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A Further Realization of Binary Genetic Algorithm to Design a Dual Frequency Band Rectenna for Energy Harvesting in 5G Networks

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ABSTRACT

Energy-autonomous systems have evolved in response to the quick deployment of 5G networks and growing presence of Internet of Things (IoT) devices. One reasonable approach is hybrid RF energy collecting using rectenna designs. Optimizing antenna performance for multi-band operation is a significant design difficulty. This article presents a complex rectenna design targeted toward hybrid energy harvesting in 5G networks. The design maximizes the geometry of a microstrip patch antenna running at 2.4GHz and 5.8GHz using a Binary Genetic Algorithm (BGA) based on Artificial Intelligence (AI). By use of binary representation of the antenna's patch form, the problem becomes combinatorial optimization. Using Schottky diodes from the Skyworks SMS7630 and Avago HSMS 285B families, the optimized antenna combines a commercial RF rectifier with nine-stage voltage doubler branches. After 250 generations with a 50,000-population count, the BGA produced antenna designs with widths of 810 MHz (5.14–5.95 GHz) and 200 MHz (2.38–2.58 GHz). Obtained were return losses of –41 dB at 2.4 GHz and –38 dB at 5.8 GHz along with matching gains of 6.2 dBi and 7.12 dBi. With input power levels kept at 6 dBm, the rectifier showed maximum conversion efficiencies of 70% at 2.4 GHz and 42% at 5.8 GHz. Using a 1 kΩ load resistor to provide impedance matching and preserve a power conversion efficiency of 40%, outside testing generated DC output voltages of 92.6 mV and 64 mV. For ambient RF energy collecting in 5G and IoT devices, the suggested AI-optimized rectenna design shows great efficiency and dependability. The effective manufacturing and experimental validation show how well AI-driven design approaches might improve sustainable wireless power solutions.

1. Introduction

Over the past decade, researchers have documented several RF energies harvesting system designs, categorizing them into single-band, multi-band, and broadband categories. These systems use various antenna and rectifier configurations to enhance gain and efficiency [1]. There are impedance matching circuits that connect rectifiers to antennas. These circuits have voltage doubler rectifiers with an open stub matching network and a radial stub for impedance alignment [2]. Different designs use small L-probe patch antennas to collect RF energy. These include dual-port rectennas with two superimposed single-port patch antennas

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that achieve output voltages above 600 mV and power densities above 500 µW/m² [3]. By using an inter-digital capacitor instead of lumped components, slot antennas with triple-band rectifiers working at 2GHz, 2.5GHz, and 3.5GHz have reached peak efficiencies of 53%, 31%, and 15.56%, in that order [4]. A microstrip line-fed open-loop hexagonal antenna with a ground plane has been made to work across a wide frequency range, from 0.8 GHz to 2.5 GHz [5]. A quad-band multiport harvester that can collect ambient RF energy across available frequencies in the sub-6GHz bands has been shown to be more efficient than previous designs, with a rectification efficiency of up to 66.52% [6]. Methods based on artificial intelligence, such as Machine Learning (ML) and Genetic Algorithms (GA), offer complex ways to design and improve rectennas, which makes them better at collecting energy [7]. Researchers have used GA to optimize antenna settings and configurations, leading to enhanced gain and bandwidth performance. Machine learning models have been used to guess and change the design parameters of rectennas, which has made the conversion from RF to DC more efficient and given more accurate design results. The use of twin rectenna devices for energy harvesting in 5G networks has attracted considerable research attention. This review encapsulates significant advancements, benefits, and constraints from 10 relevant investigations. This review examines many rectenna designs and their uses in 5G energy harvesting. The design emphasizes resonance at dual frequencies while maintaining a small antenna size, thereby improving its suitability for space-restricted settings. The research mostly focuses on Wi-Fi frequencies, perhaps limiting its direct relevance to wider 5G frequency ranges. A rectenna for 5G applications, featuring a novel topology that reduces coupling between input and output lines was developed in [8], thereby boosting rectification efficiency. The rectenna can charge a 3V, 1mA rechargeable battery with a diameter of 4.8mm, underscoring its potential for energizing tiny devices. Nonetheless, the existing design employs a solitary antenna; transitioning to an antenna array might significantly augment input power and efficiency. A two-port rectifier that can collect energy from five frequency bands: 0.94 GHz, 1.80 GHz, 2.10 GHz, 2.46 GHz, and 2.63 GHz were developed in [9]. It can achieve a peak RF-to-DC power conversion efficiency of 25.33% at an input level of -20 dBm. The efficiency rates suggest potential for improvement to satisfy the elevated power requirements of certain applications. It is suggested in [10] to use a two-port rectenna with a hybrid half-wave rectifier and back-to-back slot antennas to pick up RF energy from five commercial bands, up to 3.5 GHz for 5G uses. Nevertheless, the research lacks explicit efficiency criteria, complicating the quantitative assessment of success. Future rectenna systems for 5G energy harvesting were developed in [11], highlighting the significance of RF energy harvesting in achieving environmental autonomy for IoT devices. The study is mostly conceptual, devoid of detailed design implementations or actual data to substantiate the suggested notions. For microwave power transmission, a small printed rectenna circuit with Wi-Fi and GSM frequencies was created in [12]. This makes it easier to integrate into a wider range of devices and makes energy harvesting more flexible. However, the rectenna's efficacy in elevated frequency ranges relevant to 5G applications remains unexamined. For wireless energy harvesting at 2.4 GHz and 5 GHz, a dual-band rectenna with a single rectifier was realized in [13]. This type of antenna can work with both bands by using a single feed point. Nevertheless, the research lacks comprehensive efficiency measurements, hindering a quantitative assessment of the rectenna's performance. Several research papers were developed for MIMO systems at 5G networks. For example, a paper in [14] was realized based on a triple band-rejection MIMO/Diversity UWB antenna designed for microwave access WiMAX, WLAN, and X-Band communication bands. It uses mushroom Electromagnetic Band Gap structures, decoupling strips, and slotted ground plane for isolation. Another antenna MIMO array was proposed in [15] to include 10 element MIMO/Diversity antenna systems, working in Sub-6 GHz frequency range, consists of 10 isolated T-shaped slot antennas, with high efficiency and ergodic channel capacity, despite hand grip and battery presence. The work in [16] presented an 18-element antenna system for MIMO/Diversity smartphones, designed for sub-6 GHz LTE band 42 and 43. The system offers excellent impedance matching, port isolation, total efficiency, and Envelope Correlation Coefficient.

In this paper, we present an enhanced rectenna design that showcases outstanding performance characteristics. This design integrates a commercial mini-solar panel, achieving a notable level of integration efficiency. The hybrid energy harvesting system works best when it uses both RF and solar energy capture, which is made better by carefully scaling up and fine-tuning the system. This design is particularly well-suited for a wide array of low-power applications, making it an ideal candidate for systems operating in the sub-6GHz frequency range, including those used in emerging 5G networks. Being able to combine RF and solar energy sources makes the rectenna more flexible and useful, providing a strong solution for a range of energy-gathering situations.

2. Design methodology

We split the design area into identical pixel blocks using a binary mapping scheme, assigning each one as either air or conductor. This is called antenna topology optimization. This transforms the antenna topology design problem into a binary optimization challenge, aiming to identify the optimal antenna design. We employed BGA, inspired by natural selection, to achieve this. The proposed BGA begins with a randomly generated initial population of candidate solutions, represented by genes with values of 0 or 1. Putting design parameters into genes, chromosomes into genes based on fitness values, recombining pairs of chromosomes to make new gene values, and adding mutations to make the algorithm work better are some important steps. The new population includes both parents and offspring, often doubling the size of the initial population. We select the best designs for the next generation by discarding chromosomes with the lowest fitness values and replacing them with better-performing designs. The algorithm checks if the best fitness value exceeds a predetermined threshold, terminates if it does, or repeats the process until it is met. We iterate these steps to optimize the MSA geometry, ultimately aiming to enhance impedance bandwidth and achieve superior performance. The proposed antenna design is based on a conventional aperture-coupled patch antenna configuration. First, we evaluate the geometrical parameters using standard microstrip antenna design equations. However, to meet specific bandwidth or gain requirements, a full-wave analysis is necessary. This paper addresses the optimization problem using a binary coding scheme, which facilitates a straightforward industrial procedure for creating stacked antennas. Figure 1 show the proposed microstrip antenna's overall structure designed with the proposed approach. It has a strip-slot hybrid configuration and several layers. Two substrates, separated by a distance, comprise the antenna. The substrate material has a dielectric constant of 4.3 and a loss tangent of 0.02. The upper substrate has a radiating patch, while the lower substrate contains a ground plane with a coupling aperture on the top side and a feeding microstrip line on the bottom side. Four 3D-printed spacer screws secure the substrates with the required separation distance. We employ a GA to optimize the patch antenna's geometry and achieve enhanced impedance bandwidth. The GA divides the patch area into small cells, using a binary code of 0s and 1s to define the conductor regions. In the proposed BGA procedure, the key genetic operators include selection, crossover, and mutation. The selection operator randomly chooses two parent chromosomes from the population, which are then mixed by the crossover operator to produce a new child chromosome. The mutation operator introduces changes to the child chromosome with a certain probability. This process ensures genetic diversity within the population, allowing for the exploration of various potential solutions. By applying these operators over and over, the algorithm slowly finds the best configuration that makes the bandwidth allocation work as well as possible. The design optimizes a rectangular patch for efficient signal transmission and reception. Additionally, we carefully calculate the antenna's dimensions to ensure resonance at the desired frequency, thereby enhancing its performance in wireless communication applications. Based on binary coding, the first antenna design is made for a frequency of 2.4GHz using a patch antenna on a 1.5-mm-thick EPOXY GLASS substrate. To get the best patch geometry, BGA simulations are used to divide it into 160-unit cells (10×16), each of which is (1.95×1.95)mm². We encode each unit cell, treating it as a gene, with a binary value: 1 for metal pixels (yellow) and 0 for air (green). Overlaps between adjacent cells are represented by the matrix $\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$, and adjustments are made to ensure electrical contact in the fabricated antenna. A binary string of zeros and ones represents the patch geometry, and each string leads to a unique antenna structure. This unique representation allows for the design of highly customized antennas optimized for specific applications. When engineers change the binary strings, they can fine-tune the antenna's properties, like its gain, bandwidth, and radiation pattern, to meet the needs of different communication systems. We achieve performance improvements by varying the binary string values and optimizing the antenna without increasing its physical size. We employ iterative processes to identify the optimal binary string according to the flowchart in Figure 1. We convert zeros surrounded by ones to ones, and vice versa, to maintain a continuous structure. We evaluate performance using a fitness function, which aims to minimize the S_{11} and maximize bandwidth. The fitness function is calculated based on the S_{11} parameter of the antenna, with a S_{11} of less than -10dB setting it to 0. The general fitness function assesses the bandwidth if the S_{11} is greater than or equal to -10dB.

$$fitness(F) = \sum_{i=1}^{N} \omega_i . \left| M_i - M_{i,target} \right| \quad (1)$$

where: N: Number of performance metrics, Mi: Simulated value of the ith performance metric, Mi,$target$: Target value of the ith performance metric, w_i: Weight of the ith performance metric (to prioritize certain metrics over others).

In our case, the considered **target and weight are presented as following:**

1. **S_{11} (S_{11}):**
   - Target: $S_{11,target} = -10$dB
   - Weight: w_1=1
2. **Gain:**
   - Target: G_{target}=5dBi
   - Weight: w_2=1
3. **Bandwidth:**
   - Target: BW_{target}=100 MHz
   - Weight: w_3=0.5
4. **Efficiency:**
   - Target: η_{target}=90%
   - Weight: w_4=0.8

The evaluated S_{11} should be minimal at the resonance frequency within value of -10dB according the specifications in the literature [13]. The GA is employed as an electromagnetic optimization technique in conjunction with Ansoft High Frequency Structure Simulator (HFSS). The simulation, combined with BGA, is programmed using HFSS scripts, with the parameters specified in Table 1. The proposed BGA runs iteratively until either the fitness function reaches the desired value or remains unchanged for 20 generations. The binary-coded GA optimizes the patch geometry by adjusting the first 120 genes of the chromosome, resulting in a solution space of 215×25 potential designs. The relative BGA parameters used for the optimization of the antenna are summarized in Table 1.

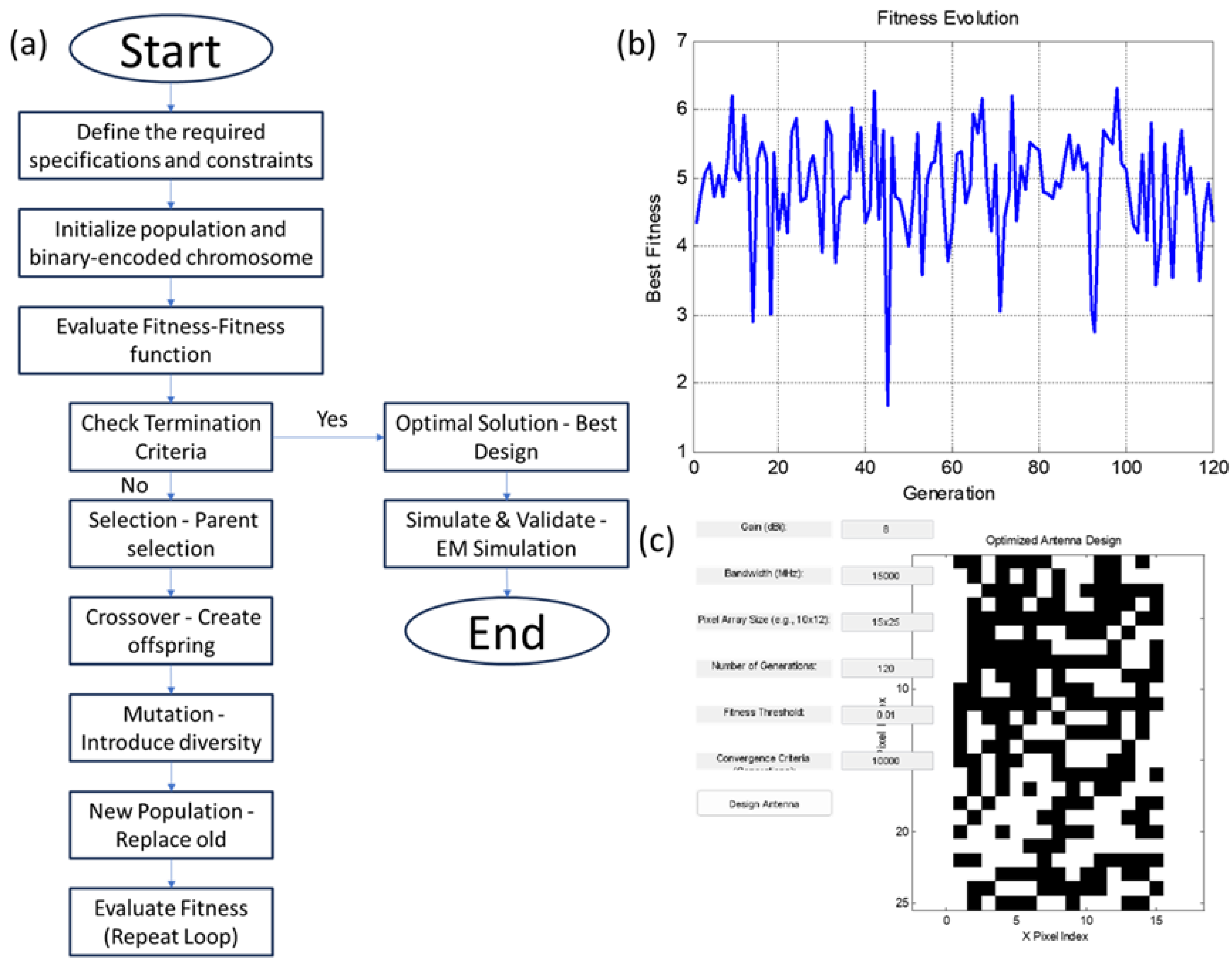

Figure 1. The proposed BGA for this work: (a) Flowchart block diagram, (b) The fitness evaluation with generations, and (c) The resulted patch geometry.

Table 1: BGA parameters used for the optimization of the antenna.

Population type	Bit String
Maximum number of generations	15×25
Population size	50
Selection	Roulette
Crossover rate	0.9
Mutation rate	0.03
Iterations	50

The resulted antenna performance is evaluated using traditional full-wave analysis techniques, which require significant time for computation; BGA can find an optimal solution within a few hours. The optimized patch exhibits S_{11} below -40dB at around 2.4GHz. The resulting optimized patch structure is shown in Figure 2. Table 2 lists all parameters of the antenna and their definitions. In this design, a horizontal slot is introduced to realize an aperture of coupling to the antenna patch inductively from the vertical conductive trace structure [13]. BGA simulations were conducted to determine the optimal patch geometry for operation at 2.4GHz and 5.8GHz. This was achieved by encoding the patch area, subdividing it into unit cells arranged in a 15×25 array. The substrate used is EPOXY GLASS with a thickness of 0.8mm, and each unit cell measures 1.2×1.2mm². Each cell, treated as a gene, is assigned a binary value: 1 for metal pixels (orange) and 0 for air (white). The BGA process optimized the radiating patch shape to enhance impedance bandwidth, as illustrated in Figure 2. Simulation results indicate that the proposed antenna achieves bandwidths ($S_{11} \leq$ -10dB) from 2.1GHz to 2.87GHz and 5.46GHz to 5.9GHz, with resonant frequencies of 2.4GHz and 5.8GHz, respectively.

The mean advantages of such design are the size reduction with dual frequency bands to motivate us to apply it for RF harvesting applications in miniaturized wireless systems. The main limitations of this design are the difficulty of matching having high harvesting efficiency at two considered frequency bands as will be seen later.

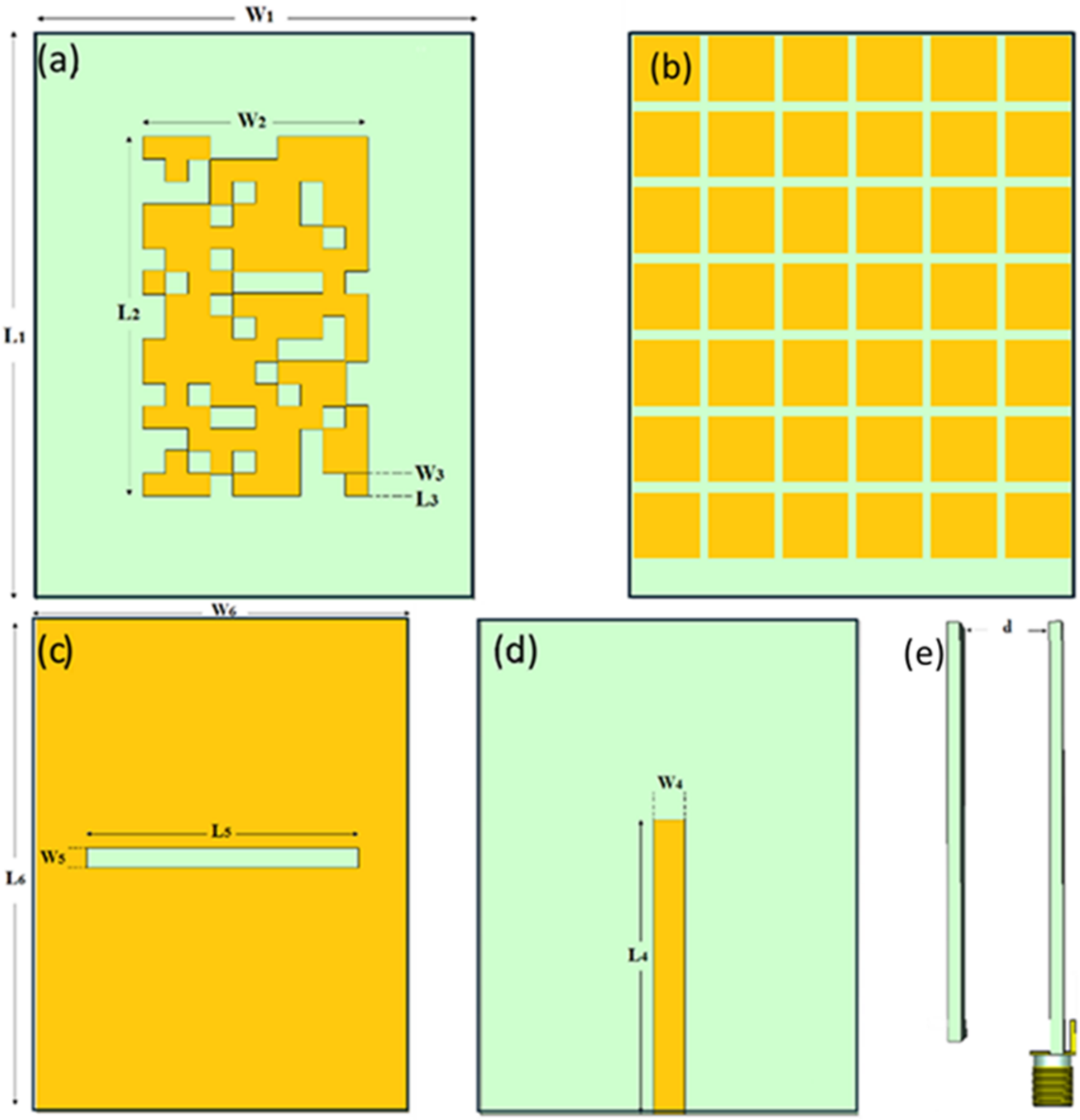

Figure 2. The proposed BGA for this work: (a) Flowchart block diagram, (b) The fitness evaluation with generations, and (c) The resulted patch geometry.

Table 2: Dimensions of the optimized antenna in (mm)and (λ)

Parameter	Dimensions/mm	Parameter	Dimensions/mm	Parameter	Dimensions/mm
W_1	30	L_3	1.4	W_6	28
L_1	41	W_4	2.5	L_6	41
W_2	12	L_4	22	R	1.24
L_2	23	W_5	2	d	7
W_3	1.4	L_5	20	h	1.5
Parameter	**Dimensions/ λ at 2.4GHz**	**Parameter**	**Dimensions/ λ at 2.4GHz**	**Parameter**	**Dimensions/ λ at 2.4GHz**
W_1	0.24	L_3	0.011	W_6	0.21
L_1	0.33	W_4	0.023	L_6	0.33
W_2	0.09	L_4	0.18	R	0.01
L_2	0.18	W_5	0.016	d	0.056
W_3	0.011	L_5	0.17	h	0.011

The circuit model is a simplified electrical analogy of the antenna structure, relating to its electromagnetic behavior. using lumped elements (R, L, C). It includes the Radiating Layer (top view of first layer), Metasurface/Reflector (back view of second layer), Defected Ground Structure (back view of first layer), Parasitic/Coupling Strip (front view of second layer), and Dielectric Layer/Substrate (side view). The Radiating Patch (top layer) has R_1, L_1, C_1 for main radiation and resonance. The Metasurface grid (back second layer) has L_2, C_2 for gain and frequency control. The Ground Slot (back first layer) has L_3, C_3 for notch or band-stop behavior.. The Coupling Strip (front second layer) has Coupled L_4-C_4 for additional resonance/matching. The Dielectric substrate (side view) represents the dielectric spacing (`d`) between layers. The circuit model in Figure 3(a) can be extended by adding Varactor diodes (voltage-controlled capacitors), Switches (PIN diodes, MEMS), and Multiple RLC branches for multi-resonance behavior. If the antenna is a dual-band or reconfigurable antenna, it can be extended with Varactor diodes (voltage-controlled capacitors), Switches (PIN diodes, MEMS), and Multiple RLC branches for multi-resonance behavior. The dispersion diagram of a periodic structure, also known as the band structure, is a crucial tool in antenna design. It shows wave propagation along high-symmetry directions in the periodic structure's reciprocal lattice and the frequency at which modes exist for each propagation direction. EBG structures are engineered periodic materials that prevent electromagnetic wave propagation in specific frequency ranges. They are similar to photonic/phononic crystals in optics and acoustics and use bragg scattering and resonance elements to block wave propagation. The periodicity and geometry determine the bandgap location and width. The results in Figure 3(b) includes colored curves representing propagating modes, solid and dashed lines representing TE/TM modes or different polarizations, and shaded blue regions (band gaps) where no electromagnetic waves can propagate in the structure at these frequencies around 2.4GHz and 5.8GHz. The proposed EBG structure can affect antenna performance by enhancing gain, reducing size, reducing mutual coupling, and suppressing surface wave at the frequency band of interest.

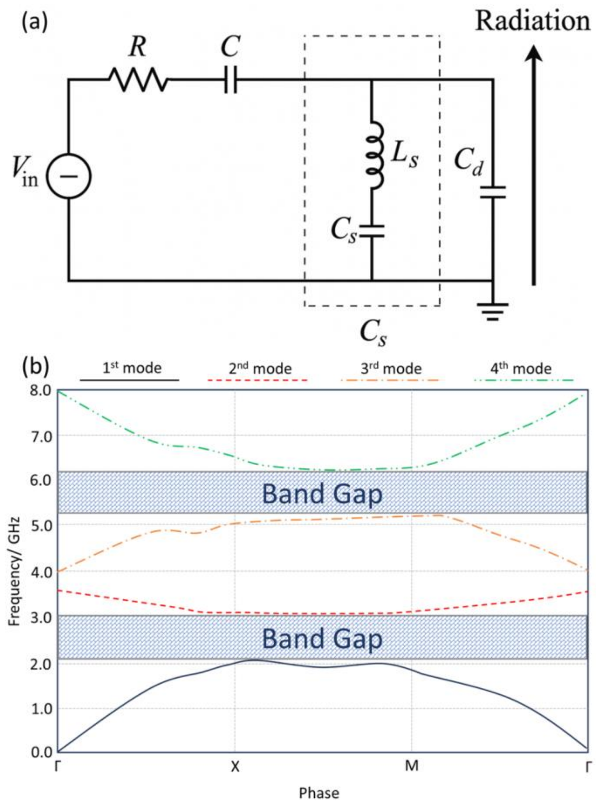

Figure 3. Antenna operation performance: (a) The equivalent circuit model of the proposed antenna and (b) The dispersion diagram.

3. Antenna performance

The performance of the optimized antenna is evaluated experimentally in terms of S_{11}, radiation pattern, and gain spectra. Simulations were conducted using HFSS software package. To validate these simulation results experimentally, the proposed antenna is fabricated as shown in Figure 4. For measuring the S_{11} of the proposed antenna, an Agilent E5071C Vector Network Analyzer (VNA) was used.

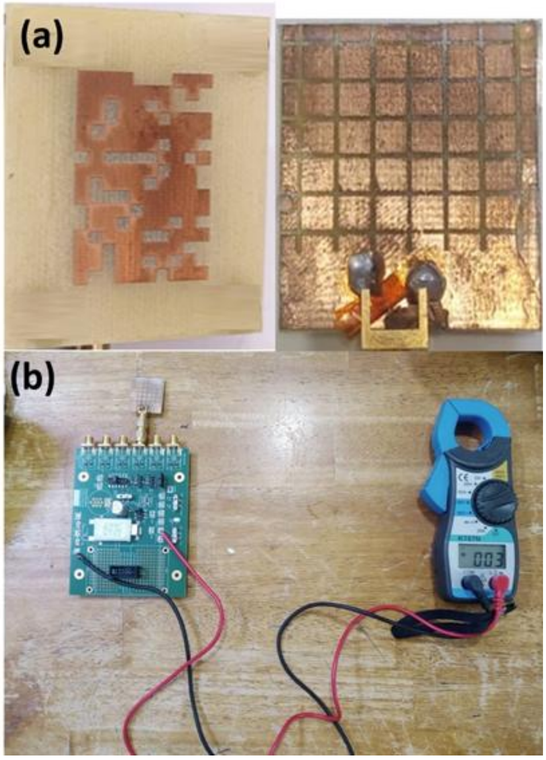

Figure 4. Prototype of the fabricated antenna used for experimental validation, including RF harvesting measurement setup: (a) The proposed antenna and (b) RF harvesting measurement setup.

The measured S_{11} for the proposed antenna is compared to the simulated results as in Figure 5(a). For proposed antenna indicates a bandwidth ranging from 2.35GHz to 2.54GHz and 5.1GHz to 5.9GHz with S_{11} below -10dB. The antenna shows peak gains of 6.2dBi at 2.4GHz and 7.12dBi at 5.8GHz. The antenna radiation patterns are found to be almost broadside radiation to the boresight direction as seen in Figure 5(c) and 4(d) for 2.4GHz and 5.8GHz, respectively. The slight discrepancies are attributed to fabrication imperfections and environmental factors such as measurement in free space. The main radiation mechanism of the proposed antenna are the advantages of having first resonance mode is generated based on TM modes from the metal part of the antenna patch, while the second antenna mode is generated as TE mode from the etched part from antenna patch [9].

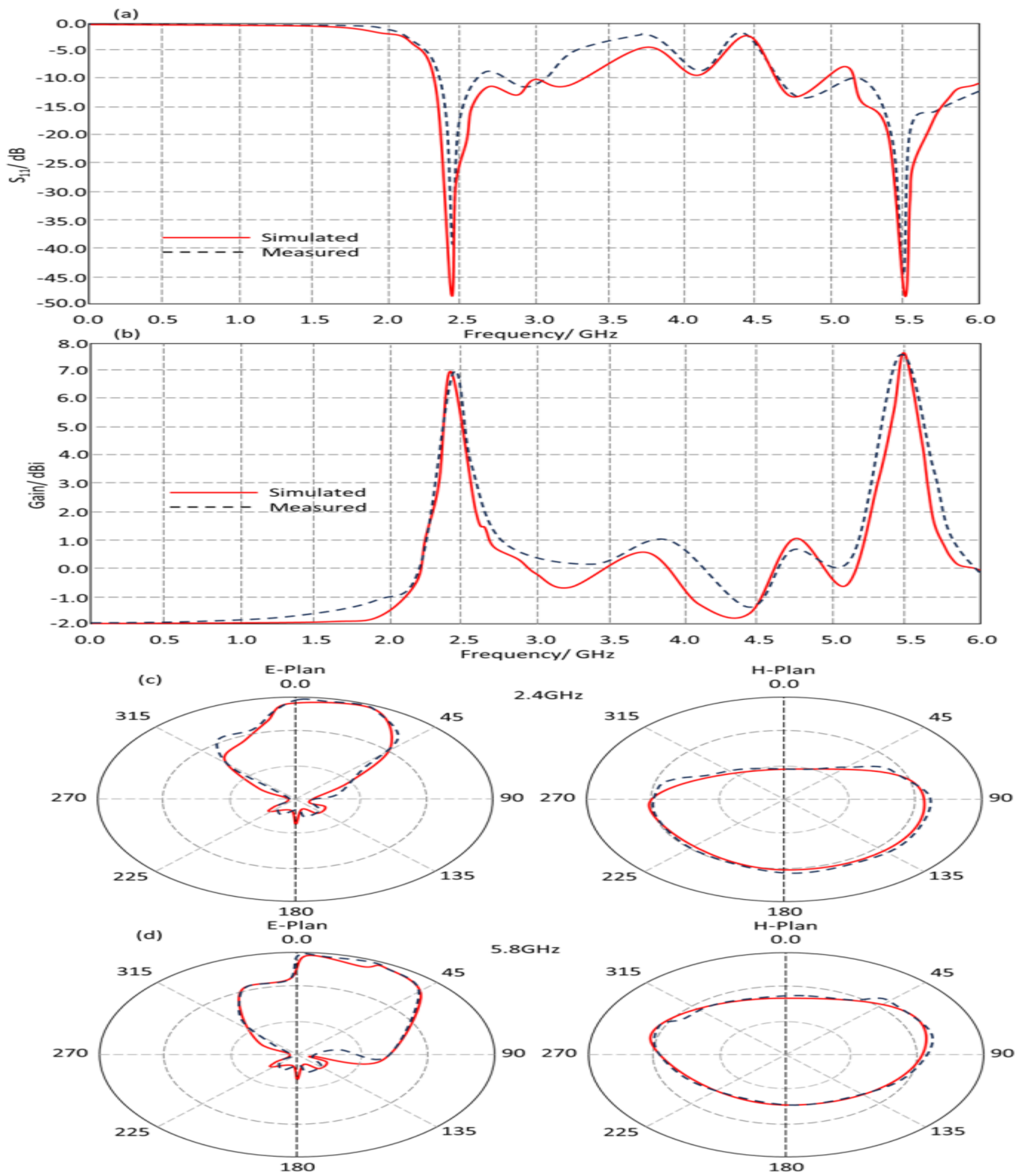

Figure 5. Measured and simulated rectenna performance in terms of RF characteristics measurements as following: (a) S11 spectra, (b) gain spectra, (c) radiation patterns at 2.4GHz at E- and H-planes, and (d) radiation patterns at 5.8GHz at E- and H-plane.

5. RF Energy harvesting

In this section we applied the use of a commercial RF harvester modulator of Powercast Corporation P21XXCSR-EVB, see Fig. 4(b), of evolution board. This rectifier has 6 channels to cover the frequencies of 2.4GHz and 5.8GHz. The dual-bands are rectified to harvest RF energy at 2.4GHz and 5.8GHz. To meet the requirements of high-power handling capability, low input voltage, and doubled output DC voltage, a voltage doubler topology is utilized. This rectifier is constructed with Skyworks SMS7630 and Avago HSMS 285 B Schottky diodes, chosen for their low threshold voltage and high sensitivity at low input power levels, making them ideal for RF power harvesting applications. The impedance matching performance of the rectifier is influenced by operating frequency, input power, and the load resistor-inductor circuit. Precise selection of these factors ensures the rectifier's suitability for its environment. A 1 kΩ load resistance is used and single-stub tuning, a radial stub meander-line, taper, and inter-digital capacitor is employed to achieve optimal impedance matching at a 0dBm input power level. A 68-pF capacitor functions as a low-pass filter, passing only DC power to the load. A deeper understanding of the dual-band rectifier's performance can be gained through a parametric study. The RF-to-DC conversion efficiency ($\eta_{(RF-DC)}$) of the rectifier is influenced by the available RF power in the environment. Figure 6 illustrates the measured and simulated $\eta_{(RF-DC)}$ at 2.4GHz and 5.8GHz as functions of input power. At 2.48GHz and 5.8GHz, the peak $\eta_{(RF-DC)}$ values are 70% and 42%, respectively, achieved with an input power of 6dBm. For an input power of 0dBm, the conversion efficiencies are 57% at 2.4GHz and 30% at 5.8GHz. Overall, the proposed RF energy harvesting system stands out for its superior efficiency and its integration of both RF and solar energy sources. Additionally, the use of GA further enhances its performance, marking it as a significant advancement over previous systems. For this, we applied a comparison study between our proposed antenna design and other published results. We found that the proposed antenna shows two frequency resonances at 2.4GHz and 5.8GHz, with excellent harvesting efficiency about 70% at 2.4GHz and 17.8% at 5.8GHz. The proposed antenna shows the minimum size in comparison to other published results with excellent harvesting efficiency, see Table 3.

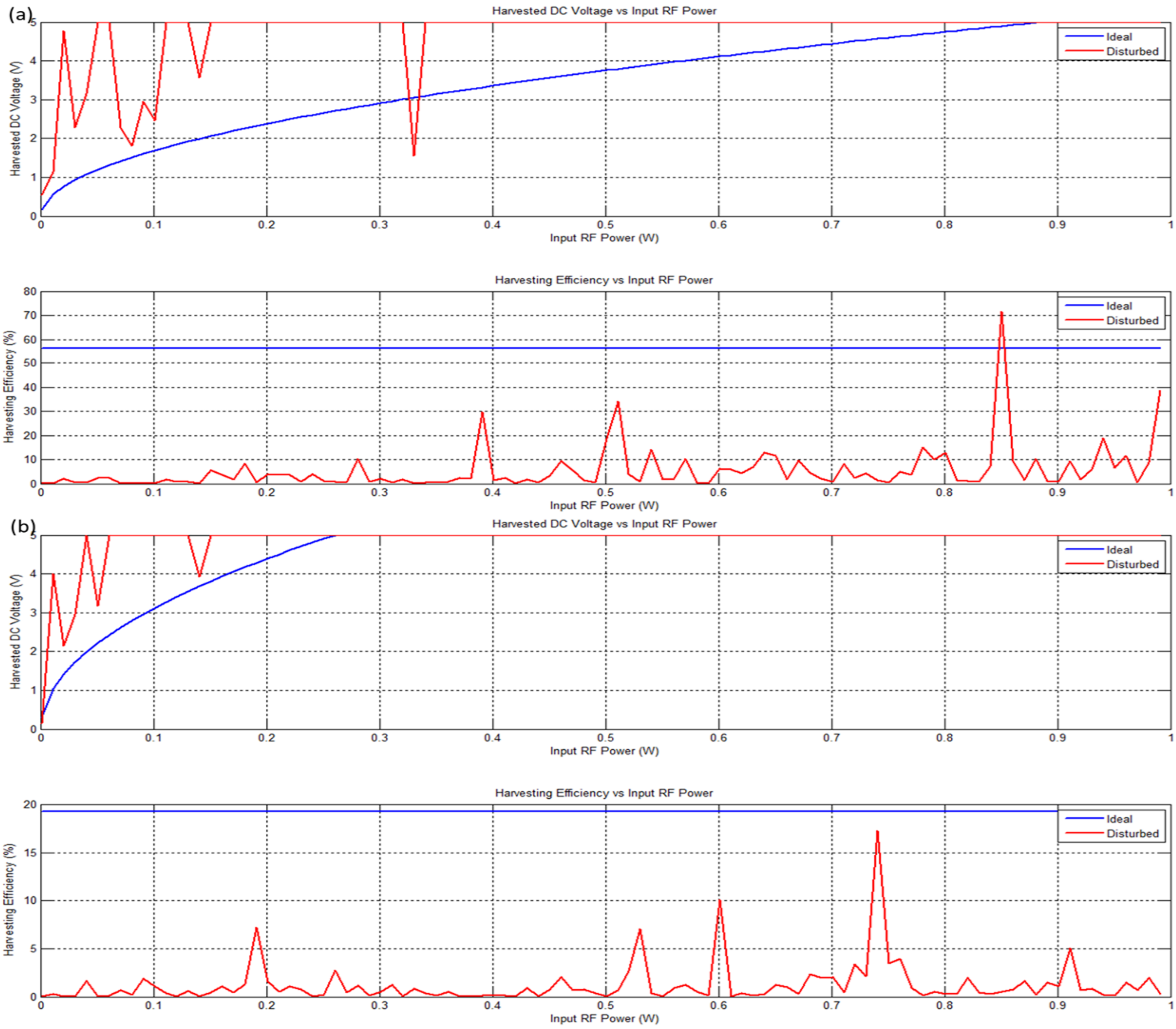

Figure 6. Measured and simulated conversion efficiency as the function of input power at (a) 2.4GHz, and (b) 5.8GHz.

Table 3: Comparison of the RF energy harvesting systems with the proposed work.

Reference	Freq. (GHz)	Peak η (%) @ Pin(dBm)	Gain (dBi)	Size (mm^2)
[17]	0.9	63@0	2.8	30×110
[18]	1.8/2.5	24@-20	3.1/4	60×60
[19]	1.8/2.5	24@-20	6.1/7	100×60
[20]	0.3-16	30@0	4.5	60×50
[21]	2.4/5.8	30@14	2.2/5.3	60×70
[22]	1.8	51@-10	3.1	53×69
[23]	2.5/3.6	59.4@2	3.5/4.4	58×63
This work	**2.4/5.8**	**70.4@8.5/17.8@7.5**	**6.2/7.6**	**35×48**

5. Conclusion

In conclusion, the proposed design, incorporating rectennas with advanced features optimized through BGA, represents a significant advancement for RF energy harvesting technology. The proposed approach realized an antenna with size 35×48mm^2 when printed on Epoxy glass substrate. Such compact and low cost-effective rectenna demonstrates notable efficiencies of 70.4% and 17.5% at 8.5dBm and 7.5dBm power levels, respectively. The obtained DC outputs voltages are found of 8.5µW and 4µW at 2.4GHz and 5.8GHz, respectively. This dual-frequency bands rectenna source approach enhanced the validity of the system for a range of low energy devices including: Wireless sensor networks, IoT devices, remote monitoring systems, smart city infrastructures, wearable technology, and emergency power systems. The ability to sustainably power devices in diverse environments, while ensuring reliable operation and reducing maintenance needs, underscores the potential impact of this innovative energy harvesting solution. The proposed AI-optimized hybrid rectenna is promising for ambient RF energy harvesting in 5G and IoT environments. Future work could focus on multi-band and wideband operation, AI algorithm enhancement, dynamic reconfigurability, miniaturization, on-chip rectifier design, energy storage and management, environmental robustness, security-aware applications, massive MIMO and smart surfaces, and sustainability and green networking. The rectenna could be extended into arrays or integrated within intelligent reflecting surfaces to boost energy harvesting and signal enhancement. Future studies could explore the use of advanced machine learning models, dynamic reconfigurability, miniaturization, on-chip rectifiers, energy storage and management, and sustainability and green networking.

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