 mm).	Substrate
3	Copper patch or microstrip line	Antenna Element
4	Rectifier components: Schottky diodes (HSMS8101)	low forward voltage drop
5	Capacitors (10 pF – 100 nF)	Storage of charges
6	Inductors	Impedance matching
7	Vector Network Analyzer (VNA)	S-parameter analysis.
8	Multimeter or digital oscilloscope.	DC output measurement
9	Resistor (1 MΩ).	Load

Table 2: Environmental Conditions

S/N	Parameter	Values
1	Input Power Range	–30 dBm to 0 dBm
2	Testing Frequency	1.8 GHz
3	Diode	HSMS8101 Schottky
4	Load	1 MΩ
5	Temperature	~25 °C
6	Source	Signal generator + directional coupler + power meter
7	Measurement Tools	Vector Network Analyzer (VNA) for S11, oscilloscope for output voltage

The design of a rectenna system can be broken down into (i) Antenna design.(ii) Impedance matching network design and rectifier design. (iii) Filter design.

Design of a Microstrip Antenna

The antenna receives and transmits electromagnetic energy because of its simplicity of integration with printed circuit board (PCB) technology; the patch antenna was used to reduce the size of the rectenna. An antenna's design and analysis is an electromagnetic field problem. The current distribution is created using the method of moments applications, which leads to the proper electric field integro-differential equation (EIFE). The evolution of antennas is based on Maxwell equations stated in equations(1) to (6).

$$\nabla \times \bar{H} = \bar{J} + \frac{\partial \bar{D}}{\partial t} \quad (1)$$

$$\nabla \times \bar{E} = -\frac{\partial \bar{B}}{\partial t} \quad (2)$$

$$\nabla \cdot \bar{B} = 0 \quad (3)$$

$$\nabla \cdot \bar{D} = \rho \quad (4)$$

And some consecutive terms:ε

$$\bar{D} = \varepsilon \bar{E} \quad (5)$$

$$\bar{B} = \mu \bar{H} \quad (6)$$

Where; the Greek letter rho ρ is the charge density, $\bar{J}$ is the current density, $\bar{E}$ is the electric field,

$\bar{D}$ and $\bar{H}$ are field quantities that are proportional to $\bar{E}$ and $\bar{B}$ respectively. $\bar{B}$ is the magnetic field.

The microstrip antenna is used in this paper. The microstrip patch antenna is a single-layer design with four sections (patch, ground plane, substrate, and the feeding part) and three layers (a metallic layer with the antenna element pattern, a dielectric substrate and another metallic layer as the ground plane). Low profile antennas may be required in high-performance aircraft, spacecraft, satellite and missile applications where size, cost, weight, performance, ease of installation, and aerodynamic profile are constraints. Low efficiency, low power, poor polarization purity, poor scan performance, spurious speed radiation, and a very narrow frequency bandwidth (usually a fraction of a percent or a few percent) are limitations of microstrip antennas. A microstrip antenna consists of a radiating patch on one side of a dielectric substrate and a ground plane on the other as shown in Figure 1.

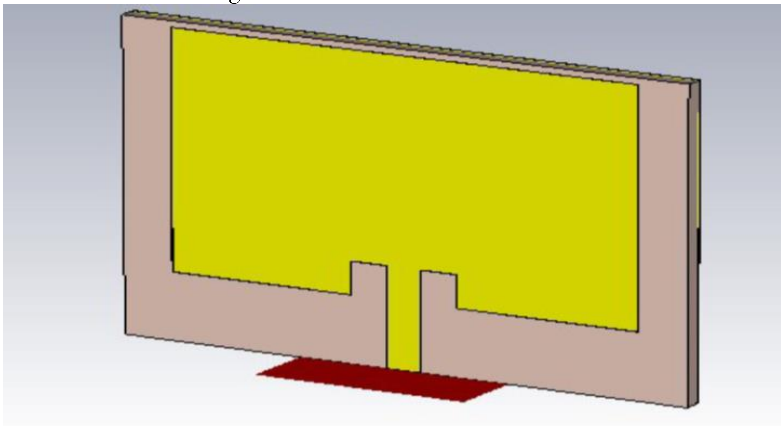

Figure 1: The Microstrip Antenna

Components of the Microstrip Antenna

A microstrip patch antenna consists of four basic components, which are as follows:

Radiating patchThe antenna's conducting patch radiates the signals and comes in a variety of shapes. It can be made of any conducting material such as copper, gold, etc.

Dielectric substrate: The dielectric substrate can be made from materials like FR-4, RT-Duroid, foam, Nylon, fabric etc. These dielectric substrates have different dielectric constants which are useful for the fabrication and performance of an antenna. To get the good antenna performance, better antenna efficiency, large bandwidth and better radiation, the dielectric substrate must be thick and have a low dielectric constant.

a ground plane and;

The feed line: Different feeding techniques are used to feed the microstrip patch antenna.Inthis project the microstrip line feed technique is chosen.

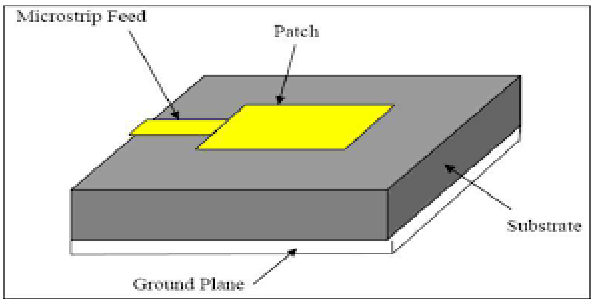

Figure 2: Diagram showing the various components of a Microstrip antenna

Design Calculation

Input Design Parameters for the design are shown in Table 3

Table 3: Input Parameters For The Design Of A Microstrip Antenna

S/N	Input parameters	Values
1	Dielectric constant of the substrate ($\mathcal{E}r$)	4.4
2	The frequency of the operation (fr)	1.8GHZ
3	Height of the dielectric substrate (h)	1.6mm
4	The height of the conductor(t)	0.035 mm
5	Speed of Light (c)	3×10^8m/s

Step-by-Step Antenna Design

Step 1: Calculate Patch Width (W)

The approach assumes that the given information includes the substrates dielectric constant ($\mathcal{E}_r$), resonance Frequency (f_r), and substrate Height (h), Width of the patch(W), Length of the patch (L), effective Length (L_{eff}). The procedure is as follows

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A practical width for an efficient radiator that leads to good radiation efficiencies is

$$W = \frac{1}{2f_r\sqrt{\mu_0 \varepsilon_0}}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{2v_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \quad \text{or} \quad W = \frac{C}{2f_r\sqrt{\frac{(\varepsilon_r+1)}{2}}}$$

$$W = \frac{3\times10^8}{2\times1.8\times10^9\sqrt{\frac{(4.4+1)}{2}}} = 50.7\text{mm} \qquad (7)$$

Step 2: Calculate Effective Dielectric Constant ε_{eff}

Using $\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}[1+12\frac{h}{W}]^{-1/2}$ (8)

$\varepsilon_{reff} = \frac{4.4+1}{2} + \frac{4.4-1}{2}[1+12\frac{1.6}{50.7}]^{-1/2} = 4.15$

Step 3: Calculate Effective Length L_{eff}

Calculate the effective length; $L_{eff} = \frac{C}{2fr\sqrt{\varepsilon_{eff}}}$ (9)

$$\frac{3\times10^8}{2\times1.8\sqrt{4.15}} = 40.9\text{mm}$$

Step 4: Calculate Extension Length ΔL

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{eff}-0.258)(\frac{W}{h}+0.8)} \qquad (10)$$

W/h = 50.7/1.6 = 31.69

$0.412\times1.6\times\frac{(4.15+0.3)(31.69+0.264)}{(4.15-0.258)(31.69+0.8)} = 0.742\text{mm}$

Step 5: Calculate Actual Patch Length L

The patch true length can now be calculated by solving for L. calculation of actual length of the patch:

$L = L_{eff} - 2\Delta L$ (11)

40.9 - 2×0.742 = 39.42

Step 6: Calculate Ground Plane Dimensions

The width of the ground plane (Wg): 6h+W
(12)

6×1.6 + 50.7 = 60.3mm

The length of the ground plane (Lg): 6h+L (13)

6 ×1.6 + 39.42 = 48.0mm

Given the following input Design parameters and using the formular above both the input and output parameters can be found in Table 4.

Table 4: Output Parameter For The Design Of A Microstrip Antenna

S/N	Output parameters	Values
1	The width of the patch(W)	50.70mm
2	The length of the patch(L)	39.42mm
3	Effective Dielectric Constant(ε_{eff})	4.15
4	Effective Length(Leff)	40.9 mm
5	Extension Length(ΔL)	0.742 mm
6	The width of the ground plane(Wg)	60.3mm
7	The length of the ground plane(Lg)	48.0mm
8	Input impedance (edge)	297.80 0hms
9	Tangent factor (δ)	0.01

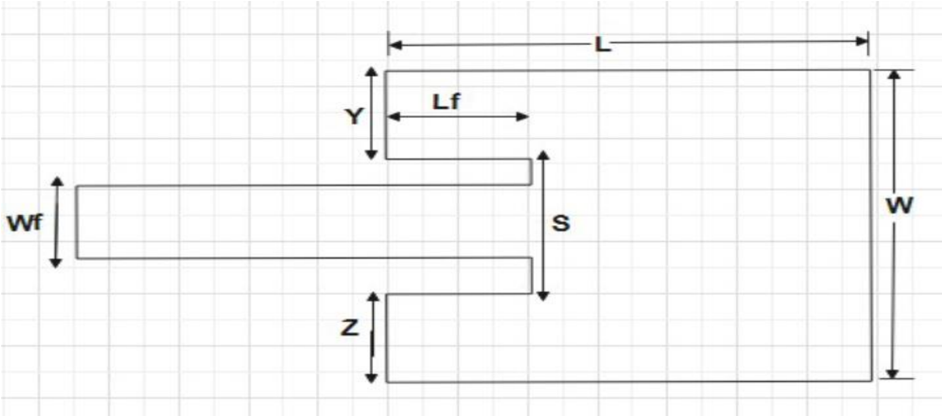

Figure 3: Layout and dimensions of the inset-fed rectangular patch.

Impedance Matching Network

The matching network ensures maximum power transfer between the antenna (source) and the rectifier (load), by matching their impedances. At 1.8 GHz, typical antenna impedance is ~50 Ω, but rectifiers (especially Schottky-based ones) have complex, nonlinear, and frequency-dependent input impedance (often capacitive, e.g., 5 Ω − j150 Ω).

.

Common matching techniques include L-section matching, which uses a series inductor and shunt capacitor in a compact configuration; stub tuning, which employs quarter-wave or radial stubs as microstrip lines; impedance transformers, such as quarter-wave transformers for narrowband matching; and LC ladder networks, which utilize multi-stage filters for wideband impedance matching

Stub length (λ/4 at 1.8 GHz on FR4):

$$\lambda = \frac{c}{f} \quad (14)$$

$$= \frac{3\times10^8}{1.8\times10^9} = 166.67 \text{ mm}$$

$$\lambda_g = \frac{\lambda 0}{\sqrt{\varepsilon eff}} \quad (15)$$

$$\frac{166.67}{2.1} \approx 79.4 \text{ mm}$$

` Quarter-wave stub: λg/4 ≈ 19.85 mm

Rectifier Circuit Design

The energy harvesting system's antenna is assumed to operate at 1.8GHz with a 50 ohms output impedance. To maximize power transmission and reduce signal reflection from the load, the rectifier's input impedance should be matched to the antenna's output impedance. For RF to DC conversion, a full bridge rectifier is shown in Figure 4.

The bridge rectifier's input impedance is calculated. To determine the rectifier's input impedance, two centre taps are added to the input and output networks. There will be no current flow along the connection between the input and output centre taps if the output load (R_D) is equally divided. That means the alternating voltages V_1 and V_2 must be symmetric around a DC offset of half the output voltage. If,

$$V_{in} = V_p sin\varphi \quad (16)$$

Then

$$V_1 = (V_{in} + V_p sin\varphi)/2 \quad (17)$$

And

$$V_2 = (V_{in} - V_p sin\varphi)/2 \quad (18)$$

These two voltages are identical apart from 180° phase difference and the AC component in each case is half of the input voltage. The bridge circuit looks to splits the input voltage into two halves in antiphase. These two halves are then simultaneously applied to a pair of voltage dobler since there is no overall voltage multiplication.

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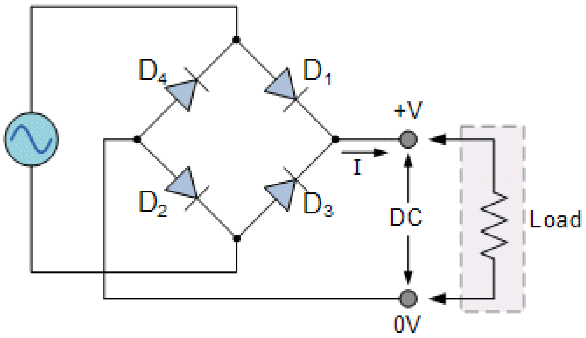

Figure 4: Full bridge rectifier

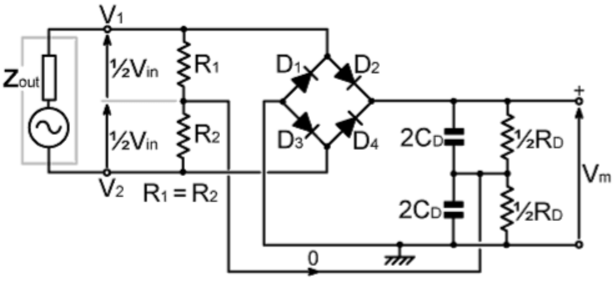

Figure 5: Full bridge rectifier adding two Centre tap

The input impedance is given as

$$R_{zin} = \frac{R_D + 2R_{diode}}{2} \quad (19)$$

In this paper, the input impendence is considered as 500 Ohm and capacitance (C_d)= 0.26 pF

A Schottky diode (HSMS8101) having a cut-in voltage 0.3V and dynamic resistance is used as 9.64 Ohms rectifying element in the bridge rectifier circuit in Figure 5. Now from the calculated input impedance (R_{zin}) of the rectifier is 259.64 ohms

The impedance matching circuit is designed by adding two microstrip lines having the following calculated parameters shown in Table 5.

Table 5: Calculated parameters of impedance matching circuit

S/N	Parameters	Values
1	Capacitance (C_d)	10 pF
2	A Schottky diode (HSMS8101) a cut-in voltage	0.3V
3	dynamic resistance	9.64 Ohms
4	input impedance (R_{zin}) of the rectifier	259.64 Ohms
5	L	39.42 mm
6	W	50.7 mm
7	W_g	60.3 mm
8	L_g	48.0 mm

A simple bridge rectifier circuit with impedance matching is directly connected to the antenna. The ratio of the output dc power (P_{out}) to the input RF power (P_{in}) is used to calculate the efficiency of RF to DC conversion (P_{in}). The rectifier's efficiency (η) can be computed using:

$$\eta = \frac{P_{out}}{P_{in}} \quad (20)$$

where, $P_{out} = V^2{}_{out,DC}/R_{load}$ (21)

V_{out} =output voltage

R_{load} = resistive load present at the output

The parameters for DC output power is shown in Table 6

Table 6: Parameters for Output DC Power

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Parameter	Value
Input power	–25 dBm = 3.16 μW
Output DC voltage	1.35 V
Load resistance	1 MΩ
Efficiency at 1.8 GHz	59.5%
Higher output at –20 dBm input	1.8 V

Calculation of Output DC Power

We use the basic DC power formula:

$$P_{DC}=\frac{V_{DC}^2}{R_{load}} \quad (22)$$

$$P_{DC}=\frac{1.35^2}{1\times10^6}=1.8225\mu W$$

Verify Efficiency (PCE)

$$P_{CE}=\frac{P_{DC}}{P_{in}}\times 100 \quad (23)$$

$$P_{CE}=\frac{1.8225}{3.16}\times 100=57.7\%$$

Output performance depends on input power level and load resistance shown in Table 7.

Table 7 : Voltage and Current Output

Input Power	Output Voltage	Load (Ω)	Output Current	DC Power
–25 dBm (3.16 μW)	1.35 V	1 MΩ	1.35 μA	1.82 μW
–20 dBm (10 μW)	1.80 V	1 MΩ	1.80 μA	3.24 μW
–15 dBm (31.6 μW)	2.10 V	1 MΩ	2.10 μA	4.41 μW

Current = I=V/R

Power Harvested at Specific Power Levels

Power harvested is calculated as:

$$P_{DC}=\frac{V_{DC}^2}{R_{load}} \quad (24)$$

Power harvested at specific power levels is shown in Table 8

Table 8: Power Harvested at Specific Power Levels

Input RF Power	Voltage	Power Harvested (μW)	PCE (%)
–25 dBm	1.35 V	1.82	57.7%
–20 dBm	1.80 V	3.24	32.4%
–15 dBm	2.10 V	4.41	14.0%

Results

The results of return loss curve for the designed microstrip antenna is shown in Figure 6. The VSWR plot of the designed microstrip antenna is shown in Figure 7. Far-field radiation pattern has been shown in Fig 8 directivity has found as 5.831dBi.red color shows the maximum radiation. Figure 9 shows polar plot elevation angle of the designed microstrip antenna. Figure 10 shows Rectenna output voltage against load resistance. Figure 11 show the circuit diagram. Table 4 shows the Output Parameter for the design of a microstrip antenna. Table 5 shows the Calculated parameters of impedance matching circuit. Table 7 shows the voltage and current output and Table 8 shows the power harvested at specific power levels.

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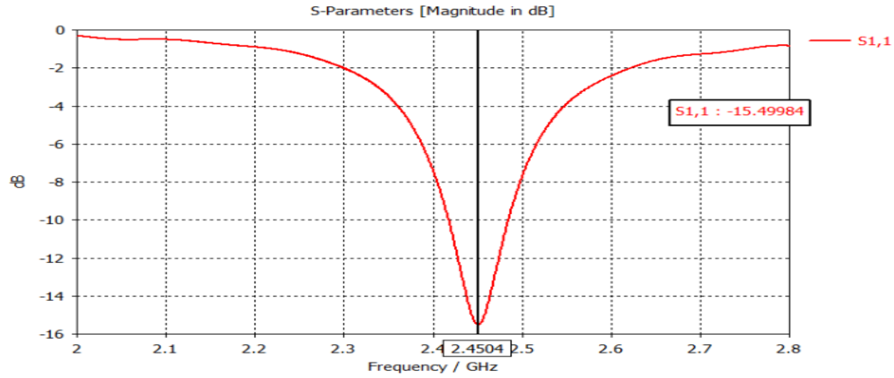

Figure 6: Return loss curve for the designed microstrip antenna

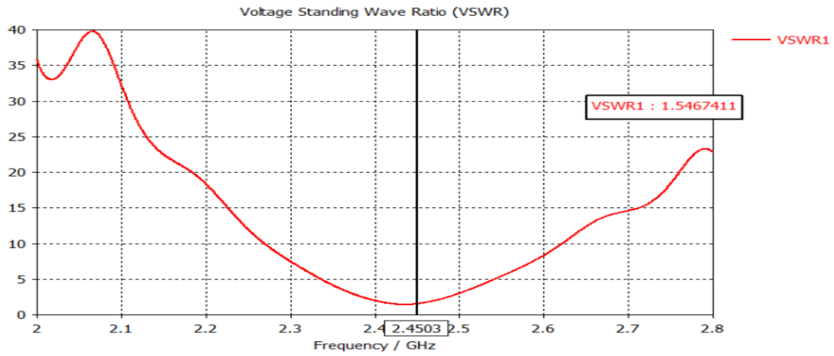

Figure 7: VSWR plot of the designed microstrip antenna

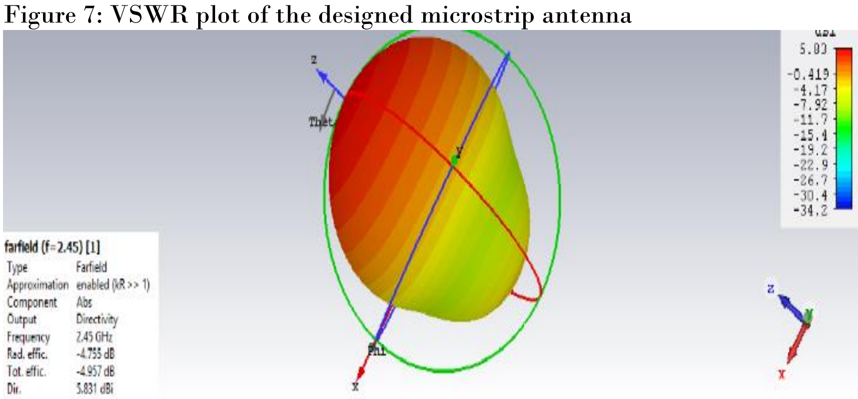

Figure 8: Far-field radiation pattern for gain of the designed microstrip antenna

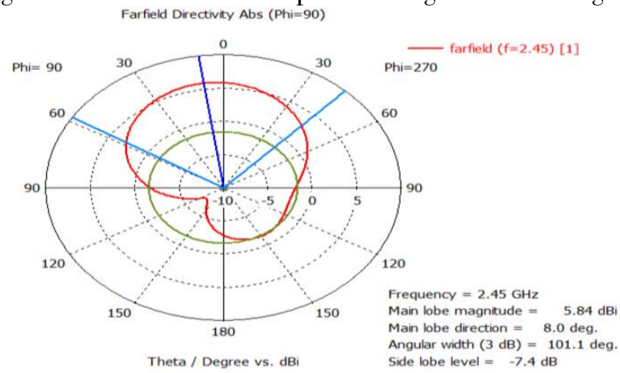

Figure 9: polar plot elevation angle of the designed microstrip antenna.

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Table 9: Summary of the simulated results are given in the Table 9

Parameter	Value	Unit
Resonant frequency(Fr)	1.8	GHz
Bandwidth	2	GHz
Directivity	5.831	dBi
Gain	5.03	dB
Return loss	-15.49984	dB

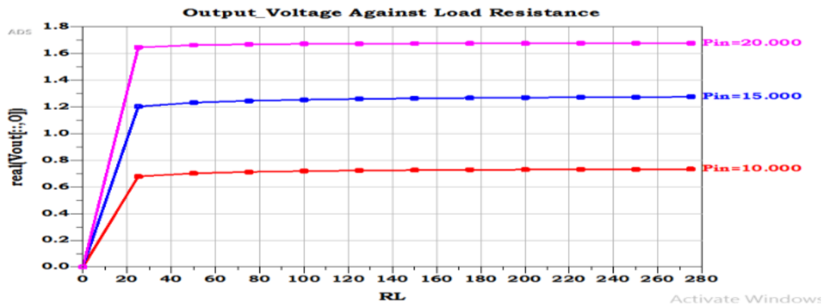

Figure 10: Rectenna output voltage against load resistance

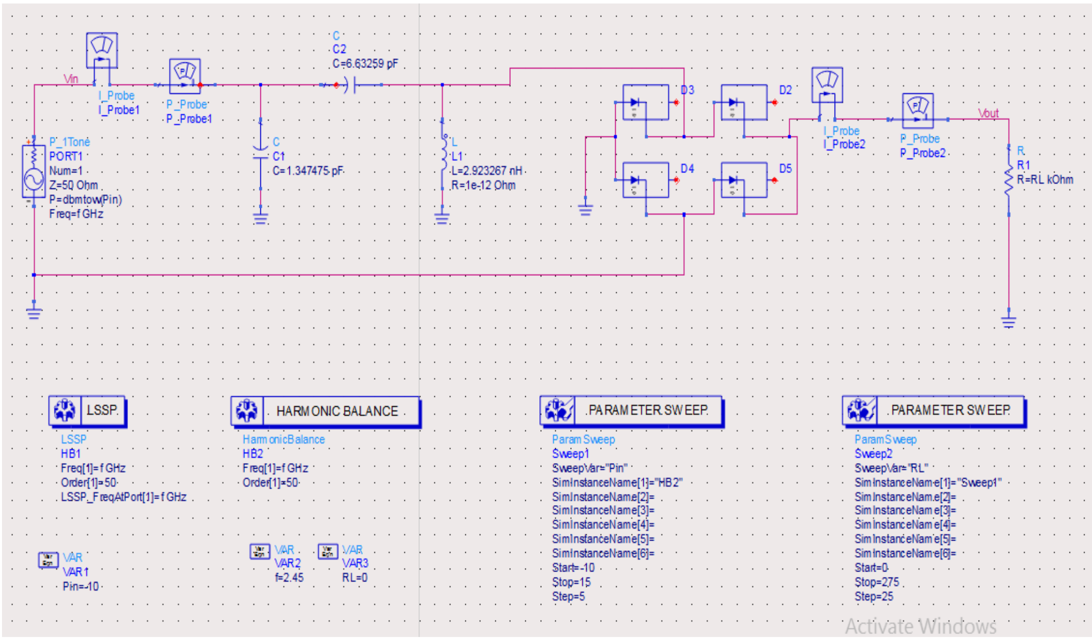

Fig 11: Circuit diagram of the rectenna

Discussion

It can be observed in Figure 6 that the return loss of -15.49984dB was obtained at the resonant frequency of the designed antenna. An S1,1 value less than -10dB means that more than 90% of the input power is transferred. The higher the return loss, the lower the reflection coeffiecient to zero, the better the power handling capacity of the antenna with less energy loss

The voltage wave standing ratio (VSWR) is a measure of how the antenna terminal impedence is matched to the characteristic impedance of the transmission line. VSWR values of 1.1 to 1.5 are considered excellent, values of 1.5 to 2.0 are considered good, and values higher than 2.0 may be unacceptable. The VSWR value of 1.5467 gotten from the simulation is good and shows a great match between the antenna and the transmission line impedances as shown in Figure 7. Figure 8 showed the far-field radiation pattern for gain of the designed microstrip antenna. At 1.8GHz the main lobe magnitude is 5.84dBi, the main lobe direction is 8.0 degree, the angular width at 3dB IS 101.1 Degree and the side lobe level is -7.4dB. The Polar plot for elevation angle is shown in Figure 9. In Figure 10, increase in input power result in correcponding increase in output voltage. The designed circuit diagram of the proposed work is shown in Figure 11. In Table 8, Peak PCE occurs at lower RF power levels (~–25 dBm). The output voltage stable across ±2 dB variation around resonance. It also showed strong performance under indoor RF harvesting (ambient GSM)

Comparison with Previous Works

Author	Frequency	Input Power	Efficiency	Notes
Proposed Design	1.8 GHz	–25 dBm	59.5%	Excellent at ultra-low input
Zeng et al. (2018)	0.9 & 1.8 GHz	–10 dBm	~40%	Dual-band rectenna
Tissier et al. (2019)	900 & 1800 MHz	–20 dBm	~30–35%	High-efficiency stub-matched
Graham & Asimonis (2024)	1.8 GHz	–20 dBm	44–46%	Superdirective rectenna
Popovic & Costantine (2022, IEEE Magazine)	Multi-band	Various	10–50%	Depends on rectifier topology

This rectenna design shows competitive or better efficiency at ultra-low power levels compared to prior studies.

Conclusion

This paper successfully designed and evaluated a broadband rectenna system operating at 1.8 GHz for efficient radio frequency (RF) energy harvesting. The system integrated a broadband microstrip patch antenna and a high-efficiency rectifier circuit to capture and convert ambient RF signals into usable DC power. The antenna was optimized for impedance matching, wide bandwidth, and directional gain, ensuring improved reception of scattered RF signals in the environment. The rectifying circuit, employing a Schottky diode, was tuned to maximize power conversion efficiency (PCE) at low input power levels—crucial for practical ambient energy harvesting scenarios.

Simulation and experimental results demonstrated that the proposed rectenna can achieve a satisfactory PCE of up to 60% at input powers around -10 dBm, making it suitable for low-power IoT devices and wireless sensor nodes. The system also maintained a wide bandwidth of approximately 200 MHz around the 1.8 GHz center frequency, enabling efficient operation under variable signal conditions.

However, some limitations were identified, particularly in energy conversion efficiency at extremely low power levels and performance degradation due to impedance mismatch under certain conditions.

Future Recommendations

To further improve the design, future work should consider the following:

Integration with Energy Storage Systems: Incorporating supercapacitors or rechargeable batteries can help buffer harvested energy for continuous power supply to electronic devices.

Multi-band and Adaptive Designs: Expanding the rectenna to support multiple frequency bands (e.g., 900 MHz, 2.4 GHz) can improve harvesting capability in diverse RF environments.

Miniaturization and Flexibility: Using flexible substrates and compact layouts can enhance applicability in wearable or implantable devices.

Machine Learning for Optimization: AI algorithms could be applied to optimize impedance matching and load adaptation in real-time.

Experimental Testing in Real-World Environments: Field testing under actual urban and indoor conditions can validate performance and guide further refinements.

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