A NOVEL TRIANGULAR CONFIGURATION OF A RECTANGULAR PATCH ANTENNA ARRAY FOR 2.45 GHz RF ENERGY HARVESTING

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Abstract – *In this paper, a novel compact-sized 3-element rectangular patch antenna array with triangular configuration is proposed for radio frequency (RF) energy harvesting applications. The antenna operates effectively within the 2.45 GHz Wi-Fi band and measures a high gain of 11.24 dBi. Rogers RT 5880 is used as the dielectric substrate, with a dielectric constant of ε_r = 2.2, a loss tangent of δ = 0.0009 and the overall antenna size is 165 mm x 200 mm x 1.65 mm. The return loss and Voltage Signal Wave Ratio (VSWR) are recorded as -32.886 dB and 1.0464 respectively indicating minimal reflection and excellent impedance matching. The antenna achieved a total efficiency of 89.41 %. The design and simulation were performed using Computer Simulation Technology (CST) Microwave Studio 2019 software. The proposed antenna demonstrates satisfactory performance, making it suitable for deployment in RF energy harvesting applications.*

Key Words: **RF Energy Harvesting, Microstrip Patch Antenna, Antenna Array, CST-MWS software**

1. INTRODUCTION

The recent rapid development in technology and improvements in wireless communication systems have resulted in a significant increase in the use of low-power wireless devices [1]. These portable electronic devices facilitate fluid communication among themselves and with their users by emitting electromagnetic (EM) energy through free space. Therefore, their energy requirements must be met in a sustainable and cost-effective manner [1], [2]. In the pursuit of adopting renewable energy sources, energy harnessed from ambient environment emerges as an ideal solution for powering these low-power devices [3], particularly given the environmental concerns associated with non-renewable power sources such as batteries and the cost involved in replacing them [2]. Additionally, these wireless devices are often installed on equipment with high maintenance costs, in inaccessible places such as ocean depths and dangerous locations [4]. Energy harvesting provides the means of capturing ambient energy from sources such as thermal, wind, solar power and radio frequencies [5]. However, scavenging energy from solar, wind and thermal entails high establishment and maintenance cost [6]. In contrast, RF proves to be most favourable for ambient energy harvesting due to its low cost and the increasing availability of RF sources [2], including smartphones, radio and TV transmitters, Wi-Fi routers, radar systems and mobile base stations. A significant portion of the EM energy transmitted by these sources go to waste in free space even before reaching their intended target. Consequently, there exist an abundance of EM energy in space that can be trapped and converted into usable DC voltage to power these low-power electronic devices [1], [6], [7]. Thus, RF energy harvesting plays an imperative role in facilitating the development of battery-free devices [8].

The RF energy harvesting process involves collecting ambient RF power, primarily from wireless power transmission between a transmitter and receiver across long distances [2]. This technique has acquired significant research interest, driven by the increasing availability of RF energy from frequency bands such as GSM (900 MHz, 1800 MHz), UMTS (2100 MHz), LTE (2600 MHz), Wi-Fi (2.4 GHz, 5 GHz), and WiMAX (3.5 GHz) [1]. Studies indicate that RF energy is densely concentrated within the 1700 MHz to 2650 MHz range [8]. An RF-EH system typically includes an impedance matching network (IMN), a rectifier, receiving antenna [2], and an energy storage system (ESS) [3] as depicted in Figure 1.

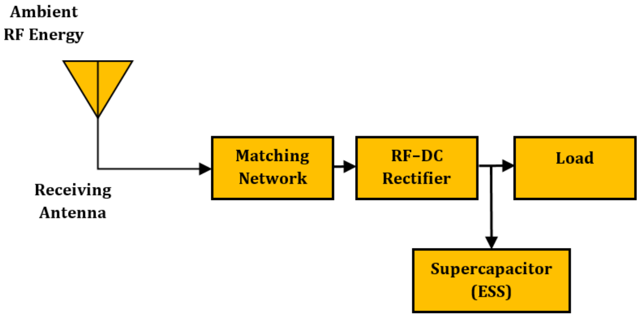


Fig. 1 Schematic diagram of the RF Energy Harvesting System

The antenna plays a crucial role by gathering ambient RF signals in space and converting them into AC voltage. An optimised matching network is essential to ensure that maximum RF signal power from the antenna is transferred to the rectifier circuit. The rectifier then converts this AC voltage into DC voltage, which can be used by these wireless devices or to charge their batteries.

RF power density is typically much lower compared to other ambient sources such as thermal, solar and wind due to the long propagation distance between the transmit and receiving antenna. Theoretical principles, such as the inverse square law, indicate that longer propagation distances result in reduced power density. Moreover, RF power density is further diminished by free space path loss (FSPL) [1]-[3]. Therefore, it is empirical for an RF-EH system to employ a highly efficient antenna for effective RF signal capture, a good IMN to maximise power transfer to the rectifier, and a rectifier with enhanced power conversion efficiency (PCE) to generate the expected DC output voltage [3]. RF energy harvesting presents a promising solution for powering miniaturised, self-sustaining, low-power devices, such as wireless sensor networks and Internet of Things (IoT) devices [2].

The microstrip patch antenna (MPA) has emerged as the preferred choice for wireless communication systems [16] and RF-EH over the past twenty to thirty years, owing to its advantageous design characteristics, including compact size, robustness, lightweight nature, and the capability to be mounted on both planar and non-planar surfaces [10]. Its simplicity and cost-effectiveness facilitate easy fabrication on printed circuit boards (PCBs) [1], [12]. An MPA comprises a radiating element known as the patch, which is situated alongside a feedline on top of a dielectric substrate, with a metallic ground plane etched beneath the substrate, as illustrated in Figure 2 below.

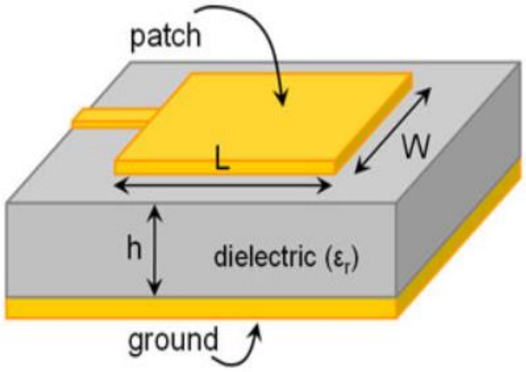


Fig. 2 Simple rectangular microstrip patch antenna

The radiating patch is constructed from conductive materials such as gold or copper and can adopt various random shapes. However, regular geometries, including rectangular, square, elliptical, triangular, dipole, circular, and circular ring configurations, are predominantly employed for ease of fabrication [10], [12].

MPAs are versatile and compact, finding applications in numerous wireless devices, including smartphones, wearable technology, GPS receivers, Wi-Fi routers and medical implants [13], as well as in RF energy harvesting systems [14]. Given that the antenna plays a critical function in determining the quantity of electromagnetic (EM) energy that can be harvested and transformed into usable DC voltage, it is essential for the antenna to exhibit omnidirectionality (to capture RF energy from all directions), high gain (to improve the reception of signals from a designated direction), and wide bandwidth characteristics (to facilitate the capture of RF energy across multiple frequency bands simultaneously) [9], [13], [14]. Despite the MPA's suitability for RF energy harvesting, it faces several challenges, including low efficiency, poor polarisation, low power-handling capacity, narrow bandwidth [12], and low gain when implemented as a single patch antenna [14]. To address these limitations, this study investigates and presents a patch antenna array designed for RF energy harvesting.

2. Related Work

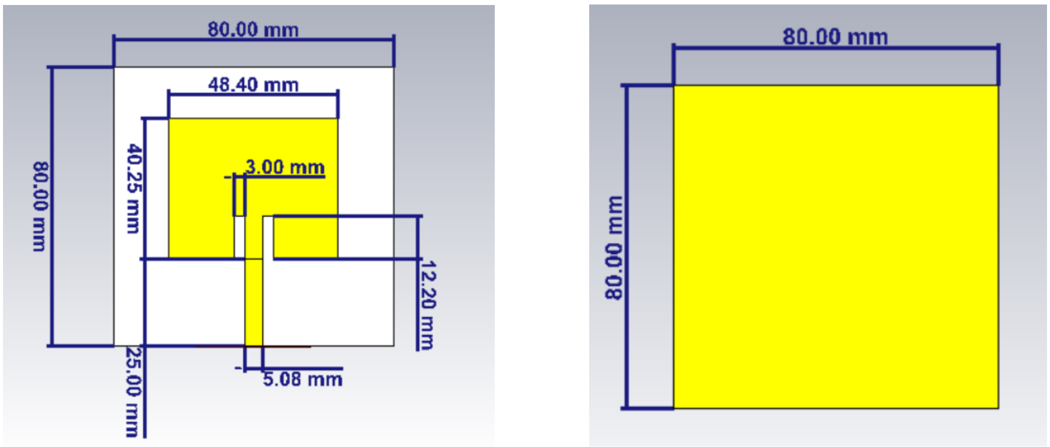
Researchers have designed and implemented microstrip patch antennas for RF-EH applications. In RF-EH, it is essential to use receiving antennas with high gain and wideband characteristics to optimise performance [13], [14]. High-gain antennas are crucial as they enhance the received power, thereby improving the overall DC output voltage of the RF-EH system. In instances where the ambient RF energy source is unknown, omnidirectional antennas are often employed to capture signals from all directions. However, these antennas face challenges such as limited range, reduced efficiency, and low gain [2]. Enhancing the gain of microstrip patch antennas can be achieved by increasing the width of the patch or by constructing patch antenna arrays. While increasing patch width improves both gain and bandwidth, it also leads to higher surface wave losses and reduces the compactness of the antenna [15]. Conversely, patch antenna arrays offer higher gain, improved bandwidth, better polarisation control, and increased efficiency, making them more suitable for RF energy harvesting applications [1].

An edge-fed MPA was designed for Wi-Fi applications, as detailed in [17]. The antenna resonates at two distinct frequencies due to the presence of three rectangular slots carefully created in the radiating element. The operating frequencies are 2.41 GHz and 5.8 GHz, with corresponding gains of 0.5102 dBi at 2.41 GHz and 1.175 dBi at 5.8 GHz. In [9], a multiband fractal antenna, designed in the shape of a drone and featuring a defected ground structure, has been developed and implemented for RF energy harvesting. The antenna operates at six different frequency bands, covering mobile communication services, WLAN frequencies, and WiMAX services. The design achieves a maximum bandwidth of 428.1 MHz at 5.8 GHz and the highest gain (2.83 dBi) is realised at 2.45 GHz. A hexagonal-shaped patch antenna with a partial ground structure, operating at the 5.8 GHz Wi-Fi frequency, is presented in [5]. The partial ground structure facilitates omnidirectional radiation characteristics, enabling the antenna to capture RF energy from all directions. Additionally, a stub is introduced to extend the bandwidth and improve impedance matching. The antenna achieves a low gain of 2.88 dBi and appreciable bandwidth of 680 MHz. In [18], the authors designed and simulated a dual-band

MPA using HFSS software. The antenna operates at 3.6 GHz and 5.25 GHz frequencies, exhibiting bandwidths of 300 MHz and 2110 MHz, with corresponding gains of 2.77 dBi and 3.34 dBi, respectively. Although the antenna operates effectively at these two separate frequencies, the radiation efficiency at 5.25 GHz is recorded at 69.96%, indicating a need for improvement. A compact sized dual-band MPA is designed and analysed [1] for RF energy harvesting applications. FR-4 is used as the substrate, with height of 1.6 mm. The antenna works at 2.4 GHz and 5.2 GHz frequencies and has overall dimension as $28 \times 47 \times 1.6$ mm^3. The gain at the two operating frequencies is measured at 1.6 dBi and 3.95 dBi, with corresponding bandwidths of 340.5 MHz and 293.4 MHz. While the antenna demonstrates favourable radiation efficiencies at both frequencies, its overall efficiency remains moderate. A reconfigurable MPA is designed and presented in [16], featuring three switching modes: OFF-OFF, ON-OFF, and ON-ON. The frequency tuning is achieved using an RF MEMS shunt capacitor switch. The antenna achieves a bandwidth of 110 MHz and maintains a return loss below -20 dB across all switching modes. The corresponding gains for the three modes are 4.2 dBi, 4.2 dBi, and 4.3 dBi, respectively. In [7], a b-shaped MPA was presented. To accelerate the simulation process, machine learning techniques were employed. A partial ground plane was implemented to provide the antenna with omnidirectional radiation characteristics. The antenna supports frequencies for both mobile communication and WLAN. It demonstrates total and radiation efficiencies exceeding 85% across all four resonant frequencies, with a maximum gain of 4.74 dBi observed at the 2.6 GHz LTE frequency. In [8], a wideband patch antenna with two open ring resonators was designed and implemented for RF-EH applications. The antenna records maximum gains of 5 dBi at 2.45 GHz, and 2 GHz. In [19], a circular monopole MPA was designed and implemented for ultra-wideband applications. The antenna obtains a gain of 5.92 dBi and a bandwidth of 8.2 GHz, from 1.8 GHz to 10 GHz. In [10], an MPA was simulated and analysed using CST software for wireless applications. The antenna exhibits resonance at 3.5 GHz, covering a bandwidth of 144.1 MHz. It obtains a return loss value of -30.611 dB and a gain of 6.05 dBi. Researchers in [14] simulated and fabricated a 2x2 patch antenna array, specifically targeting the GSM 1800 MHz frequency band. It obtained a gain of 9.2 dBi, indicating its potential as an effective candidate for RF energy harvesting. In [13], a circular concentric MPA with seven rectangular patch elements was designed and simulated using CST-MWS software. Initially, a single-element antenna was developed, achieving a gain of 8.22 dBi at the resonant frequency. Subsequently, the proposed antenna array was simulated, resulting in a gain of 15.8 dBi, which is approximately twice the gain of the single-element antenna. These findings clearly shows that the implementation of antenna arrays significantly enhances gain. In [4], a 2.4 GHz 2x4 antenna array was designed and simulated using MATLAB for RF energy harvesting applications. The antenna reached a high gain of 17.5 dBi. However, the presence of high side lobe levels adversely affects the radiation efficiency, thereby reducing the overall performance of the antenna. In [14], [13], and [4], it has been shown that antenna arrays significantly enhance gain, which is a critical factor for RF energy harvesting. Theoretically, increasing the number of elements in an array leads to higher gain, as it results in constructive interference that allows the antenna to concentrate radiated power in a specific direction, thereby improving both gain and directivity [12]. However, while an increased number of elements generally boosts gain, factors such as inter-element spacing can introduce challenges, including higher side lobe levels and impedance matching difficulties [15]. Patch antenna arrays are typically constructed in square or rectangular configurations, as seen in [14] and [4]. Common configurations include 1x2, 1x4, 2x2, 2x4, and 3x3 arrays [12]. In [13], a seven-element circular concentric patch array achieved a high gain of 15.8 dBi. This paper introduces a novel triangular configuration of a three-element rectangular patch antenna array, resonating at 2.45 GHz for RF-EH applications. The design and simulation are performed using CST-MWS 2019 simulation software.

3. Design Principle

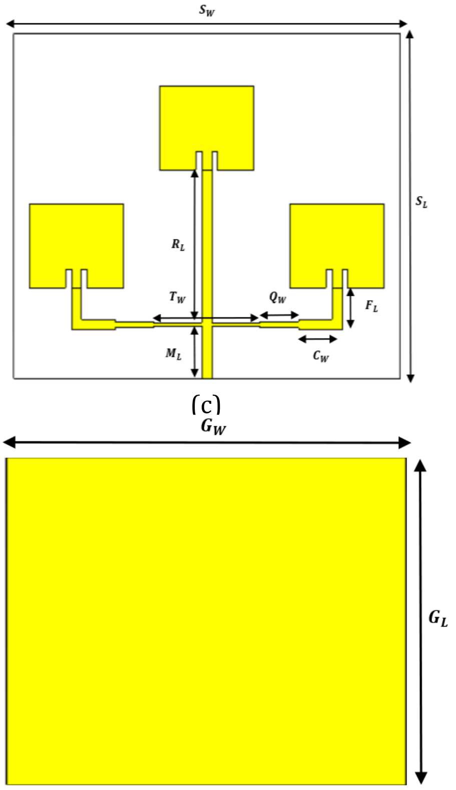
We began our work by designing and simulating a single-element inset-fed rectangular MPA using CST-MWS software. Rogers RT 5880 was used as the dielectric substrate, with a height of h = 1.65 mm, a dielectric constant of $\varepsilon\_r = 2.2$, and a loss tangent of $\delta = 0.0009$. The patch and ground plane were fabricated from annealed copper with a thickness of Mt = 0.035 mm. The operating frequency was selected as 2.45 GHz, a widely used frequency band, making it a suitable candidate for harvesting ambient RF energy to power low-power wireless devices. Figure 3 below presents the structure and dimension of the 1x1 patch antenna.



(a) (b)

Fig. 3 Design structure and dimension of the 1x1 patch antenna (a) top view (b) bottom view

Additionally, a novel triangular configuration of the three-element rectangular patch antenna array was developed building upon the design of the 1x1 patch antenna, to further improve performance and increase suitability for the intended application.



(c)

(d)

Fig. 4 Design structure and dimension of the proposed 3 – element patch antenna array (c) top view (d) bottom view

Table 1 below presents the dimensions of the proposed three-element patch antenna array.

Table -1: Dimension of the Proposed Three -Element Patch Array

Variable		**Optimised Value (mm)**	
SL	SW	165	200
GL	GW	165	200
ML	MW	25	5.08
INL	INW	9	3
TL	TW	1.48	55
QL	QW	2.92	20
CL	CW	5.08	20
FL	FW	20	5.08
RL	WL	73	5.08

4. Results and Discussion

The simulation results and analysis of both the single-element patch antenna as well as the proposed three-element antenna array are presented in this section.

4.1 Simulation Results of the 1x1 Patch Antenna

The simulation results show that the antenna resonates at 2.45 GHz, as observed from the scattering parameter |S11|, with a return loss of -47.635 dB. The antenna operates effectively within the frequency range of 2.4319 GHz – 2.4679 GHz, giving a bandwidth of 36 MHz. At the resonant frequency, the VSWR is seen as 1.0083, indicating minimal reflection and excellent impedance matching [12]. The gain and directivity are obtained as 6.966 dBi and 7.784 dBi respectively. Additionally, the radiation and total efficiencies of the 1x1 patch antenna are both observed to be 82.84 %, demonstrating good overall antenna performance. The |S11| graph and VSWR are presented in Figure 5 and 6, respectively. The gain and 3D radiation pattern are shown in Figure 7 while the 2D polar plots are given in Figures 8(a) and 8(b).

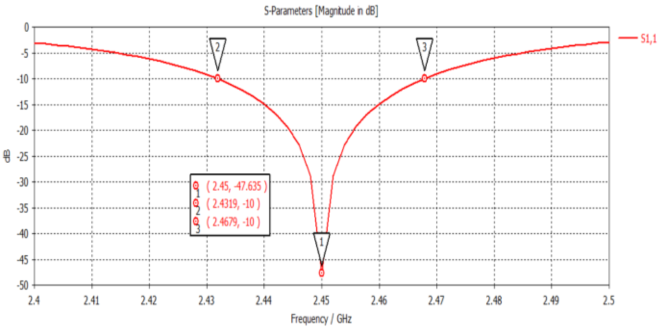


Fig. 5 S11 parameter of the 1x1 patch antenna

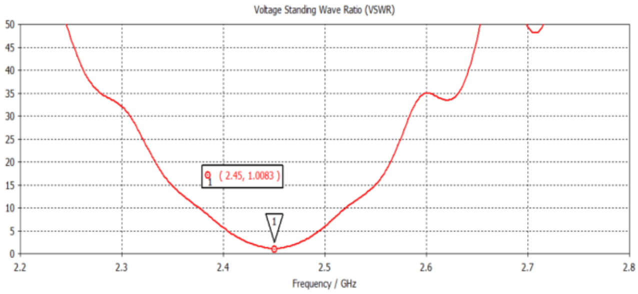
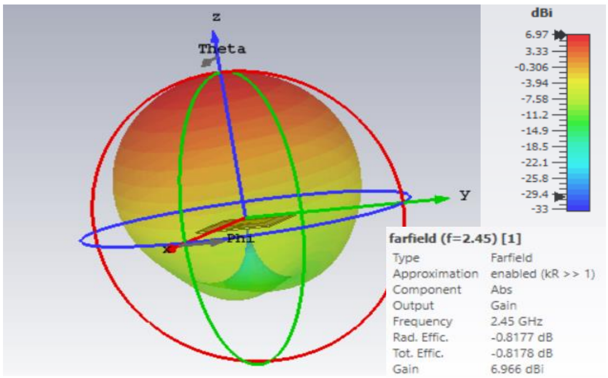


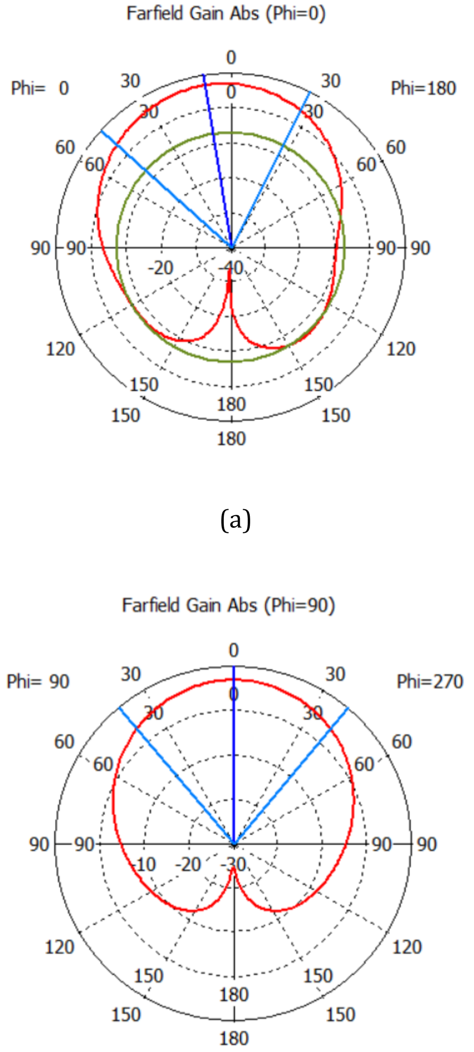
Fig. 6 VSWR graph of the 1x1 patch antenna



farfield (f=2.45) [1]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Gain
Frequency	2.45 GHz
Rad. Effic.	-0.8177 dB
Tot. Effic.	-0.8178 dB
Gain	6.966 dBi

Fig. 7 3D Radiation pattern of the 1x1 patch antenna



(a)

(b)

Fig. 8 (a) E-plane and (b) H-plane radiation patterns of the 1x1 patch antenna

4.2 Simulation Results of the 3-element Patch Antenna Array

The simulation results showed that, the 3-element antenna array resonates at 2.45 GHz, having a return loss of -32.886 dB. The antenna has a bandwidth of 31.5 MHz, and operates effectively between 2.4342 GHz and 2.4657 GHz. The VSWR is observed to be 1.0464, and the realised gain and directivity is obtained as 11.24 dBi and 11.72 dBi respectively. Furthermore, the radiation efficiency and total efficiency are both observed to be 89.45 % and 89.41 %, indicating the antenna's high performance in energy transmission and overall efficiency. Figure 9 and 10 present the |S11| graph and VSWR of the 3-element patch antenna array. Additionally, the gain and 3D radiation pattern are given in Figure 11 and the 2D polar plots are given in Figures 12(a) and 12(b).

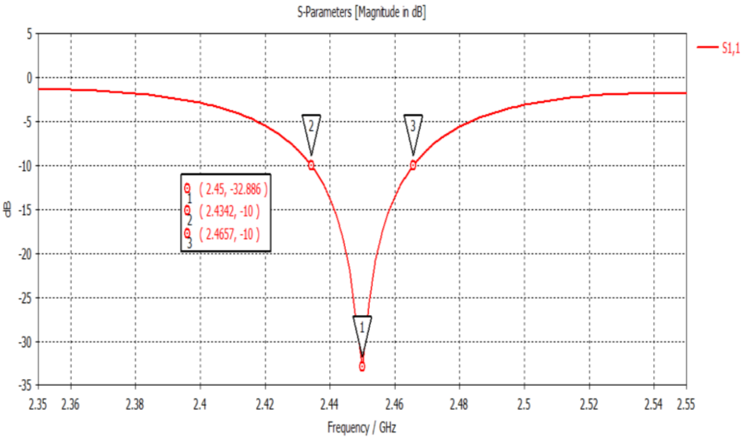


Fig. 9 S11 parameter of the proposed 3-element patch antenna array

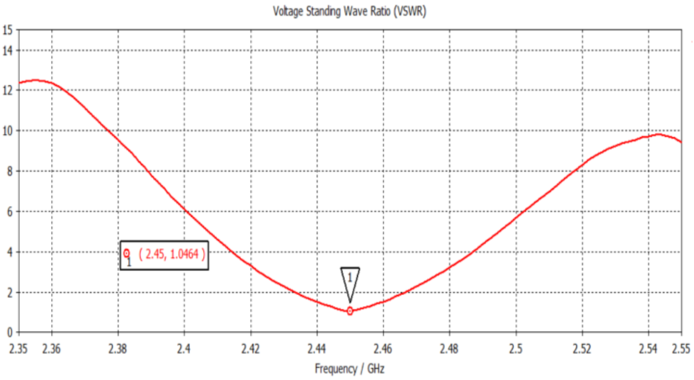
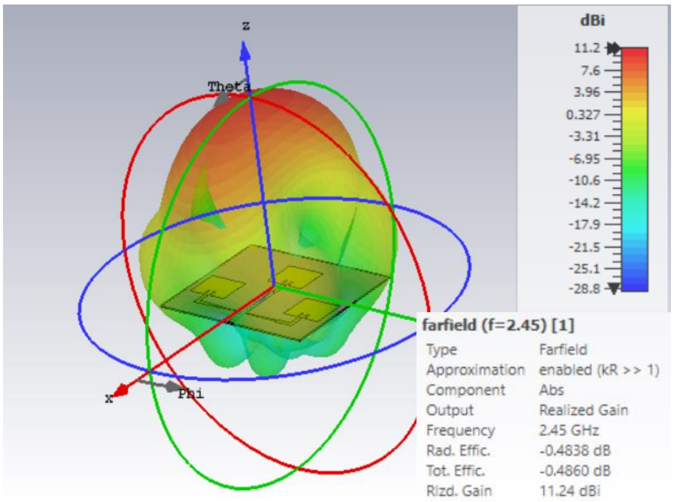
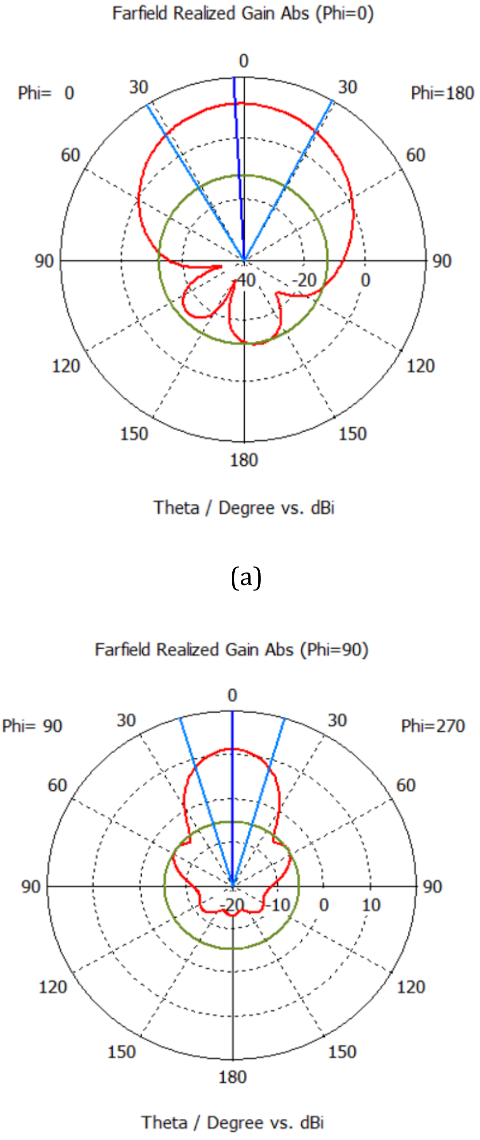


Fig. 10 VSWR graph of the proposed 3-element patch antenna array



farfield (f=2.45) [1]
Type Farfield
Approximation enabled (kR >> 1)
Component Abs
Output Realized Gain
Frequency 2.45 GHz
Rad. Effic. -0.4838 dB
Tot. Effic. -0.4860 dB
Rlzd. Gain 11.24 dBi

Fig. 11 3D Radiation pattern of the proposed 3-element patch antenna array



(a)

(b)

Fig. 12 (a) E-plane and (b) H-plane radiation patterns of the 3-element patch antenna array

Table 2 below provides a summary of the simulation results, highlighting the key findings.

Table -2: Summary of simulation results and key findings

Array	1x1	3-Element
Return Loss (dB)	-47.635	-32.886
Bandwidth (MHz)	36	31.5
R. Gain (dBi)	6.966	11.24
Directivity (dBi)	7.784	11.72
Rad. Effic. (%)	82.84	89.45
Tot. Effic. (%)	82.84	89.41

4.3 Discussion

In this research, it is observed that the gain of an antenna increases significantly with an increase in the number of patch elements. However, this is dependent on ensuring the necessary inter-element distance between the patches. Patch antenna arrays are usually constructed in square and rectangular configurations, as seen in [4] and [14]. Popular square or rectangular configurations include 1x2, 1x4, 2x2, 2x4 and 3x3 [12]. In [14], the gain of a 2x2 rectangular patch antenna array is seen as 9.2 dBi. The gains for 2x2, 2x3 and 2x4 triangular patch arrays designed in [20] were recorded as 11 dBi, 10.4 dBi and 10.3 dBi respectively. The 7-element rectangular patch antenna array with circular concentric configuration gave a gain of 15.8 dBi, while the 2x4 rectangular array in [4] measured 17.5 dBi as gain. In [4], it is realised that, even though it produces a very high gain of 17.5 dBi, the overall antenna efficiency is expected to be fairly lower due to high side lobe levels in its radiation pattern. In this paper, a compact 3-element rectangular patch antenna array with triangular configuration is designed for RF energy harvesting applications. This antenna measures a gain of 11.24 dBi at the resonant frequency, which is higher than the gains observed in the 2x2 array in [14] and the 2x2, 2x3 and 2x4 in [20]. It is noticed that aside from increasing the number of patch elements, ensuring the required inter-element distance significantly impacts the gain of the antenna, including the shape of the patch element. Table 3 below presents a comparison between the proposed design and previous related works.

Table -3: A comparative analysis of the proposed design to previous related works.

Reference	Frequency (GHz)	Array Size	Return Loss (dB)	Peak Gain (dBi)	Rad. Effic. (%)	Tot. Effic. (%)
[1]	2.4, 5.2	1x2	-20.6, -16	1.6, 3.95	81, 69	80,67
[7]	1.8, 2.1, 2.45, 2.6	1x2	-13.08, -16.67, -11.48, -12.51	3.28, 3.84, 4.47, 4.74	90, 91, 90, 89	85, 89, 84, 84
[14]	1.8	2x2	-25	9.2	-	-
[13]	2.4	7-element	<-50	15.8	96	94
[4]	2.4	2x4	-26.2	17.5	-	-
[20]	2.4	1x1, 1x2, 2x2, 2x3, 2x4	-17.33, -19.29, -12.26, -26.86, -42.33	5.28, 7.20, 11.0, 10.4, 10.3	-	-
This work	2.45	3-element	-32.886	11.24	89.45	89.41

5. CONCLUSIONS

In this paper, a novel triangular configuration of a 3-element rectangular patch antenna array is designed and proposed for RF energy harvesting. The antenna achieves a high gain of 11.24 dBi at 2.45 GHz with radiation and total efficiencies of 89.45% and 89.41 % respectively. The antenna operates effectively between 2.4342 GHz and 2.4657 GHz covering a bandwidth of 31.5 MHz. The return loss and VSWR are observed to be -32.886 dB and 1.0464 respectively, indicating minimal reflection and excellent impedance matching [12]. The proposed antenna demonstrates satisfactory performance, making it suitable for deployment in RF energy harvesting applications. Future work will focus on designing an efficient rectifier using ADS (Advanced Design System) software to convert RF power into DC power, thereby enabling energy harvesting within the 2.45 GHz Wi-Fi band. Additionally, further research should explore various array configurations to optimise gain. This approach could potentially achieve high-gain performance with fewer patch elements, enhancing the efficiency of antenna systems in high-gain applications.

REFERENCES

[1] B. Kanboz and M. Palandöken, "Microstrip patch antenna array design for RF energy harvesting applications," *Eur. J. Sci. Technol.*, no. 49, pp. 34–37, 2023.

[2] Y. C. Lee *et al.*, "High-Performance Multiband Ambient RF Energy Harvesting Front-End System for Sustainable IoT Applications—A Review," *IEEE Access*, vol. 11, pp. 11143–11164, Jan. 2023, doi: 10.1109/access.2023.3241458.

[3] M. Cansız and D. Altınel, “Multiband RF energy harvesting for zero-energy devices,” *Electrical Engineering*, vol. 105, no. 3, pp. 1013-1023, 2023. doi: 10.1007/s00202-022-00769-9.

[4] U. Nnamdi, B. Omijeh, and I. Asianuba, “Design and optimization of a 2.4 GHz antenna array for energy harvesting,” *Eur. J. Theor. Appl. Sci.*, vol. 1, no. 6, pp. 676–683, 2023.

[5] R. Das and G. S. Baghel, “Design of a hexagonal patch defected ground antenna for energy harvesting applications,” in *Proceedings of the International Conference on Innovations in Electronics and Communication Engineering (IECE)*, 2024, pp. 1-5.

[6] R. Agrahari et al., “Triple-band metasurface absorber for RF energy harvesting applications,” *Microwave Opt. Technol. Lett.*, vol. 65, no. 8, pp. 2252–2261, 2023.

[7] Y. E. Kuşin and M. Palandöken, “Machine learning based b-shaped monopole antenna for RF energy harvesting applications,” *Int. J. Adv. Nat. Sci. Eng. Res.*, vol. 7, no. 6, pp. 33–38, 2023.

[8] M. Zeng, Z. Li, Y. Ding, and X. Lin, “A wide-band antenna with dual open rings resonator for RF energy harvesting,” *Microwave and Optical Technology Letters*, vol. 64, no. 11, pp. 2019–2023, Jun. 2022, doi: 10.1002/mop.33383.

[9] M. M. Hasan and A. M. A. Sabaawi, “Drone Shaped Fractal Antenna with Defected Ground Structure for RF Energy Harvesting Applications,” *Periodica Polytechnica Electrical Engineering and Computer Science*, Jun. 2024, doi: 10.3311/ppee.24041.

[10] Md. S. Rana, Md. N. Khurshid, S. K. Joy, Md. S. I. Sourav, Md. J. Hassan, and Md. J. Nazmul, “A 3.5 GHz microstrip patch antenna design and analysis for wireless applications,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 32, no. 2, p. 828, Sep. 2023, doi: 10.11591/ijeecs.v32.i2.pp828-837.

[11] N. U. Khan, S. Ullah, F. U. Khan, and A. Merla, “Development of 2400–2450 MHz frequency band RF Energy harvesting System for Low-Power Device Operation,” *Sensors*, vol. 24, no. 10, p. 2986, May 2024, doi: 10.3390/s24102986.

[12] Y. Huang and K. Boyle, *Antennas: From theory to practice*. 2008. [Online]. Available: https://www.amazon.com/Antennas-Theory-Practice-Yi-Huang/dp/0470510285

[13] A. A. Kabeel, A. H. Hussein, A. E. ElMaghrabi, and R. H. Elabd, “Design of a circular concentric microstrip patch antenna array for WI-FI band energy harvesting,” *Journal of Engineering Research - Egypt/Journal of Engineering Research*, vol. 7, no. 5, pp. 156–159, Nov. 2023, doi: 10.21608/erjeng.2023.237512.1253.

[14] T. Sharma and G. Saini, “Microstrip Antenna Array for RF Energy Harvesting System,” *International Journal of Advanced Information Science and Technology (IJAIST)*, vol. 48, no. 48, pp. 1-5, Jan. 2016.

[15] R. Garg, P. Bhartia, I. Bahl, and A. Ittipiboon, *Microstrip Antenna Design Handbook*. Norwood, MA: Artech House, 2001.

[16] J. Navarajan, M. R. E. Jebarani, and V. G. Krishnan, “Frequency Reconfigurable Microstrip Patch Antenna for Multiband Applications with RF MEMS Shunt Capacitor Switch,” *International Journal of Intelligent Systems and Applications in Engineering*, vol. 11, no. 3s, pp. 01-07, 2023.

[17] S. Küçükcan and A. Kaya, “Dual-Band microstrip patch antenna design for Wi-Fi applications,” *European Journal of Science and Technology*, Mar. 2022, doi: 10.31590/ejosat.1084147.

[18] P. Ramineni, “Design and analysis of a Dual-Band Microstrip patch antenna for sub-6 GHz applications,” *Journal of Engineering Research and Reports*, vol. 26, no. 7, pp. 210–221, Jun. 2024, doi: 10.9734/jerr/2024/v26i71204.

[19] B. S. Taha and H. M. Marhoon, “Simulation and manufacturing of modified circular monopole microstrip antenna for UWB applications,” *International Journal of Advances in Applied Sciences*, vol. 10, no. 1, p. 70, Mar. 2021, doi: 10.11591/ijaas.v10.i1.pp70-78.

[20] T. Jayanthy, J. Harini, A. Haseena, and N. C. L., "Design and Analysis of Triangular Patch Antenna Array," *International Journal of Engineering Research and Technology (IJERT)*, vol. 8, no. 12, pp. 123-128, 2024.