ENERGY HARVESTING RECTENNA DESIGN FOR ENHANCED NODE LIFETIME IN WSNS

Prakash K Sonwalkar[1, 2] and Vijay Kalmani[2]

[1]Research Scholar, VTU, Belagavi, India
[2]Department of Computer Science and Engineering,
Jain College of Engineering, Belagavi, India

ABSTRACT

With the rising popularity and advent of many services on Wireless Sensor Networks (WSNs), there is a compelling need to have energy-efficient solutions. The sensors and devices are powered by batteries whose life is limited, and at times it is impossible to replace the batteries, especially in remote applications. In such a scenario, Energy Harvesting (EH) stands as an undisputed candidate for enhancing the network lifetime. Radio Frequency (RF) energy is the most commonly available, ubiquitous, and reliable energy source among all the available energy sources. While RF signal carries both information and energy, EH is possible for long-distance and mobile environments. This work discusses initial research in the domain of EH in wireless networks via Radio Frequency (RF) signals. The paper presents an EH rectenna for energy harvesting over 2.45 GHz (Wi-Fi band). The receiving antenna is designed to pick up the radio signal in the RF range (2.45 GHz) from the free space. The four patch elements design has an antenna substrate made with RT with a dielectric constant of 2.2. The paper presents the simulation results of the basic parameters of the antenna, such as return loss, input impedance, bandwidth, gain, directivity, and efficiency. H-shaped slot antenna and modified H-shaped antenna (with circular slot) are designed with a gain of 8.24 dB and 8.32 dB, return loss of -10 dB and -16 dB, and bandwidth of 64.8 MHz and 868 MHz. The high gain, large bandwidth, properly matched impedance for minimum return loss, and high efficiency of the modified H-shaped patch antenna makes it eligible for energy harvesting.

KEYWORDS

Antenna Design, Back Scattering, Beam Forming, Energy Harvesting, Sequential Rule, Wireless sensor network.

1. INTRODUCTION

With the proliferation of edge devices and extensive study on deployment, WSNs find their applications ranging from remote applications to body area networks. A typical WSN intends to monitor the environment with the aid of sensor(s), micro-controller(s), transceiver data storage, and energy storage facilities (batteries). The battery acts as an energy source for a node, and its power decides the life of a WSN. Energy Harvesting is perceived as an amicable solution for the bottleneck created by the limited lifetime of the battery. Recently, many researchers have attempted to achieve EH with various harvesters and energy resources depending on the applications. At the same time, there are many sources for EH such as solar, wind, thermal, vibrational, temperature, electromagnetic, etc. RF energy is the most commonly available, ubiquitous, and reliable energy source [1]. An essential block diagram representation of the RF harvesting system is shown in fig 1. A typical Rectenna consists of a transceiver antenna, optional Low pass filter, matching network, energy conversion unit, and load/storage device. The antenna first detects the RF signal in the ambiance. This sensitivity of antennas to RF signal induces an AC signal fed to the rectifier.

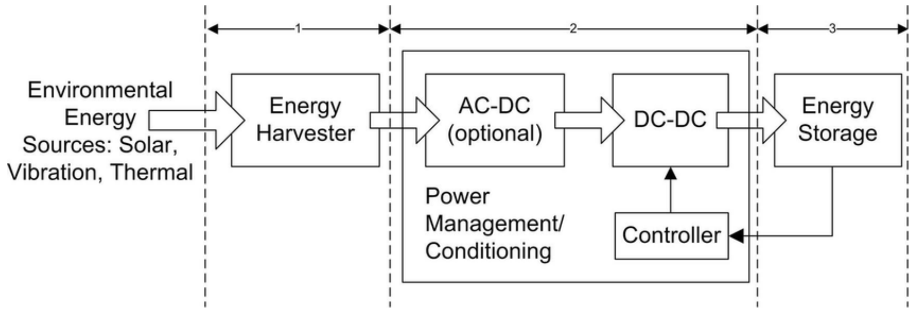


Figure 1. Typical Block diagram representation of RF Energy Harvesting System.

The rectifier comprises diode(s) whose fast switching action is exploited to convert AC signal into DC. A low pass filter is employed to achieve optimal power transfer for impedance matching between antenna and rectifier. For an increased level of output voltages, a voltage multiplier can be employed. The storage and controlling unit provide an uninterrupted power supply. In contrast to other energy harvesters, RF harvesters are robust as they require no mechanical movements [2]. RF is an ambient source of energy, arising due to the radiations from TV broadcast, Radio (FM and AM), wireless LAN, Wireless Fidelity (Wi-Fi), and cellular transceiver stations [3]. Although ambient signals can be harvested with simple electronic circuitry, there are many challenges to be addressed by RF harvester. Since RF signals are available with a wide range of frequencies, the RF harvester must ensure proper impedance matching for maximum power transfer. The RF should employ large broadband antennas to harvest sound energy from the signals spread over a broad spectrum. The harvesting circuits must be positioned close to the RF power source since the ambient levels are deficient. The low energy density and low efficiency demand a dedicated RF energy supply as even a high-gain antenna cannot generate enough power densities. With small-sized, high gain, and impedance-matched broadband antennas and a dedicated RF energy supply system, the energy harvesting in low-power WSNs seems to be more promising and feasible.

With the spectacular growth in mobile phones and Wi-Fi networks, RF energy has become significant in urban areas [4]. Wireless Power Transmission (WPT) can be classified into three categories, as depicted in fig 2.

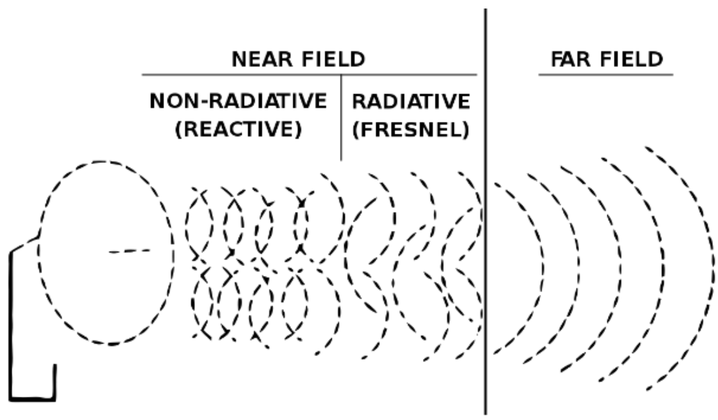


Figure 2. Three categories of WPT. Near-field, far-field - directional, and far-field ambient wireless energy harvesting.

The first category - Near field inductive or resonant coupling. This occurs between two entities where the primary coil transfers power to the secondary. It is suitable for wireless charging devices separated by a few centimeters. The second category refers to far-field directive powering. RF energy can be harvested from mobile phones in proximity, potentially providing power-on-demand for short-range sensing applications. Here power transmission occurs in the far-field but with Line of Sight (LOS). This WPT is intentionally power sensors equipped with a rectenna [5]. The third category refers to far-field energy harvesting. The receiver doesn't know where the RF energy is emitted (no LOS/loss between the base station and the harvesting device). High gain antennas with wide beamwidth and wideband resonance are employed for enhanced and efficient energy harvesting in long-range operation. The selection of the type of rectenna and the entire energy harvesting system varies from application to application [6], [7], [8].

Rectenna is a combination of rectifier and antenna. Diodes are used for rectification, while antenna can be either dipole, planar, or microstrip patch. Many attempts have been made to harvest energy from various RF signals. Among all the frequencies, 2.45 GHz is the favorite. Most of our electronic devices, such as routers, cordless phones, Bluetooth earpieces, baby monitors, and garage openers, all love and live on this radio frequency, as it is in Industrial, Scientific, and medical radio bands (license is not required to operate in this band) [9]. It requires small antennas and can operate over a long- range (with Los). Our objective in this paper is double folded: first, review the attempts made in EH from RF signals, and second, to design and develop a high-gain broadband antenna for harvesting over 2.45 GHz signal. The remainder of the paper is organized below: Section II provides a brief background with theoretical foundations and a literature review of rectennas employed in EH. Section III presents designs of 4-element micro-strip patch antennas for efficient EH. Section IV presents the discussion on designed antennas and the merits and demerits of each design. Paper concludes in section V.

2. BACKGROUND AND RELATED WORK

Affordable and clean energy is the seventh Sustainable Development Goal (SDG) which aims to cater to the rising demands for energy while reducing the carbon footprint and burden on nature [10]. Energy harvesting seems to be one of the best prospects to realize this goal. EH refers to a process of capturing and storing the energy from sources around us that are free to use. EH, also referred to as Energy Scavenging (ES), makes it possible to overcome the inconvenience of frequent replacement of batteries [11] while being less expensive and eco-friendly. EH stands as a viable solution for continuous powering of low power loads such as wireless nodes. Many attempts have been made to design EH schemes based on the availability of energy sources such as solar, piezoelectric, wind, hydroelectric, and RF signals. RF-EH is most suitable as the energy source is readily and abundantly available in transmitted energy. Other key benefits are being economically viable, eco-friendly, and having small form factor implementation [12]. RF-EH has the potential to revolutionize low-power applications - especially WSNs. Excessive use of batteries results in their disposal, causing extreme toxic pollution to the environment [13]. RF-EH can increase the lifetime of nodes and provide power indefinitely [14]. Passive energy scavenging nodes without batteries will be the next generation of WSNs, driven by RF-EH because of its sustainability [15].

2.1. Theoretical Foundations

A proper understanding of EM waves is necessary while designing an RF-EH system. EM waves broadly vary w.r.t. distance, frequency, and conducting environment. Based on the application, the designer needs to take a call on the parameters of EM waves to make the most out of the design. The relation between EM waves and distance from transmitting antenna can be categorized into 2 segments: near-field and far-field. These two fields are marked by Fraunhofer's distance given by

$$d_f = {2D^2}/{\lambda}$$

where d_f is the Fraunhofer distance, D is the maximum dimension of the antenna, and λ is the wavelength of EM wave. For a transceiver antenna, in far-field the received power is given by

$$P_R = {(P_T G_T\, G_R \lambda^2)}/{(4\pi\, R^2)}$$

where P_R is the power received; G_T andG_R are transmitter and receiver gains respectively. The RF-DC conversion efficiency is given by

$$\eta = {(V_{D.C}^2) * 100}/{(P_R R_L)}$$

where VDC is measured DC output voltage, PR is received RF input power and RL is resistive load. P_R is given by $P_D * A_{eff}$ where P_D is the RF power density and A_{eff} is the effective aperture of the antenna [16]. The RF power density for GSM900/1800 MHz is around 0.1µW/cm2 while for Wi-Fi 2.4 GHz it is around 0.01µW/cm2 Typically, RF power conversion will be around 45% to 50% [17].

2.2. Energy Harvesting Antenna Design

The design of the Energy harvesting antenna has attracted many researchers due to its sustainable and eco-friendly nature. A rectenna is a wireless power transfer system subsystem that can function anywhere in the range of 1 GHz to 35 GHz. Many factors such as transmitted power, transmitter gain, received power, receiver gain, conversion efficiency, will dictate the design of an energy harvesting antenna. Many other things need to be considered and implemented to enhance efficiencies, such as arrays of the antenna and circular polarization. The resonant frequency of a circular patch antenna is given by

$$f_{r,n,m} = \frac{\alpha_{nm}\, C}{2\pi\alpha_{eff}\, \sqrt{\varepsilon_{r,eff}}}$$

Reconfigurable antennas got tremendous momentum recently due to their tuning, polarization, and selectivity of operating frequency. RF reconfigurability is achieved via dynamic modification of physical structure, thereby attaining polarization diversity. The advantage of automatic frequency tuning to accommodate wideband frequency makes reconfigurable antennas more popular. Though they seem promising, the other constraints like miniaturization, lightweight, beamforming, impedance matching, gain, radiation pattern need to be reworked every time the frequency is switched. While we fine-tune the efficiencies of individual modules, the integration of all modules should be in harmony and result in inefficiency if a Wireless Power Harvesting (WPH) system.

Designing an efficient WPH system involves rigorous testing, making several adjustments, tuning many parameters, evaluating the entire system. Operating frequency is the prime parameter that dictates the entire design. The operating range also needs to be specified. GHz frequencies are selected for long-range power harvesting, while MHz is sufficient for short-range operations. In a dense environment, electromagnetic waves with very low frequency (in kHz) are preferred. The topology of the electronic circuit(s) such as rectifier and voltage multiplier is decided based on the distance, operating frequency, and the required power output. Antenna design is the essential part of the entire system design, based on the type and application. Antenna design should satisfy the expected gain, frequency, and size. Rectifier and voltage multiplier design must match the power conversion efficiency. Though the capability of a WPH system critically depends on the antenna, it is one of the overlooked parts of energy harvesting system design. This slight inclination will significantly impact system performance as antennas are selected and deployed irrespective of the operating conditions, material to which it is attached, and mobility of the tagged object. To avoid degraded performance due to improper antenna design, the design process must go through various steps, as depicted in fig 3. Understanding the application and deploying environment will select an operating frequency, bandwidth, and required antenna parameters.

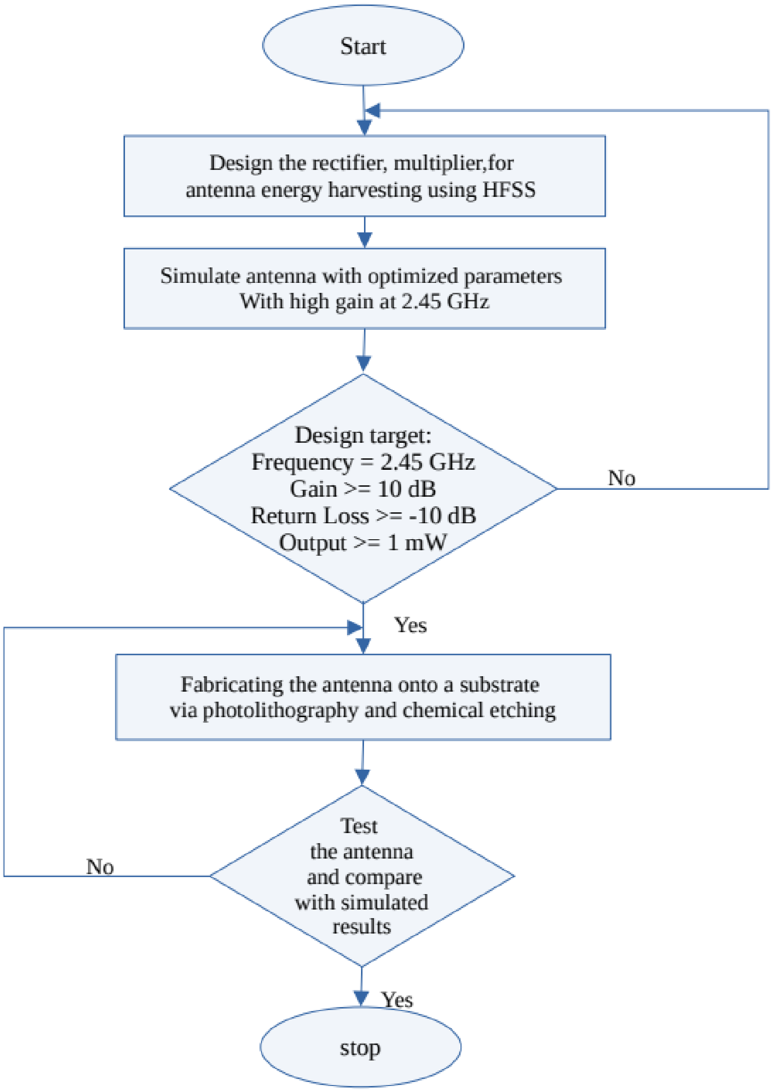


Figure 3. RF Energy Harvesting Antenna Design Flow

These requirements determine the material for antenna construction and ASIC packaging. Antenna parametric study and optimization are done until the simulation's design requirements are met. The antenna is first modeled, simulated, and optimized on a computer by monitoring the read range, antenna gain, and impedance, providing good insight into antenna behavior. In the last step of the design process, prototypes are built, and their performance is measured extensively. If the design requirement is satisfied, the antenna design is ready. Otherwise, the design is further modified and optimized until conditions are met.

2.3. Previous Work

Communication antennas have been explored for a century (since World War-I). However, energy harvesting antennas have gained momentum very recently. A narrowband antenna achieves good energy conversion from RF to DC but can harvest only a few frequencies. On the other hand, wideband antennas retrieve a large amount of energy but come with ~~a~~ large aperture size and poor conversion efficiency. One argument for a multi-band antenna is at any given time; an antenna cannot be made to resonate at two frequencies [18]. Table 1 summarizes the prior art of power-harvesting antennas. Patch antennas have been explored extensively for harvesting energy from RF signals, especially at 2.45 GHz [19], [20], [22], and [25]. In [26], antennas with a resonant frequency of 2.45 GHz and 5.8 GHz were designed with Power Conversion Efficiencies (PCEs) of 65% and 46 % @ 10 µW/cm2 Two different frequency bands, i.e., 900/1800 MHz (for short-range) GSM band and 2.4 GHz ISM band was targeted by designing a microstrip antenna with joint feeding line implemented in a Multilayer substrate in [27]. A double patch antenna was employed by [28] to operate at 1.8 GHz and 2.4 GHz with Simultaneous Wireless Information and Power Transfer (SWIPT) mechanism.

The arrangement of antennas in the array is one of the best techniques to achieve high gain and obtain high voltage/current. Another advantage of array antennas over large aperture antennas is that they do not require large breakdown voltage diodes to operate. Connecting the antenna array before rectification improves retrieved power at the main beam while placing the array after rectification will expand the ability to retrieve power from wide angles. Combining RF waves before rectification demands a large breakdown diode~~,~~ while combining RF waves after rectification and consolidating DC will be an issue. Series connection of array antennas will enhance voltage, whereas parallel fashion opts for large current. Increasing the array elements will yield better outputs but reduce conversion efficiency.

Table 1. Comparison of published work regarding power harvesting antennas

Ref	**Antenna Type**	**Frequency (GHz)**	**Gain(dBi)**	**Dimension (mm)**	**RF-DC DPCE**
[19]	Air substrate patch	2.45	7	261*5	30%
[20]	Patch	2.45	-	100*70	73.9% @ 207 μWcm^2
[21]	Dual Linear polarized patch	2.45	7.45-7.63	70*47.5	78% @ 295.3 μWcm^2
[22]	Dual polarized patch	2.45	-	100*100*3.8	82.3% @ 22 μWcm^2
[23]	Dipole	2.45	-	60*60*60	39%@0dBm
[24]	Microstrip	2.45	8.6	-	83%
[25]	Patch	2.45	4	-	70%
[26]	Patch	2.45	2.19	40*43	65%@10 μWcm^2
[27]	Microstrip	2.45	-	72*94	74%@0.3 μWcm^2
[28]	Double Patch	1.8 & 2.4	-	40*30	19%@5 μWcm^2
[29]	Single fed Microstrip patch	2.4	7.19	60*60	79%
[30]	Microstrip patch	35	19	-	67%@7mW

	Antenna Array 4*4				

2.4. Antenna Design

2.4.1. Estimation of Width of patch antenna:

Width of microstrip antenna given by

$$W_p = \frac{c}{2_{f0}\sqrt{\frac{\varepsilon_r + 1}{2}}}$$

Where f_o is the operating frequency, c is the speed of light in air is 3x108 m\sec and ϵr is dielectric permittivity of substrate is 4.4.

2.4.2. Estimation of effective dielectric constant ε_{eft}:

Where h is thickness or height of the substrate which is 1.6mm.

When $\frac{W_p}{h} > 1$,

$$\varepsilon_{eft} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r + 1}{2} [\left(1 + 12\frac{h}{W_p}\right)^{-\frac{1}{2}} + 0.04 \left(1 - 12\frac{W_p}{h}\right)^2$$

When $\frac{W_p}{h} < 1$,

$$\varepsilon_{eft} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r + 1}{2} [\left(1 + 12\frac{h}{W_p}\right)^{-\frac{1}{2}}$$

2.4.3. Estimation of effective Length L_{eft}:

$$L_{eft} = \frac{c}{2_{f0}\sqrt{\varepsilon_{eft}}}$$

2.4.4. Estimation of length extension (ΔL)

$$\Delta L = 0.412h \frac{(\varepsilon_{eft} + 0.3)\ (\frac{W_p}{h} + 0.264)}{(\varepsilon_{eft} - 0.258)\ (\frac{W_p}{h} + 0.8)}$$

2.4.5. Estimation of actual length of proposed patch antenna (L_P)

$$L_P = L_{eft} - 2\,\Delta L$$

2.4.6. Estimation of Ground Dimensions (Lg, Wg):

$$L_g = 6h + L_P, \quad W_g = 6h + W_P$$

2.4.7. Estimation of Length of feed L_f:

$$L_f = \frac{\lambda_g}{4}, \lambda_g = \frac{\lambda}{\sqrt{\varepsilon_{eft}}}, \lambda = \frac{c}{f_0}$$

Where, λ_g is the Guide wavelength

3. PROPOSED ENERGY HARVESTING ANTENNA

By using the above equations, we got the value of each dimension of the antenna, as shown in Table 2. The rectangular Patch antenna array with the dimensions mentioned in table 2 is depicted in fig 4.

Table 2. Calculated Parameters for the microstrip patch antenna

Parameters	**Value**
Effective Dielectric Constant	2.11
Patch Width 'W'	49mm
Patch Length 'L'	39mm
Microstrip Line Length y_0	11.5mm
Microstrip Line Width W_l	47mm
Inset Gap W_S	47mm
Width of Substrate W_g	57mm
Length of Substrate L_g	49mm

3.1. 4-element rectangular Patch Array

The antenna array is designed using four patch elements to increase the gain, as shown in fig.4. Equidistant placement of the patch elements on the substrate forms a planar array. A feed network connects patch elements and is adequately designed to enable equal radiation. Among all the available options, one side feed network (all patch elements oriented in one direction) provides high gain, low loss, and a single central beam with the null deviation between electric and magnetic fields.

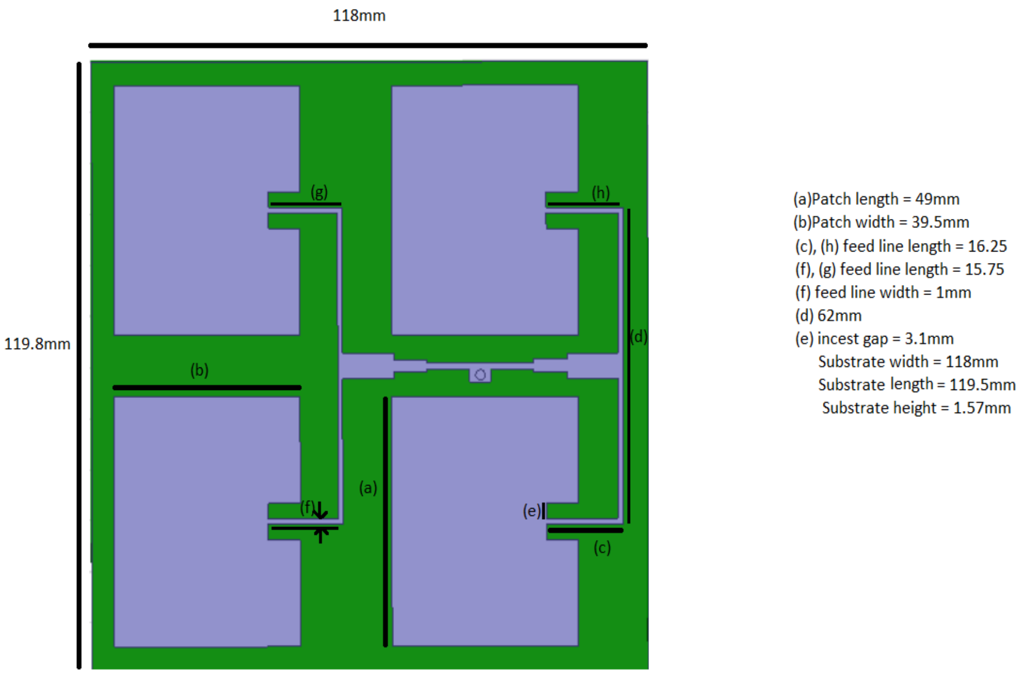


Figure 4. 4-element Rectangular Antenna Array

3.2. H-shaped Patch Antenna Array

Though the antenna exhibits acceptable behavior, bandwidth is not superior to previous works. To improve the bandwidth, one needs to tweak antennas' geometry without affecting other parameters and properties. Many techniques such as changing or removing the substrate and introducing slots either in radiating patch or ground plane have been investigated.

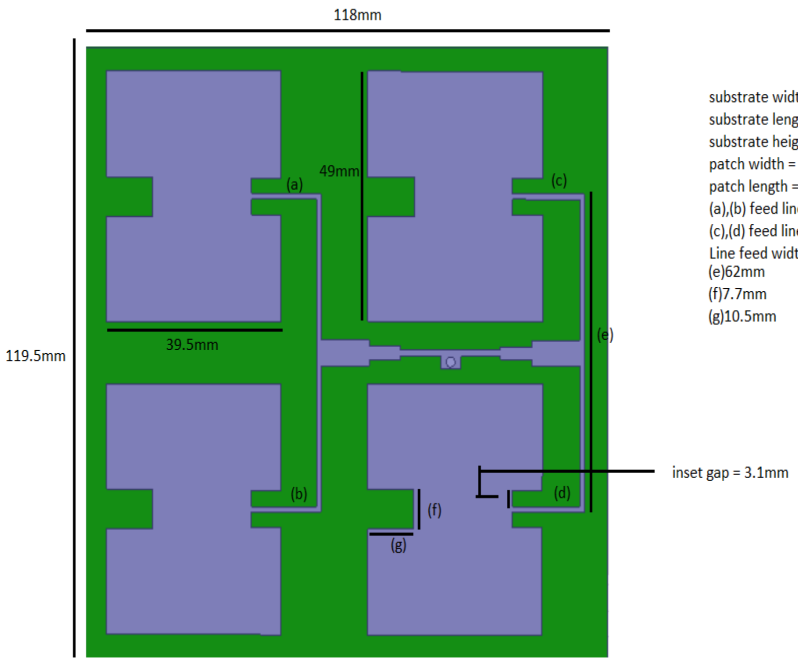


Figure 5. 4-element Rectangular Antenna Array

Table 3. 4-element H shaped microstrip patch antenna array dimensions

Parameters	Value
Path array dimensions	119.5 * 118(in mm)
Gain	17.2dBi
Return Loss	-12.49
Input Impedance	44 + j2.3
Bandwidth	52 MHz (~= 2.1%)

3.3. Circular slot, Modified H-shaped Patch Antenna Array

To investigate the influence of various shapes and sizes of slots on bandwidth, simulations have been carried out. If we place a slot at the middle of the radiating edge, it may take the form of a U or H shape. The simulation of the H shape antenna array resulted in improved bandwidth. The width is designed as per the equations and $W_S = \lambda/60$ and $L_S = {}^{c}/_{2f\sqrt{\varepsilon_{eff}}} - 2(L + \Delta L - W_S)$.

Table 4. 4-element modified H-shaped microstrip patch antenna array properties.

Parameters	Value
Path array dimensions	119.5 * 118(in mm)
Slot Dimensions	7.7 * 10.5 (in mm)
Gain	17.2dBi
Input Impedance	40 + j 5.5
Bandwidth	64.8 MHz (~= 2.65%)

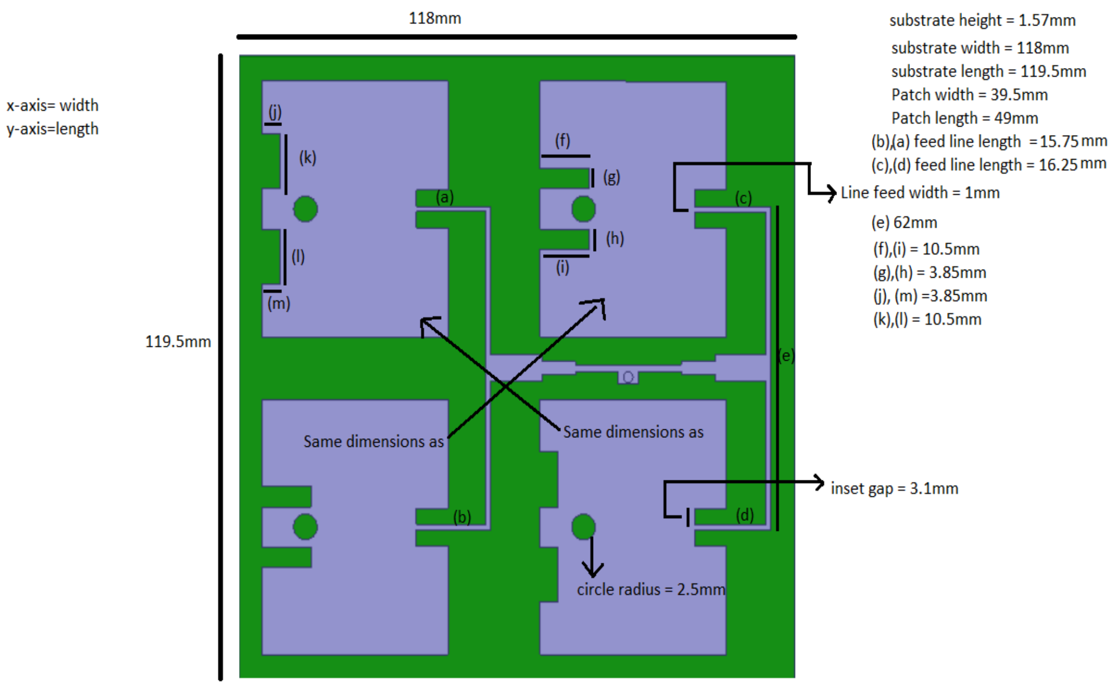
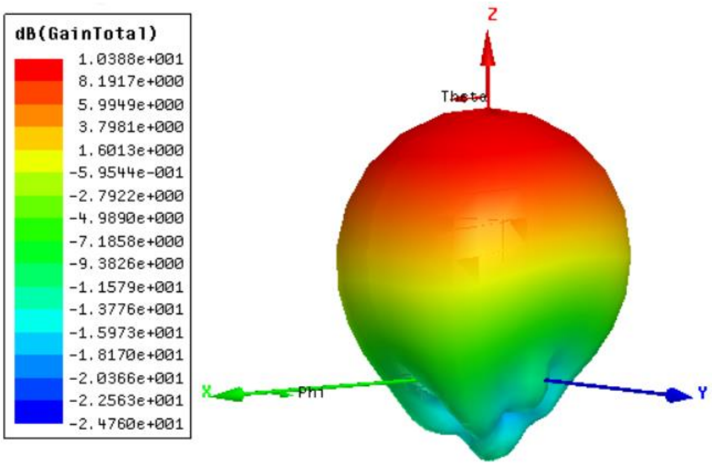


Figure 6. 4-element modified H-shaped Patch Array Antenna

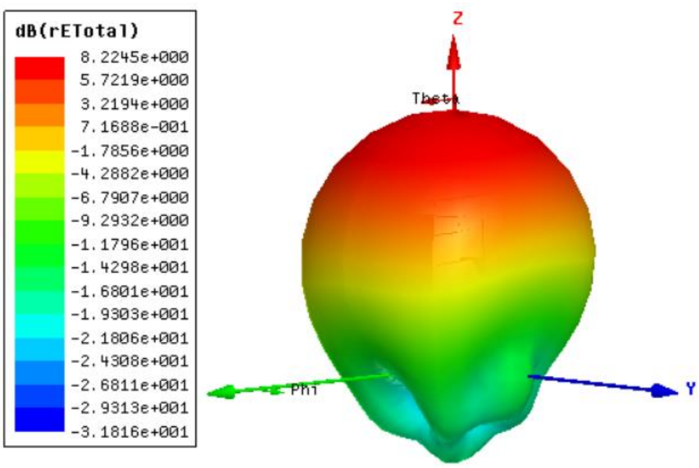
Though the focus will be on directivity and efficiency while designing an antenna, the aim will be to have excellent power reception and conversion in the larger picture. Multiband antennas are designed when energy must be harvested from RF signals of a wide range of frequencies. The author's primary focus is on enhancing the rectennas' bandwidth (4-element array) designed to harvest energy at a central frequency of 2.45 GHz.

4. RESULTS & DISCUSSIONS

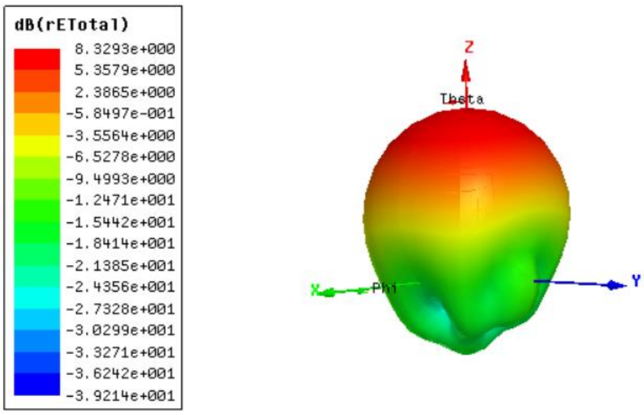
The IoT using wireless motes has perpetuated the demand for self-reliant electronics. Recent research has emphasized fulfilling this requirement via energy conservation. The energy crisis of these remotely placed devices needs to be taken care of. The energy crisis can be studied at various levels, either at the energy resources level (choosing an appropriate and abundantly available energy resource), or at energy conservation level (energy-transformation mechanisms), or energy storage level (power management), or at energy consumption level (harvested energy is consumed responsibly).



(a)

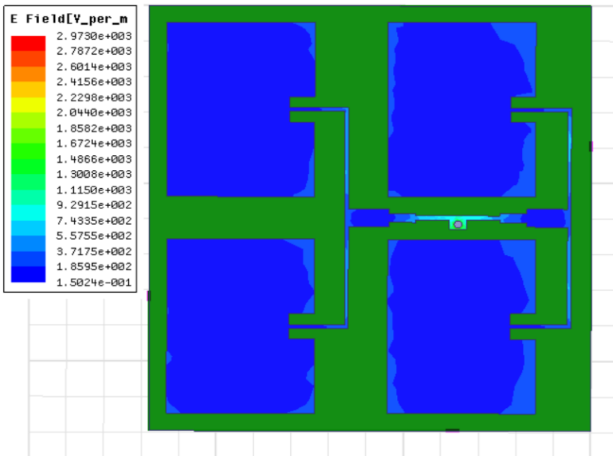


(b)

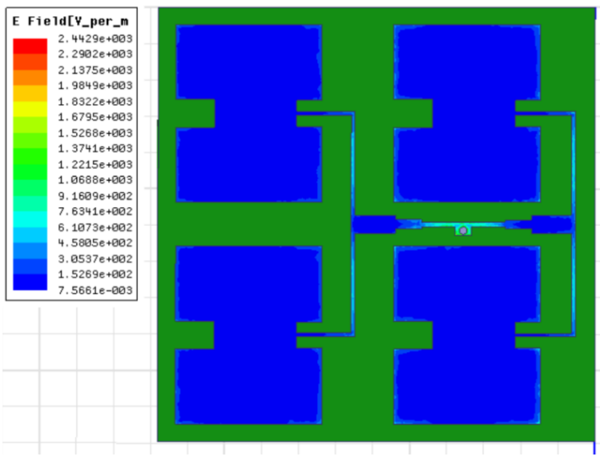


(c)

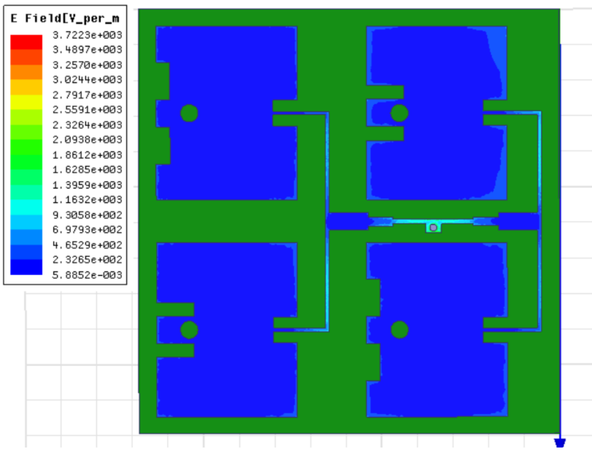
Figure 7. 3D polar plots of (a) single Microstrip patch element (b) H shaped 4-element antenna array (c) Modified H-shaped 4 element antenna array



(a)



(b)



(c)

Figure 8. The current distribution of (a) single Microstrip patch element (b) H shaped four-element antenna array (c) Modified H-shaped 4-element antenna array

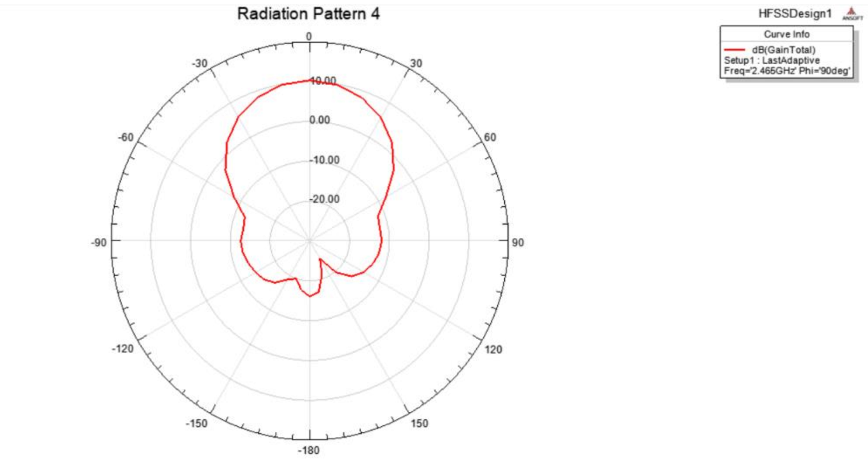
Energy sources available for harvesting are thermal, solar, vibrational, chemical, Radiofrequency, electromagnetic, and mechanical. All the sources demand bulkier devices with mechanical movements for energy harnessing except RF. In contrast to all available sources, RF is ubiquitous, readily available, and is present in the ambiance due to signal transmissions by all wireless transmitters. RF energy harvesting is much suited for IoT devices as there is a significant restriction on the size of energy conversion devices and energy storage devices. RF energy harvesting has garnered significant attention due to its consistent availability in the ambiance from radio, TV, Cellular, and Wi-Fi communications.

Many energy-saving mechanisms are being investigated, including Radio optimization, Data optimization, scheduling schemes, Routing and Topology Control, and messaging protocols. Among all options, Radio optimization has shown massive potential in energy saving as it deals with energy harvesting. Radio optimization tries to save energy via transmission power control, Directional antenna, and Cognitive Radio. Wireless transmission of energy has no bounds. Wireless power transfer is the transmission of electrical energy from a transmitter connected to a power source via beamforming to one or more receivers without power cords. At the receiver, the electromagnetic signal is converted back to an electric current and then used by either 1) inductive, capacitive, or resonant reactive near-field coupling, or 2) far-field directive power beamforming, or 3) far-field non-directive power transfer. Since near field and far field with line-of-sight are conducive for energy harvesting, it is implied that much of the research should be focused on the third type, i.e., far-field non-LOS WPT. The two challenges in such deployment are the low power densities of incident power and the dynamics of position and orientation of the receiver.

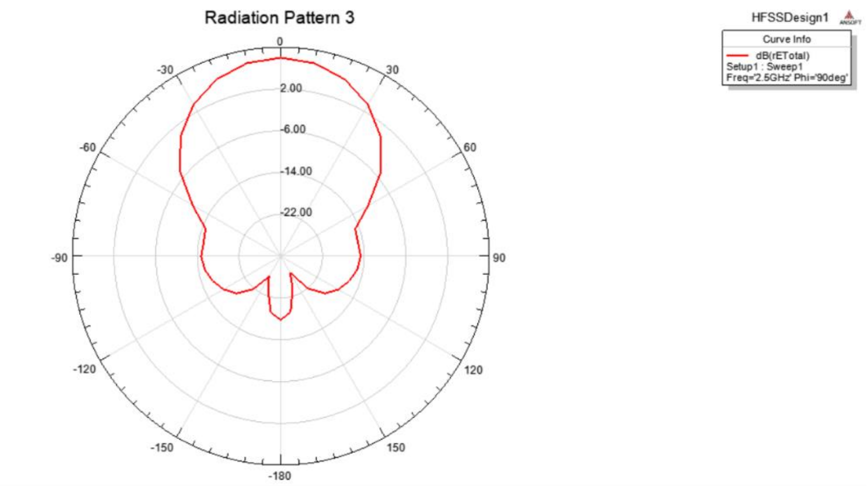
The sudden variation in the location brings in much chaos in the power levels, which can be addressed by designing a rectifier capable of operating over a wide range of incident power. The challenge of low power densities can be partially overcome by having high RF-DC power conversion efficiency (PCE). But it should be noted that if more energy is sucked or scavenged from the ambiance, the RF-DC will result in much higher PCE. Hence, Rectennas (receiver antennas with rectifiers) need to be designed with broadband to scavenge a large amount of low power energy from the ambiance. The voltage multiplier will boost the level, and the rectifier will take care of the variation in levels.

The learning from various sections of this work can be summarized as below:

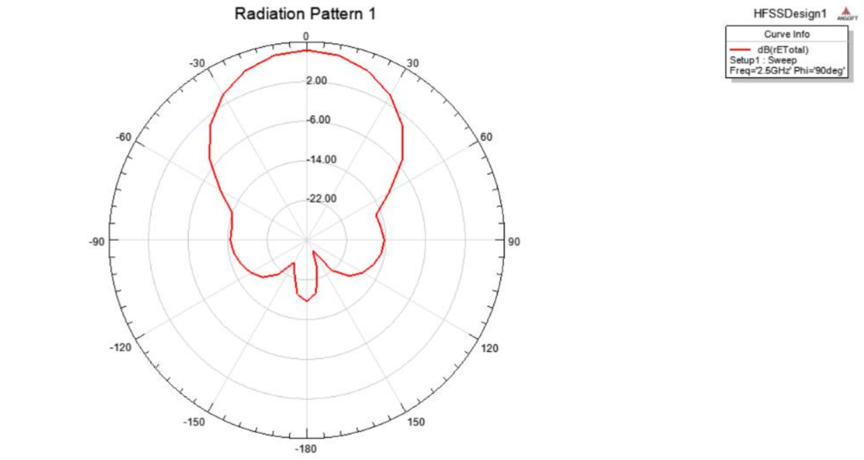
1) Energy concerns in IoT devices can be rightly addressed by employing energy harvesting mechanisms.
2) Among all available sources of energy, RF energy harvesting is best due to its ubiquitousness and simple design requirement without any mechanical movements and no demand for ample storage.
3) 2.4 GHz is best for long-range wireless power transmission among all available ambient frequencies.
4) A Microstrip patch antenna is best suited for a central operating frequency of 2.4 GHz.
5) One side feed network is providing better results.
6) The 4-element antenna array is the best arrangement for energy harvesting in low-power applications.
7) Creating a circular slot is the best option for increasing the bandwidth instead of going for multi-band antennas (which have their switching limitation), as demonstrated in this work.



(a)

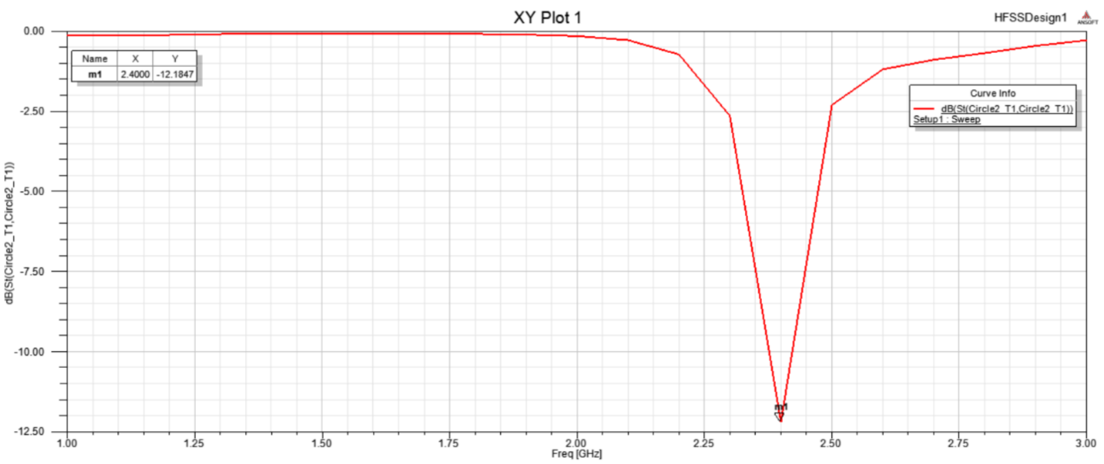


(b)

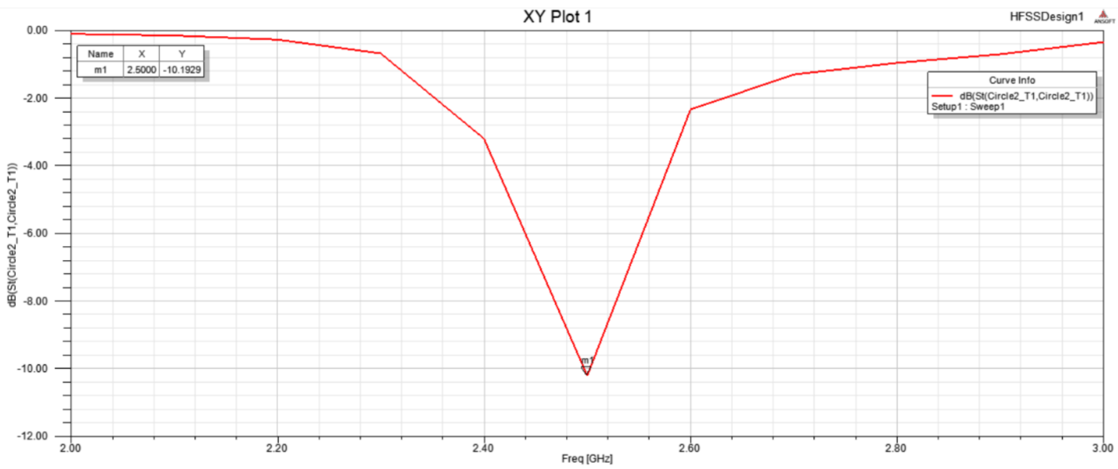


(c)

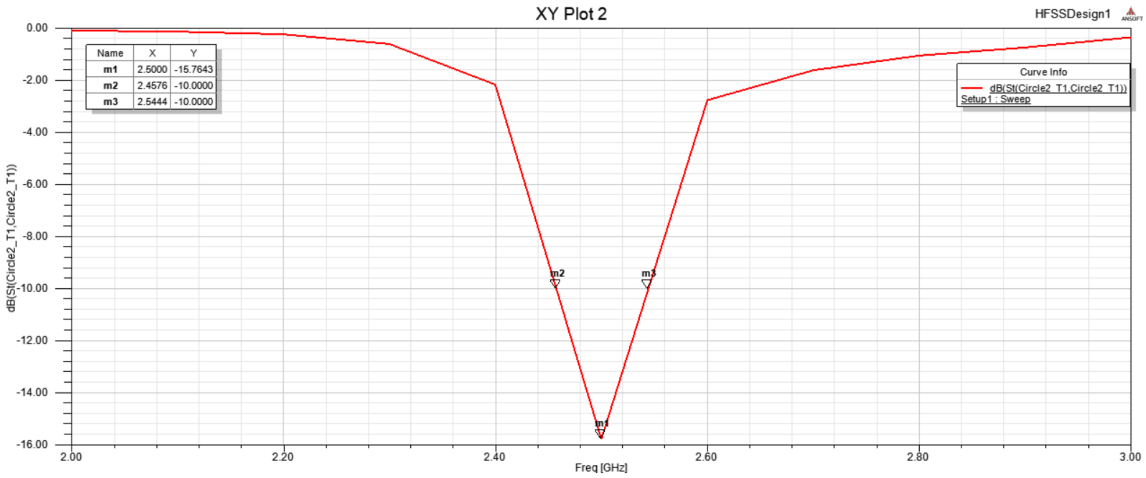
Figure 9. The radiation pattern of (a) single Microstrip patch element (b) H shaped four-element antenna array (c) Modified H shaped four-element antenna arrays



(a)



(b)



(c)

Figure 10. Return Loss of (a) single Microstrip Patch element (b) H shaped 4-element antenna array (c) Modified H shaped 4-element antenna array

This work has attempted to demonstrate the receiving antenna array design development starting from a primary rectangular patch antenna. A simple rectangular patch antenna has four elements to form an array. The parameters are optimized by the equations defined in section II, taken from [16]. The center frequency of 2.4 GHz is accurately achieved. Motivated by this, the authors have attempted to recreate an H-shaped antenna with a slight improvement in bandwidth from work [31]. Here, a tiny H-shaped antenna is designed based on tuned slot size. The simulation result shows an incremental change in bandwidth, i.e., 2.1% to 2.65%. Even if we appreciate the delta enhancement, the practical results were not as encouraging as demonstrated in [31]. Therefore, the authors have introduced a circular slot in the patch antenna to have significant bandwidth. This inclusion of circular slot has shown a remarkable change in bandwidth, i.e., from 52.2 MHz (for rectangular patch antenna array) and 64.8 MHz (for H-shaped patch antenna array) to a large bandwidth of 868 MHz. This accounts for 36.17% bandwidth against the 2.65% of H-shaped antenna. The comparison of results is tabulated in Table V.

Table 5. 4 element patch antenna array properties

Parameters	Value of Rectangular patch antenna array	Value of H-shaped patch antenna array	Modified H-shaped antenna with a circular slot
Path array dimensions	119.5 * 118(in mm)	119.5 * 118(in mm)	119.5 * 118(in mm)
Slot Dimensions	Not Applicable	7.7 * 10.5 (in mm)	7.7 * 10.5 (in mm)
Gain	10.4dBi	8.225 dBi	8.33dBi
Input Impedance	-12.49	-10.49	-15.49
Bandwidth	258 MHz (~= 10.75%)	64.8MHz (~= 2.65%)	868MHz(~= 36.617%)

5. CONCLUSION

Given the SDGs, the energy crisis is inevitable, exploited by resources. In a low-power device placed remotely, energy scavenging is the preferred mechanism to enhance the node's lifetime. This work considers RF signals to harvest at 2.4 GHz, readily available and free to use. The antenna design at this frequency is selected to be a microstrip patch with a suitable one-side feed network. The work has considered bandwidth to enhance the power conversion efficiency by

designing a wideband rectenna with a 4-element arrangement for energy harvesting in low-power devices such as IoT devices, Radio Frequency Identifier (RFID), and remote wireless motes. The simple flow from the rectangular antenna to the circularly slotted modified H-shape antenna, along with the theoretical foundations and the antenna design flow chart, acts as a primer for any communication engineer enthusiast to start simulating various slots and enhance various properties of antennas without affecting the other parameters. The authors are confident that the fabricated antenna would give better results and provide a bandwidth enhancement of at least 20% while considering all non-linearities and implementation losses.
This work has paved the way towards radio optimization. It can be extended to the transmitter side, where beamforming for energy transmission with receiver location-aware pre-coding can be explored. The authors also look forward to working on other rectenna modules: Rectifier, voltage multiplier, power divider, and power management schemes in Wireless Sensor Networks.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

ACKNOWLEDGEMENTS

The authors would like to thank the anonymous reviewers of this work and the Doctoral Committee members of VTU, Belagavi, whose suggestions and insights have shaped this work.

REFERENCES

[1] Adu-Manu, Kofi Sarpong, et al.” Energy-harvesting wireless sensor networks (EH-WSNs) A review.” ACM Transactions on Sensor Networks (TOSN) 14.2 (2018): 1-50.
[2] Zeadally, Sherali, et al. ”Design architectures for energy harvesting in the Internet of Things.” Renewable and Sustainable Energy Reviews 128 (2020): 109901.
[3] Sangare, Fahira, and Zhu Han. ”RF Energy Harvesting Networks: Existing Techniques and Hardware Technology.” Wireless Information and Power Transfer: A New Paradigm for Green Communications. Springer, Cham, 2018. 189-239.
[4] Khemar, Adel, et al. ”Design and experiments of a dual-band rectenna for ambient RF energy harvesting in urban environments.” IET Microwaves, Antennas & Propagation 12.1 (2018): 49-55.
[5] Costanzo, Alessandra, and Diego Masotti. ”Wirelessly powering: An enabling technology for zero-power sensors, IoT and D2D communication.” 2015 IEEE MTT-S International Microwave Symposium. IEEE, 2015.
[6] Sanil, Nischal, Pasumarthy Ankith Naga Venkat, and Mohammed Riyaz Ahmed. ”Design and performance analysis of multiband microstrip antennas for IoT applications via satellite communication.” 2018 Second International Conference on Green Computing and Internet of Things (ICGCIoT). IEEE, 2018.
[7] Punith, S., et al. ”A Novel Multiband Microstrip Patch Antenna for 5G Communications.” Procedia Computer Science 171 (2020): 2080-2086.
[8] Sanil, Nischal, Pasumarthy Ankith Naga Venkat, and Mohammed Riyaz Ahmed. ”Design of aU-shaped slotted patch antenna for RFID Vehicle Identification.” 2018 Second International Conference on Green Computing and Internet of Things (ICGCIoT). IEEE, 2018.
[9] Firestone, Mary. Wireless technology. Lerner Publications, 2008.
[10] Assembly, General. ”Sustainable development goals.” SDGs TransformOur World 2030 (2015).
[11] Anjum, Shaik Shabana, et al. ”Energy management in RFID-sensor networks: Taxonomy and challenges.” IEEE Internet of Things Journal, 6.1 (2017): 250-266
[12] Williams, Alexander J., et al. ”Survey of Energy Harvesting Technologies for Wireless Sensor Networks.” IEEE Access (2021).
[13] Dehghani-Sanij, A. R., et al. ”Study of energy storage systems and environmental challenges of batteries.” Renewable and Sustainable Energy Reviews 104 (2019): 192-208.

[14] Ahmed, Sheeraz, et al. ”Energy harvesting techniques for routing issues in wireless sensor networks.” International Journal of Grid and Utility Computing 10.1 (2019): 10-21.
[15] Perera, Tharindu D. Ponnimbaduge, et al. ”Simultaneous wireless information and power transfer (SWIPT): Recent advances and future challenges.” IEEE Communications Surveys & Tutorials 20.1 (2017):264-302.
[16] Balanis, Constantine A. Antenna theory: analysis and design. John Wiley& sons, 2015.
[17] Pinuela, Manuel, Paul D. Mitcheson, and Stepan Lucyszyn. ”Ambient RF energy harvesting in urban and semi-urban environments.” IEEE Transactions on microwave theory and techniques 61.7 (2013): 2715-2726.
[18] Kandakatla, Radha Anil, and Mohammed Riyaz Ahmed. ”Design and Performance Analysis of Dual-band Microstrip patch antennas for Smart Apparels.” 2018 Second International Conference on Green Computing and Internet of Things (ICGCIoT). IEEE, 2018.
[19] Momenroodaki, Parisa, Ricardo Dias Fernandes, and Zoya Popovic.´”Air-substrate compact high gain rectennas for low RF power harvesting.” 2016 10th European conference on antennas and propagation (EuCAP). IEEE, 2016.
[20] Sun, Hucheng. ”An enhanced rectenna using differentially-fed rectifier for wireless power transmission.” IEEE Antennas and Wireless Propagation Letters 15 (2015): 32-35.
[21] Sun, Hucheng, and Wen Geyi. ”A new rectenna with all-polarization receiving capability for wireless power transmission.” IEEE Antennas and Wireless Propagation Letters 15 (2015): 814-817.
[22] Chou, Jui-Hung, et al. ”All polarization receiving rectenna with harmonic rejection property for wireless power transmission.” IEEE Transactions on Antennas and Propagation 62.10 (2014): 5242-5249.
[23] Niotaki, Kyriaki, et al. ”A compact dual-band rectenna using slot-loaded dual-band folded dipole antenna.” IEEE Antennas and Wireless Propagation Letters 12 (2013): 1634-1637.
[24] Sun, Hucheng, et al. ”Design of a high-efficiency 2.45-GHz rectenna for low-input-power energy harvesting.” IEEE Antennas and Wireless Propagation Letters 11 (2012): 929-932.
[25] Olgun, Ugur, Chi-Chih Chen, and John L. Volakis. ”Wireless power harvesting with planar rectennas for 2.45 GHz RFIDs.” 2010 URSI International Symposium on Electromagnetic Theory. IEEE, 2010.
[26] Ren, Yu-Jiun, Muhammad F. Farooqui, and Kai Chang. ”A compact dual-frequency rectifying antenna with high-orders harmonic-rejection.” IEEE Transactions on Antennas and Propagation 55.7 (2007): 2110-2113.
[27] Shuvo, Md Abdul Kader, and Md Mahmudul Hasan. ”Multi-Band Microstrip Antenna Design for Wireless Energy Harvesting.” American Journal of Energy and Environment 3.1 (2018).
[28] Silva, Vin´ıcius S., et al. ”Double Patch Antenna Array for Communication and Out-of-band RF Energy Harvesting.” Journal of Microwaves, Optoelectronics and Electromagnetic Applications 19 (2020): 356-365.
[29] Kumar, N. Rajesh, and P. D. Sathya. ”Design of RF Energy Harvesting Patch Antenna for Wireless Communications.”
[30] Mavaddat, Ali, Seyyed Hossein Mohseni Armaki, and Ali Reza Erfanian. ”Millimeter-Wave Energy Harvesting Using 4 × 4 Microstrip Patch Antenna Array.” IEEE Antennas and wireless propagation letters 14 (2014): 515-518.
[31] Chaour, Issam, Ahmed Fakhfakh, and Olfa Kanoun. ”Patch Antenna Array for RF Energy Harvesting Systems in 2.4 GHz WLAN Frequency Band.” 2018 15th International Multi-Conference on Systems, Signals & Devices (SSD). IEEE, 2018.