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ELECTROMAGNETIC ENERGY HARVESTING USING 2.40 GHZ COMPACT HIGH GAIN PATCH ANTENNA

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Abstract

Self-powered electronic devices have found application in several fields, for instance, the Internet of Things (IoT), smart buildings, remote sensing, and wireless sensor network. Energy harvesting devices are gaining more interest in these devices due to the maintenance problem and short lifespan of batteries. Moreover, a lower gain of the antenna, coupled with the compact size and low conversion efficiency of the rectifier imposes further limitations to the application of antenna-based energy harvesting systems. This paper presents a high gain antenna of 6.69 dBi within an electrical dimension of $0.3248\lambda \times 0.3248\lambda$; this antenna exhibited a resonance of 2.4 GHz and can be adopted for microwave energy harvesting from the available Wi-Fi band. A commercially available RF-DC converter module, RFD-ASSY-01, was coupled to the proposed antenna for the conversion of the received RF signal to DC. The available output DC voltage of this converter was measured, and the power conversion efficiency was calculated for a 7 dBm transmitted power of NETIS (AC1200) WLAN router placing it 1 meter away from the receiving antenna. The experimental result showed that the transmitted power by the proposed rectenna achieved 71% power conversion efficiency. The comparison of this system with some existing works showed that the proposed energy harvesting system performed better even with a small-sized antenna. Thus, the system can energize low-power electronic devices using power sourced from nearby electromagnetic sources.

Keywords: Conversion efficiency, Electromagnetic energy harvesting, Rectenna.

1. Introduction

Technology advancement has broadened the application areas of self-powered electronic devices; for instance, the number of base stations around the world in 2012 was approximately 12 million but in 2013, the number of devices that used radio frequency identification card RFID was nearly 68 billion, while around 40 billion wireless fidelity Wi-Fi electronic equipment were utilized in 2014 [1]. In recent years, these numbers have been doubled, leading to an increase in electromagnetic EM sources and a boost in the use of low-power electronic devices. Mostly, these devices are battery-operated that may need frequent replacement of the batteries. To overcome the ever-increasing power demand for low-power electronic devices, electromagnetic energy harvesting techniques have gained more attention compared with other major sources, such as heat, vibration, solar, microwave piezoelectricity, and pyro electricity because it is potentially more available even through opaque walls. Therefore, EM energy harvesting has become a promising technology for the continuous supply of power to RFID and movable smart devices to increase the reliability and sustainability of low-power wireless devices.

To design an efficient EM energy harvesting system, it is essential to achieve a high-power conversion efficiency; however, numerous challenges limit the achievement of high conversion efficiency, such as:

- The finite sensitivity of the connected circuit, as well as losses related to each component.
- The uncertain availability of the incident RF power and the distance from the receiver to the transmitter.
- The restrictions at the maximum radiated power.
- The alteration of the frequency and the antenna output impedance due to the alteration of the input power causes mismatch losses.
- The high nonlinearity reliance of the output voltage on the input when the input power is low.

Numerous forms of rectenna operating at a frequency band of 2.4 GHz have been proposed by various researchers for energy harvesting from EM sources. Niotaki et al. [2] selected two frequency bands (0.915 and 2.45 GHz) to operate their compact dual band rectenna. This rectenna comprises a slot loaded dual band folded dipole antenna with a dimension of 60×60 mm, and a dual band rectifier. The power conversion efficiencies of this rectenna at frequency bands of 0.915 and 2.45 GHz were 37% and 30% respectively at 9 dBm the input power and a load resistance of 2.2 kΩ. A power processing circuit operating at 2.4 GHz has been used in another study for indoor harvesting of RF energy [3]. The circuit was connected to an antenna and a power management unit; the analytical analysis of this circuit showed an overall conversion efficiency of 30%. The circuit operates smoothly at a Wi-Fi power of -20 dBm and can work efficiently at -50 dBm Wi-Fi power. The performance of a wideband rectenna in RF energy harvesting from Wi-Fi/LAN signal work at 2.4 GHz frequency band has been evaluated by Huang et al. [4]. This rectenna achieved different conversion efficiencies (4.3%, 24.3%, 48.5%, 63%) at different input power (-30, -20, -10, 0 dBm). Alneyadi et al. [5] presented the design and assessment of an RF harvester. The harvester operates at a 2.42 GHz WiFi band; its design comprised several microstrip patch antennas (dimension = 45.1×45.1 mm), a voltage quadruple Greinacher rectifier circuit, a power combiner, and a supercapacitor. The conversion efficiency of this design was 57.8% when the input power values are 6 to 8 dBm.

Amjad et al. [6] simulated and analysed the design of an RF energy scavenging system. The system consisted of a microstrip patch antenna, an impedance matching network, a four-stage voltage doubler, and a storage circuit. The microstrip antenna functions at 2.4 GHz and 5.8 GHz frequency bands. Based on the simulated and measured results, the system achieved an overall efficiency of 45% at 10 mW input power. Fayçal and Dibi [7] presented the design and fabrication of a compact sensor for EM energy harvesting. The sensor utilizes a dual-polarization antenna that operates at 2.45 GHz within the ISM band. The maximum conversion efficiency of the sensor was 41% at 2.49 GHz frequency and −10 dBm input power.

The aforementioned works show that the researchers either strive to reduce the antenna size (leading to degradation in the overall rectenna performance) or design a bulky-sized antenna to rise the power conversion efficiency (such a large-sized antenna may not be suitable for applications that require small-sized rectenna). Thus, the proposed rectenna system in this paper has the merits of compact size and high-power conversion efficiency compared to the previous designs operating at the same frequency band. The rectenna system was developed using a square-shaped truncated corner compact high gain patch antenna connected with RFD-ASSY-01 RF to a DC converter operating at 2.4 GHz.

2. Theory on Rectenna System

A typical energy harvesting system contains an antenna, a rectifier, the necessary matching circuit, and an output load, as revealed in Fig. 1. The antenna's role is to get the incident RF power for onward transformation to DC by the rectifier circuit. An impedance matching circuit is required to control the RF energy received by the antenna, whereas the impedance matching network is required for the blocking of the reversal of the RF energy to free space; thus, it assists in raising the voltage power of the RF signal and the peak input voltage toward the rectifier circuit. The main challenges during the design of the rectenna are the nonlinearity of the rectifier with identical frequencies, and the rectenna's power losses [8]. To ameliorate the execution of the rectifier circuit with steady load resistance, a proper matching network is needed [9, 10]. A filter is placed between the rectifier and the antenna to enhance the conversion efficiency and eliminate the high-order harmonics created by the nonlinear circuit [11, 12]. The performance of the energy harvesting system can be evaluated by measuring the output voltage at low input power; the performance metric is normally the total RF-DC conversion efficiency.

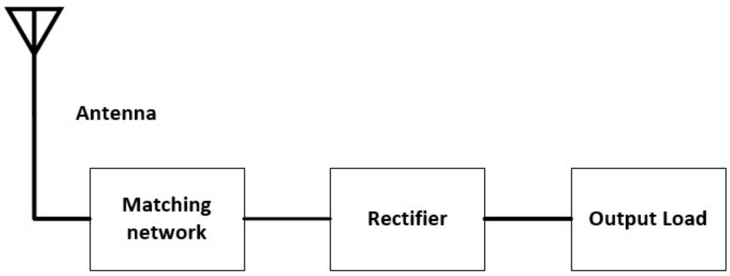

Fig. 1. Typical energy harvesting system.

In Fig. 1., the earned power by the receiver antenna can be connected to the transmitted power using Eq. (1):

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} \tag{1}$$

where P_t and P_r indicate the transmitted and received power, respectively, G_t and G_r are the transmitted and received antenna gain respectively, R represents the distance between the received and transmitted antenna, and λ refers to the wavelength of the RF signal.

3. Rectifier Analysis

Rectifier circuit design plays a crucial role in the harvesting of energy from electromagnetic sources because it is required to operate at maximum power efficiency and through a broad domain of input power levels. Usually, the rectifier is designed by an assembly of Schottky diodes due to its lower threshold and higher breakdown voltage. In this experiment, RFD-ASSY-01 the RF-DC converter module was used to set up the whole system. Figure 2 shows an RFD-ASSY-01 that utilizes 4 RFD102A modules and 1 RFD88A energy harvesting engine module. This converter can achieve around 60 mA of CW output current under drive at the DCIN pin of the RFD102As. This flexible design is meant to be used with a >5.5V rated supercapacitor, and by connecting to the RFD88A DCOUT pin, it can achieve about 140 mA of burst current. With the RFD-ASSY-01, energy can be harvested in the range of 0.001 GHz to 6 GHz when attached to an antenna to extract the energy of wireless sources. Figure 3 shows the assembly diagram of the RFD-ASSY-01.

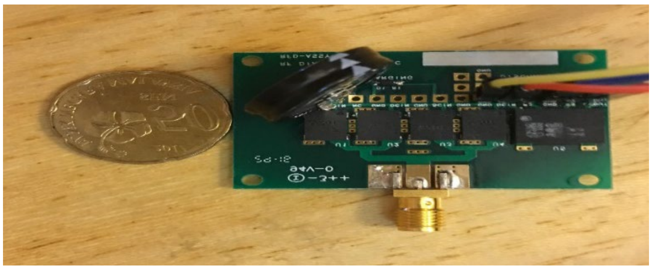

Fig. 2. RFD-ASSY-01 RF to DC converter module with the capacitor.

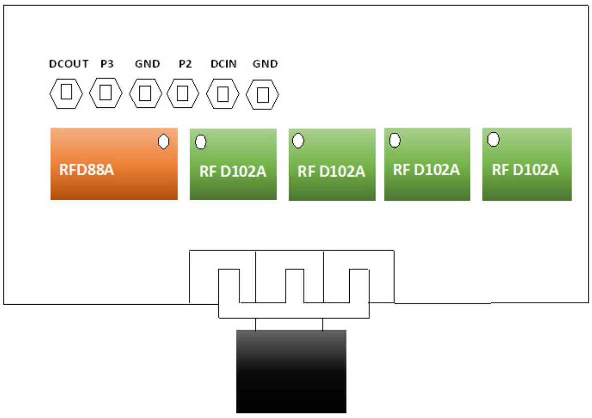

Fig. 3. Assembly diagram of RFD-ASSY-01.

4. Antenna Design and Analysis

The proposed antenna comprised a simple wide square slot patch with two truncated corner cuts. Square-shaped ground plane. The antenna was fabricated on Rogers RT-duroid5880(TM) substrate with a thickness of 1.575, loss tangent of 0.0009, and a dielectric constant of 2.2. The direct feed method was employed here to attach the patch; the ground plane was printed within the patch as shown in Fig. 4. The measured maximum gain of 6.69 dBi was achieved, with a variation of 0.5 dBi [12]. The antenna exhibited resonance at 2.4 GHz frequency; the total antenna dimension is 40.6 mm × 40.6 mm. Figure 4 depicts the front and back views of the proposed antenna.

(a) Front sight of the proposed antenna (b) Back sight of the proposed antenna

Fig. 4. Front and the back sight of the proposed antenna.

5. Experimental Setup

The rectenna for energy harvesting systems is formed by attaching the proposed antenna to the RFD-ASSY-01 power converter as shown in Fig. 5. The NETIS (AC1200) WLAN router is positioned one meter from the rectenna; the output is derived by measuring the voltage using a multimeter connected across a variable resistance of 50 KΩ. The resistance is joined to the output terminal of the rectenna module. The router serves as the RF source with an inbuilt option of changing RF signal power using software; this eases the measurement of the rectenna performance. The experimental setup of the energy harvesting system proposed in this study is shown in Fig. 6.

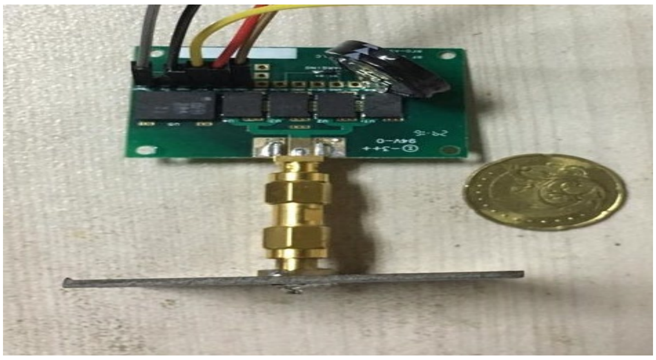

Fig. 5. Complete Prototype of the rectenna system.

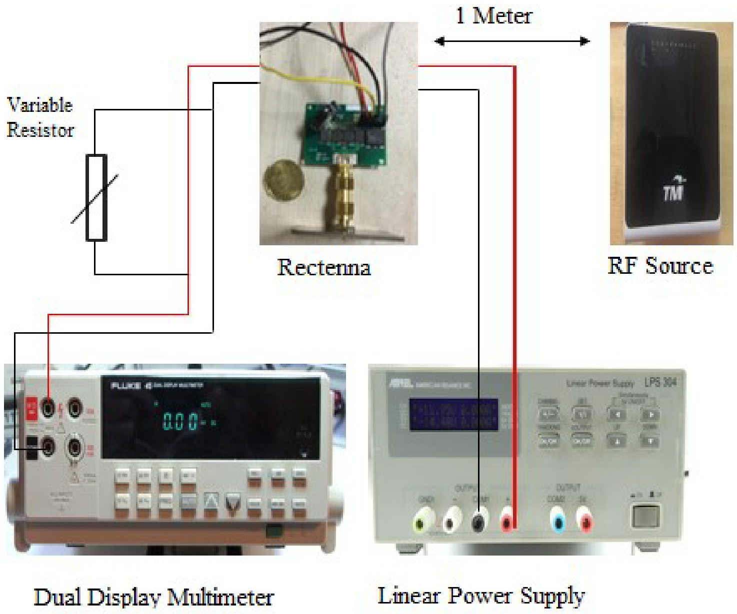

Fig. 6. Experimental setup for the rectenna system.

6. Result and Discussion

A linear power supply system was connected to the rectifier to keep the system ready to respond with incident RF signal; the output was measured utilizing a Dual Display Millimetre as shown in Fig. 7. The input power of the RF source was set by changing the ratio of radio power of NETIS (AC1200) WLAN Router using the software shown in Fig. 8. The change of the output voltage via the modification of the input RF power and the change of load resistance were discussed as follows.

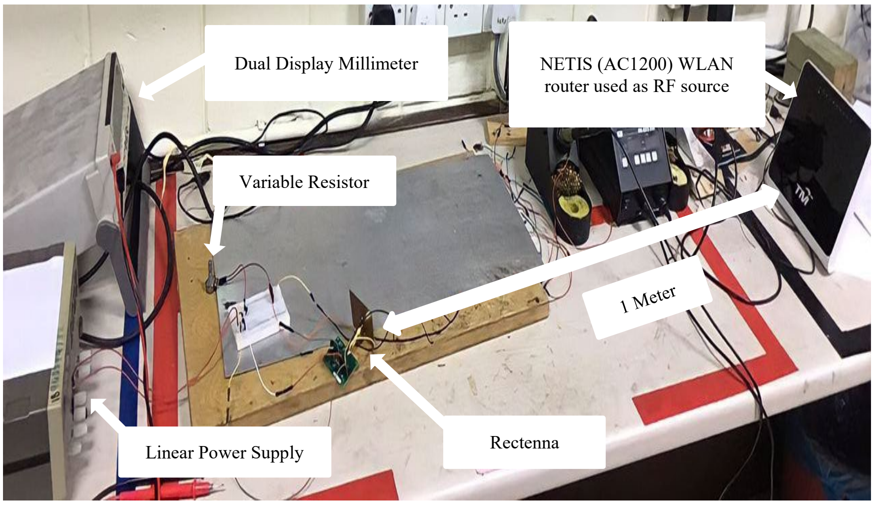

Fig. 7. The actual figure of the experimental setup taken in Microwave Lab, University Kebangsaan Malaysia.

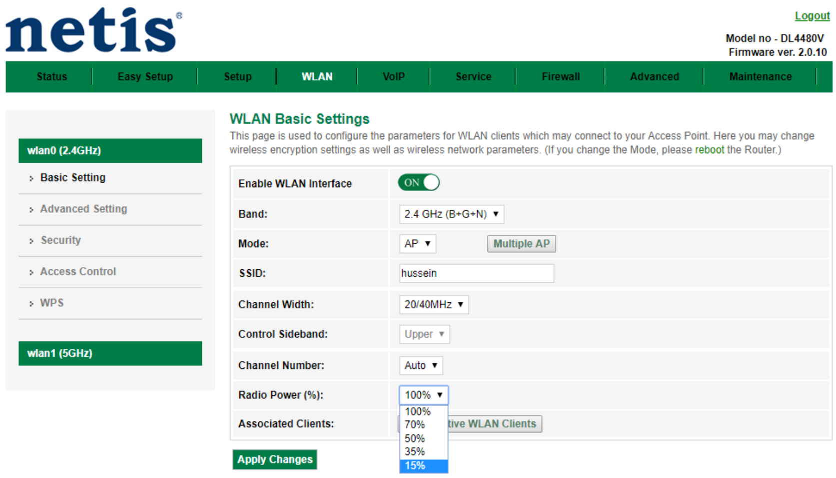

Fig. 8. NETIS (AC1200) software to change RF transmitting power.

Figure 9 showed the response of the rectenna when the load resistance values of 5, 30, and 45 kΩ were selected to provide similar output voltage levels with minor variations while keeping the input power of the RF source stable at 20 dBm with the frequency band of 2.4 GHz at a preset supply voltage of 2.57 V. It was noticed that sufficient output voltage levels were achieved at the selected resistance values without any form of deterioration in the conversion efficiency at 2.4 GHz frequency band. The results showed that the achievable output voltage values at the load resistance values of 5, 30, and 45 kΩ were 2.51, 2.52, 2.57 V, respectively.

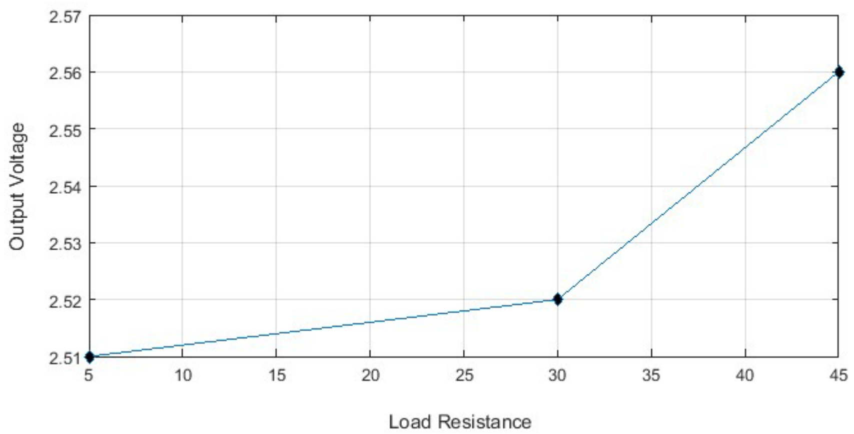

Fig. 9. Output voltage versus resistance where resistance is measured in kΩ and voltage in Volt unit.

The variations in the output voltage at various RF input power values were shown in Fig. 10; observably, increases in the transmitted power (up to 10 dB) linearly increases the sensitivity of the output voltage. Furthermore, increases in input RF power above 10 dB caused a decline in the output voltage response to almost a constant value.

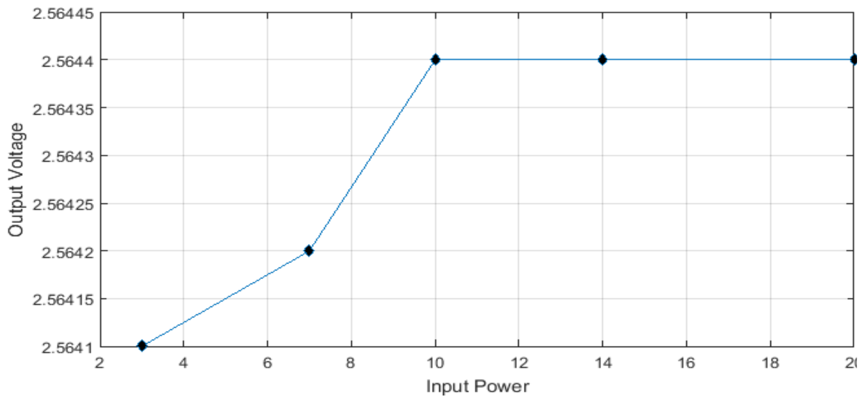

Fig. 10. Output voltage versus input power at 45 kΩ load resistance.

The minimum input supply voltage of the RFD-ASSY-01 power converter was 2.57 V while the maximum level was 5.04 V. Upon the modification of the input supply voltage from the minimum to the maximum level, and repeating of the measurements, the observed outcomes were as shown in Figs. 11 and 12. As seen in Fig. 11, the variations in the output voltage with input RF power at the input power values of 3, 7, 10, and 14 dB were 5.014, 5.016, 5.021, and 5.022 V, respectively. Figures 12 and 13 show the output response for the variations in load resistance at the load resistance values of 5, 30, and 45 K; at these load resistance values, the output voltage values were 5.014, 5.016, and 5.017 V, respectively. We observed that when we increase the distance between the rectenna and the RF source, the output voltage will decline to lead to degradation in overall the rectenna performance. To verify the results in this experiment and prevent the loss in the radiated signal we can add a bandpass filter that decreases the ripples and harmonics at the output voltage. The efficiency of the rectenna system was calculated based on the measured data using Eq. (2).

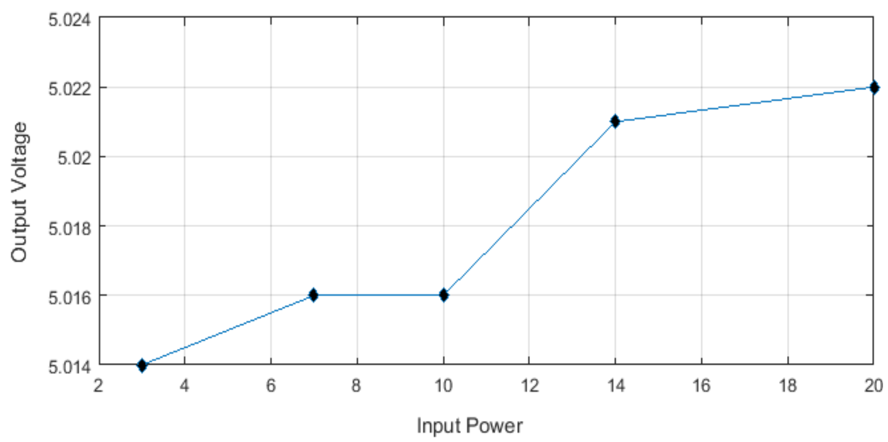

Fig. 11. The output voltage versus input power at 45 kΩ.

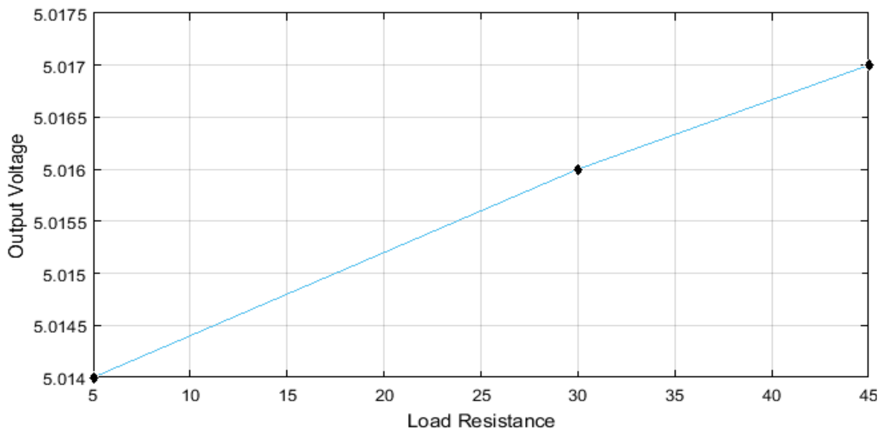

Fig. 12. Output voltage versus load resistance at 7 dBm.

Fig. 13. Snapshot of the result of output voltage versus load resistance at 7 dBm.

6.1. Power conversion efficiency of the proposed rectenna

The proposed rectenna conversion efficiency calculated by:

$$\eta = \frac{P_{DC}}{P_{in}} \quad (2)$$

where $P_{DC} = (V_{DC})^2/R_L$, . V_{DC} represents the direct current output voltage and P_{in} indicates the incident power level sensed by the rectenna. The maximum conversion efficiency in this experiment for the proposed rectenna is 71% has been achieved when we set the input voltage at 5.04 V and the variable resistor at 5 kΩ, while the input power is 7 dBm.

6.2. The proposed rectenna comparison with related works

It is necessary to compare the proposed rectenna with the previous studies conducted on the generation of electromagnetic energy using an antenna. Hence, the competitive advantage (s) of the proposed rectenna can be illuminated. Table 1 shows the conducted comparisons with the previous related work based on five main factors; frequency, input power, harvested output voltage, antenna size, and conversion efficiency.

Table 1. Evaluation of the proposed rectenna with related works.

References	Operating frequency GHz	Input power (dBm)	Output voltage, V	Antenna size mm	Power conversion efficiency%
[13]	2.45	5	3.24	30×18	68
[14]	2.45	2.5	1.6	-	70
[15]	2.45	15	-	238×304	61
[5]	2.42	6-8	1.6	48.8×45.1	57.8
[16]	2.45	-5	-	50×40	61.4
Proposed rectenna	**2.45**	**7**	**5.022**	**40.6×40.6**	**71**

From Table 1 it is observed that our proposed rectenna provides better conversion efficiency compared to some of the recent works within its small dimension.

7. Recommendations for Future Research Directions

The following recommendations are necessary on the existing RFD-ASSY-01 power converter to ensure more efficient energy harvesting systems:

- Adding a leaded capacitor in the DC input pin to the GND of the power converter.
- Setting the RFD88A module at 4.3 V for low voltage and 5.2 V for high voltage.
- Enhancing the match for a specific power range and frequency.
- Performing further optimization to enhance the conversion efficiency and improve the absorption of lower input energies.
- Improve the response of the harvester by investigating different antenna designs.

8. Conclusions

This article described an electromagnetic energy harvesting system that was designed by integrating a high gain antenna (electrical dimension = $0.3248\lambda \times 0.3248\lambda$; maximum gain = 6.69 dBi) with the RFD-ASSY-01 rectifier module. The experiments were performed using a transmitter of 2.4 GHz and the output voltage was measured at different levels of changes in parameters. The proposed rectenna achieved 71% power conversion efficiency at 7 dBm transmit power which is better than the performance of some existing rectenna systems. Thus, the rectenna system can energize low-power electronic devices.

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Nomenclature

dBi	Ratio to measure antenna performance
dBm	Power ratio expressed in decibels regarding one milliwatt
G_t	Transmitted antenna gain
Gr	Received antenna gain
P_{DC}	Output direct current power
P_{in}	The incident power

P_r	Received power
P_t	Transmitted power
R	Distance between the transferred and received antenna
V_{out}	Output voltage
Greek Symbols	
η	The ratio of output direct current power to incident power
λ	Wavelength of the RF signal.
Abbreviations	
DC	Direct Current
EM	Electromagnetic
IoT	Internet of Things
ISM	Industrial, Scientific and Medical
RF	Radio Frequency
RFID	Radio Frequency Identification Card
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network

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