Design of Enhanced Dual Band Rectenna with Binary Coding Technique of Genetic Algorithm

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***Abstract*—In this paper, an artificial intelligence-based rectenna design is proposed for Wi-Fi applications. The rectenna design is optimized using a Genetic Algorithm (GA) integrated with a Binary Coding (BC) scheme. The proposed rectenna is configured to operate at 2.45 GHz and 5.8 GHz with a maximum size of 27×30×10 mm3. The performance of the optimized rectenna has been characterized in terms of S-parameters, bandwidth, radiation patterns, and gain. For this, a dual-bandwidth patch is designed to suit the applications of 2.45 GHz and 5.8 GHz. The measured radiation patterns and S11 spectra are evaluated to obtain a peak radiation efficiency of 52% and 56% to realize a gain of 6.2 dB at 2.45 GHz and 7.12 dB at 5.8 GHz, respectively. The proposed rectenna is integrated with an RF–DC rectifier (RFD102A module) to evaluate the harvested power in terms of DC output voltage under outdoor conditions. The maximum obtained harvested DC output voltage is found to be 2.27V and 2.3V at 2.45GHz and 5.8GHz, respectively. Finally, the obtained measurements are compared to the simulated results to realize good agreements between them.**

***Index Terms*—Binary coding, energy harvesting, genetic algorithm, microstrip rectenna, rectifier, Wi-Fi, sub-6GHz.**

I. Introduction

THIS growing demand for wireless technologies has led to an environment increasingly surrounded by microwave sources [1]. In addition to mobile communication systems, everyday life extensively utilizes wireless applications like Bluetooth, Wi-Fi, WLAN, and the Internet of Things (IoT) [2]. These wireless systems operate within standardized frequency bands [1]. Consequently, both indoor and outdoor environments contain abundant microwave energy across the frequency spectrum, which can be harvested using single- or multiband rectennas [3]. Recently, many designs have been reported for RF energy harvesting systems [4], which can be classified into three categories: single-band, multi-band, and broadband. These systems use different rectennas to improve gain and rectification efficiency by connecting impedance-matching circuits using GA techniques. Such research studies provided various optimization algorithms, including GA and particle swarm optimization, to enhance antenna design performance for multiple applications in modern wireless communication networks. In [5], a microstrip patch antenna array was designed using defective ground structure with the aid of GA to realize a dual-band of operation at 2.45 GHz and 5.8 GHz for wireless power transfer applications. The design of an antenna array was optimized to minimize side lobe effects by utilizing a microstrip patch antenna element that offers improved bandwidth, directivity, and efficiency at multiple resonant frequencies [6]. A study was developed in [7] with the aid of web-tool-based GAs to integrate seven empirical propagation loss models to optimize antenna performance and improve wireless coverage and network capacity. A report was published in [8] to optimize a 28 GHz microstrip antenna with GA in terms of width, microstrip line width, and dielectric permittivity to achieve remarkable performance. A tri-band miniaturized rectangular patch antenna based on a defected ground structure optimized using GA to achieve a size reduction of about 82% smaller than a conventional single-band structure that covers the frequency bandwidths between 3.2 GHz and 3.5 GHz, 5.5 GHz and 5.9 GHz, and 6.3 GHz and 7.1 GHz with gains of 0.7 dBi, 1.76 dBi, and 2.93 dBi, respectively [9]. The proposed antenna in [10] was optimized from a single microstrip patch with a binary-coded genetic algorithm (BCGA) to achieve triple-band operation at 28 GHz, 40 GHz, and 47 GHz for mm-wave applications; this antenna showed a gain of 7.7 dBi, 12.1 dBi, and 8.2 dBi, respectively. The published work in [11] proposed a method to enhance miniaturized microstrip antenna performance using GA to realize bandwidths with sub-6 GHz. An antenna patch design was created using GA, featuring a miniaturized size that operates within the frequency band of 1.8 GHz to 3 GHz, resulting in an array of 9×9 elements [12]. A model that utilizes a high-frequency electromagnetic simulator was proposed in [13] to analyze binary mixtures, employing GA to operate between 8.2 GHz and 12.4 GHz. A comprehensive study on GA for optimizing electromagnetic problems, including complex issues, was presented in [14]. A broadband triple-band frequency patch antenna for WLAN applications was designed with the aid of GA optimization [15]. The study referenced in [16] introduced a compact, cost-effective microstrip antenna for a V2V communication system by implementing a defected ground structure to reduce antenna losses through GA optimization. In another context, the application of GA in antenna design has revolutionized the field by offering an efficient solution to the optimization of complex, multi-parameter problems. One of the most significant benefits of using BCGA in antenna design is the simplification of the encoding process [17]. The application of BCGA in antenna design has been extensively studied, with numerous successful implementations. For example, the effectiveness of GAs in optimizing linear array antennas was demonstrated in [15]. By encoding the array elements' positions and excitation amplitudes as binary strings, they were able to optimize the array radiation pattern, achieving significant improvements in

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DOI: 10.36244/ICJ.2025.4.3

directivity and sidelobe levels. Similarly, in [18], GA was used to optimize microstrip patch antennas, focusing on parameters such as the patch dimensions and feed position to enhance bandwidth and radiation patterns. In phased antenna arrays, BCGA has proven particularly useful, as in [17], which employed GAs to optimize the design of phased arrays, targeting improvements in sidelobe levels and directivity. In [19], a design was explored using GAs to optimize the antenna multiband performance by encoding the antenna geometry and metamaterial properties as binary strings. In [20], a GA was used to optimize wire antennas, focusing on the adaptability of BC to manage complex design challenges. In this paper, an enhanced rectenna design with distinguished performances is introduced for RF energy harvesting at Wi-Fi frequency bands. It is built to achieve excellent conversion efficiency when introduced to an RF energy harvester. Suitable scaling and slight tuning can make the energy harvester system applicable for a wide range of low-power applications, including those operating within the sub-6 GHz band applications and Wi-Fi bands.

II. RECTENNA DESIGN AND GEOMETRICAL DETAILS

The basic rectenna configuration is based on a conventional printed monopole design with coplanar waveguide (CPW) 50Ω feed, as seen in Figure 1(a). Next, the rectenna back panel is covered with a fractal based on Minkowski geometry, as shown in Figure 1(b). The rectenna is printed on an FR4 substrate of 1.6 mm thickness. The rectenna is mounted below another FR4 substrate of the same dimensions. The back panel of the second substrate, see Figure 1(c), is covered with a copper layer of a square aperture, while the other side of the substrate is a rectangular patch designed with a BC scheme, as seen in Figure 1(d). The first layer enables the 2.45 GHz resonant mode, which is achieved through the fractal-based geometry. The second mode is realized from the second rectenna patch based on the BC scheme, as will be shown later.

Now, to obtain the proposed rectenna performance, a full wave analysis is conducted to realize the optimal design by using a parametric study. However, the optimization issue that is defined in this paper is resolved using a BC scheme. This geometry is designed using a straightforward procedure to create the proposed rectenna. The main design challenge lies in optimizing the second-layer BC scheme used to form the patch shown in Figure 1(d). The upper and the lower layers are coupled to realize a 3D-printed geometry with a separation distance of 10 mm. For this, GA is used to find the best rectenna bandwidth with the optimal gain at Wi-Fi bands. The binary-coded patch area is divided into small cells, and the GA uses a code of 0s and 1s to define the conductor regions of the patch. In a binary genetic algorithm (BGA) procedure, the important genetic operators are selection, crossover, and mutation [20].

The selection operator chooses two parent chromosomes from the population at random. The crossover operation mixes two parents' chromosomes to create a new child chromosome [21]; then a mutation introduces changes to the generated chromosome with a certain probability [22].

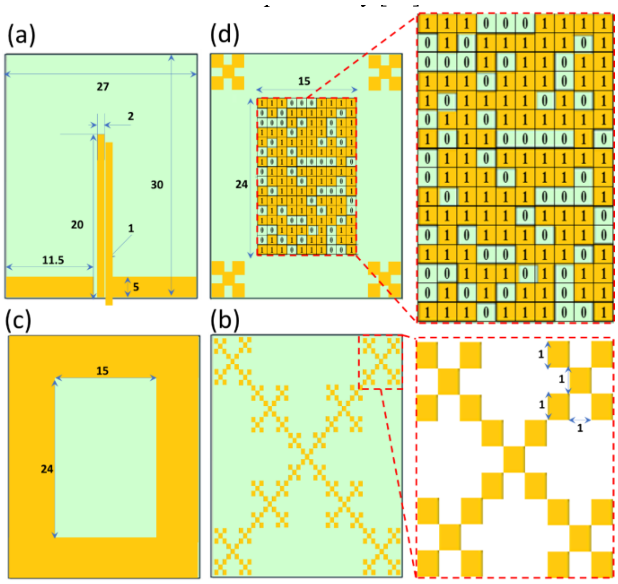

Figure 1: Rectenna design: (a) The printed monopole, (b) the Minkowski geometry, (c) rectangular patch, and (d) BC patch.

The initial rectenna design based on BC is performed at 2.45 GHz and 5.8 GHz on FR4 substrate. The conducted BGA simulations are used to access the optimum patch pattern by dividing it into 160-unit cells (10×16) with a size of 1.5×1.5 mm². A single unit cell is treated as a gene and is encoded with a binary value of 1 if it is a metal pixel and 0 if it is not a metal pixel. The overlaps between adjacent unit cells are minimized to maintain electrical continuity during fabrication. Since the material of each unit cell is directly mapped into a binary value, the patch geometry is arranged as a binary string involving a series of zeros and ones. Each binary string will lead to an arbitrary structure for the radiating patch of the rectenna. The performance of the rectenna can be improved by varying the values in the binary string. Thus, the desired performance can be achieved without increasing the physical size of the rectenna by controlling the patch surface current. The optimal binary string for the patch rectenna is investigated by a number of iterations. However, to preserve the continuity of the structure, zeros are replaced with ones if they are surrounded by ones, and vice versa. This method is applied to the patch rectenna by using a fitness function that is meant to minimize the reflection coefficient and increase the bandwidth of the rectenna. The fitness function is considered to be the rectenna gain bandwidth product (G*BW) and gain as given in equations (1) and (2). If the gain-bandwidth product exceeds 50%, the fitness function is assigned a value of 1; otherwise, it is set to 0. The multiplication is evaluated as a fitness function.

$$fitness(F) = \frac{1}{N}\sum_{i=1}^{N} G * BW \qquad (1)$$

where

$$G * BW(\%) = \begin{cases} \geq 50\%\ than\ set\ 1 \\ < 50\%\ than\ set\ 0 \end{cases}. \qquad (2)$$

N is the number of sampling frequencies in a given band. The coefficient G*BW should be maximum at the resonance frequency. GA is one of the EM optimization techniques integrated with electromagnetic software packages such as CST MWS and HFSS. The simulation, along with the BGA script, is fetched to the CST MWS macro command code window with Visual Basic scripts based on the listed parameters in Figure 1(d). The code iterations are executed after reaching the desired value of the fitness function with an error of 2% or reaching the best fitness function value that shows no significant change for 20 generations.

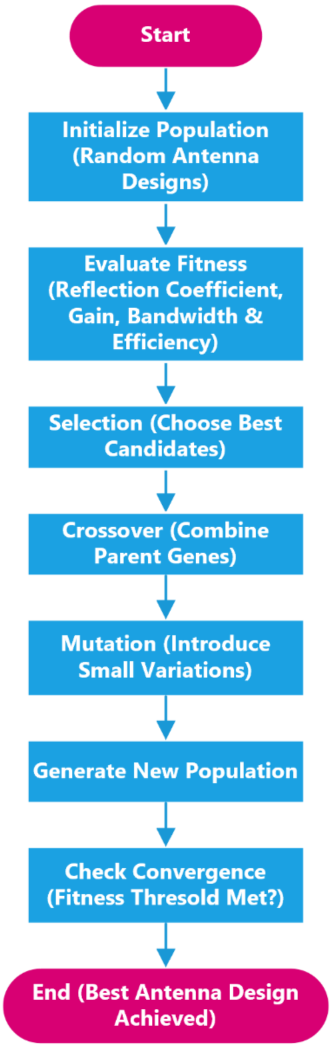

Figure 2. Flowchart of BGA optimization process.

The computing performance is related to the full-wave electromagnetic simulation time for the structure; therefore, the proposed BGA algorithm provides the most robust solution among potential solutions. The optimal patch geometry was achieved after evaluating 120 chromosome genes. The solution space consists of 2160 solutions in comparison to the traditional full-wave analysis techniques, which require a substantial amount of time for analysis. However, the proposed solution based on the proposed BGA algorithm takes only a few attempts to find the solution. The optimized patch exhibits S11 below -10dB at 2.45GHz and 5.8GHz with gains of 6.2dBi and 7.12dBi, respectively. The optimized patch structure is presented in Figure 1 with all geometrical details. For further details, the proposed method is represented as flowchart as shown in Figure 2. The considered algorithm iteratively refines the rectenna geometry to maximize efficiency while minimizing computational overhead. The step-by-step workflow of the GA-based rectenna optimization process used in this study.

III. Rectenna Design and Geometrical Details

The performance of the optimized rectenna has been characterized in terms of S11, radiation pattern, and gain; these characteristics are shown in Figure 3. The simulations are performed and compared to the experimental measurements for validations. The rectenna is fabricated using chemical etching and measured inside an RF chamber, as seen in Figure 3. By considering the operating frequencies of the rectenna, the reflection coefficient is measured by the Agilent E5071C Vector Network Analyzer (VNA).

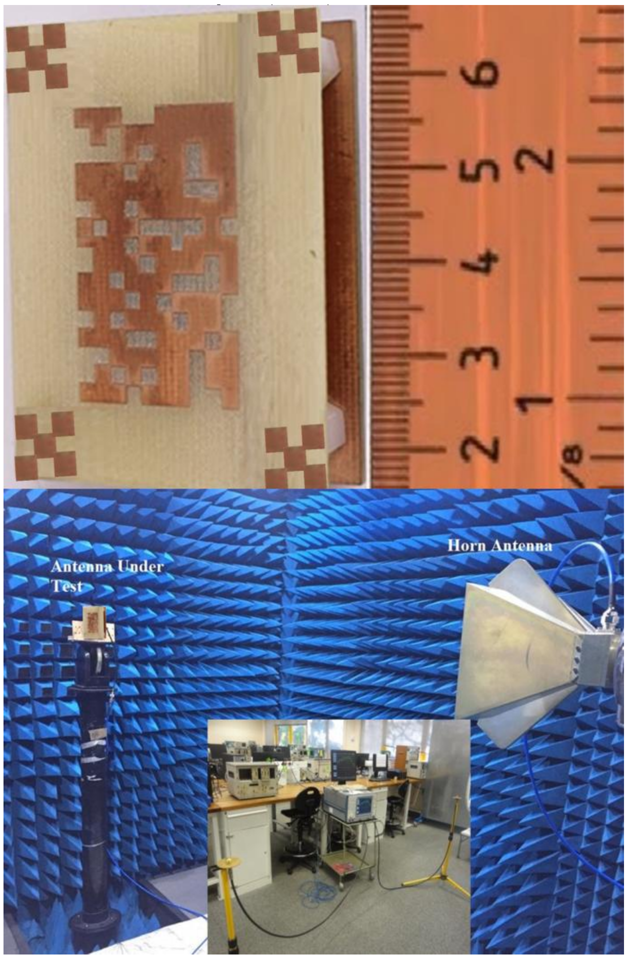

Figure 3: The fabricated rectenna prototype.

The experimental validation of the simulated results is carried out from a software package of CST MWS as given in

Figure 4. The measured and simulated S_{11} spectra of the proposed rectenna is shown in Figure 3(a). The obtained results show that the rectenna bandwidth found between 2.25GHz and 2.64GHz with S_{11} below -10dB. The measured bandwidth of the proposed rectenna, see Figure 4(a), at the second band is found from 5.38GHz to 5.86GHz with S_{11} lower than -10dB. Figure 4(b) shows the measured and simulated radiation patterns at 2.45GHz and 5.8GHz for azimuth and zenith for both co-polarization and cross-polarization. The measured radiation patterns are presented in Figure 4(c) for both azimuth and elevation planes, showing co- and cross-polarization components. The simulated results show excellent agreements with the obtained from measurements. Minor discrepancies between the simulated and measured results are attributed to fabrication tolerances.

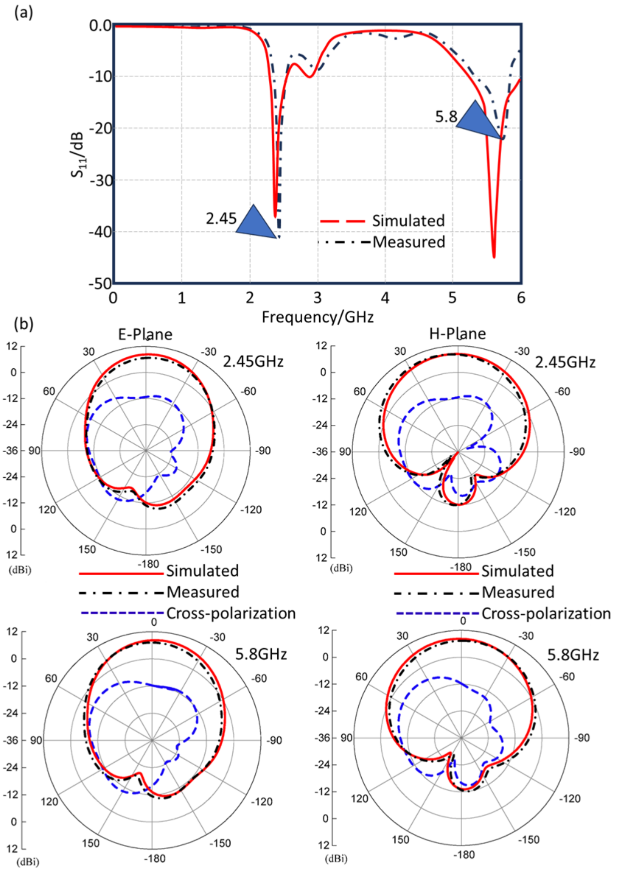

Figure 4. Measured and simulated rectenna performances (a) S11 spectra (b) Radiation patterns.

Figure 5(a) shows the surface current distributions for the proposed rectenna at 2.45 GHz and 5.8 GHz on the second patch. From the obtained distributions, the aperture slots are found to realize significant effects on the surface current distributions. Consequently, such observation shows a significant effect on the rectenna gain to realize a broadside directional radiation pattern as seen in the 3D far field in Figure 5(b). The rectenna gain is improved 6.2 dBi and 7.12 dBi at 2.45 GHz and 5.8 GHz, respectively.

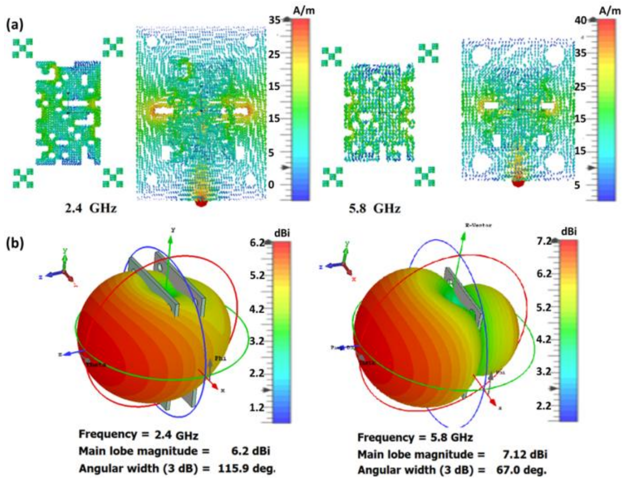

Figure 5. Simulated results for the proposed rectenna at 2.45GHz and 5.8GHz: (a) Surface current distributions and (b) 3D radiation patterns.

IV. RF ENERGY HARVESTING MEASUREMENTS

Figure 6 shows the experimental setup for testing how well the RF–DC energy harvesting works. The optimized dual-band rectenna is connected to the RFD102A-TB RF harvester module by a SMA coaxial cable. The tests took place in a semi-anechoic RF chamber to reduce outside noise and reflections. The RF source was a signal generator (Agilent E8257D PSG), and the power amplifier (Mini-Circuits ZHL-42W) was used to control and boost the RF power sent at the right frequency bands. The rectenna was placed 1.5 meters away from the transmitting antenna (a standard gain horn antenna with 10 dBi gain) and was set up so that both antennas would be as direct as possible. The transmitting antenna received continuous-wave (CW) signals at 2.45 GHz and 5.8 GHz. We looked at three different RF power levels at the rectenna terminals: 0 dBm, 8 dBm, and 16 dBm. To make sure that the calibration was consistent, we used a power meter (Keysight N1914A) to measure the corresponding incident power densities.

A high-impedance digital voltmeter connected to the RFD102A-TB output terminals was used to measure the rectified DC output voltage. The harvested voltage was recorded over several measurements for each input power level to make sure the results were consistent and averaged for accuracy. We also used the Agilent E5071C Vector Network Analyzer (VNA) to get the measured S11 spectra for the rectenna–harvester system. This was done to make sure that the impedance was matched under the same test conditions. In these controlled tests, the highest DC output voltage that could be harvested was 2.27 V at 2.45 GHz and 2.3 V at 5.8 GHz when the RF power was 16 dBm. The RF-to-DC conversion efficiencies were 52% and 56%, respectively. This shows that the GA-optimized dual-band rectenna design works well for collecting energy from Wi-Fi signals below 6 GHz.

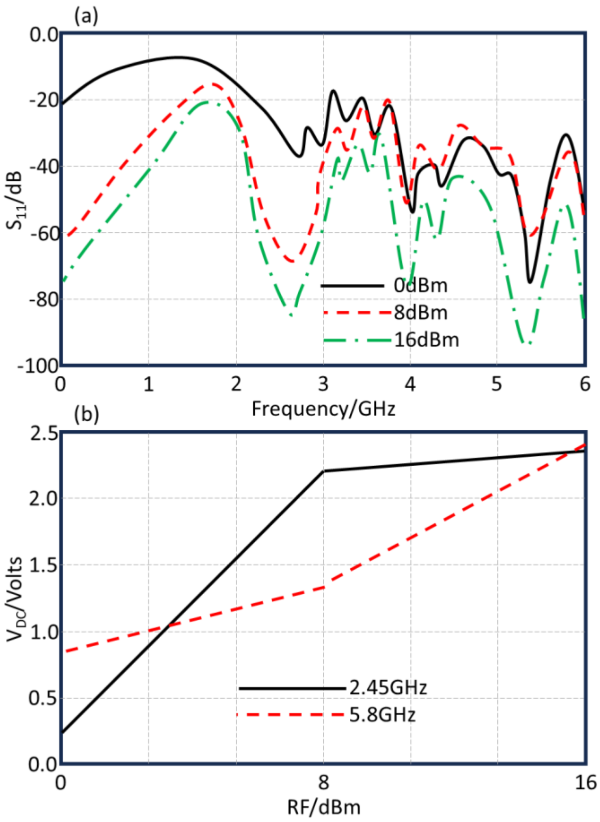

Figure 6: The evaluated results at the considered input RF energy: (a) S_{11} spectra and (b) Harvested DC voltage.

V. Results Comparison and Discussion

In Table 1, a comparison between the proposed work and other published designs is listed. The comparison between the proposed rectenna performance with their relatives is considered in terms of size, substrate, efficiency, frequency band, gain, and V_{DC}. It is observed that the proposed rectenna shows an excellent size reduction with an observable gain enhancement and harvested VDC. This realizes an advancement over other published designs using traditional techniques. The archived results in Table 1 indicate that the proposed rectenna achieves a significant gain enhancement at 2.45 GHz and 5.8 GHz by controlling the surface current on the rectenna patch, as illustrated in Figure 5(a). This gain enhancement is reflected in the energy harvesting that reached 2.3 volts, as seen in Figure 6(b).

TABLE I
Comparison of the RF energy harvesting systems with the proposed work.

Size/ mm²	Substrate	Efficiency/ %	Freq./ GHz	Gain/ dBi	V_{DC}/Volt	Reference
28×32	Taconic	50-80	2.4, 5.8	5-8	0.5-1.5	**[23]**
280×280	Taconic	42	2.45	11	3.4	**[24]**
60×70	Polymer	55	3.4	5.5	2	**[25]**
55×74	FR4	49-62	2.4, 5.8	2-4	0.4-1.2	**[26]**
38×52	Polymer	70-90	2-3	1.8-4	1.0-3.0	**[27]**
68×102	FR4	45	0.9	2.4	0.8	**[28]**
45×68	FR4	65-90	2.45, 5.8	3-5	0.7-1.5	**[29]**
27×30	FR4	52-56%	2.45, 5.8	6.2-7.12	2.3	**proposed work**

VI. Conclusion

The application of BCGA to antenna design represents a breakthrough for renewable energy research, opening new perspectives in RF energy harvesting. In the framework of this work, we have proposed a backup as RF energy harvesting for different applications, including wireless sensor networks. The use of hybrid RF energy harvesting systems prevents different realizations of low-energy devices that were previously not possible to be functionalized. The proposed design uses rectennas with enhanced characteristics that are designed with the aid of the BCGA scheme. AI-based designs of the rectennas are developed using the GA with the BC method to realize enhanced bandwidth and gain. The proposed rectenna shows a compact and low cost with enhanced performance to provide efficiency of 52% and 56% at 2.48 GHz and 5.8 GHz, respectively. The output DC power of the RF energy harvesting system is increased by using dual frequency bands. The proposed rectenna size is miniaturized to 27×30 mm² with a harvested real voltage of 2.3 volts. Finally, the measured and simulated results show excellent agreement, validating the proposed design methodology.

Acknowledgment: The authors would like to express their thanks to the International Applied and Theoretical Research Center, (IATRC), Baghdad, Iraq.

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