

# Dual-Band Multi-Port Rectenna for RF Energy Harvesting

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**Abstract**—In this article, a novel dual-band multi-port compact rectenna design for RF energy harvesting is proposed. An E-shaped coaxial fed microstrip antenna combined with an inverted L-shaped structure is used to achieve a dual-band operation at 0.9 GHz (GSM900) and 2.4 GHz (WiFi) frequency bands with gains of 0.8 dBi and 4.4 dBi, respectively. A shorting post is incorporated in the design, which restricts the antenna size to 50 mm × 47 mm, making the overall rectenna compatible with any sensor nodes. Further, a compact rectifier circuit covering both the frequency bands is designed to obtain a conversion efficiency up to 50% for an input power as low as −20 dBm. The matching circuit ensures that the nonlinear impedance of the rectifier matches with that of the antenna under varying operating conditions. Finally, the rectennas designed are combined and arranged together to form a cubical structure to produce an output voltage as large as 0.5 V for an input power of −20 dBm. With 360° coverage and orthogonal polarization reception, the cubical antenna arrangement ensures improved harvesting efficiency making the proposed design suitable for powering low power IoT devices.

## 1. INTRODUCTION

With the rapid growth in VLSI and embedded system technology, self supporting low power devices suitable for Internet of Things (IoTs), RFIDs, Smart Cities, Wearable Electronics, Wireless Sensor Networks, etc. have attracted noteworthy attention in the last few years. The power requirement of these devices positioned at remote places is accomplished generally using batteries. These batteries, once exhausted, are usually replaced. This in itself is a tedious task in addition to being hazardous to the environment. Thus, there is a demand for sustainable and green solution for improving the battery life time. Energy harvesting (EH), wherein the ambient energy from the environment is absorbed and converted into a DC source for storage or powering devices, is the most suitable solution [1].

Sun, tides, wind, geothermal, piezoelectric vibrations, and RF are the various sources of ambient energy. Though abundantly available and a mature technology, solar energy suffers from intermittent supply and reachability issues compared to RF energy sources [2]. Due to widespread growth of mobile users, base stations, WiFi routers, TV users, etc., RF energy is available abundantly and can be used in EH systems. Only a small percentage of the transmitted RF power from the base stations is used in mobile communication while the remaining is wasted in the environment. This, along with the fact that it is omnipresent, makes it very attractive for harvesting. Though the incident RF power density is relatively low, RF Energy Harvesting (RFEH) can find use in powering low power devices — increasing the battery life and reducing maintenance costs [3]. This ideology was known since as early as 1990s, when the first rectenna was developed by W.C. Brown [4].

A rectenna is a combination of a receiving antenna, rectifier circuit, matching network, low pass filter, DC to DC converter, and a battery or super-capacitor. Its performance is evaluated by the overall RF to DC Power Conversion Efficiency (PCE). The main challenge in designing an RFEH system based

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on ambient sources is its low PCE. The losses associated with the components, the restrictions on RF power transmission, and the gap between the transmitting and receiving antennas further worsen the PCE [5].

Some reported works have achieved a high PCE,  $> 80\%$  [6–9]. However, these designs operate at a single frequency band with high incident RF power (5 dBm to 15 dBm). Studies indicate that the available ambient RF power is in the  $-20$  to  $-60$  dBm range [10]. As the PCE decreases drastically for any small reduction in the incident RF power, the reported RFEH designs with high incident power become ineffective in the case of ambient RFEH systems [11].

DC combining method is one solution in which the DC outputs from various rectennas are combined to increase the output. However, the overall PCE is still low due to the intrinsic power consumption associated with the rectenna circuits. Broadband and multi-band rectennas are designed to harvest ambient RF energy from different GSM and WiFi bands simultaneously. Due to the nonlinear element present in the rectifier, the circuit input impedance varies with input power, frequency of operation, and load which makes broadband or multi-band rectenna designs very difficult. Recently published broadband rectennas have used DC to DC converter or power management units at the output [12]. These rectennas are designed with a fixed load which essentially makes it a low PCE design due to the mismatch in the input impedance. This is however overcome by using resistance compression networks which use tuned RF inverter to reduce variations in the load resistance, but this happens at the expense of increased size and reduced efficiency at very low input voltages.

Ambient RFEH is characterised by random incident angles and arbitrary polarizations which makes accurate prediction of incident power difficult. It requires an antenna with omnidirectional radiation pattern, wide operating bandwidth, and orthogonal polarisation for maximum coverage. Loop antennas, patch antennas, dipoles, and monopoles have been traditionally used to harvest RF energy, but they are mostly suitable for single frequency operations and have reported high PCE only for higher incident RF power. To enable ambient RF energy harvesting, multi-band antennas are preferred as they improve the PCE by combining the input power at each frequency band. A rectenna operating at 900 MHz has offered an output voltage of 0.87 V when the separation distance between the system and cell tower is 50 m [13]. A 2.45 GHz rectenna with a high gain of 8.6 dBi has shown an efficiency of 50% at  $-17$  dBm input power [14]. A differential microstrip antenna operating at GSM900 band has achieved an efficiency of 65% for optimum load resistance [15].

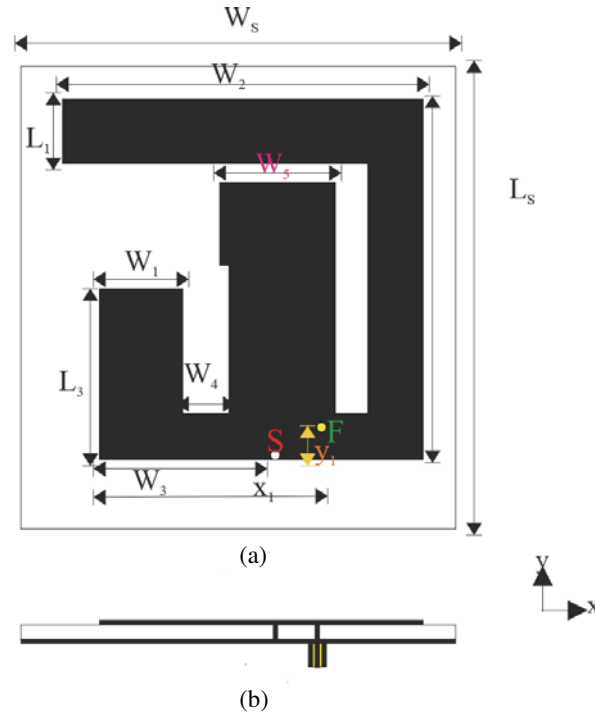
So far, multi-port antennas have been reported operating in a narrow band and receiving only single polarization. The antenna size at 900 MHz is also large [16]. In this article, a novel compact dual-band multi-port rectenna design operating at 900 MHz and 2.4 GHz with a cuboidal arrangement and orthogonal polarization is presented. The antenna has a gain of 0.9 dBi at 900 MHz and 5.3 dBi at 2.4 GHz with an overall size of  $50 \text{ mm} \times 47 \text{ mm}$  wherein a shorting pin is used to achieve size reduction at the lower operating frequency. A compact rectifier operating at the two frequencies is designed wherein a combination of pi based network and stub matching is used. The output from each rectifier circuit is DC combined to improve the output power especially in the case of low incident power. Multiple ports, from the dual-band dual-polarised rectennas in a 3D arrangement, enable more power for DC combining and hence improve the overall harvesting efficiency.

Section 2 explains the antenna design, and Section 3 consists of details of the rectifier design. Section 4 deals with results and discussion followed by conclusion.

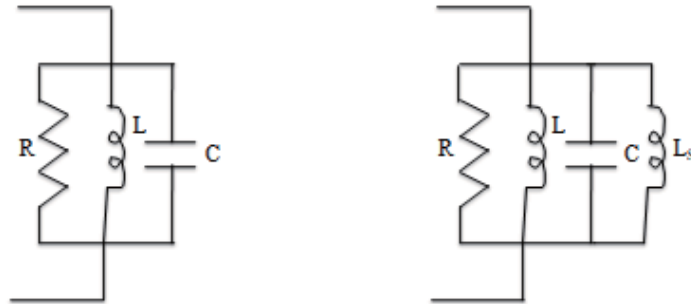
## 2. ANTENNA DESIGN

The antenna used is a planar microstrip patch as a combination of an inverted L and an E-shaped structure as shown in Figure 1. The antenna is fed by a coaxial probe at  $(x_1, y_1)$  where  $S$  is the shorting pin position, and  $F$  represents the feed position. GSM900 band operation is controlled by width  $W_1$  and length  $L_1$ . The size reduction at 900 MHz is achieved by placing a shorting pin at  $S$ , and the operation at 2.4 GHz is determined by the inverted L structure.

Equivalent circuit of a patch antenna is represented as a parallel combination of an inductor  $L$ , a capacitor  $C$ , and a resistor  $R$  representing losses as shown in Figure 2.  $L$  and  $C$  determine the frequency of operation. At resonant frequency, the reactive part of impedance is zero, and the input impedance is real and equal to  $R$ . Matching at resonant frequency is obtained by changing the feed location, so that



**Figure 1.** Antenna element, (a) top and (b) side view.



(a) Equivalent circuit of patch antenna (b) Equivalent circuit of short path antenna

**Figure 2.** Equivalent circuit.

the value of  $R$  is adjusted to match the coaxial cable impedance. The shorting post, when being placed in a microstrip antenna, can be modelled as an inductor in parallel with the equivalent circuit of the antenna. This lowers its resonance frequency for the same overall size, hence giving the benefit of size reduction.

The resistance  $R$  is given by [17]

$$R = \frac{Q_r}{\omega C} \quad (1)$$

$$C = \frac{\epsilon_e \epsilon_0 L W}{2h} * \cos^2 \frac{\pi x_0}{L} \quad (2)$$

$$L = \frac{1}{\omega^2 C_1} \quad (3)$$

The resonant quality factor  $Q_r$  is given by Equation (4)

$$Q_r = \frac{c\sqrt{\epsilon_e}}{fh} \quad (4)$$

where  $c$  = velocity of light,  $f$  = design frequency,  $\epsilon_e$  = effective permittivity of the medium.

The impedance due to the effect of shorting post becomes

$$Z_{is} = \frac{j\omega R}{j\omega L_{Tot}R + RC\omega^2} \quad (5)$$

where

$$L_{Tot} = \frac{L + L_S}{L_S L} \quad (6)$$

$L_S$  = inductance due to shorting pin and defined as

$$L_S = 0.2h \left[ \log \left( \frac{2h}{s+t} \right) + 0.22335 \frac{(s+t)}{(h+0.5)} \right] \quad (7)$$

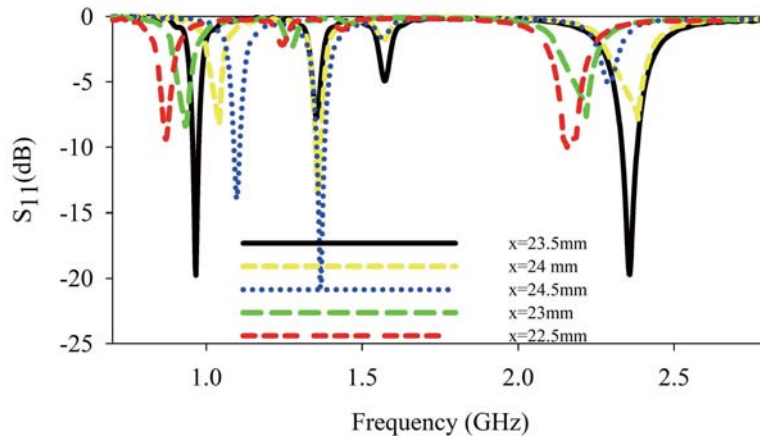
where  $s$  = length of the shorting pin,  $h$  = height of the substrate,  $t$  = thickness of the shorting pin. The total input impedance is given by

$$Z_T = \frac{j\omega L_S Z_{msa}}{Z_{msa} + j\omega L_S} \quad (8)$$

where

$$Z_{msa} = \frac{1}{\frac{1}{R} + \frac{1}{j\omega L} + j\omega C} \quad (9)$$

In the proposed design, a commonly available and cheap glass epoxy substrate with dielectric constant of 4.4 and thickness of 1.6 mm is used. The antenna is fed at the centre using an SMA connector with  $50\Omega$  impedance. The inner conductor of the SMA connector is soldered to the top of the radiating patch, and outer conductor is connected to the ground. The entire substrate dimension is  $50 \text{ mm} \times 47 \text{ mm}$ . The square patch has dimension  $W_2$  as 39 mm. The feed location is selected at position  $(x_1, y_1)$  for maximum impedance matching by parametric study as shown in Figure 3.



**Figure 3.** Feed position variation

The simulations are performed using software CST Microwave studio.  $W_1$ ,  $L_1$ ,  $L_3$ ,  $W_2$  are varied to study their effect on the resonant frequency at 900 MHz and 2400 MHz. The optimized dimensions of the patch are given in Table 1.

**Table 1.** Antenna dimensions.

| parameter | length (mm) |
|-----------|-------------|
| $W_1$     | 9           |
| $L_3$     | 5           |
| $L_1$     | 20          |
| $L_2$     | 29          |
| $W_3$     | 19.5        |
| $W_4$     | 5           |
| $W_5$     | 3           |
| $W_6$     | 11.5        |
| $W_7$     | 12          |
| $x_1$     | 23.5        |
| $y_1$     | 4           |

### 3. RESULTS AND DISCUSSION

The antenna prototype is constructed and checked using Keysight Network Analyzer N9917A. The simulated and measured results are in agreement as shown in Figure 4. The little differences between the measured & simulated results is due to the difference in dielectric models as well as losses in soldering.

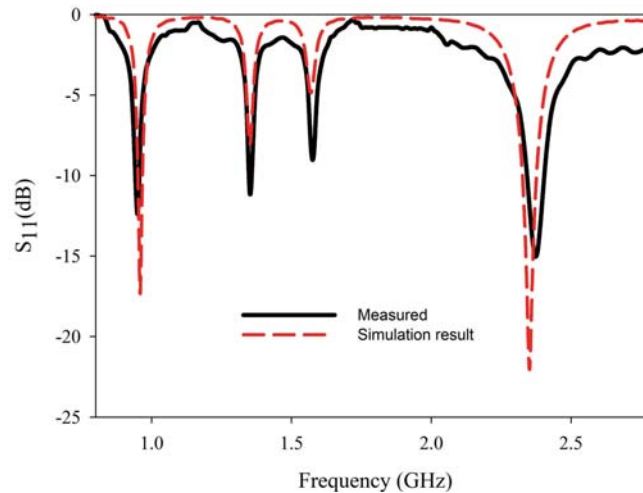
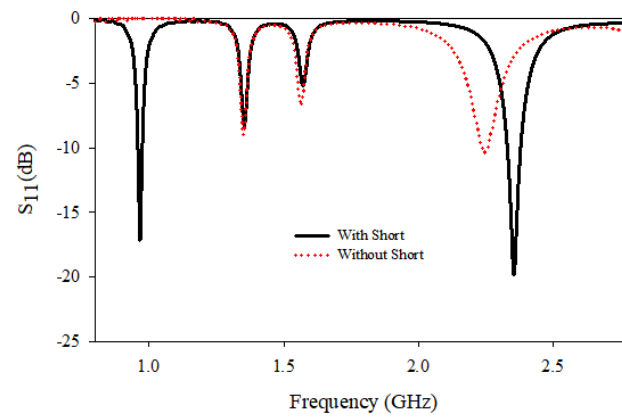
**Figure 4.** Reflection coefficient (dB) of the proposed antenna element.

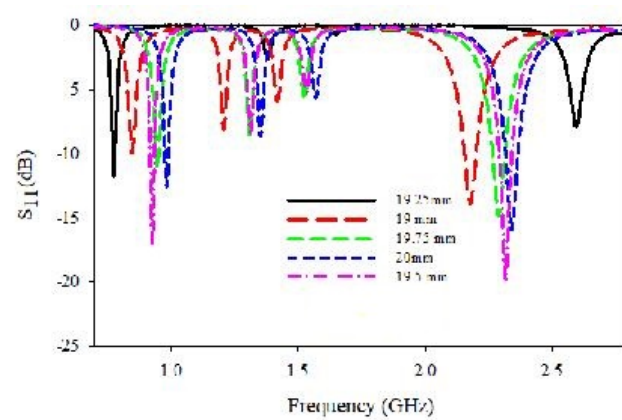
Figure 5 shows the effect of varying shorting pin position on the antenna performance. The introduction of short helps to achieve antenna resonance at 900 MHz and also increases the matching at 2.4 GHz. The position of short is determined by varying the short position from one end to another along the  $x$  coordinate with an optimum obtained at  $x = 19.5$  mm.

Figure 6 shows the variation of short position along the  $x$  axis. We find that as short is moved from  $x = 19.5$  mm towards  $+x$  direction, matching is obtained at unwanted frequencies, and return loss is high. Similarly, when the short is moved to the left of  $x = 19.5$  mm, mismatch between antenna impedance and coaxial cable occurs resulting in increased return loss.

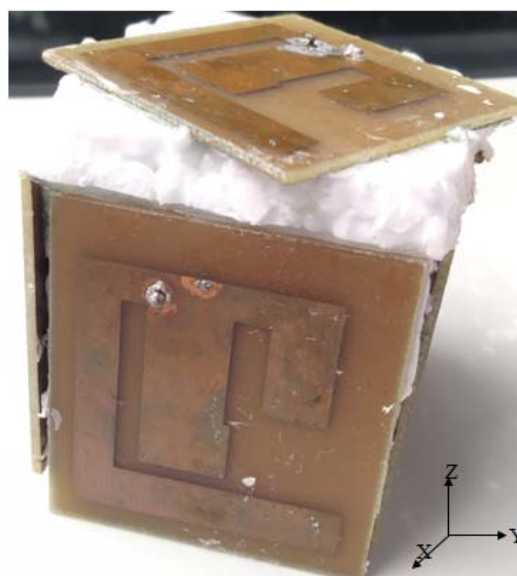
The antenna structure is positioned on all sides of a cube as shown in Figure 7, so that it can accept RF energy from everywhere with orthogonal polarizations. This square 3D antenna with a corresponding rectifier circuit for each antenna, when being hung at any location, is a suitable solution



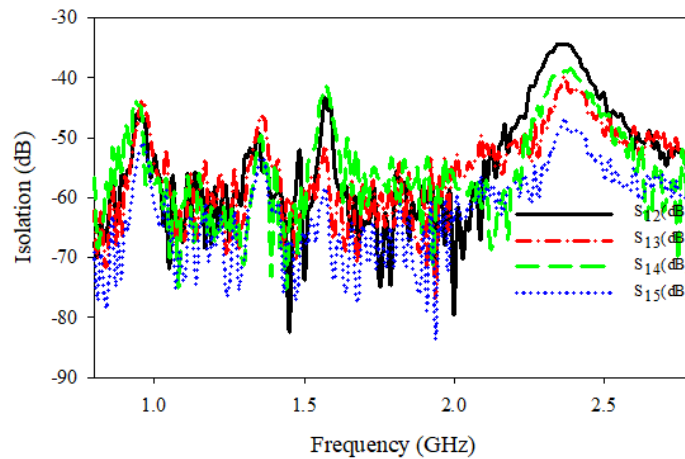
**Figure 5.** Effect of shorting pin on the antenna return loss.



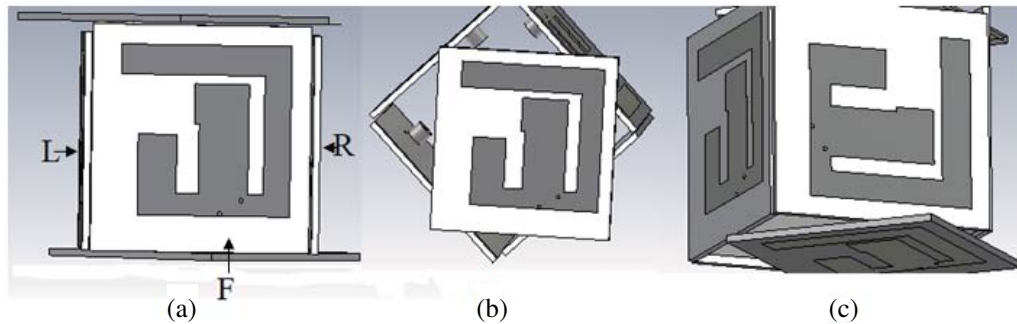
**Figure 6.** Variation of position of shorting pin along the  $x$  axis.



**Figure 7.** 3D cube antenna prototype.



**Figure 8.** Isolation between the various ports (dB).

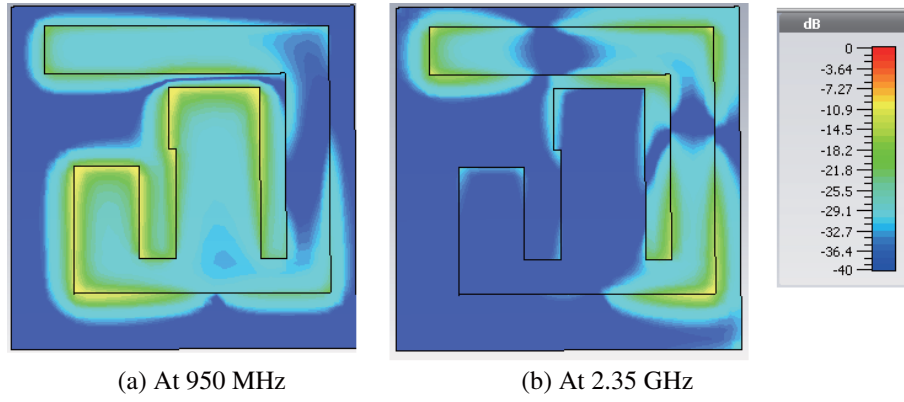


**Figure 9.** Antenna view. (a) Front. (b) Top. (c) Side.

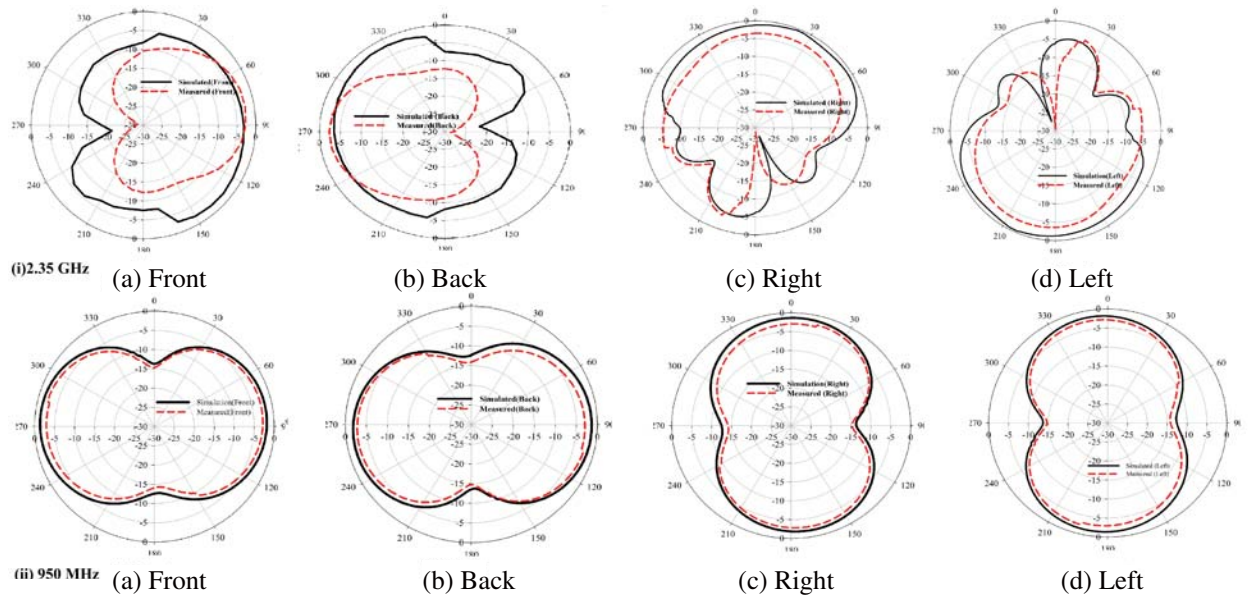
to charge low power IoT devices. The prototype of the 3D antenna system is shown in Figure 7, where identical antennas are placed on all the six sides of the cube with different orientations. The isolation between the ports, as shown in Figure 8, is below  $-30$  dB ensuring minimum interference between the antenna elements. The lateral, top, and side views of the cubical structure are shown in Figure 9, where F indicates the front, L the left, and R the right.

Figure 10 shows the current distribution of single antenna at 950 MHz. It shows that current flows through the U-shaped structure and also flows outwards from the shorting pin. Figure 11 shows the  $E$  plane radiation pattern of the complete antenna system at 950 MHz and 2.35 GHz when the antennas are operated one at a time with the others terminated in a matched load. Antennas on the top and bottom of the cube are inclined at  $45^\circ$ , and the remaining antennas are placed in horizontal and vertical alignment on all sides of the cube to ensure maximum RF power absorption. From the radiation patterns, it is explicit that antenna is able to acquire power from all directions making it appropriate for efficient ambient RF energy harvesting. This can be confirmed from the 3D pattern of the antenna when all the antennas are operated simultaneously as shown in Figure 12. Due to the presence of ground at the back of the substrate, the back radiation from the device is curbed particularly at 2.35 GHz. The gain of the antenna is 0.8 dBi at 950 MHz and 4.4 dBi at 2.4 GHz. Since the antenna is shorted for achieving size reduction at lower frequency, effective aperture area decreases, and hence the gain which is directly proportional to effective area is less than the gain for the same antenna operating at a higher frequency.

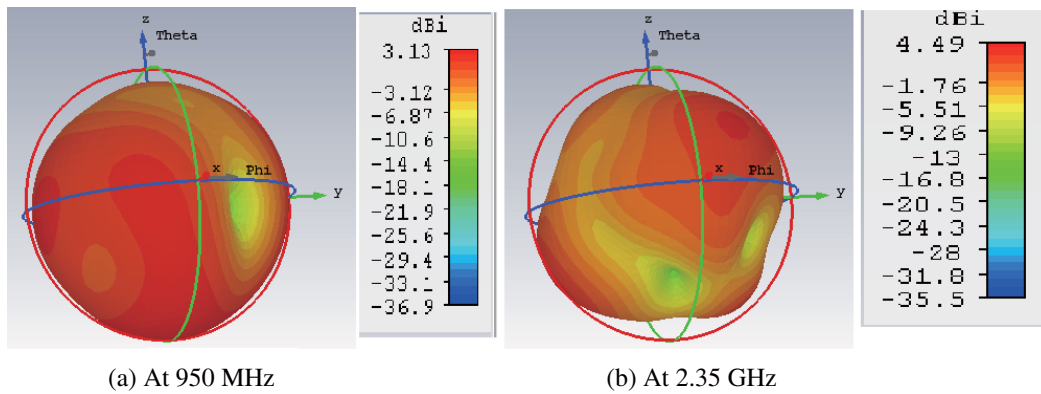
Table 2 shows the comparison of the suggested design with those formerly reported. From the table, it is clear that the proposed design is compact compared with others and also has the superiority of a wider coverage.



**Figure 10.** Current distribution on the antenna element.



**Figure 11.** *E* field radiation pattern — (a) Front, (b) Back, (c) Right and (d) Left antennas operated one at a time.



**Figure 12.** 3D radiation pattern.

**Table 2.** Comparison with those previously reported.

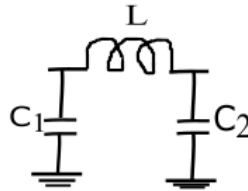
| Ref.          | Frequency ( GHz) | No. of ports | Polarization | Size ( $a \times b$ ) mm <sup>2</sup> | Gain ( dBi)       |
|---------------|------------------|--------------|--------------|---------------------------------------|-------------------|
| [16]          | 0.9, 1.8         | 16           | Dual LP      | $240 \times 240$                      | 3,1.5             |
| [18]          | 2.14, 2.45       | 1            | LP           | $380 \times 100$                      | not specified     |
| [19]          | 2-18             | 64           | Dual CP      | $185 \times 185$                      | dependent on load |
| [20]          | 1.8              | 3            | LP           | $98 \times 56$                        | 3.83              |
| Proposed work | 0.9, 2.35        | 6            | Dual LP      | $50 \times 47$                        | 0.8, 4, 4         |

#### 4. RECTIFIER

The rectifier is the heart of a rectenna system as it determines the power conversion efficiency of the entire system. During power transmission, there are two major reasons for reduction in efficiency, namely, leakage in the various components and impedance mismatch between the antenna and the rectifier. An impedance matching circuit will not only ensure identical source and load impedance but also act as a low pass filter rejecting harmonics generated from the nonlinear rectifier which otherwise would be reradiated back causing further losses.

Transistors and diodes, along with a resistive load, are used for RF to DC voltage conversion. The antenna impedance should be matched with the input impedance of the rectifier to maximise the output voltage. However, antenna impedance is a function of the incident RF power [23]. Hence a matching circuit is required to match the antenna impedance with the rectifier input impedance under these dynamic conditions. Stub based matching circuit is used as it ensures a degree of freedom in matching and also boosts the network quality factor.

Commonly used matching circuit is an L-section network due to structural simplicity, but it suffers from a limited Q. This restriction is overcome in a pi section matching network, shown in Figure 13. It is a combination of L-section circuits connected back to back.

**Figure 13.** Pi-section matching network.

If  $Q_n$  is the quality factor,  $Z_i$  the input impedance  $X_{in}$  the input reactance,  $R_{in}$  the input resistance,  $X_{C1}$  the reactance of capacitors  $C_1$ ,  $X_{C2}$  the reactance of capacitor  $C_2$ ,  $R_L$  the resistive impedance, and  $X_L$  the reactance part of the inductor, we can relate them as [21].

$$Q_n = \frac{X_{in}}{R_{in}} \quad (10)$$

$$X_{C1} = \frac{R_{in}}{Q} \quad (11)$$

$$X_{C2} = \frac{R_{load}}{\sqrt{\frac{R_{load}}{1 + Q^2} - 1}} \quad (12)$$

$$X_L = QR_L \quad (13)$$

$$Z_i = \left( (R_L + jX_L) \parallel \frac{1}{j\omega C_2} \parallel \frac{1}{j\omega C_1} \right) \quad (14)$$

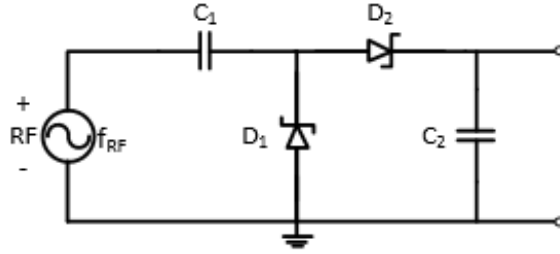
From the above relations, the value of inductor is found to be 50 nH;  $C_1$  is 100 fF; and  $C_2$  is 0.01 pF at 2.4 GHz. Since these capacitance values are small, we can realize them by using open circuit stubs enabling minimum loss.

The length  $l$  of open stub is given as [22]

$$l = \frac{1}{\beta} \left[ (n+1)\pi - \tan^{-1} \left( \frac{1}{\omega C Z_0} \right) \right] \quad (15)$$

where  $C$  is the capacitance value,  $\omega$  the desired angular frequency of operation, and  $Z_0$  the characteristic impedance. From the above equations, the length of stub corresponding to  $C_1$  is 1.75 mm, and  $C_2$  is 0.75 mm. Another inductor,  $L_2$ , of 20 nH is used to boost the input signal reaching the rectifier, and hence an improvement in efficiency is achieved.

The rectifier converts incoming RF signal into DC. Characteristics of a good rectifier are low power consumption, good dynamic range and power sensitivity. Various rectifier topologies like single series diode rectifiers, single shunt diode rectifiers, voltage doublers, Greinarcher multipliers, and Dickson charge pumps have been reported. In comparison, the single stage voltage doubler, shown in Figure 14, is a good choice due to its higher efficiency as well as better output power than other rectifier configurations [23]. Extra losses introduced by the multistage rectifiers are not present here.



**Figure 14.** Single stage voltage doubler.

Consider an RF input  $V_{in} = V_{ac} \sin \omega t$  applied at the rectifier output where  $V_{ac}$  is the amplitude of RF signal,  $\omega$  is the input frequency. During the negative half cycle of the input signal, the wave is rectified by the diode  $D_1$ , and the energy is stored in capacitor  $C_1$ . In the next half cycle, diode  $D_2$  is forward biased, and the energy is stored in  $C_2$ . Also, the energy stored in  $C_1$  during previous cycle is discharged through  $C_2$ , doubling the output voltage. Thus the output voltage is given as [24]

$$V_{DC} = 2V_{ac} \sin \omega t - 2V_F \quad (16)$$

where  $V_{DC}$  is the output DC voltage,  $V_{ac}$  the input RF signal,  $\omega$  the frequency of operation, and  $V_F$  the forward diode drop.

$$I_d = I_s \left[ \exp \left( \frac{V_{ac} \sin \omega t - 0.5V_{DC}}{mV_T} \right) - 1 \right] \quad (17)$$

where  $I_d$  is the diode current,  $I_s$  the reverse saturation current,  $V_T$  the thermal voltage, and  $B_0$  the zeroth order Bessel function.

$$I_d = I_s \left[ B_0 \left( \frac{V_{ac}}{mV_T} \right) \exp \left( \frac{-0.5V_{DC}}{mV_T} \right) - 1 \right] \quad (18)$$

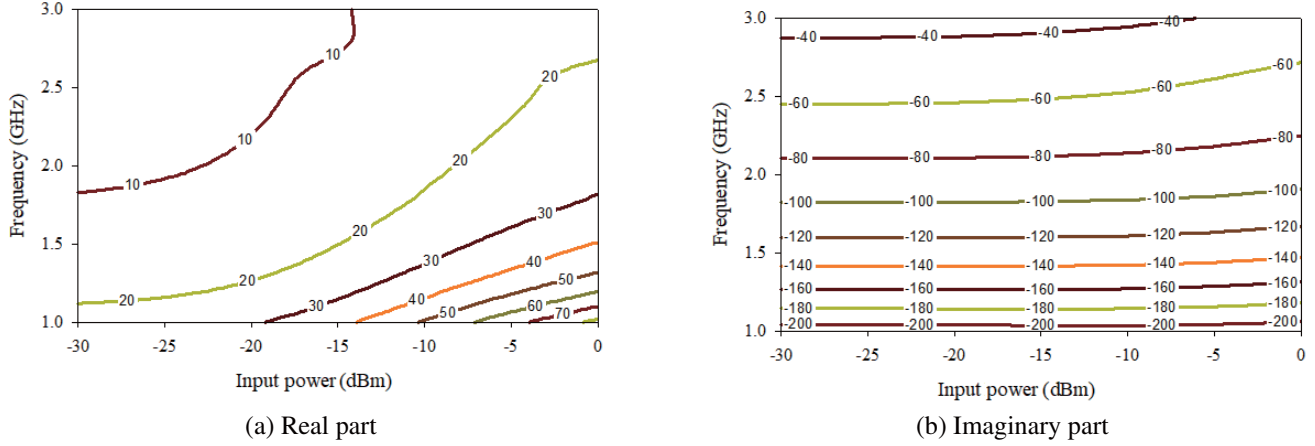
$$Z_d = \frac{V_F}{I_d} = \frac{2V_m \sin \omega t - V_{DC}}{I_s \left[ B_0 \left( \frac{V_{ac}}{mV_T} \right) \exp \left( \frac{-0.5V_{DC}}{mV_T} \right) - 1 \right]} \quad (19)$$

From Equation (10), the diode input impedance ( $Z_d$ ) varies with input power level  $V_{ac}$  and angular frequency  $\omega$ . Since the output voltage is calculated as  $V_{dc} = I_d * R_L$  where  $R_L$  is the load resistance,

Equation (19) can be rewritten as

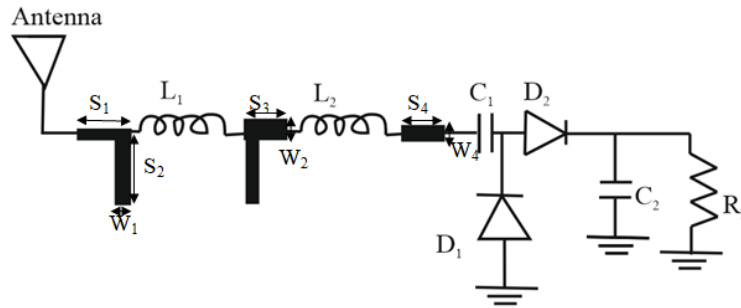
$$Z_d = \frac{V_F}{I_d} = \frac{(2V_m \sin \omega t - V_{DC})R_L}{V_{dc}} \quad (20)$$

So from above equation,  $Z_d$  is also seen varied by the load impedance. The input impedance variation of the voltage doubler circuit with input power as well as frequency is shown in Figure 15. It can be seen that the real part of the input impedance variation against frequency is large while the variation in the imaginary part of the input impedance is nearly constant. This poses a major challenge in the matching circuit design.



**Figure 15.** Rectifier input impedance versus frequency and input power at  $R_L = 40 \text{ K}\Omega$ .

The rectifier circuit designed is shown in Figure 16, and the measurement setup is shown in Figure 17. The width of two open stubs is given by  $W_1$  (4 mm). The length  $S_2$  is 18 mm;  $S_1$  is 9 mm;  $S_3$  and  $S_4$  are 6 mm;  $W_2$  is 5 mm;  $W_4$  is 4 mm. Series shunt Schottky diode SMS7630 is used in the voltage doubler due to its low junction capacitance, low forward cut-in voltage, and low parasitic losses. High output voltage and improved efficiency make single stage voltage doubler a good choice. The rectifier circuit was printed on a glass epoxy substrate with dielectric constant 4.4. Figure 18 shows the reflection coefficient of the rectifier circuit, and the slight change in measured and simulated results is due to soldering effects and the change in permittivity value of the substrate used.



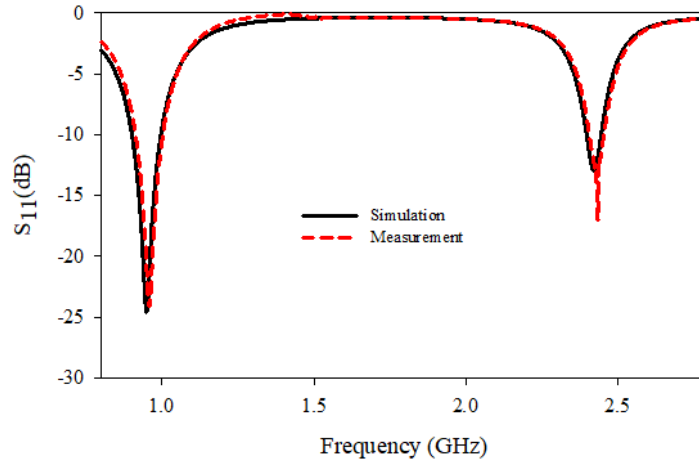
**Figure 16.** The designed rectifier.

The efficiency of rectenna is defined as the ratio of output DC power  $P_{DC}$  to the input RF power  $P_{RF}$ .

$$\eta = \frac{P_{DC}}{P_{RF}} = \frac{V_{dc} X I_{dc}}{P_{RF}} \quad (21)$$



**Figure 17.** Prototype testing.



**Figure 18.** Reflection coefficient of the proposed rectifier.

where  $V_{dc}$  is the output DC voltage, and  $I_{dc}$  is the output DC current.  $R_L$  is the output load resistance. Various resistor values like 5, 10, 20, 25, 30, 35, 40, 45, 50, 55, 60  $K\Omega$  were tested, and the system obtained maximum efficiency for 40  $K\Omega$ .

## 5. RFEH SYSTEM

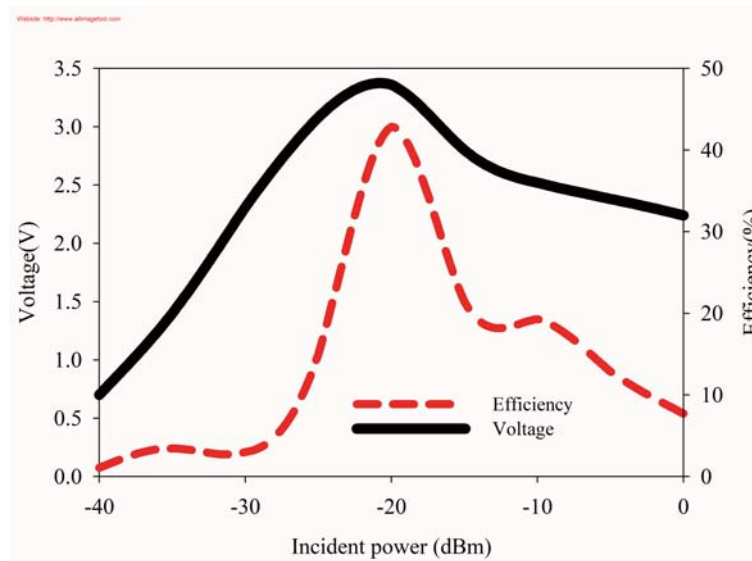
The harvested RF energy can be increased if we capture electromagnetic waves from all the possible directions. This is accomplished in this work by connecting antenna structures in such a way that it forms six sides of a cube. Two antennas on lateral edges are inclined at  $45^\circ$  to receive vertically polarised, horizontally polarised as well as circularly polarised RF signals. On the back side of each designed coaxially fed patch antenna, rectifier circuits with a common ground can be connected to the antenna input through SMA joint. The ground structure also provides isolation between antenna and rectifier circuit to minimise interference losses.

The proposed rectenna circuit is shown in Figure 19. The measurements show that at  $-20$  dBm input power using a single rectenna circuit we were able to obtain nearly  $0.5$  V DC output. So by connecting all rectenna circuits using DC combining we would be able to get nearly  $3$  V output at  $-20$  dBm input which is sufficient for powering IoT devices as shown in Figure 20. Hence the proposed cubical rectenna system can ensure that IoT devices can be recharged easily by RFEH.

This compact cube structure can be hung anywhere and can harvest RF energy in all directions using the six antennas. The maximum output power from the device is  $5$  mW. Table 3 shows the comparison of output power and the frequency bandwidth of proposed RF energy harvesting cube device with similar works reported previously.



**Figure 19.** Prototype of the proposed rectenna element.



**Figure 20.** Efficiency and output voltage of the proposed RFEH system.

**Table 3.** Comparison with existing works.

| Ref.          | Frequency (GHz) | No. of ports | Rectifier efficiency (%) | Output voltage (V) | Input Power (dBm) |
|---------------|-----------------|--------------|--------------------------|--------------------|-------------------|
| [25]          | 1.8, 2.1        | 1            | 36                       | 0.220              | -18               |
| [26]          | 2.4, 5.8        | 1            | 30                       | 1                  | -5                |
| [27]          | 1.8, 2.1        | 4            | 53                       | 2.3                | 0                 |
| [20]          | 1.8             | 3            | 22                       | 0.8                | -20               |
| Proposed work | 0.9, 2.35       | 6            | 48, 38                   | 3                  | -20               |

## 6. CONCLUSION

A novel dual-band rectenna system operating at GSM900 band and Wi-Fi 2.4 GHz for ambient radio frequency harvesting is proposed. An E-shape combined with inverted L-shape patch antenna is used to achieve dual frequency operation. Compact size is achieved with the help of a shorting pin, making the patch to resonate at 950 MHz and 2.35 GHz and radiate with gains of 0.8 dBi and 4.4 dBi, respectively. It is then arranged on six sides of a cubical structure to enable reception from all directions and

polarisations. A T-section based matching circuit is used to achieve impedance matching at the desired frequencies. Villard voltage multiplier is connected at the back side of the antenna structure with a common ground and combined using dc combining method to ensure maximum output voltage. The rectenna system has obtained an efficiency of 48% at  $-20$  dBm input power. Cubical arrangement of the rectennas ensures maximum energy acquirement from all sides and for all polarizations, and provides a maximum of 3 V output voltage which is sufficient to power low energy devices.

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