

Design and Experimental Evaluation of a 2.4 GHz Circular Microstrip Patch Rectenna with a Three-Stage Voltage Doubler for RF Energy Harvesting

Ester Novi Andriani, Gurum Ahmad Pauzi, Junaidi, and Sri Wahyu Suciayati*

Department of Physics, Faculty of Mathematics and Natural Sciences, University of Lampung, Bandar Lampung 35145, Indonesia

Article Information

Article history:
Received February 22, 2023
Received in revised form
April 7, 2026
Accepted August 9, 2026

Keywords: Radio
Frequency, Energy
Harvesting, Antenna,
Voltage Doubler, Rectenna

Abstract

This study presents the design and experimental evaluation of a 2.4 GHz rectenna for radio-frequency (RF) energy harvesting. The system integrates a circular microstrip patch antenna fabricated on an FR-4 epoxy substrate with a three-stage voltage-doubler rectifier employing BAT17 Schottky diodes. Antenna parameters were optimized using ANSYS HFSS, and the selected configuration comprised an 18 mm patch radius, 24 mm feedline length, and 5 mm feedline width. The simulated antenna exhibited a VSWR of 12.7312 and a return loss of -4.0849 dB. The fabricated rectenna was experimentally tested using a Wi-Fi source during morning, afternoon, and evening periods. The maximum measured DC output voltages were 74.69, 56.77, and 80.78 mV, respectively, with the highest output obtained during the evening measurement. The results demonstrate the feasibility of harvesting RF energy from Wi-Fi signals using the proposed rectenna. However, the relatively high VSWR indicates that further impedance-matching optimization is required to improve RF power transfer and overall energy-harvesting performance.

Informasi Artikel

Proses artikel:
Diterima 22 Februari 2023
Diterima dan direvisi dari 7
April 2026
Accepted 9 Agustus 2026

Kata kunci: Radio
Frequency, Energy
Harvesting, Antenna,
Voltage Doubler, Rectenna

Abstrak

Penelitian ini menyajikan rancangan dan evaluasi eksperimental sebuah rectenna 2,4 GHz untuk pemanenan energi frekuensi radio (RF). Sistem ini mengintegrasikan antena patch mikrostrip berbentuk lingkaran yang difabrikasi pada substrat epoksi FR-4 dengan penyearah pengganda tegangan tiga tingkat yang menggunakan dioda Schottky BAT17. Parameter antena dioptimalkan menggunakan ANSYS HFSS, dan konfigurasi yang dipilih mencakup jari-jari patch 18 mm, panjang saluran pencatu 24 mm, dan lebar saluran pencatu 5 mm. Antena hasil simulasi menunjukkan nilai VSWR sebesar 12,7312 dan return loss sebesar -4,0849 dB. Rectenna yang telah difabrikasi diuji secara eksperimental menggunakan sumber sinyal Wi-Fi pada pagi, siang, dan malam hari. Tegangan keluaran DC maksimum yang terukur masing-masing adalah 74,69 mV, 56,77 mV, dan 80,78 mV, dengan keluaran tertinggi diperoleh pada pengukuran pada malam hari. Hasil penelitian menunjukkan kelayakan pemanenan energi RF dari sinyal Wi-Fi menggunakan rectenna yang diusulkan. Namun, nilai VSWR yang relatif tinggi mengindikasikan perlunya optimalisasi lebih lanjut pada pencocokan impedansi untuk meningkatkan transfer daya RF dan kinerja pemanenan energi secara keseluruhan.

1. Introduction

The growing demand for electrical energy has driven the development of alternative and renewable energy sources that reduce dependence on conventional energy resources. In addition to solar, wind, and other renewable sources, electromagnetic energy available in the surrounding environment has attracted increasing attention as a potential energy source for low-power electronic devices. One promising approach is radio-frequency (RF) energy harvesting, in which ambient electromagnetic waves generated by communication systems are captured and

* Corresponding author.
E-mail address: sri.wahyu@fmipa.unila.ac.id

converted into usable electrical energy (Nechibvute et al., 2017; Ibrahim et al., 2022). RF energy harvesting is particularly attractive for powering low-power wireless sensors, Internet of Things (IoT) devices, and other autonomous electronic systems because RF signals are widely available indoors and outdoors.

Radio-frequency (RF) signals are continuously generated by wireless communication technologies such as cellular networks, Wi-Fi, Bluetooth, and other radio communication systems (Ibrahim et al., 2022). Although the available RF power density in ambient environments is generally low, these signals represent a continuously available energy source that can potentially be harvested for low-power applications. Wi-Fi signals in the 2.4 GHz band are particularly relevant because this frequency band is widely used in wireless communication systems. However, the amount of harvestable RF energy depends strongly on the distance between the RF transmitter and receiving antenna as well as the surrounding electromagnetic environment (Luo et al., 2019). Therefore, RF energy harvesting provides an opportunity to recover a fraction of electromagnetic energy that would otherwise propagate through the environment without being utilized (Saputri et al., 2023).

A commonly used RF energy-harvesting technology is the rectifying antenna, or rectenna, which integrates an antenna and a rectifier circuit. The antenna captures incident electromagnetic waves and converts them into an RF electrical signal, while the rectifier converts the RF signal into direct-current (DC) voltage (Mustofa et al., 2015; Tamlarasi et al., 2021; Panigrahi et al., 2023). A rectenna system generally consists of a receiving antenna, impedance-matching network, rectifier, and load, and its overall performance depends on the interaction among these components (Surender et al., 2022; Wagih et al., 2020). In particular, proper impedance matching between the antenna and rectifier is essential because impedance mismatch can reduce the RF power transferred from the antenna to the rectifier. Therefore, antenna gain, impedance matching, operating frequency, rectifier topology, diode characteristics, input RF power, and load resistance are important parameters that determine the performance of an RF energy-harvesting system (Wagih et al., 2020).

Several studies have investigated RF energy harvesting using rectenna systems. Rivaldo et al. (2018), for example, designed and experimentally realized a rectenna operating over 800–2500 MHz using a coplanar Vivaldi (tapered slot) antenna and a five-stage voltage-doubler rectifier based on a BAT17 diode. Their experimental results showed a maximum output voltage of 474.2 mV at an antenna distance of 30 cm. The study showed that an integrated antenna-rectifier system could convert RF signals into DC voltage; however, the output voltage decreased as the distance between the RF source and receiving antenna increased (Rivaldo et al., 2018). These results indicate that the distance between the RF source and receiving antenna is an important factor affecting the harvested energy. Nevertheless, the study mainly investigated a broad frequency range of 800–2500 MHz, while optimizing a rectenna specifically for the 2.4 GHz Wi-Fi band remains important for practical RF energy-harvesting applications.

A related study by Suandi et al. (2018) investigated a circular patch microstrip antenna integrated with a rectifier employing a Schottky diode to develop a rectenna for RF energy harvesting. The study demonstrated that a circular microstrip patch antenna could be integrated with a rectifier to convert RF signals into DC voltage. However, the reported output voltage remained relatively low, indicating that further optimization of the antenna and rectifier circuit was needed to improve the harvested electrical output (Suandi et al., 2018). This limitation provides a basis for investigating an improved rectenna configuration, particularly by optimizing the rectifier stage and operating frequency.

Aritonang et al. (2018) subsequently investigated the design and implementation of an antenna operating at Wi-Fi frequencies combined with a three-stage voltage-doubler rectifier. Their results indicated that the output voltage increased as the distance between the RF source and antenna decreased. The study also showed that the operating frequency affected the obtained voltage. These findings confirm that the distance and operating frequency are important parameters in RF energy harvesting (Aritonang et al., 2018). However, the relatively low output voltage obtained in previous studies indicates that additional optimization of the antenna and rectifier configuration is still required.

Research on 2.45 GHz rectennas has since focused on improving the system's ability to operate under low RF input power. Koohestani et al. (2020) developed a compact printed rectenna operating around 2.45 GHz using a rectangular patch with U-shaped slots and a 50- Ω coplanar feed. At an incident power of -20 dBm, the measured RF-to-DC conversion efficiency was approximately 20%, producing an output voltage of 97 mV across a 4.7-k Ω load. Although the compact design was advantageous for integration into low-power wireless devices, the relatively low output voltage under low incident power conditions indicates that further optimization of the antenna and rectifier remains necessary (Koohestani et al., 2020).

A circular rectenna operating in the 2.45 GHz ISM band has also been investigated using a compact circular antenna, an impedance-matching network, and a voltage-doubler rectifier employing a Schottky diode. Such studies demonstrate the suitability of the 2.45 GHz ISM band for RF energy harvesting and emphasize the importance of combining an appropriate antenna structure with impedance matching and a low-barrier Schottky diode. More generally, studies of rectenna systems show that the antenna, impedance-matching network, and rectifier must be considered as an integrated system because the performance of one component can directly influence overall RF-to-DC conversion efficiency (Surender et al., 2022; Wagih et al., 2020).

The limitations identified in previous studies indicate that achieving sufficient DC output from weak RF signals remains a major challenge. Ambient RF energy generally has low power density, and harvested power is strongly affected by available input power, antenna characteristics, impedance matching, rectifier topology, and distance from the RF source (Wagih et al., 2020). In addition, increasing the number of voltage-doubler stages does not necessarily yield a proportional increase in output voltage because diode losses, parasitic effects, impedance mismatch, and available input RF power also affect rectifier performance. Consequently, designing a rectenna for practical low-power applications requires an appropriate balance between antenna gain, impedance matching, rectifier stages, circuit simplicity, and operating frequency.

Based on the previous studies, several research gaps can therefore be identified. First, previous research has demonstrated RF-to-DC conversion using different antenna configurations, but the output voltage obtained under practical low-power conditions remains relatively limited (Koohestani et al., 2020; Natalia et al., 2018; Rivaldo et al., 2018; Suandi et al., 2018). Second, the output voltage strongly depends on the distance between the RF source and the receiving antenna, underscoring the need to experimentally evaluate the proposed rectenna's distance dependence. Third, although several rectifier configurations have been reported, further investigation is required to

determine whether a three-stage voltage-doubler configuration combined with a circular microstrip patch antenna can provide improved DC output at the 2.4 GHz Wi-Fi frequency. Finally, antenna-rectifier impedance matching remains an important design consideration for maximizing the RF power delivered to the rectifier (Wagih et al., 2020).

Therefore, this study focuses on designing and realizing a circular microstrip patch antenna integrated with a three-stage voltage-doubler rectifier for RF energy harvesting in the 2.4 GHz Wi-Fi band. A circular patch configuration is selected because of its relatively simple structure and favorable characteristics for the intended operating frequency. A three-stage voltage-doubler rectifier is employed to increase the DC voltage generated from the received RF signal while maintaining a relatively simple circuit configuration. The proposed rectenna is experimentally evaluated by investigating the effect of RF source distance on the output DC voltage and harvested power. The main objective of this study is to develop and experimentally evaluate a compact 2.4 GHz rectenna that converts RF energy into the highest possible usable DC output for low-power electronic applications.

2. Research Methods

The research was conducted through the sequential design, simulation, fabrication, integration, and electrical testing of a radio-frequency (RF) rectenna for energy harvesting. The main materials and instruments included double-sided printed circuit board (PCB) as the substrate for the rectifier and antenna, FeCl₃ solution for removal of the unused copper layer during PCB preparation, BAT17 diodes as the RF rectifying elements, MKM capacitors with nominal capacitances of 1 nF and 220 nF for charge storage and output-voltage smoothing, an SMA connector for RF interconnection between the antenna and rectifier, and a digital multimeter for measuring the rectified DC output voltage. The overall methodology is illustrated in Figure 1.

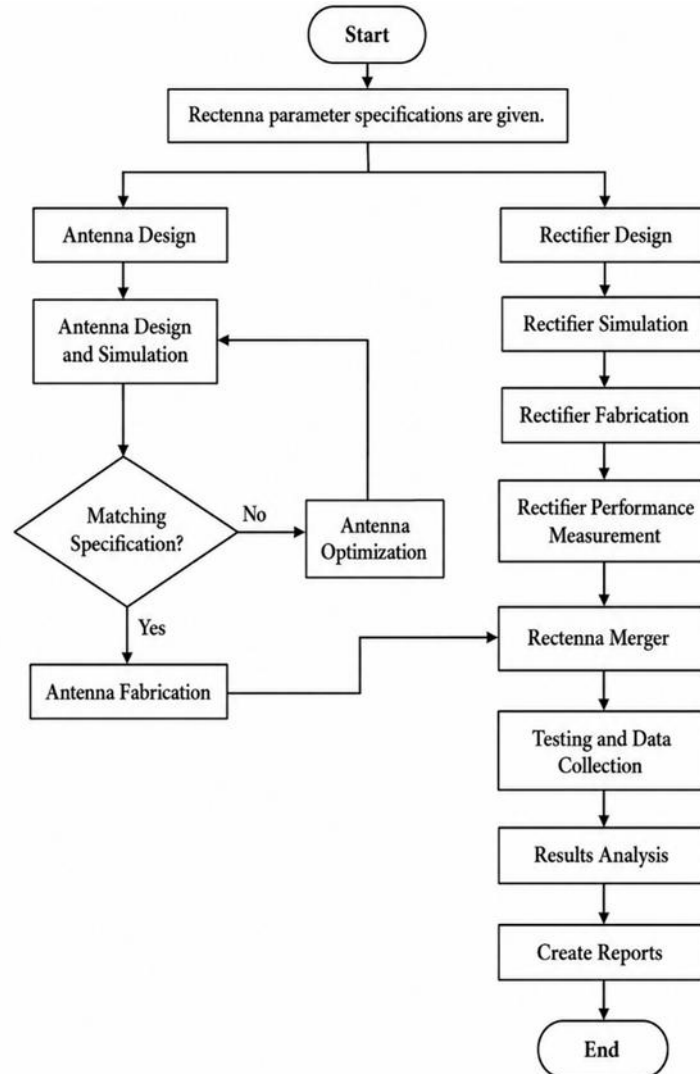


Figure 1. Research workflow for the RF rectenna, showing the parallel development of the antenna and rectifier, iterative antenna optimization, fabrication, integration, testing, and data analysis

Figure 1 establishes the experimental sequence used in the study. The antenna and rectifier were developed as two interconnected subsystems. The antenna branch comprised electromagnetic modelling, simulation, evaluation against the required matching specification, optimization when necessary, and subsequent fabrication. In parallel, the rectifier branch comprised circuit design, simulation, fabrication, and performance measurement. After both subsystems satisfied their respective design requirements, the antenna and rectifier were mechanically and

electrically integrated to form the rectenna. The completed device was then subjected to testing and data collection, followed by analysis of the measured results. This workflow provides a traceable relationship between the simulated design parameters, fabricated hardware, and experimentally obtained output voltage.

2.1 Rectifier Design

The rectifier was implemented as a three-stage voltage-doubler circuit. As shown in Figure 2, the circuit employs six BAT17 diodes (D1-D6) and six 1 nF MKM capacitors (C1-C6) as the voltage-multiplying stages. A 220 nF capacitor (C7) is connected at the output to provide additional charge storage and to suppress voltage fluctuations at the rectified output. The RF input applied in the circuit simulation is specified as 0.5 Vrms at 1.8 GHz. The diode-capacitor network progressively transfers and accumulates charge so that the RF AC input is converted into a higher DC voltage at the output terminal. The simulated output shown in the figure is 2.471 V, which was used as an initial reference for the subsequent hardware implementation.

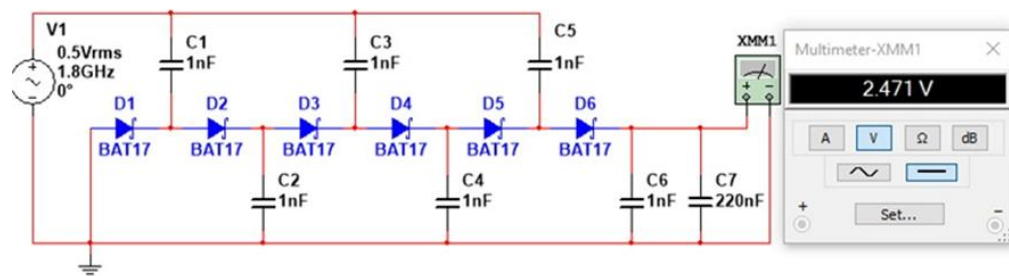


Figure 2. Schematic representation of the three-stage voltage-doubler rectifier using six BAT17 diodes and six 1 nF capacitors, with a 220 nF output capacitor for voltage smoothing; the simulation indicates an RF input of 0.5 Vrms at 1.8 GHz and a displayed output voltage of 2.471 V

The rectifier configuration was selected to increase the usable DC voltage obtained from the incident RF signal while maintaining a relatively simple circuit topology. During fabrication, the circuit layout obtained from the design stage was transferred to the double-sided PCB, after which the diodes and capacitors were mounted according to the simulated schematic. The electrical output of the fabricated rectifier was then evaluated prior to integration with the antenna, as indicated in the research workflow.

2.2 Antenna Design

A circular patch microstrip antenna (Figure 3) was designed and simulated using Ansys HFSS 15.0 at the target Wi-Fi operating frequency. The antenna geometry was optimized by systematically varying the patch radius and feedline dimension. Three patch-radius values of 17, 18, and 19 mm were investigated to evaluate their influence on the resonant frequency. The radius was varied around the initial theoretical design dimension to provide fine tuning of the antenna resonance toward the target frequency, considering that an increase in patch radius generally shifts the resonant frequency toward a lower frequency.

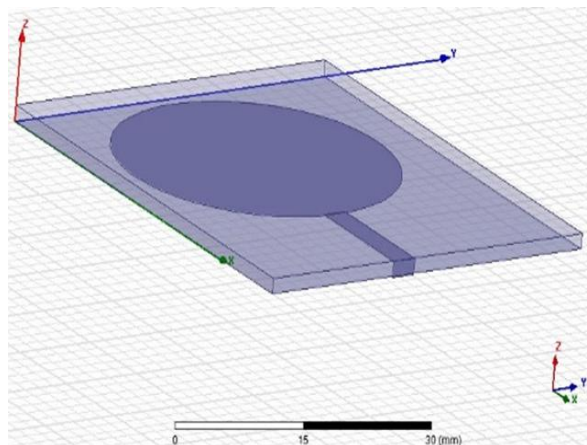


Figure 3. Three-dimensional HFSS model of the circular patch microstrip antenna used for electromagnetic design and simulation; the model illustrates the circular radiating patch, feed line, substrate plane, and coordinate system used in the analysis

Once the simulated antenna met the required specification, the optimized geometry was used as the basis for physical fabrication. The antenna therefore served as the RF receiving element of the rectenna, while its feed point provided the electrical interface to the rectifier. Maintaining consistency between the simulated geometry and the fabricated structure was essential so that the experimentally measured response could be compared with the design-stage prediction.

2.3 Rectenna Design

The rectenna was assembled by integrating the fabricated circular patch microstrip antenna with the PCB-based rectifier, as illustrated in Figure 4. The antenna fabricated from the HFSS design was connected to the rectifier through an SMA connector to provide a defined RF interconnection. The rectifier board contains the BAT17 diodes and MKM capacitors corresponding to the circuit in Figure 2, while the output terminal is provided through a two-pin socket for electrical access. A digital multimeter was connected at the output to measure the resulting rectified DC voltage.

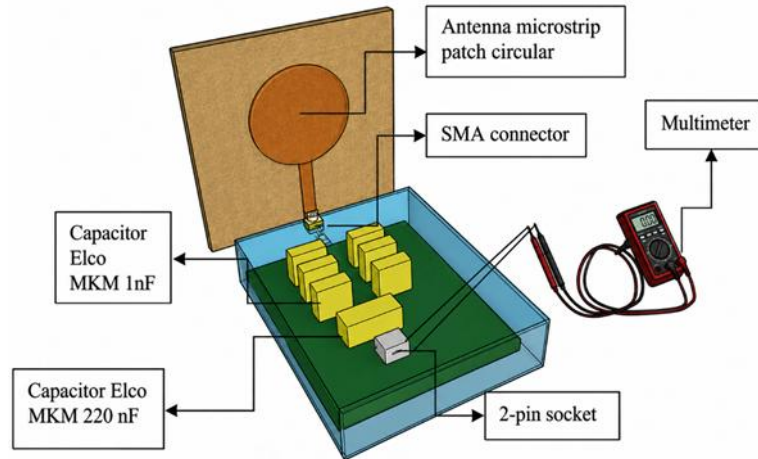


Figure 4. Integrated rectenna configuration showing the circular microstrip patch antenna, SMA RF interconnection, PCB-mounted BAT17 diode/capacitor rectifier, two-pin output socket, and digital multimeter used for DC output-voltage measurement

The fabrication and assembly procedure followed the sequence defined in Figure 1. First, the antenna pattern obtained from the HFSS model was fabricated on the PCB substrate. In parallel, the rectifier layout was fabricated on a double-sided PCB and populated with the specified diodes and capacitors. The antenna and rectifier were subsequently joined through the SMA port to form the complete rectenna. The assembled system was then subjected to testing and data collection, with the measured output voltage serving as the primary electrical response used in the evaluation of the RF energy-harvesting system.

3. Results and Discussion

3.1 Antenna Simulation Before Optimization

The initial antenna model was evaluated in Ansys HFSS to determine its impedance-matching performance before geometric optimization. Two parameters were considered, namely the voltage standing wave ratio (VSWR) and the reflection coefficient (S_{11}), commonly discussed together with return loss. VSWR is dimensionless and is defined as the ratio between the maximum and minimum voltages of the standing-wave pattern. A VSWR of 1 represents an ideal impedance match, whereas increasing VSWR indicates increasing impedance mismatch and, consequently, a larger fraction of incident RF power being reflected toward the source. For antenna systems, a VSWR below approximately 2 is commonly regarded as a good practical matching target, corresponding to a return loss of about 9.5–10 dB or better. Figure 5 displays the simulation outcomes obtained using the HFSS VSWR program.

Before optimization (Figure 5), the minimum reported VSWR was 12.7016 at 2.7 GHz, while the value at the intended 2.4 GHz operating frequency was 22.8093. These values indicate a severe impedance mismatch and are substantially higher than the target VSWR of 2. Therefore, the initial geometry was not suitable for efficient RF power transfer at 2.4 GHz. This observation is particularly important for a rectenna because impedance mismatch at the receiving antenna reduces the RF power delivered to the rectifier, thereby limiting the amount of energy that can ultimately be converted to DC power.

The initial reflection-coefficient results also indicate poor matching (Figure 6). The reported values were -4.0994 dB at 2.7 GHz and -1.2593 dB at 2.4 GHz. These values should preferably be described as S_{11} values in dB. If they are intended to represent return loss, the corresponding return-loss magnitudes are 4.0994 and 1.2593 dB, respectively. Thus, the 2.4 GHz condition exhibits particularly strong reflection. The need for geometric optimization is therefore justified because the receiving antenna must present an impedance close to the feedline impedance to maximize accepted RF power.

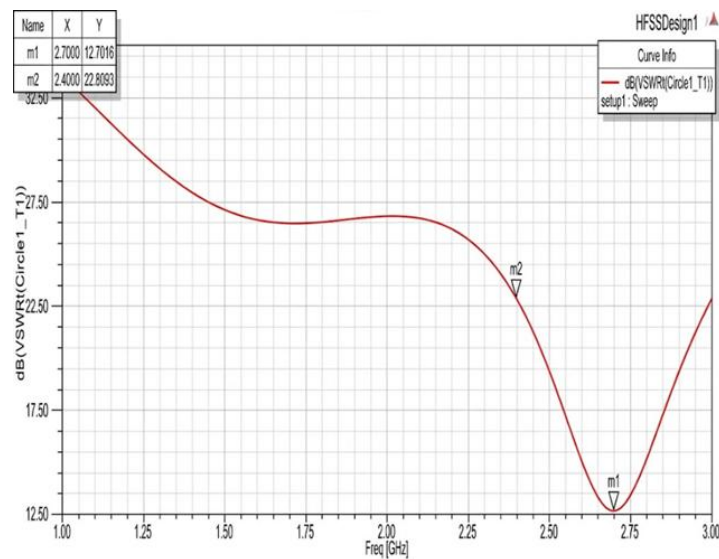


Figure 5. VSWR Before Optimization

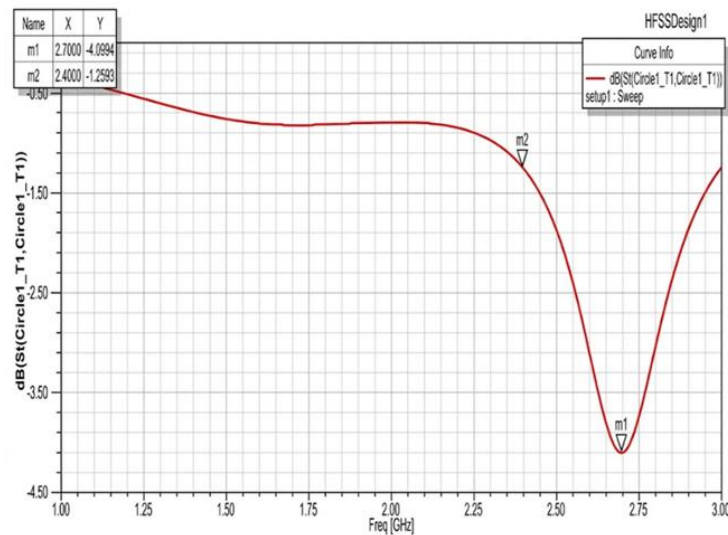


Figure 6. Return Loss Before Optimization

The relationship between antenna matching and RF energy harvesting has been emphasized in recent RF-energy-harvesting studies. Ambient RF harvesting operates under relatively low input-power conditions, making efficient transfer of the available RF power to the rectifier especially important. In practical rectenna systems, the antenna, impedance-matching network, and rectifier must be considered as an integrated RF-to-DC conversion chain rather than as independent components (Garcia-Garcia, 2022; Ibrahim et al., 2022).

3.2 Antenna Simulation After Optimization

Because the initial design exhibited substantial impedance mismatch, geometric optimization was performed by varying the circular patch radius and the microstrip feedline width. Patch radii of 17, 18, and 19 mm were evaluated, while the feedline width (Wf) was varied from 3 to 7 mm. These parameters directly influence the electromagnetic field distribution, input impedance, and resonant behavior of a microstrip antenna. Consequently, changing Wf can modify both the impedance seen at the feed point and the resonance location. Figures 7, 8, and 9 show VSWR values for variations in the patch radius.

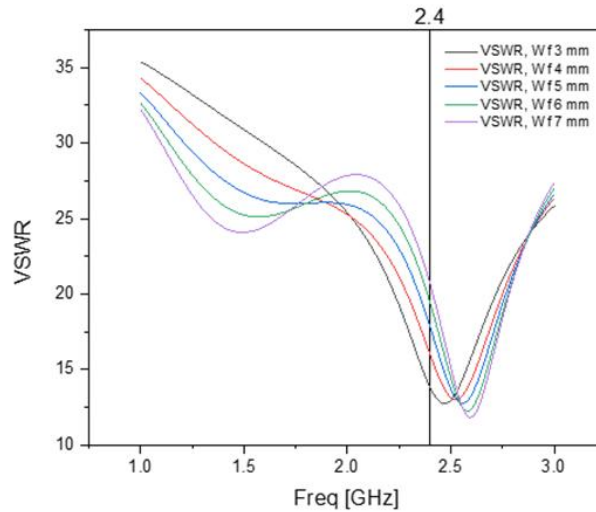


Figure 7. VSWR of the antenna with a 17 mm patch radius

For the 17 mm patch (Figure 7), the simulations show that changing W_f modifies the VSWR response, with $W_f = 3$ mm giving the lowest reported VSWR of 12.7857. Nevertheless, this value remains far above the commonly accepted practical target of approximately 2. Hence, the result should be interpreted as the best case within the tested 17 mm geometry rather than as satisfactory antenna matching. For the 18 mm patch (Figure 8), the minimum VSWR was obtained for $W_f = 5$ mm, leading to the selection of an 18 mm radius and 5 mm feedline width as the optimum configuration among the tested geometries.

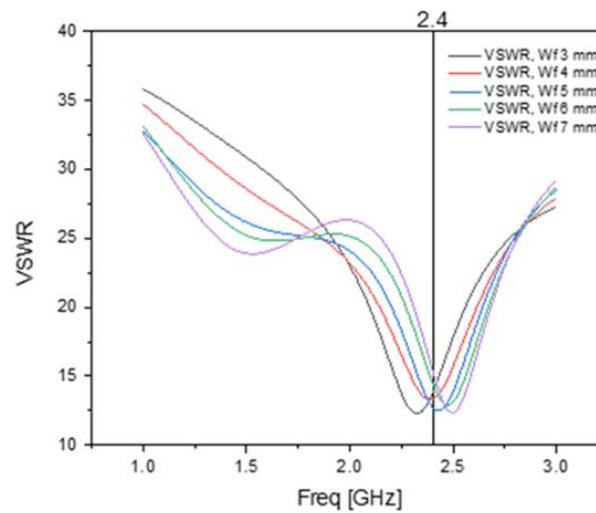


Figure 8. VSWR of the antenna with a radius of 18 mm

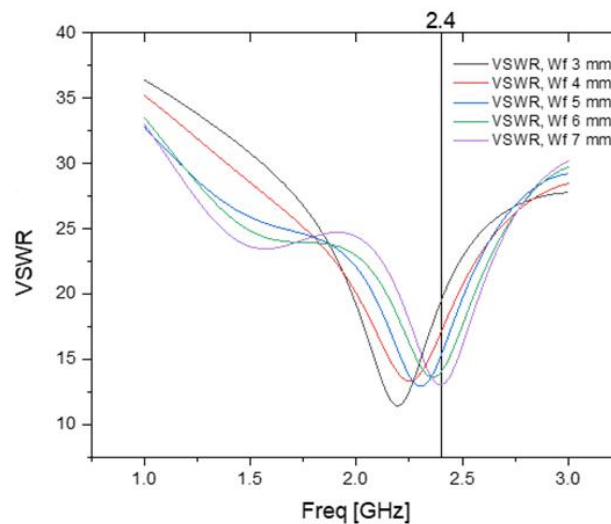


Figure 9. VSWR of the antenna with a radius of 19 mm

As shown in Figure 9, varying the feedline width (W_f) from 3 to 7 mm influences both the resonance frequency and impedance matching of the antenna with a fixed radius of 19 mm. Among the investigated values, $W_f = 7$ mm provides the lowest VSWR around the target frequency of 2.4 GHz and was therefore selected as the optimum feedline width (Koubar et al., 2025). The slight shift of the resonance minimum below 2.4 GHz indicates that further geometrical tuning may be necessary for precise frequency matching.

The frequency shift observed when the feedline width or patch radius is changed is physically reasonable because the dimensions of a microstrip antenna determine its effective electrical length and input impedance. Small changes in geometry can therefore shift the resonant frequency. In a practical fabricated antenna, additional differences may arise from substrate-property tolerances, conductor dimensions, fabrication accuracy, connectors, soldering, and measurement setup. Consequently, agreement between simulation and experiment should be assessed quantitatively rather than assuming that identical resonance frequencies will be obtained.

For RF energy harvesting, the importance of impedance matching is even greater than in a communication-only antenna because the objective is to maximize the RF power accepted by the rectenna. Recent rectenna research at 2.45 GHz demonstrates that matching networks and carefully controlled antenna/rectifier interfaces are routinely used to improve RF-to-DC conversion under low-power conditions (Garcia-Garcia, 2022; Koubar et al., 2025). Thus, the present optimization is a necessary first step, while further optimization of S_{11} , VSWR, antenna gain, and antenna-to-rectifier matching would be expected to improve the harvested output.

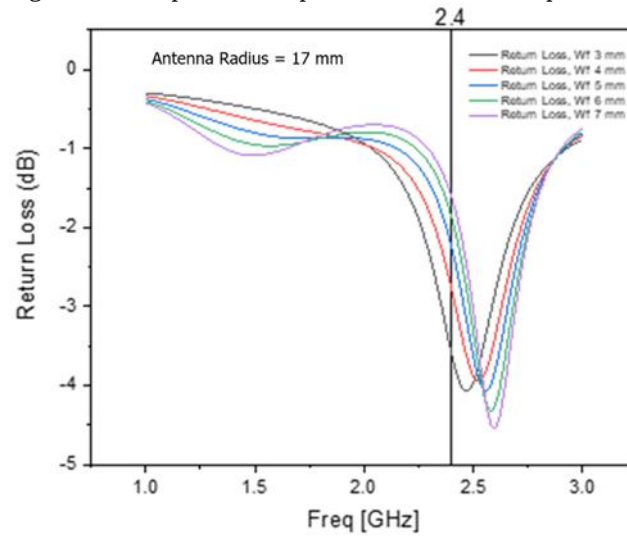


Figure 10. S_{11} pattern from a 17 mm radius antenna with a W_f variation of 3 to 7 mm

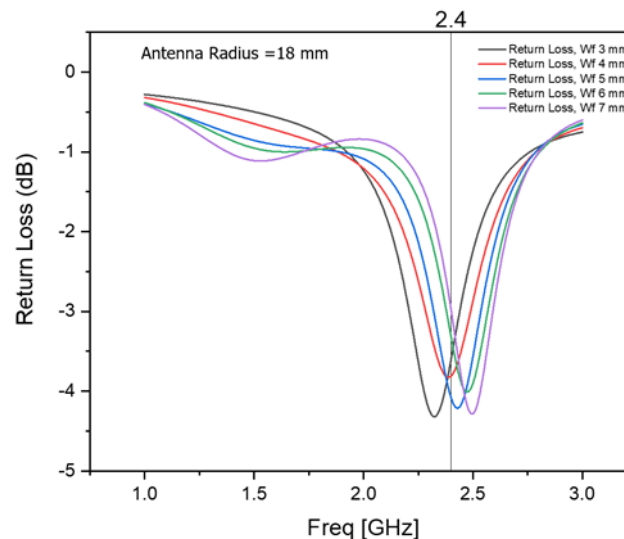


Figure 11. S_{11} pattern of the antenna with an 18 mm patch radius and feedline width variation from 3 to 7 mm

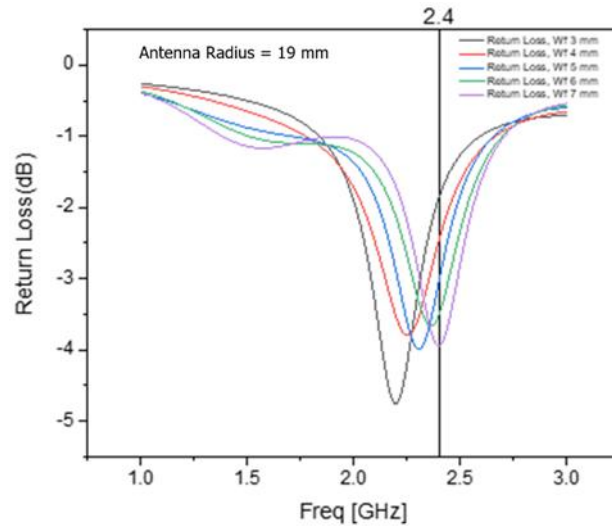


Figure 12. S₁₁ pattern from a 19 mm radius antenna with a Wf variation of 3 to 7 mm

Figure 11, 12, and 13, present the simulated return-loss (S₁₁) characteristics of the antenna for patch radii of 17, 18, and 19 mm with feedline widths (Wf) ranging from 3 to 7 mm. The results indicate that both the patch radius and feedline width significantly affect the resonant frequency and impedance-matching characteristics. Increasing the patch radius generally shifts the resonance toward the target operating frequency of 2.4 GHz, while variation in (Wf) modifies the position and depth of the resonance minimum. Among the investigated configurations, the antenna with a radius of 19 mm and Wf = 7 mm exhibits a resonance closest to the target frequency of 2.4 GHz. Although the configuration with Wf = 3 mm produces a deeper minimum at a lower frequency, its resonance is shifted away from the intended operating frequency. Therefore, the R = 19 mm and Wf = 7 mm configuration was considered the most suitable geometry for subsequent optimization at 2.4 GHz.

The return-loss results are directly related to the VSWR characteristics, since a more negative S₁₁ corresponds to a lower reflection coefficient and consequently a lower VSWR. However, the minimum S₁₁ values observed in the present simulations are only approximately -4 to -5 dB, corresponding to VSWR values of approximately 3.6–4.4. These values remain above the commonly used VSWR < 2 criterion, indicating that further impedance-matching optimization is required before the antenna can be considered well matched at 2.4 GHz.

3.3 Experimental Measurement of the Rectenna Output

Following the simulation study, the selected antenna geometry (18 mm patch radius, 24 mm feedline length, and 5 mm feedline width) was used for experimental measurements with a ZTE F609 Wi-Fi router as the ambient RF source. Measurements were performed during three time windows: 09:00–10:00, 14:00–15:00, and 20:00–21:00. The measured output voltages reached maximum values of 74.69 mV in the morning, 56.77 mV in the afternoon, and 80.78 mV in the evening. Figure 13 shows the experimental data.

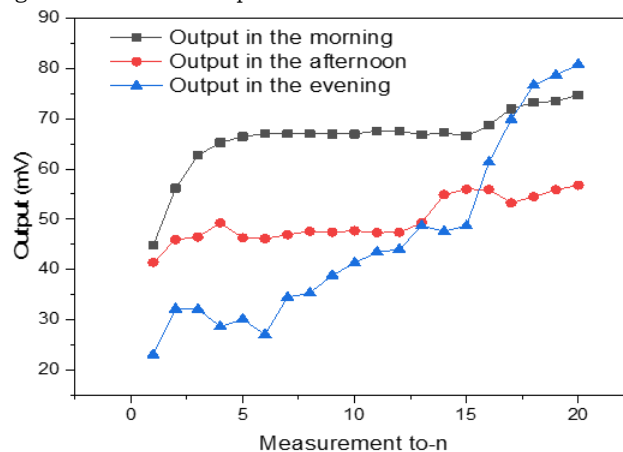


Figure 13. Graph of rectenna measurements for various time conditions

The measured voltage therefore varied with measurement time, with the highest value occurring during the evening period (Figure 13). Such temporal variation is plausible for ambient RF energy harvesting because the available RF power in an environment is not constant; it depends on the activity of RF transmitters, propagation conditions, distance, antenna orientation, multipath effects, and other environmental factors. Reviews of RF energy harvesting emphasize that ambient RF power density can be relatively low and variable, which makes experimental harvesting strongly dependent on the measurement environment (Ibrahim et al., 2022; Mouapi, 2022).

However, the present data in Figure 13 do not by themselves demonstrate that the evening voltage was higher specifically because the Wi-Fi network was used less frequently. The statement that lower Wi-Fi activity produces

more 'wasted energy' is not sufficiently supported by the measurements. A more defensible interpretation is that the three time periods produced different RF environments and therefore different incident RF power at the antenna. To establish a relationship with router activity, the experiment would need simultaneous measurements of received RF power or power spectral density, router traffic/activity, antenna orientation, distance from the router, and repeated measurements over multiple days.

The use of a Wi-Fi source at approximately 2.4 GHz is appropriate for an ambient RF-energy-harvesting study because Wi-Fi is one of the commonly available RF sources in the 2.4–2.45 GHz region. Previous studies have demonstrated rectenna systems specifically intended to harvest RF energy in the 2.45 GHz ISM/Wi-Fi band, confirming the relevance of this frequency range for ambient RF harvesting (Garcia-Garcia, 2022; Ibrahim et al., 2022). Nevertheless, the amount of energy available from a commercial Wi-Fi router is generally much smaller and more variable than the power available from a dedicated RF transmitter, so the experimental conditions should be clearly specified

4. Conclusion

Overall, the simulation and experimental results demonstrate that antenna geometry significantly influences impedance matching performance. Among the investigated configurations, the antenna with an 18 mm patch radius and a 5 mm feedline width provided the most favorable response within the evaluated design space, although its matching performance did not yet meet the conventional criteria of $VSWR < 2$ or $S_{11} < -10$ dB. Therefore, this configuration should be regarded as the most promising geometry among those tested rather than a fully optimized design. For ambient RF energy-harvesting applications, further optimization should consider the complete antenna-rectifier system, particularly conjugate impedance matching between the antenna and the actual rectifier input, to improve the overall RF-to-DC conversion performance.

5. Bibliography

- Aritonang, S. S. N., Wijanto, H., & Wahyu, Y. (2018). Perancangan dan realisasi rectenna pada frekuensi WiFi untuk elektromagnetik harvesting (panen gelombang elektromagnetik). *eProceedings of Engineering*, 5(2), 2229–2237. <https://doi.org/10.34818/coe.v5i2.6651>
- Garcia-Garcia, J. J. (2022). Considerations for the design and implementation of ambient RF signal rectifiers in the 2.45 GHz WiFi band. *Applied Sciences*, 12(15), 7884. <https://doi.org/10.3390/app12157884>
- Ibrahim, H. H., Singh, M. J., Al-Bawri, S. S., Ibrahim, S. K., Islam, M. T., Alzamil, A., & Islam, M. S. (2022). Radio frequency energy harvesting technologies: A comprehensive review on designing, methodologies, and potential applications. *Sensors*, 22(11), 4144. <https://doi.org/10.3390/s22114144>
- Koohestani, M., Tissier, J., & Latrach, M. (2020). A miniaturized printed rectenna for wireless RF energy harvesting around 2.45 GHz. *AEU - International Journal of Electronics and Communications*, 127, 153478. <https://doi.org/10.1016/j.aeue.2020.153478>
- Koubar, G., Haddad, F., Gadacha, A., Sadek, S., & Rahajandraibe, W. (2025). A comprehensive numerical analysis of a 2.45 GHz energy harvesting rectenna system and a proposal for a figure of merit for rectenna systems. *Electronics*, 14(4), 716. <https://doi.org/10.3390/electronics14040716>
- Luo, Y., Pu, L., Wang, G., & Zhao, Y. (2019). RF energy harvesting wireless communications: RF environment, device hardware and practical issues. *Sensors*, 19(13), 3010. <https://doi.org/10.3390/s19133010>
- Mouapi, A. (2022). Radiofrequency energy harvesting systems for Internet of Things applications: A comprehensive overview of design issues. *Sensors*, 22(21), 8088. <https://doi.org/10.3390/s22218088>
- Mustofa, A., Mujahidin, I., & Yuwono, R. (2015). Rancang bangun rectifier antenna mikrostrip UFO pada frekuensi ultra wideband (UWB) sebagai pemanen energi elektromagnetik. *Jurnal Mahasiswa Teknik Elektro Universitas Brawijaya*, 3(2), 2–7. <http://repository.ub.ac.id/id/eprint/143409>
- Nechibvute, A., Chawanda, A., Taruvinga, N., & Luhanga, P. (2017). Radio frequency energy harvesting sources. *Acta Electrotechnica et Informatica*, 17(4), 19–27. <https://doi.org/10.15546/aei-2017-0030>
- Panigrahi, A., Paul, D., Gupta, S., Chourasia, S., & Nath, T. (2023). A comparative study of integrated RF to DC power conversion system for RF energy harvesting. *Materials Today: Proceedings*, 80, 1885–1890. <https://doi.org/10.1016/j.matpr.2021.05.633>
- Rivaldo, R., Wijanto, H., & Wahyu, Y. (2018). Rectenna (rectifier antenna) 800 MHz–2500 MHz. *Jurnal Teknik*, 5(2), 2281–2288.
- Saputri, R. F., Sunarno, S., & Hawibowo, S. (2023). Design and measurement of the receiving antenna for electromagnetic field energy harvesting in UHF band. *Indonesian Journal of Electrical Engineering and Computer Science*, 31(2), 681. <https://doi.org/10.11591/ijeecs.v31.i2.pp681-691>

-
- Suandi, I., Hanafi, & Rachmawati. (2018). Pemanenan energi frekuensi radio 1.800 MHz menggunakan rectifier antena untuk perangkat portable. *Jurnal Litek: Jurnal Listrik Telekomunikasi Elektronika*, 15(2), 21–28. <https://doi.org/10.30811/litek.v15i2.1622>
- Surender, D., Khan, T., Talukdar, F. A., De, A., Antar, Y. M. M., & Freundorfer, A. P. (2022). Key components of rectenna system: A comprehensive survey. *IETE Journal of Research*, 68(5), 3379–3405. <https://doi.org/10.1080/03772063.2020.1761268>
- Tamilarasi, D., Ramesh, P., Krishnamoorthy, R., Bharatiraja, C., & Jayasankar, T. (2021). Design of radio frequency integrated circuit for RF to DC power converter for bio-medical application. *Materials Today: Proceedings*, 45, 2139–2144. <https://doi.org/10.1016/j.matpr.2020.09.733>
- Wagih, M., Weddell, A. S., & Beeby, S. (2020). Rectennas for radio-frequency energy harvesting and wireless power transfer: A review of antenna design. *IEEE Antennas and Propagation Magazine*, 62(5), 95–107. <https://doi.org/10.1109/MAP.2020.3012872>