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RF RECTENNA: FUNDAMENTAL DISCUSSIONS AND APPLICATIONS IN MODERN WIRELESS TRENDS

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Abstract
Wireless energy harvesting is a new concept for a modern wireless communication system that provides an alternative replacement of the primary batteries. Apart from this, it can enhance battery life and battery-free operation for low powered devices. This paper presents a comparative study of a suitable antenna for efficient energy harvester. Moreover, it also reviews the methodologies mainly designed for RF energy harvesting networks (RF-EHNs). Some extensive research and future research directions are also discussed along with trade-offs of RF energy harvesting tech- nology that opens the possibility of directly recharging electricity or secondary batteries for electronics on ambient RF energy harvesting. This review paper concentrates on the concept of a wideband antenna to recover wideband energy from available sources rather than a conventional antenna and to develop a battery-free environment addressed in the proposed objectives. Consequently, this approach explored an efficient and effective compact wideband antenna for the applications of wireless energy harvesting devices.

Keywords Radio Frequency, Energy Harvesting, Rectenna, Radio Frequency Identification (RFID), WLAN, Wi-Fi

1 Introduction

As the demand for wireless transmission increases, the external power supply also increases drastically. In addition to recharging and replacement, size and weight problems, batteries are an inclusive source with adverse environmental effects. On behalf of these reasons, it is highly desirable to find alternative solutions to overcome their electrical limitations. In this perspective, energy harvesting is a substitute for primary batteries, where energy is obtained from the ambient sources. Energy is often harvested from a variety of available sources such as light, vibration, motion, heat, magnetic fields, pressure, and RF/microwave signals [1]. Preservation of energy initiates through the recycling of energy that has been used by now. This energy is always available in terms of electromagnetic, to operate several wireless devices such as cellular base stations, wireless local area networks with short-range distances and dedicated RF power sources, etc. The Power cast transmitter [13] presents an example of a dedicated radio frequency energy source produced commercially is at an operating frequency range of 915 MHz and 1–3 W transmission power. However, the implementation of a dedicated radio frequency energy source leads to higher costs for the operating system. The key to harvesting this “expended” energy begins with a dedicated receiver. This can receive the available wireless signal, along with some means of converting the received signal power into an electric power supply [2, 3]. And store that received energy in the storage unit. When the available power is insufficient the stored power would be able to operate low power devices at any time. Energy harvesting minimizes the maintenance and cost of the system; thus batteries can eventually be removed in portable electronic devices. All these devices are commonly referred to as “zero-power” devices for their ability to provide data directly over a wireless channel, using a wireless channel with available ambient sources of energy. The “battery-less” approach is commonly used with radiofrequency-identification (RFID) tags that transmit a detection signal based on the power received from the RFID reader’s transmitted signal [4, 5].

As a result of many high-frequency technologies, ambient radio frequency (RF) energy is abundant in urban envi- ronments. Radiofrequency bands include signals from 3 kHz to 300GHz and are used for many applications, including radiofrequency identification (RFID) tags, Wi-Fi, television, wireless sensor networks (WSN) , radio broadcasting and cellular phones [6]. In wireless sensor networks (WSN), batteries can be considered unreliable, especially for certain appli- cations that require continuous operation. To overcome power consumption constraints, the sensor nodes were configured to operate in different modes. However, energy harvesting is still a better long-term solution. It involves capturing and storing unused energy from the environment. For these applications, the specified frequency spectrum is used Wi-Fi (2.41 to 2.46 GHz, 5.18 to 5.82 GHz), microwave oven (2.45 GHz), frequency modulation (FM) radio (88 to 108 MHz) and amplitude modulation (AM) radio (535 to 1705 kHz). RF energy can be transmitted in unaccredited bands like 868 MHz, 915 MHz, 2.4 GHz, and 5.8 GHz when additional estimated energy is required at the ambient sources. The authorized rules control the production energy of the unaccredited signal band to 4 W EIRP (effective isotropic radiated power) applied in RFID at 915 MHz. The ambient RF energy with lower power density unluckily makes a dependable work harvesting the amount of energy consumed, for which both antenna and processing circuitry requires careful anal- ysis and design [7]. However, particularly for biomedical applications, radiation exposure should be carefully considered. Electromagnetic wave affects the human body individually. Considered frequency range 1 MHz to 10 GHz, the EMF potentially enters via the tissue and generates heat due to energy absorption. Generally, skin blocks the EMF over 10 GHz Such as heat create eye glaucoma or skin begins to burn due to increased area density above 1,000 W/m2 [8]. Major contributions that we have discussed here are as follows:

– This review has been focused on the suitability of antenna structure. Existing antenna structure and rectifier topologies have been discussed [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26] as well as we have introduced the new approach for antenna structure [27]. Fractal patch antenna [27, 28] is more efficient for energy harvester circuit in terms of antenna miniaturization and increment in gain.
– Comparative study of multiple antenna structure in terms of size, bandwidth, radiation pattern, multiband behavior and feeding difficulty level has been discussed in Table 1. Here it is observed that fractal patch [28] and spiral antenna shows the good characteristics compare to another antenna structure mentioned in the table 1.
– Basically, authors has been discussed the single band harvester [10, 12, 14, 19, 20, 21, 22, 25, 26, 29, 30] which will be work for considered bands, now if we need to receive signal at other frequency band then that designed antenna will not able to receive signal with the same strength. So there is need to design another antenna for that particular application. That will create limited application problem and that problem have been analyzed here.
– Availability of different type of RF sources in an environment.
– The principle of rectenna, terminology related to designing of harvester circuit.

Major advantages of the RF energy harvesting in our daily life is - easily available, works in hazardous location, can take advantage of electricity tariffs can track mobility and replace batteries is the most efficient application in our practical life. So it is required to design an efficient harvester circuit is important here.

2 Overview of Radio Frequency Energy Harvesting System

The basic needs to design an efficient RF energy harvester we have required: 1) an RF source (available in the nearby environment) 2) Transceiving antenna 3) a Suitable Rectifier/ Voltage Multiplier and at the end 4) Storage Unit as shown in figure 1 [31]. These units fulfill the requirement of an efficient harvester circuit. RF sources are available in the ambient environment that is received by an antenna, received RF waves are converted through the rectifier in electrical power. Two antennas have been considered here, the primary antenna transmits the RF signal and the secondary antenna will receive that power and forward to it at the rectifier input. The integration of the antenna and rectifier is known

as a rectenna (Energy harvester device). Antenna integrated into a rectenna could be any type of antenna appropriate for the frequency band of interest. The options included microstrip patch fabricated PCB, monopole, bipolar, or meandered line antenna structure along with the different rectifier topology. Rectenna considers antenna with rectifying circuitry, impedance matching network circuits, and filters to prevent any harmonics generated by non-linear devices.
The model of the rectenna energy harvesting structure usually has a receiving antenna that could be a radio frequency antenna [32]. The network's efficiency depends on the antenna's capability to accept the RF signal. When signals are higher, the more efficient the system is. The matching system network follows some antenna patterns that maximize energy and also ensures that signal reflection through the load resistor is minimized [33, 34, 35]. In the rectenna device, the use of the matching network allows the structure to maximize the use of the antenna's RF energy. Whenever the energy is transmitted in the network of matching systems, the rectification is needed for noise cancellation and the accepted RF and AC components are transformed into DC components. The use of a voltage multiplier changes the lower input voltage into a much higher DC voltage. Whenever the signal transmits via a multiplexer, the network model can accept a power storage capacitor that keeps the flow of power relatively stable at a high rate [36]. It can be optional because different applications need a different setting and separate output from a structure. Cell phones constitute a big source of radio transmitters by that RF power is harvested and possibly modify network users to supply power on demand by the diversity of short-range sensor utilization (e.g. Wi-Fi routers along with wireless terminals like laptops). In some urban environments, plenty of Wi-Fi devices can be detected from a single location. In a low range, like in the hall, a low quantity of power can be harvested via a regular Wi-Fi transmitter in the energy range of 50–100 mW. The higher gain broad antenna is required to perform harvesting analysis of RF power from a cellular base station as well as a broadcasting radio station for longer operations.
The rectifying elements based on semiconductors are applied to almost all modern energy-harvesting electronic circuits in various topological networks to convert DC power from RF [37]. While semiconductors are capable of handling electricity in relatively small quantities, for various applications, these low-cost and small Form factor conditions are perfect. Schottky diode is selected due to its lower junction capacitance with a low voltage threshold in place of the PN diode [38]. For more efficient operation on low power, this low threshold is ideal and lower junction capacity enhances the maximum frequency on which the diode may operate.

2.1 Selection Criteria of Diode

The diode is an important building block when designing a rectifier. This application is especially the Schottky diode used. The Schottky diode is a metal-semiconductor junction that differs from an ordinary semiconductor junction. Particularly, for RF energy harvesting, The Schottky diode is an ideal component that provides high switching speed for low forward

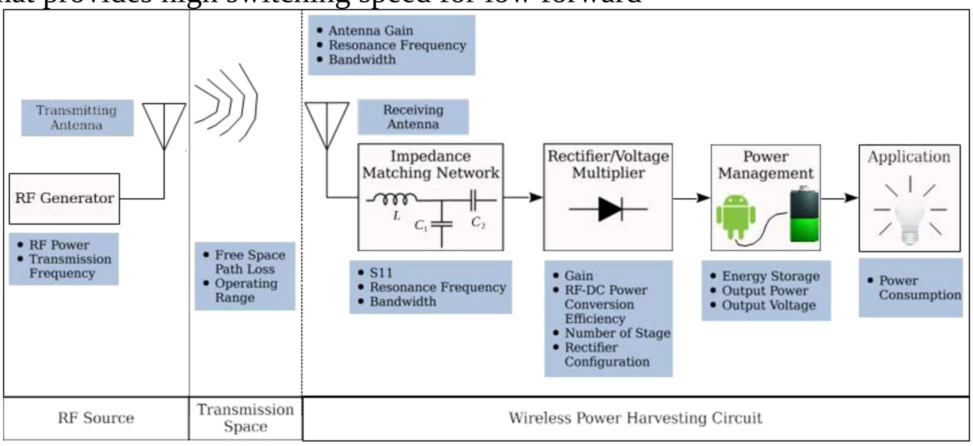

Fig. 1 Functional Model of an Energy Harvesting System [31]

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voltage. Schottky diodes are often used in RF applications with frequencies up to 50 GHz due to the rapid switching action. As presented in Figure 2, by the nonlinear relationship, the Schottky diodes are usually modeled. With the help of three major regions, the I-V curve is defined and characterized. The diode presents reverse the biased condition if voltages are below the reverse breakdown voltage Vbr and it carries on current in the reverse direction. When the diode is off then merely an extremely low leakage current flows through Vbr to VT, which is called turn-on voltage. The diode in this case is set to forward biased condition above VT and the current probably accumulates correspondingly to the voltage [39]. Whenever the diode works as an ideal rectifier, then the highest DC voltage of V0, DC controls by the reverse breakdown

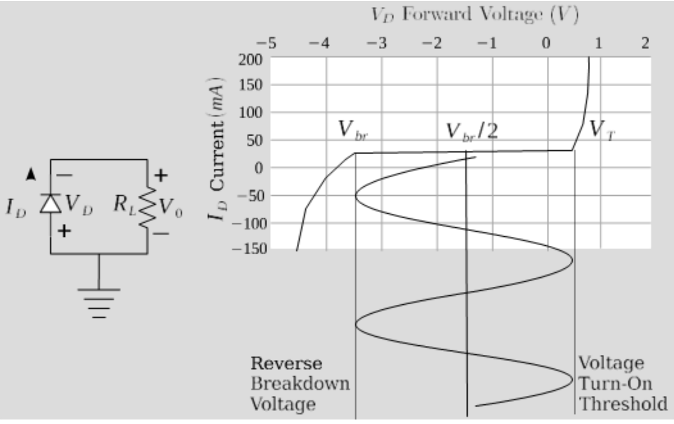

Fig. 2 V-I characteristics curve of breakdown and turn-on voltages

voltage and is presented as

$$V_{0,DC} = \frac{V_{br}}{2} \quad (1)$$

This condition usually occurs due to this DC voltage that controls the high AC voltage generated from the input waveform. However, in the case of continuous wave excitation, input waveforms are balanced symmetrically, the highest peak-to-peak voltage becomes close to the Vbr breakdown voltage, and Equation 1 presents the highest DC voltage. The waveform exceeds the breakdown voltage if this limit is crossed by the peak-to-peak voltage then the DC level never arises. Therefore, as a result, the maximum DC power PDC-max is controlled by

$$P_{DC\text{-}max} = \frac{V_{br}^2}{4R_L} \quad (2)$$

For applications that operate near the breakdown voltage, the maximum efficiency assured is generally 1.3–1.4 times of intrinsic diode of load resistance RL [40]. This value is similar to the trade-off among the similar values of resistance at the highest energy transmission with a high resistive load to reduce the loss produced by the switch of the voltage diode. RF (radio frequency) power harvesting methods have the salient attributes of the following:

– Over feasible ranges, it allows a constant and uniform energy transfer.

– Harvested power in the immovable RF-EHN is predictable and comparatively stable over time due to consistency with the distance.

– However, the magnitude of the radio frequency power harvested relies on the length of the RF energy source to the network of sensor nodes in other locations that have a noticeable change in the harvested energy.

2.2 Receiving Antenna

As we know, the antenna receives a signal from nearby sources in any energy harvester circuit. This technique requires an efficient antenna with an appropriate rectifier circuitry to convert EM waves into electrical power. And that electrical power will later be used to power the integrated system.

In many applications of wireless communication such as mobile radio, satellite, etc. low-profile planner antennas, which also include microstrip patch antennas (MPA), are preferred to meet the requirement in which there are weight, cost, ease of installation, and size constraints [41, 42, 43, 44]. An MPA typically resonates at the same frequency. Although there are many other methods by which an antenna can resonate and present with different slot sizes at multiple frequencies [45, 46, 47, 48, 49, 50, 51] and slits [52, 53] in main patches. Usually one wants to achieve a broader spectrum of frequencies or a multi-band spectrum. The Fractal antenna is a good example of a multiband antenna that can be used for a considerably larger bandwidth. It can be easily calculated through the fractal dimension. The first time, fractal Koch appeared in 1904 [54]. The fractal geometrical shape utilizes a self-similar structure to enhance the inside perimeter length. Consequently, it is very efficient and effective in the multiband antenna compact design for applications regarding power harvesting.
V. Hebelka et al. [27] applied an altered Koch geometry architecture to construct an antenna basically dual-band type for applications of power harvesting. Some existing research in the field of the fractal antenna (as a rectenna) is reported. [28] Studies the design of a fractal multiband antenna. The antenna area increases significantly even as the 900 GSM band is included. Wideband and narrowband antennas are also used for RF energy harvesting [55, 56]. Fractal shapes can be used for the production of broadband and multiband antennas.
However, the design of the rectifier circuit, in particular, the construction of a network of single impedance matching for broadband antennas is extremely challenging [57]. For the selection of power harvesting properties from resonating bands of available frequency, a multiband antenna is preferred. Gain, resonance frequency, and bandwidth, these parameters directly affect antenna performance. With unobstructed space and isotopic sources of communication, the spread of waves in all directions is similar. Therefore, the distance between the source and the distance of the electric distance is proportional to the per unit area:

$$P_{isotropic} = \frac{P_T}{4\pi R^2} \quad (3)$$

The antenna distance from sources is R, P is the power per unit area at distance R, and PT denotes transmitted power.
This can be noticed, however, that antenna does not always transmit electricity (isotropic antenna) in a circular form; even in certain directions, they transmit energy according to their designs. At the same distance, the ratio among the highest power density of an antenna at the distance granted to the optimum Omni-directional and the power density of the isotropic antenna with similar energy radiation, familiar as the antenna gain (G) and antenna accuracy is represented by this parameter.
Gain = grD (4)
Where D represents the directivity of an antenna and gr is the relative permitivity or dielectric constant of an antenna material. As a result, the density of power is usually given at the distance of R from the antenna.

$$P_d = \frac{P_T G_T}{4\pi R^2} \quad (5)$$

where PT is an transmitted power of an antenna and GT is the transmission antenna gain. It is identified that always
GT = 0 dBi for an ideal isotopic antenna.
The preceding formula also applies to receiving antennas. Generally, for energy harvesting applications, a rectenna is used as a receiving antenna that comprises a rectifier. Based on the application requirements, for a higher gain type antenna, the priority is decided. For RF transmission, the high gain rectenna is beneficial though if the source is aware of the status and receiving antennas. Whereas, if the position is not defined for the receiving antenna and source, then simultaneously the low gain antenna is better for collecting signals from different directions. The antenna bandwidth is a multiple frequency range within the antenna that efficiently works. The signals can be collected by

large antenna bandwidth from a wide frequency range compared to the narrow antenna bandwidth. Therefore, the antenna of broad bandwidth phenomenon presents benefits for energy harvesting but represents a high risk of noise signal interference mostly at unwanted frequencies.

Awais et al. [29] presented that antenna made from a lower-cost FR4 substrate in which the absolute permeability is (gr) of 4.4, the tangent loss is 0.02, with the thickness is (h) of 1.6 mm. The total substrate size is 18 × 30 mm2, which is 0.14λ0 × 0.24λ0 GHz shown in Figure 3. A feeding technique for the Coplanar waveguide (CPW) is used with the 50 ω transmission line to stimulate the antenna. After simulation conversion efficiency at the peak point of 75.5% is achieved, whereas the noticed conversion efficiency is assumed approximately 68% with a signal strength of 5 dBm at 2.45 GHz.

Yang et al. [58] proposed an antenna consisting of corrugated plasmonic metal-isolator metal formations including triple frequency bands, such as UTMS 2100, GSM-900, and TD-LTE. The power size at 900 MHz is just 0.21λ × 0.2λ. The gain amounted to 1 dBi, 2.64 dBi, and −0.19 dBi 0.9GHz, 2.025 GHz and 2.36 GHz respectively presented in Figures 4 and 5. The achieved gain of the proposed antenna is not suitable for efficient transmission. So antenna array has been supposed to.

For Antenna array, Sun et al. proposed [59] that connected four semi-yagi antennas to the invention of T-junction. The progress in the task is that the T-junction is adaptable from an array of 1 × 4 to a topology of 2 × 2. As a result, the structure was capable to work at less than 455 µW/cm at a low atmospheric power level while receiving 40% PCE. Received conversion efficiency of the proposed antenna is not showing the better response. So need to design another structure.

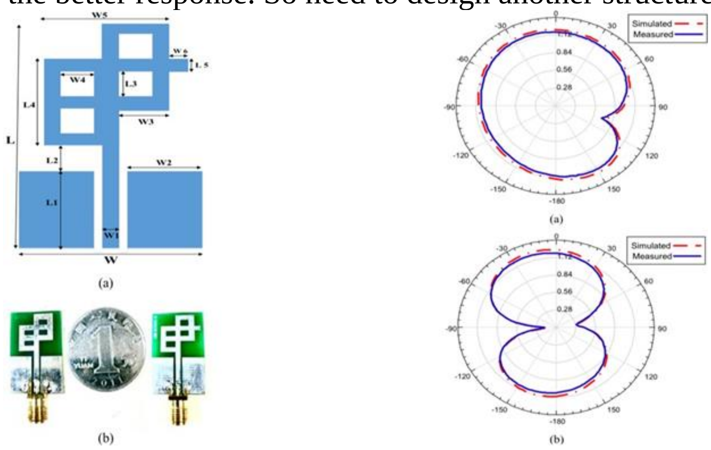

Fig. 3 (a) Geometry of the antenna proposed (b) with tuning stub and 2D radiation pattern at 2.45 GHz and without prototype (a)

H−plane (Y Z−plane, φD90 (b) E−plane (XZ−plane, φD0)

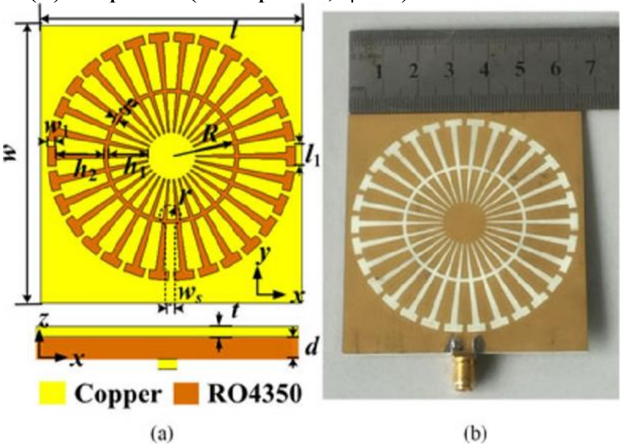

Fig. 4 (a) Front and side view of the antenna. Measured Dimensions: R = 16 mm, H1 = 10 mm, H2 = 12 mm, w1 = 2.2 mm, L1 = 5 mm, g = 1 mm, r = 2.85 mm, was = 2.33 mm, t = 0.018 mm, d = 1.016 mm, L = 66 mm, W = 70 mm (b) Fabricated antenna

Moon et al. [60] offered an interesting new RF power harvesting antenna design based on two radiators: a loop structure is the main one printed bipolar radiator and parasite. To receive RF energy from the principal radiator in all directions, the parasite radiator is appropriate for efficient energy harvesting.

Table 1 intends to evaluate the topologies of the antenna based on the above discussion [61]. Now, physical size concerning wavelength is described, the behavior of multiple bands informs the capability of the topology to address one or more operating bands simultaneously and the range of frequency close to the central operating frequency is described by the bandwidth. Analytical description can be applied to the theoretical pattern for radiation, the problem of manufacturing, the capability to rapidly map the structure to operate different frequencies and the problem of correctly feeding/tapping the antenna. Table 1 shows that to meet tight sizing constraints and target multiple operational bands, the fascinating selection is slot-coupled multi-resonators, spiral-shaped antennas, PIFA (planar inverted 'F' antennas), and a fractal type implementation, like the Koch. For simple and regular fabrication to be evaluated, the planar inverted 'F' antennas and spiral-shaped antenna patterns are applicable for the commercialization process. The spiral antenna is also quite directional, which does not fit the use we seek. The fractal loop implementation stands above the slot coupled multi-resonator through its ability to be quickly and methodically re-scaled/refabricated for different frequency bands. By maintaining a repetitive segmentation process during a meandering, the figure can be parameterized by the number of sides in the starting shape and the length of a segment. This should allow rapid scaling to a new frequency band via a single parameter change.

The received signal can arrive from any direction due to the location randomness of the RF energy source in ambient RF energy harvesting; therefore the omnidirectional antenna is a better option in the RF energy harvesting applications. The size of the harvester circuit with antenna and its performance is always been trade-off. An antenna as a component plays an important role in any harvesting device because its performance has a direct impact on the complete harvester efficiency; hence, the selection of the suitable antenna is an important issue. In many research work, conventional antennae [14, 17, 23, 25] like Monopole, Dipole, Yagi-Uda, Microstrip patch antenna, and various antenna arrays are used for multiple

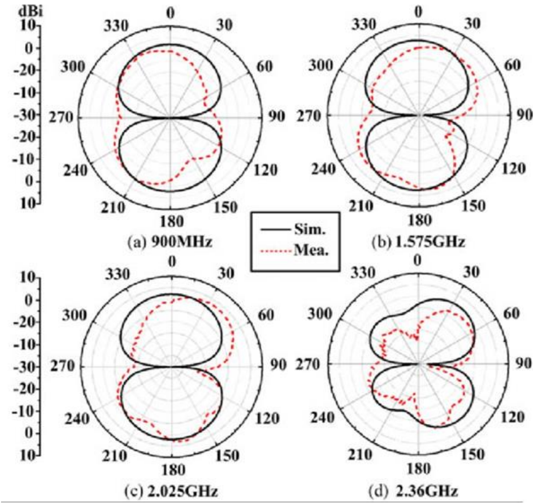

Fig. 5 Simulated and measured radiation patterns of an antenna at (a) 0.9 GHz, (b) 1.575 GHz, (c) 2.025 GHz, and (d) 2.36 GHz

Table 1 Comparison of Antennas

Antenna Type	Electric Size	Bandwidth	Radiation Pattern	Multiband Behavior	Structure Difficulty	Scalability with Frequency	Level of Feeding complexity
Microstrip Rectangular Patch	$\lambda/2 \times \lambda/2$	Small	Directional (especially in array)	Good (with modification)	Low	Easy for a simple patch	Low
Microstrip circular Patch	(Circle inside:) $\lambda/2 \times \lambda/2$	Medium	Directional (broadside)	Poor	Low	Easy for center feed	Medium

Gap Coupled Microstrip patch	$\lambda/2 \times \lambda/2$ Plus parasitic elements	Medium	Directional (broadside)	Good (with modification)	Low	Difficult	Low
Slot Coupled Multi Resonator	$\lambda/2 \times \lambda/2$ (of lowest freq)	Medium	Directional (broadside)	Excellent	Medium	Difficult	High
Folded dipole	$< \lambda/2 \times \lambda/2$	Small	Toroidal	Poor	Low	Easy	Low
PIFA	$\lambda/4\times < \lambda/4$	Good	Semi Toroidal	Good (with modification)	High	Difficult	Medium
Spiral	$\lambda/2\pi \times \lambda/2\pi$	Excellent	Directional (broadside)	Excellent	Medium	n/a	Low
Koch Fractal	$\lambda/4 \times \lambda/8$	Good	Semi Toroidal	Excellent	Low	Easy	Low

frequency bands. Due to this, the harvester designing circuit would be more complex. To reduce the complexity of the system and to obtain higher gain along with wider bandwidth rather than a conventional antenna, a Fractal wideband/multiband antenna will be a good agreement. This antenna makes the system more compact because of smaller in shape and lighter in weight and easy to fabricate. Microstrip patch fractal shape (like Koch fractal, Sierpinski, and Minkowiski loop) antenna with multiple iterations could be better option to get maximum achievable frequency due to its higher gain and stronger signals capability. This antenna will give better results in terms of novel compact rectenna circuitry along with various rectifier topologies.

2.3 Impedance Matching Network

In most circuit designs, the impedance matching networks have already been applied in antennas to maximize the energy transmission over a network or to minimize the signal loss throughout the network [62].

In electrical systems, low energy utilization, electricity leakage while power transmission results in a loss of energy. In this situation, additionally, highest power between load and RF source is transmitted that are ensured by the impedance matching network. The received antenna works as a primary source for energy harvesting applications whereas rectifier (voltage multiplier) works as a load. Power transfer in DC is accepted to be optimal if resistance to source and load is different. Impedance as a parameter is referred in place of resistance in an RF circuit. The impedance mismatch created by the source and the load produces an electric current that is reflected in the circuit, reducing the system's efficiency.

L, T and π Matching Network are three types of basic configuration (Figure 6). The most ordinarily applied network is L−Matching because it usually takes two parts that make it easier to design and control. Furthermore, L−Matching does not change the network circuit quality factor (Q). From the point of comparison, configuration that match T and π are usually complicated than networks L.

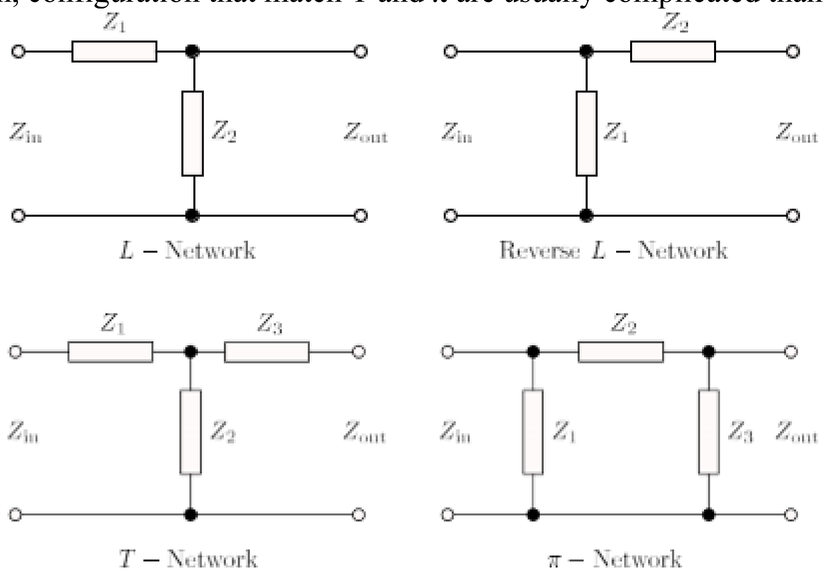

Fig. 6 Common Impedance matching network topology (a) L−network (b) Reversed L−network (c) T−network (d) π−network

For maximum power transfer, a complex conjugate is used when maximum power transfer is required.

ZLoad = ZS∗ource (6)

Where ZLoad represents the load impedance and ZSource represents the source impedance. This shows the superscript
* for complex conjugate.
Reflection coefficients are also a more important parameter for the maximum power transfer. It is a parameter that describes how much of a wave is reflected by an impedance discontinuity in the transfer medium. Formal reflection coefficients of figure 6 are as follows:

$$\Gamma = \frac{Z_t - Z_o}{Z_t + Z_o} = \frac{Z_{out} - Z_{in}}{Z_{out} + Z_{in}} = \frac{V_r}{V_{in}} \quad (7)$$

Where
Zt = Zout = Termination Impedance
Zo = Zin = Characteristic Impedance
Vr = Reflected Voltage
Vin = Incident Voltage

Quality factor Q is the dimensionless unit and it is defined as the ratio of stored energy in a circuit component and dissipated energy by the circuit component. It represents

Q = 2π · maximum stored energy/ energy dissipated per cycle (8)

In addition, the latest matching results are retained by arranging T and π configurations in several stages, but the Q factor changes. This strategy is useful to improve voltage stimulation. IMN has trade-offs that contain bandwidth, frequency adjustment with complexity. In case, the above multiport ladder matching and impedance matching techniques have been proposed in [63] for enhancing performance of the matching network as well as the antenna harvesting capabilities. However, if this configuration is implemented then some additional components are required as opposed to the conventional network matching, so it results as the complexity increment of the system. Etor et al. [64] proposed an IMN which used self-designed metal-insulator diodes with transmission lines in place of ordinary ingredients for fixed IMN THz frequencies as well as tunable IMN [65, 66, 67] have also been introduced to better match broadband and multiband antennas. In the case of rectenna a major problem among the wideband rectenna is the rectification behavior of operating bands of interest. For the maximum power reception proper impedance matching such as L type network should be implementing between antenna and rectifier. Several impedance matching topologies is used when we design the complete harvester circuit. Basics matching techniques such as T , π and L techniques improved the circuit performances in terms of minimization of complexity in system. While other structure like Cockcroft voltage multiplier, Dickson charge pump voltage multiplier and voltage multiplier with PMOS and NMOS also shown compatible results. With the implementation of the suitable rectifier structure we can definitely improve the harvester circuit performances.

2.4 Rectifier/Voltage Multiplier Topologies

A rectifier is a circuit that transforms AC voltage into a DC voltage. In the easiest configuration this consists of a single diode and a capacitor. The conversion between AC to DC is required because most electronics are using DC. The conversion is also required in order to store energy in a battery or capacitor. Generally, the circuit within energy

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harvesting system modifies received RF power into DC components. Many other methods are also available for doing this; the most commonly used technique is diode-based rectifier circuits. Figure 7 and 8 represents the most familiar topologies. The Schottky diodes have higher power handling capabilities compared to normal CMOS, and high output voltages are essential. For energy harvesting, sensor node without battery power and the RFID circuitry utilize the topology of charge pump presented in Figure 8c. The rectifying diode is the most common application referring for AC–DC current conversion. The situation of energy harvesting application, there is a sinusoidal waveform in antenna retrieved RF signal. After the change through IMN, the signal will be modified and extended to fulfill the power demand of the application.

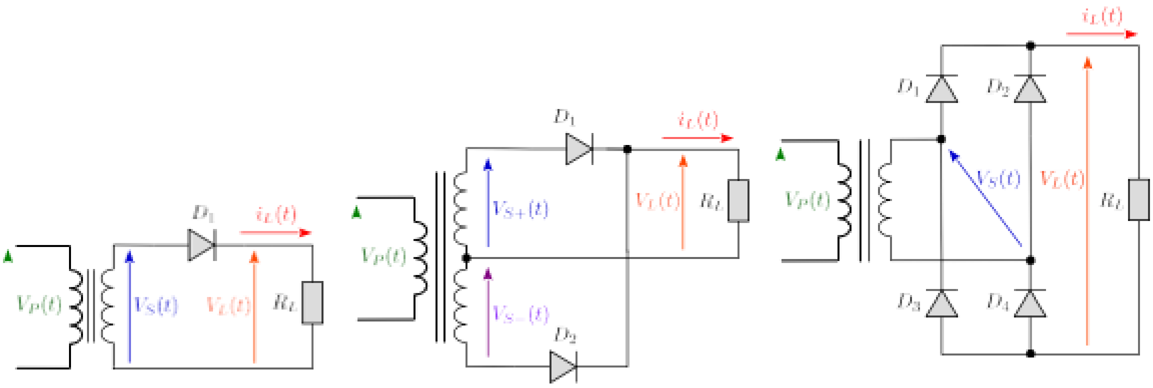

Fig. 7 Rectifier configurations (a) Half wave rectifier (b) Full wave rectifier (c) Full wave bridge rectifier

The half wave rectifier is the most important rectifier topology consisting of a single diode D1 (Figure 7a). Merely the positive cycle goes away, whenever the AC voltage is transferred via D1, and the negative cycle is ignored.
In the place of the simple diode, the Schottky diode has been used to design the rectifier for energy harvesting. It is generally applicable in RF application and also used in power applications such as rectifier, due to its low forward voltage drop of 0.2 to 0.3 volts. This diode works as a uni polar device and it has the electron as the majority charge carriers on both sides of the junction. This forms the interface between both the sides of the junction. This contact increases the voltage across the diode and makes smooth current conduction among the circuit. It has several advantages, such as it works on high frequencies, generates less noise, highly efficient, low junction capacitance, and low turn-on voltage, etc. The output power of the circuit for the half-wave rectifier, no-load output DC voltage of the half-wave rectifier

$$V_{rms} = \frac{V_{peak}}{2} \quad (9)$$

$$V_{dc} = \frac{V_{peak}}{\pi} \quad (10)$$

In the figure 7 (a) D1 represents the diode for the rectification, and RL represents load resister. From Figure 7(b) full-wave rectifier the average, and RMS no-load output voltage of the circuit is

$$V_{dc} = V_{av} = \frac{2 \cdot V}{\pi} \quad (11)$$

$$V_{rms} = \frac{V_{peak}}{\sqrt{2}} \quad (12)$$

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Volume : 52, Issue 12, No. 2, December : 2023

Where
Vdc = Vav = DC output voltage
Vpeak = Peak value of the phase input voltages
Vrms = Root Mean Square value of output voltage
Vp = Primary binding voltage
Vs = Secondary binding voltage VL = Load voltage
RL = Load resister

In addition, the output is discontinuous because of the negative cycle is cut off. Generally, the half-wave rectifier is not enough for ordinary applications, due to its simplicity. Therefore, preference is given to a full-wave rectifier. Figure 7b represents a full- wave rectifier circuit design. The D1 diode transmits the positive half-wave of the voltage and the D2 diode transmits the negative half in the full-wave rectifier. The current is always flown from a common diode point through the load and back to the tap center of the transformer. Figure 7c presents the full-wave rectifier and its design in the circuit. The rectification process in the full wave bridge rectifier is occurred by way of couples of diodes current conduction. D1 and D4 are carried out, in the voltage period of positive half-wave, while D2 and D3 are carried out in the negative half. It represents the dual topology. In the secondary winding during each half cycle, the current always flows in dual directions but it is always in the similar direction towards the load. Within the winding, the DC component is not present and the core is usually smaller as compared to the centered tap rectifier at the same

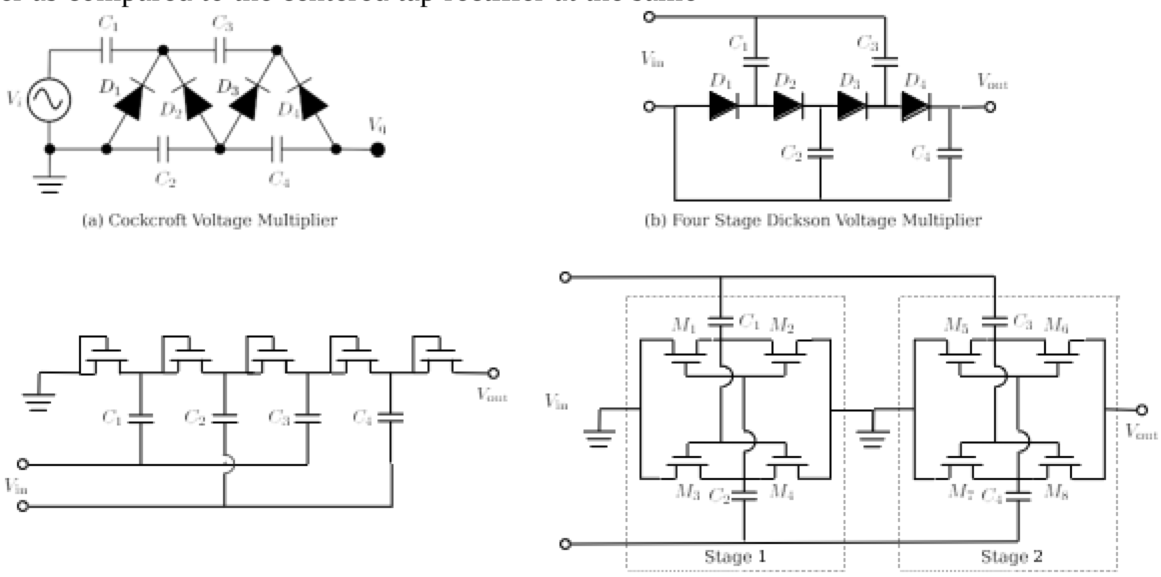

Fig. 8 Common voltage multiplier topology (a) Cockcroft voltage multiplier (b) Four stage Dickson voltage multiplier (c) Dickson charge pump voltage multiplier (d) Differential drive voltage multiplier

DC power rating. Voltage multipliers circuits can be designed by diodes and capacitors which can enhance the input voltage by two, three, or even four times, individual half or full stage multipliers are cascaded together in series gives the desired DC voltage at given load and a step-up transformer is not required. Situations where modified power is not sufficient for many applications, it is required to promote stacking to output DC is to create single rectifier and voltage multiplier in the series [48]. Many configurations available for voltage multiplier are presented in Figure 8. The Cockcroft-Walton voltage multiplier presented in (Figure 8a) is the most significant and common configuration. The operating principle of this circuit is same as the full-wave rectifier (Figure 8b) but for maximum voltage gain, there are more steps. The Dickson multiplier shown in Figure 8b is an improvement of the configuration of Cockcroft-Walton, to reduce parasitic effects, stage capacitors are being shunted.

Thus, for small voltage applications, Dickson multiplier is the first choice. though, achieving high conversion efficiency due to high threshold voltage between the diode making the leakage current is challenging, thus reducing overall efficiency. Since, rectenna is efficient RF energy harvesting technique, but, the produced output DC voltage is inadequate to control the logical point of current electronics which is usually 1 to 3 V on the applications of low power RFID [5]. The charge pump rectifies RF to DC and the voltage is steppedup into operational stage by using cascaded diode-capacitor steps. For biasing reference, the earlier stages are used by each stage, and as a consequence, a higher voltage is acquired. Moreover, the CMOS processes can be influenced by RFID circuit for producing loss-less harvesters [5] and diode properties are manipulated. It is noted that sometimes a collection of these proposals is used as rectenna harvesting energy for producing low voltage which usually give power to the high efficient DC to DC converter supported by the conventional Dickson charging pump [68] raise the voltage to levels sufficient for powering the electronics. It is also noted the original model of Dickson charge pump uses digital periodic signal with low frequency to enhance the DC voltage in place of applying RF signal for the same application. DC output of the harvesting circuit totally depends on the number of rectifier stages. So, selection of the rectifier stages is also more important in the designing of energy harvester.

3 Energy Harvesting Circuit Characterization (Parametric Analysis)

There are many parameters which are required to be evaluated, that make decision to show the design of the energy harvesting system. Evaluability varies depending on different properties. Nevertheless, standards are defined as the value to compare those important values like efficiency, sensitivity, operating distance, antenna gain and output power. However, there are trade-offs among these parameters, like the frequency and the total conversion efficiency. Moreover, other commercial subsidiaries, such as low cost, manufacturing process maturity and wholesale manufacturing accessibility and availability, also dominate.

3.1 Frequency Operation Range

The operating distance is generally correlated to the operating frequency. However, transmission is higher than distinc- tive conditions over low frequencies at high frequencies, whereas lower frequency enters deeply through the substance. Therefore, if Energy Harvesting is used for transplantable devices at that time the transmission frequency should not be more than the MHz range. When choosing an inductor or capacitor for a high frequency application, it is important to select a component with a self-resonance frequency is more than operating frequency within the circuit. Self-resonance frequency of capacitor or inductor can be calculated as follows:

$$f_{resonant} = \frac{1}{2\pi\sqrt{LC}} \text{ Hz} \qquad (13)$$

We have presented the Equation 13 for the response of single resonance. During the number of resonance frequencies, this equation is considered as the ideal equation to find out the standard dimensions. After getting the standard parameter, a parametric analysis of the structure would be beneficial. The parametric analysis provides the optimist structure analysis for the relevant applications.

3.2 Power Conversion Efficiency (PCE) of RF–DC

Power conversion efficiency is determined as total energy-harvesting efficiency of circuit. It is also an important parameter to improve in rectenna circuit, so filter is better option for the enhancement of PCE. For an example, low pass filter (LPF) will be suitable choice to provide the proper impedance matching among the antenna and the rectifier circuit. Reason behind the selection of LPF, it can block the higher order harmonics which is radiated back to the antenna.

The desired power Pout-DC in both conditions is the DC voltage Vout-DC across the load resistance RL defined in Equation 14.

$$f_{resonant} = \frac{1}{2\pi\sqrt{LC}} \text{ Hz} \quad (13)$$

By this useful output power is provided to the circuitry of the device. If the power received at the input is defined as
Pin-EH at the energy harvesting circuit, the charge- pump efficiency is ηEH

$$\eta_{EH} = \frac{P_{out\text{-}DC}}{P_{in\text{-}EH}} \quad (15)$$

$$= \frac{\frac{V^2_{out\text{-}DC}}{R_L}}{P_{in\text{-}EH}} \quad (16)$$

The nonlinearity exist in diodes indicates reflection of few amount of power from energy harvesting circuit when it is not totally matched. The power-conversion efficiency ηPCE is defined as

$$\eta_{PCE} = \frac{P_{out\text{-}DC}}{P_{in\text{-}CP}} \quad (17)$$

$$= \frac{\frac{V^2_{out\text{-}DC}}{R_L}}{P_{in\text{-}EH} - P_{reflected}} \quad (18)$$

Where Pin-CP the power supplied to the charge pump usually neglects the reflected power of Preflected due to different impedance. These issues are decoupled by power-conversion efficiency by matching the energy-harvesting circuit and Instead of directing its intrinsic capacity to convert DC voltage to RF power. Whereas, the major ηEH may becomes ηPCE. At input power level, this situation occurs when the antenna absolutely corresponds to the energy harvesting system [40]. Therefore, input power of the antenna Pin-EH equals the power of the Pin-CP energy harvesting circuit. Sensitivity measurement is also more important in RF energy harvesting system. This define the received RF power in dBm. The sensitivity of an energy harvesting method is explained as the lowest incident power limit needed to activate the system.

4 Energy–Harvesting Circuit Losses

The extremely high capable energy harvesters are always preferable, particularly for nonlinear circuits like diodes and diode-connected transistors, many types of loss phenomena make it challenging and hard to reach higher efficiencies.

4.1 Threshold with Reverse–Breakdown Voltage

Generally, the highly significant diode efficiency value is the VT threshold which is a turn-on voltage. The efficiency of the low power is controlled by this value and referred to as "VT effect". If the energy harvester does not have sufficient power, then sufficient energy is not available to overcome such obstacle and the output capacitor will not charge. The diode efficiency is also controlled by the reverse diode breakdown voltage Vbr because this curve allows the diode to be shown by "Vbr Effect". These circumstances will be on the high power level whenever the diode DC bias breakdown is similar to the old mentioned voltage. When the DC output voltage is constant then the decrement in the efficiency curve can be noticed.

4.2 Impedance Matching

If there is a proper mismatch between power harvesting circuit and its antenna, then the output power produced by the antenna is returned into the environment, becomes unusable. The usable energy for modification decreases automatically if the power becomes unutilized. It becomes especially challenging to match the energy harvester circuit structure because load impedance changes with respect to the frequency as well as the power input due to non-linearity of impedance element.

4.3 Device Parasitic

The device parasite can also reduce efficiency significantly. Diode junction resistance RS can limit the capacity of the diode, as the current passing via diode ends the power at semiconductor junction [69]. The junction capacity Cj and inductance at maximum frequency, also result in considerable performance reduction due to cutoff problems. The capacitance at junction usually controls the peak frequency on which performance of the diode grows.

Extra package parasites are present however this is not discussed at this point because they have many sources to be listed. Apart from this, in energy harvesting efficiency, conventional impairments in transmission lines and substrates can act as an important activity depending on the substrate and the length of the line.

4.4 Harmonic Generation

Nonlinearity in diodes also presents degradation in source whenever it provides support to express DC power to DC. During the operation, the diode generates harmonic frequencies from power of the phenomenon, which minimizes the energy balance and converts it into DC resulting in low efficiency in energy harvester. As voltage at incident continues to grow, the lost power with harmonics tends to increase. An optimum level of efficiency is the balance among harmonic generation, threshold voltage and reverse breakdown.

Table 2 Comparative Evaluation of Radio frequency-Energy harvesting Circuit and System

Ref.	RF Source	Antenna Architecture	Antenna Gain (dBi)	Load	RF Sensitivity/ DC Output Voltage	Peak Conversion Efficiency	Matching Architecture	Technology
[29] (2018)	2.45 GHz	CPW fed rectangular with slots	5.6	5 KΩ	18% at -20 dBm, 42% at 10 dBm, 68% at 5 dBm	75.5 %	L Matching Network	HSMS–2850
[9] (2018)	LTE 700 MHz GSM 850 MHz ISM 900 MHz	Log periodic PBC antenna	6	50 Ω	-25 dBm -5 dBm	upto 45%	Modified π Network	HSMS–285C
[10] (2018)	GSM 1800 MHz	Multiport pixel antenna	3.83 (port 1) 2.36 (port 2) 3.90 (port 3)	50 Ω 6 KΩ	21.1% at -20 dBm 13.8% at -25 dBm 6.9% at -30 dBm	upto 24 %	NA	SMS7630-079
[11] (2018)	ISM 900 MHz GSM 900 MHz GSM 1800 MHz ISM 2.4 GHz	NA	NA	2 KΩ	30% at 0 dBm	63%	High Pass and Inductive L matching Network	SMS7630 -005LF
[12] (2018)	ISM 2.45 GHz	Horn Antenna	NA	370 Ω	15 dBm	61 %	L matching Network	HSMS-286P
[58] (2018)	GSM 900 MHz UMTS 2100 MHz TD-LTE 2.36 GHz	NA	1 2.64 -0.19	2 MΩ	-10 dBm	59%	NA	HSMS-2850
[13] (2017)	GSM 900 MHz GSM 1800 MHz UMTS 2100 MHz	Dual port L probe patch antenna	8.15 7.15 8.15	5 KΩ	-35 to -10 dBm	>40%	NA	SMS7630-079
[14] (2016)	ISM 868 MHz	Monopole Antenna	Indoor experiment	Sensor node	-30 dBm at 29.3mv	9% at 10 KΩ	Transmission line (microstrip)	HSMS-285C
[15] (2015)	GSM 900 MHz GSM 1800 MHz	NA	NA	2.1 KΩ	-15 dBm to 20dBm	30%	Transmission line (microstrip)	HSMS-2850 ATF34143
[16] (2014)	DTV 539 MHz ISM 915 MHz 267,400,600,900 & 1350 MHz	Wideband Antenna	6	100 KΩ	-10 dBm	5 to 10%	L matching network	HSMS-285C
[17] (2014)	ISM 915 MHz ISM 886-908MHz	Loop Antenna	NA	1 MΩ	-27 dBm at 1V	40% at -17 dBm	NA	90 nm CMOS
[18] (2014)	Simulation RF source 915MHz 900MHz 945MHz	NA	NA	50 KΩ 60 KΩ 10 KΩ	-10dBm at 1.3V	79% 80% 75%	L and π matching network with lumped elements, transmission line (microstrip)	HSMS-2852
[19] (2013)	ISM 868 MHz	PCB differential antenna	Indoor experiment	NA	-16 dBm at 2V	58% at -3 dBm	NA	130 nm CMOS
[20] (2013)	DTV 512-566 MHz	Planar log periodic	7.3	MCU	-14 dBm at single tone -37 dBm at multitone	19.5% at 1 MΩ	L matching network	NA
[21] (2013)	DTV 512-566 MHz	Printed Dipole antenna	5	T1 EZ430	-15 dBm	7% at 470 KΩ	L matching network	SMS-7630 HSMS-286C
[22] (2013)	DTV 539 MHz Cellular 738 MHz	NA	6	Sensor Node	-8.8 dBm 18 dBm	23% 26%	NA	Seiko S-882Z IC charge

								pump
[23] (2013)	GSM 900 MHz GSM 1800 MHz UMTS 2150 MHzWi-Fi 2450MHz	Multiband annular ring patch antenna	NA	50 Ω	-10 dBm NA NA -13 dBm	18% N A N A 10 %	Transmission line	SMS-7630
[24] (2013)	DTV 470-610MHz GSM 900 MHz GSM 1800 MHz 7 3G 2110-2170MHz	Horizontal & Vertical polarized antenna	4.35 4.42 4.32 4.39	100 μ (capacitor)	-25 dBm single tone -29 dBm multitone	40%	L matching Network	SMS-7630
[25] (2012)	DTV 470-810 MHz	Yagi-Uda	4.27	NA	-15 dBm at 0.725 V	NA	L matching network with lumped elements	HSMS-282C HSMS-285C
[26] (2012)	ISM 902-928 MHz	NA	Indoor Experiment	MICA2	-20 dBm at 1.8 V	NA	NA	HSMS-2852 HSMS-2822
[30] (2010)	DTV 512-566 MHz	NA	NA	T1 EZ430	-9 dBm	8% at 10kΩ	NA	NA

5 Related Work

Antenna as a component plays an important role in any harvesting device because its performance has direct impact on the harvester efficiency; hence, the selection of the suitable antenna is an important issue. Table 2 shows the different aspect of energy harvesting. Various topologies have been developed for RF–DC rectifier design. With a large range of ambient RF frequencies, most circuit designs target a single operating band, because it is more viable antenna designs. In order to achieve highest energy in wide frequency range, wide-band with compact antenna power is required for small handheld devices such as tablets, telephones, electronic clocks and other intelligent sensors.

Muncuk et al. [9] designed energy harvester in the Boston and cover 65% area. It has considered the standard sensor TI eZ430-RF2500 for battery free operation for their work. They have designed and analyzed the harvester prototype which covers the 45% city location with the considered bands such as LTE 700, GSM 850 and ISM 900. In addition, this prototype is also compatible for low power TI µ CUs such as MSP430L092 and MSP430G2553 in different operation modes. Proposed device is able to receive signal with the range of -25 dBm to 5 dBm. Received signal strength is quite good but here does not explore the achieved power conversion efficiency.

Shen et al. [10] have prepared the triple port pixel antenna for the GSM 1800 band. It has optimized the binary optimization problems using gradual binary optimization. And this prototype shows the 19% improvement in conversion efficiency when the input RF power is -20 dBm. Harvester measurement demonstrates that the proposed antenna has more than twice the DC output power compared to single-port antennas of the same size. Achieved power conversion efficiency has not shown good reception here.

Mansour et al. [11] work presented for efficient conversion efficiency over 30% from 870 MHz to 2.5 GHz which is based on the designed cascaded rectifier structure along with broadband rectifier. From 970 MHz to 3.1 GHz the standard simulation value is over 50%. Aim of the work is to design compact rectifier along with narrowband signals in particular frequency. Here authors has been considered narrowband signal which shows the limited application with the considered operating bands.

Erkmen et al. [12] FSS absorber design has been introduced. This is used for ambient RF power harvesting or controlled WPT. They have also captured the excellent absorption behavior of the periodic structure. Then integrate the FSS absorber with a matching full-wave rectifier. Measured conversion efficiency is about to 61%, which correspond to the combined efficiency of receiving Electromagnetic radiation, transmits the captured power into rectifier and converts DC power into the load. Achieved power conversion efficiency has shown quite enough for WPT.

Shen et al. [13] presented a dual-port Triple-Band L-probe microstrip patch rectenna. It has considered the bands such as GSM900, GSM-1800 and UMTS-2100 for the RF harvesting. Dual port patch antenna with stacking by two single port antennas has been analyzed. Each port separately harvests the power with the 7 dBi gain. Results has been shown proposed harvester circuit receives more than 40% of the RF power from all the considered bands. Achieved power conversion efficiency has not shown good reception here. Gain of the antenna has shown quite good results.

Assimonis et al. [14] presented a high sensitive energy harvester, which consists double diode structure with one series circuit. Antenna has been designed with a lossy FR 4 substrate. This design aimed minimum reflection coefficient along with maximum rectification efficiency. Simulated and measured results shows the rectenna efficiency 28.4% at -20 dBm power input. Achieved power conversion efficiency has not shown good reception here.

Liu et al. [15] proposed new dual-band rectifier along with absolute power range and an optimal RF power incidence scheme to design multiband RF energy harvesting circuit. With the dual bands input the power conversion efficiency is achieved more than 30% within range -15 dBm to 20 dBm. Power gain is sustained from -20 dBm to more than 10 dBm along with effects of different RF power rate ratio is also investigated. Apart from this, it could be considered as a proper reference for multiband rectenna design. Achieved power conversion efficiency has not shown good reception here.

Parks et al. [16] investigate the approach for the multiband harvester. Consider single wideband antenna along with many narrow bands rectifier. Here rectifier series consist a band pass filter with tuned impedance matching network. Rectifier output is combined through a diode which is able to analyze good performance, while the subset of the narrow band harvester is energized. This technology makes environmentally sensitive possibly for mobile applications.

Stoopman et al. [17] designed small loop antenna with the integration of CMOS rectifier. It worked on antenna and rectifier interface to improve the sensitivity. Five stages cross connected rectifier with CMOS technology has been designed and fabricated. To prevent variation in antenna, interface introduced among rectifier and antenna which boost the antenna voltage as well as to improve the sensitivity. Harvester capability has been improved with the implemen- tation of complementary MOS diode which shows the improvement in energy storage during the power insufficiency for rectification. A measurement done in anechoic chamber and shows the result -27 dBm at 868 MHz sensitivity for 1 Vout and 27 meter range for a 1.78 W when RF source has placed in an office corridor. Received conversion efficiency is equals to 40% at -17 dBm. Achieved power conversion efficiency has not shown good reception here but rectifier topology has been implemented with CMOS.

Agrawal et al. [18] presented the effects of multiplier stages on output voltage followed by power conversion efficiency. With Dickson topology this efficiency is achieved approximately 80% at the input power range of 0 to 10 dBm. Low pass filter application was also demonstrated in the work. This provides the improvement in output voltage 140 mV at -10 dBm input power. Efficiency harvested from this approach is 75% and 64% with $\varepsilon r = 9$ and substrate height $h = 0.0004$ m for microstrip line among 10 kΩ load of matching circuit at -10 dBm input power level.

Scorcioni et al. [19] demonstrated RF power harvester includes an integrated rectenna with differential antenna. Fabricated prototype has a sensitivity of -16 dBm with the 60% conversion efficiency. Although it is constant more than 40% for an input power range of above 10dB. Evaluated RF Energy Harvester works efficiently using the Wide-band differential antenna designed from ad-hoc to 840 MHz to 975 MHz band. Achieved power conversion efficiency has not shown good reception in the case of differential antenna with proposed rectifier circuitry.

Vyas et al. [20] embedded MCU operation which is powered by digital TV band at single-tone signal with 6.3 km distance from the signal source. RF–DC charge pump has been constructed at this point along with 20% of high efficiency by -3 dBm input power. Achieved power conversion efficiency has not shown good reception here due to consideration of single operating bands.

Shigeta et al. [21] introduced concern about time variation produced in TV signals by an algorithm development to direct sensor duty cycle and mitigate the consequences of leakage problems in the capacitors.

Correspondingly, Parks et al. [22], Piuela et al. [24] and Keyrouz et al. [25] used a TV band based on digital signal to give power into sensor at the distance of 10.4 km from the source on 738 MHz center frequency base transceiver station. While ambient power is typically low, highly efficient rectennas operating in a single narrow band are required. Hence, it is crucial to simultaneously harvest energy

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from more than a few frequency bands for ensuring reliable functioning. Achieved power conversion efficiency has not shown good reception here.

Nintanavongsa et al. [26] shows that optimized prototype low power incidence which can achieve increment in efficiency compared to a commercially available harvester circuit in the power range. This works represents that Mica2 sensor mote. It could be operated after their duty cycle is selected on the basis of incident RF power as less than 6 dBm. In addition, prototype LPM4 is capable of maintaining neutral energy of Texas Instruments MSP430G2553 at 20 dBm. Investigational results are in good agreement with the values seen during simulations. Also compare the efficiency of observed from Power cast to commercially available RF power harvester, where prototype is largely evaluated with the signal strength of 20 to 7 dBm. In addition, the RF–EH environment also allows battery-free communication for Internet of Things applications. Single channel, such as a TV band and GSM, ISM bands are the most existing works [30].

This work discussed a review of new rectenna system. Which introduces the development of multi-band rectennas with fractal shaped antenna. And it shows the increment in power harvesting from different sources, such as TV signals, Wi-Fi, cellular network and similar types of environmental sources, thus removing the shortcomings of this single band method. The fractal antennas application influences definite significant size and multiple resonance advantages as presented in [70]. Although a fractal antenna contains multiple resonances, it is important to control the resonant frequencies to produce power from the several on demand RF sources. In the incrementing frequency ranges and energy levels, notably on dense population urban regions, ambient radio signals are universally present. These radio signals and wave forms present a distinctive and broad available energy sources if efficient and effective energy harvesting possible.

From the existing work, it is concluded that

– There is need to do improvement in energy harvester circuit as well as antenna structure [20, 21, 22, 24, 25]. Because antenna is a heart of any transmission system so received signal strength of antenna is also more important for efficient transmission. This has not been discussed in existing literature.

– Different rectifier circuitry along with voltage doubler topologies [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 30] have been studied and discussed in this work.

– Need to design wideband [19] and multiband antenna [10, 51] structure to cover the nearby available RF sources which has not been explored by the existing authors.

In future, proposed approach will improve the considered works such as:

– To design an antenna which operates at multiple frequencies including WLAN, Bluetooth at 2.4 GHz, WiMax at
2.3 GHz, LTE/4G 2.6 at GHz and WLAN at 5.2 GHz at the same time along with single radiating patch antenna. Received signal strength (DC voltage) of the rectenna requires being modified for the purpose of efficient power transmission.

– To improve rectenna efficiency as well as reduction in size, this is more compatible with wireless applications. Minia- turization of an antenna is more important if they are to be included in compact electronic devices such as mobile, sensor networks or wearable. While passing through commute, preserving the high radiation efficiency of these anten- nas is probably a big challenge that should be resolved. And in last, reduce transmission loss along with increment in operation range.

6 Existing Application

WSNs have become the most widely used RF power harvester applications. An ideal RF power harvester system can be implemented with the help of sensor node for power supply.

– [71] Presents such as example, researchers construct transmitter with RF-power which works at 915 MHz downlink frequencies and 2.45 GHz uplink frequencies. The highest instant data rate is 5 mbps, whereas the average data rate is 5 kbps. The transmitter can operate with input threshold of -

17.1 dBm and maximum power transmission of -12.5 dBm. Also shown abundant prototypes of RF-powered sensor nodes in [30, 72, 73, 74, 75, 76, 77, 78, 79].

– In [80, 81, 82], an experimental multi- hop WSN powered by RF is presented. The RF-powered systems also consist of exciting medical and healthcare implementations like wearable body networks. Improvement by RF power harvesting system, low-power medical devices could be manufactured to achieve real time on-demand devices which can be implemented with RF sources that allow for circuit without battery with a small sized device significantly.

– The researchers also proposed the energy-efficient RF-powered ICs design patterns in [83], work as on-demand pro- tocol. The gain levels of antenna reaches 1.8-2.06 dBi and the rectenna RF to DC conversion efficiency is 77.6–84%.

– Several performance for battery- free RF- powered devices from a Wi-Fi router [84, 85] GSM signals [24, 86, 87, 88] and DTV signal bands [30, 89] the ambient mobile devices as well [24] have also been shown in existing research publications.

– In addition, RF power harvesting could be applied to supply a wider range of low-power mobile devices, like electronic clocks, hearing facilities, MP3 music player, mouse and keyboards device. Many of them use power ranges only from µW to mW.

7 Conclusion

Single radiating patch antenna has the capability to fulfil the requirement of many wireless transmissions with reduction of number of antennas or antenna array. It minimizes the maintenance and system cost effectively. Fractal antenna with various shapes is one of the best alternatives of the conventional antennas. It could be approximately 20% more efficient than conventional antennas which would be useful to upgrade research area in a novel direction. With the help of fractal antenna we can get better reception and pick up more frequencies such as Bluetooth, Wi-Fi and cellular devices all from a single radiating patch antenna at the same time. Apart from this, the lifespan can be operated with harvesting ambient energy along-with the frequency of radio waves for up to several decades. An efficient rectenna electronic circuit of gadgets reduces the need of charging for IoT devices of the upcoming generation and can also provide battery-free functionality for devices with 150 mW or smaller of power requirements.

References

1. H. J. Visser and R. J. M. Vullers, “Rf energy harvesting and transport for wireless sensor network applications: Principles and requirements,” Proceedings of the IEEE, vol. 101, no. 6, pp. 1410–1423, June 2013. [Online]. Available: https://doi.org/10.1109/JPROC.2013.2250891
2. J. A. Hagerty, F. B. Helmbrecht, W. H. McCalpin, R. Zane, and Z. B. Popovic, “Recycling ambient microwave energy with broad-band rectenna arrays,” IEEE Transactions on Microwave Theory and Techniques, vol. 52, no. 3, pp. 1014–1024, March 2004. [Online]. Available: https://doi.org/10.1109/TMTT.2004.823585
3. A. Georgiadis, G. V. Andia, and A. Collado, “Rectenna design and optimization using reciprocity theory and harmonic balance analysis for electromagnetic (em) energy harvesting,” IEEE Antennas and Wireless Propagation Letters, vol. 9, pp. 444–446, 2010. [Online]. Available: https://doi.org/10.1109/LAWP.2010.2050131
4. Pandey, K., & Sadiwala, R. (2023). Performance evaluation of FR2-based IoT and AI applications using a Quad Port Multiple Input Multiple Output Antenna. Journal of Integrated Science and Technology, 11(4), 567.
5. A. S. Korotkov, “Radio frequency identification systems. survey,” Radioelectronics and Communications Systems, vol. 59, no. 3, pp. 97–108, Mar 2016. [Online]. Available: https://doi.org/10.3103/S0735272716030018

6. Rashmi Pandey, Ashok Kumar Shankhwar, and Ashutosh Singh, "Design and Analysis of Rectenna at 2.42 GHz for Wi-Fi Energy Harvesting," Progress In Electromagnetics Research C, Vol. 117, 89-98, 2021.
7. doi:10.2528/PIERC21100409 “Ieee standard for information technology - telecommunications and information exchange between systems - local and metropolitan area networks - specific requirements - part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications,” IEEE Std 802.11-2007 (Revision of IEEE Std 802.11-1999), pp. 1–1076, June 2007. [Online]. Available: https://doi.org/10.1109/IEEESTD.2007.373646
8. G. Chen, H. Ghaed, R. Haque, M. Wieckowski, Y. Kim, G. Kim, D. Fick, D. Kim, M. Seok, K. Wise, D. Blaauw, and D. Sylvester, “A cubic-millimeter energy-autonomous wireless intraocular pressure monitor,” in 2011 IEEE International Solid-State Circuits Conference, Feb 2011, pp. 310–312. [Online]. Available: https://doi.org/10.1109/ISSCC.2011.5746332
9. U. Muncuk, K. Alemdar, J. D. Sarode, and K. R. Chowdhury, “Multiband ambient rf energy harvesting circuit design for enabling batteryless sensors and iot,” IEEE Internet of Things Journal, vol. 5, no. 4, pp. 2700–2714, Aug 2018. [Online]. Available: https://doi.org/10.1109/JIOT.2018.2813162
10. S. Shen, C. Chiu, and R. D. Murch, “Multiport pixel rectenna for ambient rf energy harvesting,” IEEE Transactions on Antennas and Propagation, vol. 66, no. 2, pp. 644–656, Feb 2018. [Online]. Available: https://doi.org/10.1109/TAP.2017.2786320
11. M. M. Mansour and H. Kanaya, “Compact and broadband rf rectifier with 1.5 octave bandwidth based on a simple pair of l-section matching network,” IEEE Microwave and Wireless Components Letters, vol. 28, no. 4, pp. 335–337, April 2018. [Online]. Available: https://doi.org/10.1109/LMWC.2018.2808419
12. F. Erkmen, T. S. Almoneef, and O. M. Ramahi, “Scalable electromagnetic energy harvesting using frequency-selective surfaces,” IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 5, pp. 2433–2441, May 2018. [Online]. Available: https://doi.org/10.1109/TMTT.2018.2804956
13. S. Shen, C. Chiu, and R. D. Murch, “A dual-port triple-band l-probe microstrip patch rectenna for ambient rf energy harvesting,” IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 3071–3074, 2017. [Online]. Available: https://doi.org/10.1109/LAWP.2017.2761397
14. S. D. Assimonis, S. Daskalakis, and A. Bletsas, “Sensitive and efficient rf harvesting supply for batteryless backscatter sensor networks,” IEEE Transactions on Microwave Theory and Techniques, vol. 64, no. 4, pp. 1327–1338, April 2016. [Online]. Available: https://doi.org/10.1109/TMTT.2016.2533619
15. Z. Liu, Z. Zhong, and Y. Guo, “Enhanced dual-band ambient rf energy harvesting with ultra-wide power range,” IEEE Microwave and Wireless Components Letters, vol. 25, no. 9, pp. 630–632, Sep. 2015. [Online]. Available: https://doi.org/10.1109/LMWC.2015.2451397
16. A. N. Parks and J. R. Smith, “Sifting through the airwaves: Efficient and scalable multiband rf harvesting,” in 2014 IEEE International Conference on RFID (IEEE RFID), April 2014, pp. 74–81. [Online]. Available: https://doi.org/10.1109/RFID.2014.6810715
17. M. Stoopman, S. Keyrouz, H. J. Visser, K. Philips, and W. A. Serdijn, “Co-design of a cmos rectifier and small loop antenna for highly sensitive rf energy harvesters,” IEEE Journal of Solid-State Circuits, vol. 49, no. 3, pp. 622–634, March 2014. [Online]. Available: https://doi.org/10.1109/JSSC.2014.2302793
18. S. Agrawal, S. K. Pandey, J. Singh, and M. S. Parihar, “Realization of efficient rf energy harvesting circuits employing different matching technique,” in Fifteenth International Symposium on Quality Electronic Design, March 2014, pp. 754–761. [Online]. Available: https://doi.org/10.1109/ISQED.2014.6783403

19. S. Scorcioni, L. Larcher, A. Bertacchini, L. Vincetti, and M. Maini, "An integrated rf energy harvester for uhf wireless powering applications," in 2013 IEEE Wireless Power Transfer (WPT), May 2013, pp. 92–95. [Online]. Available: https://doi.org/10.1109/WPT.2013.6556890
20. R. J. Vyas, B. B. Cook, Y. Kawahara, and M. M. Tentzeris, "E-wehp: A batteryless embedded sensor-platform wirelessly powered from ambient digital-tv signals," IEEE Transactions on Microwave Theory and Techniques, vol. 61, no. 6, pp. 2491–2505, June 2013. [Online]. Available: https://doi.org/10.1109/TMTT.2013.2258168
21. R. Shigeta, T. Sasaki, D. M. Quan, Y. Kawahara, R. J. Vyas, M. M. Tentzeris, and T. Asami, "Ambient rf energy harvesting sensor device with capacitor-leakage-aware duty cycle control," IEEE Sensors Journal, vol. 13, no. 8, pp. 2973–2983, Aug 2013. [Online]. Available: https://doi.org/10.1109/JSEN.2013.2264931
22. A. N. Parks, A. P. Sample, Y. Zhao, and J. R. Smith, "A wireless sensing platform utilizing ambient rf energy," in 2013 IEEE Topical Conference on Biomedical Wireless Technologies, Networks, and Sensing Systems, Jan 2013, pp. 154–156. [Online]. Available: https://doi.org/10.1109/BioWireleSS.2013.6613706
23. D. Masotti, A. Costanzo, M. D. Prete, and V. Rizzoli, "Genetic-based design of a tetra-band high-efficiency radio-frequency energy harvesting system," IET Microwaves, Antennas Propagation, vol. 7, no. 15, pp. 1254–1263, December 2013. [Online]. Available: https://doi.org/10.1049/iet-map.2013.0056
24. M. Pin˜uela, P. D. Mitcheson, and S. Lucyszyn, "Ambient rf energy harvesting in urban and semi-urban environments," IEEE Transactions on Microwave Theory and Techniques, vol. 61, no. 7, pp. 2715–2726, July 2013. [Online]. Available: https://doi.org/10.1109/TMTT.2013.2262687
25. S. Keyrouz, H. J. Visser, and A. G. Tijhuis, "Ambient rf energy harvesting from dtv stations," in 2012 Loughborough Antennas Propagation Conference (LAPC), Nov 2012, pp. 1–4. [Online]. Available: https://doi.org/10.1109/LAPC.2012.6403012
26. P. Nintanavongsa, U. Muncuk, D. R. Lewis, and K. R. Chowdhury, "Design optimization and implementation for rf energy harvesting circuits," IEEE Journal on Emerging and Selected Topics in Circuits and Systems, vol. 2, no. 1, pp. 24–33, March 2012. [Online]. Available: https://doi.org/10.1109/JETCAS.2012.2187106
27. V. Hebelka, J. Velim, and Z. Raida, "Dual band koch antenna for rf energy harvesting," in 2016 10th European Conference on Antennas and Propagation (EuCAP), April 2016, pp. 1–3. [Online]. Available: https://doi.org/10.1109/EuCAP.2016.7481818
28. Z. Zhou, W. Liao, Q. Zhang, F. Han, and Y. Chen, "A multi-band fractal antenna for rf energy harvesting," in 2016 IEEE International Symposium on Antennas and Propagation (APSURSI), June 2016, pp. 617–618. [Online]. Available: https://doi.org/10.1109/APS.2016.7696017
29. Q. Awais, Y. Jin, H. T. Chattha, M. Jamil, H. Qiang, and B. A. Khawaja, "A compact rectenna system with high conversion efficiency for wireless energy harvesting," IEEE Access, vol. 6, pp. 35 857–35 866, 2018. [Online]. Available: https://doi.org/10.1109/ACCESS.2018.2848907
30. H. Nishimoto, Y. Kawahara, and T. Asami, "Prototype implementation of ambient rf energy harvesting wireless sensor networks," in SENSORS, 2010 IEEE, Nov 2010, pp. 1282–1287. [Online]. Available: https://doi.org/10.1109/ICSENS.2010.5690588
31. L.-G. Tran, H.-K. Cha, and W.-T. Park, "Rf power harvesting: a review on designing methodologies and applications," Micro and Nano Systems Letters, vol. 5, no. 1, p. 14, Feb 2017. [Online]. Available: https://doi.org/10.1186/s40486-017-0051-0
32. C. Mikeka and H. Arai, Design Issues in Radio Frequency Energy Harvesting System, 12 2011.
33. L. Xie, Y. Shi, Y. T. Hou, and A. Lou, "Wireless power transfer and applications to sensor networks," IEEE Wireless Communications, vol. 20, no. 4, pp. 140–145, August 2013. [Online]. Available: https://doi.org/10.1109/MWC.2013.6590061

34. A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljaˇci´c, "Wireless power transfer via strongly coupled magnetic resonances," Science, vol. 317, no. 5834, pp. 83–86, 2007. [Online]. Available: https://doi.org/10.1126/science.1143254
35. W. C. Brown, "Experiments involving a microwave beam to power and position a helicopter," IEEE Transactions on Aerospace and Electronic Systems, vol. AES-5, no. 5, pp. 692–702, Sep. 1969. [Online]. Available: https://doi.org/10.1109/TAES.1969.309867
36. J. O. McSpadden and J. C. Mankins, "Space solar power programs and microwave wireless power transmission technology," IEEE Microwave Magazine, vol. 3, no. 4, pp. 46–57, Dec 2002. [Online]. Available: https://doi.org/10.1109/MMW.2002.1145675s
37. W. Brown, "Experiments in the transportation of energy by microwave beam," in 1958 IRE International Convention Record, vol. 12, March 1964, pp. 8–17. [Online]. Available: https://doi.org/10.1109/IRECON.1964.1147324
38. K. Finkenzeller, RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification, 2nd ed. Wiley Publishing, 2003.
39. C. R. Valenta and G. D. Durgin, "Harvesting wireless power: Survey of energy-harvester conversion efficiency in far-field, wireless power transfer systems," IEEE Microwave Magazine, vol. 15, no. 4, pp. 108–120, June 2014. [Online]. Available: https://doi.org/10.1109/MMM.2014.2309499
40. J. O. McSpadden, L. Fan, and K. Chang, "Design and experiments of a high-conversion-efficiency 5.8-ghz rectenna," IEEE Transactions on Microwave Theory and Techniques, vol. 46, no. 12, pp. 2053–2060, Dec 1998. [Online]. Available: https://doi.org/10.1109/22.739282
41. H. Wong, K. Luk, C. H. Chan, Q. Xue, K. K. So, and H. W. Lai, "Small antennas in wireless communications," Proceedings of the IEEE, vol. 100, no. 7, pp. 2109–2121, July 2012. [Online]. Available: https://doi.org/10.1109/JPROC.2012.2188089
42. C. G. Christodoulou, Y. Tawk, S. A. Lane, and S. R. Erwin, "Reconfigurable antennas for wireless and space applications,"
Proceedings of the IEEE, vol. 100, no. 7, pp. 2250–2261, July 2012. [Online]. Available: https://doi.org/10.1109/JPROC.2012.2188249
43. J. Costantine, K. Y. Kabalan, A. EI-Hajj, and M. Rammal, "New multi-band microstrip antenna design for wireless communications," IEEE Antennas and Propagation Magazine, vol. 49, no. 6, pp. 181–186, Dec 2007. [Online]. Available: https://doi.org/10.1109/MAP.2007.4455895
44. C. A. Balanis, Antenna Theory: Analysis and Design. Wiley-Interscience, 2005.
45. M. Ali and B. Khawaja, "Dual bandmicrostrip patch antenna array for next generation wireless sensor network applications," in PROCEEDINGS OF 2013 International Conference on Sensor Network Security Technology and Privacy Communication System, 05 2013, pp. 39–43.
46. M. Ali, B. A. Khawaja, M. A. Tarar, and M. Mustaqim, "A dual band u-slot printed antenna array for lte and wimax applications," Microwave and Optical Technology Letters, vol. 55, no. 12, pp. 2879–2883, 2013. [Online]. Available: https://doi.org/10.1002/mop.27973
47. K. F. Lee, S. L. S. Yang, and A. A. Kishk, "U-slot patch antennas for dual-band or multi-band applications," in 2009 IEEE International Workshop on Antenna Technology, March 2009, pp. 1–4. [Online]. Available: https://doi.org/10.1109/IWAT.2009.4906900
48. F. Y. Zulkifli, H. Halim, and E. T. Rahardjo, "A compact multiband microstrip antenna using u and s slots," in 2008 IEEE Antennas and Propagation Society International Symposium, July 2008, pp. 1–4. [Online]. Available: https://doi.org/10.1109/APS.2008.4619108
49. A. A. Razzaqi, M. Mustaqim, and B. A. Khawaja, "Wideband e-shaped antenna design for wlan applications," in 2013 IEEE 9th International Conference on Emerging Technologies (ICET), Dec 2013, pp. 1–6. [Online]. Available: https://doi.org/10.1109/ICET.2013.6743550
50. N. Kulkarni, S. N. Mulgi, and S. K. Satnoor, "Dual notched u–slots triple band tunable rectangular microstrip antenna," Microwave and Optical Technology Letters, vol. 55, no. 3, pp. 509–513, 2013. [Online]. Available: https://doi.org/10.1002/mop.27372

51. R. Pandey, A. Shankhwar, and A. Singh, “Design, analysis and optimization of dual side printed multiband antenna for rf energy harvesting,” Progress In Electromagnetics Research C, vol. 102, 2020.
52. X.-X. Zhang and F. Yang, “Study of a slit cut on a microstrip antenna and its applications,” Microwave and Optical Technology Letters, vol. 18, no. 4, pp. 297–300, 1998. [Online]. Available: https://doi.org/10.1002/(SICI)1098-2760(199807)18:4%3C297:: AID-MOP14%3E3.0.CO;2-1
53. D. T. Notis, P. C. Liakou, and D. P. Chrissoulidis, “Dual polarized microstrip patch antenna, reduced in size by use of peripheral slits,” in 7th European Conference on Wireless Technology, 2004., Oct 2004, pp. 273–276.
54. H.-O. Peitgen, H. Ju¨rgens, and D. Saupe, Chaos and Fractals: New Frontiers of Science. New York, NY: Springer New York, 1992. [Online]. Available: https://doi.org/10.1007/B97624
55. S. Baudha and V. D. Kumar, “Miniaturized dual broadband printed slot antenna with parasitic slot and patch,” Microwave and Optical Technology Letters, vol. 56, no. 10, pp. 2260–2265, 2014. [Online]. Available: https://doi.org/10.1002/mop.28567
56. J.-W. Zhang, Y. Huang, and P. Cao, “An investigation of wideband rectennas for wireless energy harvesting,” Wireless Engineering and Technology, vol. 05, pp. 107–116, 01 2014. [Online]. Available: https://doi.org/10.4236/wet.2014.54012
57. D. Pavone, A. Buonanno, M. D’Urso, and F. Della Corte, “Design considerations for radio frequency energy harvesting devices,”
Progress In Electromagnetics Research B, vol. 45, pp. 19–35, 01 2012. [Online]. Available: https://doi.org/10.2528/PIERB12062901
58. L. Yang, Y. J. Zhou, C. Zhang, X. M. Yang, X. Yang, and C. Tan, “Compact multiband wireless energy harvesting based battery-free body area networks sensor for mobile healthcare,” IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology, vol. 2, no. 2, pp. 109–115, June 2018. [Online]. Available: https://doi.org/10.1109/JERM.2018.2817364
59. H. Sun, Y. Guo, M. He, and Z. Zhong, “A dual-band rectenna using broadband yagi antenna array for ambient rf power harvesting,” IEEE Antennas and Wireless Propagation Letters, vol. 12, pp. 918–921, 2013. [Online]. Available: https://doi.org/10.1109/LAWP.2013.2272873
60. J.-I. Moon and Y.-B. Jung, “Novel energy harvesting antenna design using a parasitic radiator,” Progress In Electromagnetics Research, vol. 142, pp. 545–557, 2013. [Online]. Available: https://dx.doi.org/10.2528/PIER13081802
61. P. Khoury, “A power-efficient radio frequency energy-harvesting circuit,” July 2013. [Online]. Available: http://dx.doi.org/10.20381/ ruor-6293
62. N. Mahagavin Sameena, R. Konda, and S. N. Mulgi, “A novel slot for enhancing the impedance bandwidth and gain of rectangular microstrip antenna,” Progress In Electromagnetics Research C, vol. 11, pp. 11–19, 01 2009.
63. S. Shen and R. D. Murch, “Impedance matching for compact multiple antenna systems in random rf fields,” IEEE Transactions on Antennas and Propagation, vol. 64, no. 2, pp. 820–825, Feb 2016. [Online]. Available: https://doi.org/10.1109/TAP.2015.2510006
64. D. Etor, L. E. Dodd, D. Wood, and C. Balocco, “Impedance matching at thz frequencies: Optimizing power transfer in rectennas,” in 2015 40th International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz), Aug 2015, pp. 1–2. [Online]. Available: https://doi.org/10.1109/IRMMW-THz.2015.7327776
65. C. Hoarau, N. Corrao, J. . Arnould, P. Ferrari, and P. Xavier, “Complete design and measurement methodology for a tunable rf impedance-matching network,” IEEE Transactions on Microwave Theory and Techniques, vol. 56, no. 11, pp. 2620–2627, Nov 2008. [Online]. Available: https://doi.org/10.1109/TMTT.2008.2006105
66. G. Marrocco, “The art of uhf rfid antenna design: impedance-matching and size-reduction techniques,” IEEE Antennas and Propagation Magazine, vol. 50, no. 1, pp. 66–79, Feb 2008. [Online]. Available: https://doi.org/10.1109/MAP.2008.4494504

67. J. de Mingo, A. Valdovinos, A. Crespo, D. Navarro, and P. Garcia, “An rf electronically controlled impedance tuning network design and its application to an antenna input impedance automatic matching system,” IEEE Transactions on Microwave Theory and Techniques, vol. 52, no. 2, pp. 489–497, Feb 2004. [Online]. Available: https://doi.org/10.1109/TMTT.2003.821909
68. J. F. Dickson, “On-chip high-voltage generation in mnos integrated circuits using an improved voltage multiplier technique,” IEEE Journal of Solid-State Circuits, vol. 11, no. 3, pp. 374–378, June 1976. [Online]. Available: https://doi.org/10.1109/JSSC.1976.1050739
69. T. Yoo and K. Chang, “Theoretical and experimental development of 10 and 35 ghz rectennas,” IEEE Transactions on Microwave Theory and Techniques, vol. 40, no. 6, pp. 1259–1266, June 1992. [Online]. Available: https://doi.org/10.1109/22.141359
70. E. L. Chuma, L. d. l. T. Rodr´ıguez, Y. Iano, L. L. B. Roger, and M. Sanchez-Soriano, “Compact rectenna based on a fractal geometry with a high conversion energy efficiency per area,” IET Microwaves, Antennas Propagation, vol. 12, no. 2, pp. 173–178, 2018. [Online]. Available: https://doi.org/10.1049/iet-map.2016.1150
71. G. Papotto, F. Carrara, A. Finocchiaro, and G. Palmisano, “A 90-nm CMOS 5-mbps crystal-less RF-powered transceiver for wireless sensor network nodes,” IEEE Journal of Solid-State Circuits, vol. 49, no. 2, pp. 335–346, feb 2014. [Online]. Available: https://doi.org/10.1109%2Fjssc.2013.2285371
72. Z. Popovi´c, E. A. Falkenstein, D. Costinett, and R. Zane, “Low-power far-field wireless powering for wireless sensors,” Proceedings of the IEEE, vol. 101, no. 6, pp. 1397–1409, June 2013. [Online]. Available: https://doi.org/10.1109/JPROC.2013.2244053
73. D. Dondi, S. Scorcioni, A. Bertacchini, L. Larcher, and P. Pavan, “An autonomous wireless sensor network device powered by a rf energy harvesting system,” in IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society, Oct 2012, pp. 2557–2562. [Online]. Available: https://doi.org/10.1109/IECON.2012.6388696
74. D. Pavone, A. Buonanno, M. D’Urso, and F. Della Corte, “Design considerations for radio frequency energy harvesting devices,”
Progress In Electromagnetics Research B, vol. 45, pp. 19–35, 01 2012. [Online]. Available: https://doi.org/10.2528/PIERB12062901
75. F. Zhang, Y. Zhang, J. Silver, Y. Shakhsheer, M. Nagaraju, A. Klinefelter, J. Pandey, J. Boley, E. Carlson, A. Shrivastava, B. Otis, and B. Calhoun, “A batteryless 19μw mics/ism-band energy harvesting body area sensor node soc,” in 2012 IEEE International Solid-State Circuits Conference, Feb 2012, pp. 298–300. [Online]. Available: https://doi.org/10.1109/ISSCC.2012.6177004
76. A. Al-Khayari, H. Al-Khayari, S. Al-Nabhani, M. M. Bait-Suwailam, and Z. Nadir, “Design of an enhanced rf energy harvesting system for wireless sensors,” in 2013 7th IEEE GCC Conference and Exhibition (GCC), Nov 2013, pp. 479–482. [Online]. Available: https://doi.org/10.1109/IEEEGCC.2013.6705826
77. M. Al-Lawati, M. Al-Busaidi, and Z. Nadir, “Rf energy harvesting system design for wireless sensors,” in International Multi-Conference on Systems, Signals Devices, March 2012, pp. 1–4. [Online]. Available: https://doi.org/10.1109/SSD.2012.6197969
78. T. B. Lim, N. M. Lee, and B. K. Poh, “Feasibility study on ambient rf energy harvesting for wireless sensor network,” in 2013 IEEE MTT-S International Microwave Workshop Series on RF and Wireless Technologies for Biomedical and Healthcare Applications (IMWS-BIO), Dec 2013, pp. 1–3. [Online]. Available: https://doi.org/10.1109/IMWS-BIO.2013.6756226
79. K. M. Farinholt, G. Park, and C. R. Farrar, “Rf energy transmission for a low-power wireless impedance sensor node,” IEEE Sensors Journal, vol. 9, no. 7, pp. 793–800, July 2009. [Online]. Available: https://doi.org/10.1109/JSEN.2009.2022536
80. K. Kaushik, D. Mishra, S. De, S. Basagni, W. Heinzelman, K. Chowdhury, and S. Jana, “Experimental demonstration of multi-hop rf energy transfer,” in 2013 IEEE 24th Annual International

Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), Sep. 2013, pp. 538–542. [Online]. Available: https://doi.org/10.1109/PIMRC.2013.6666195
81. J. P. Olds and W. K. G. Seah, "Design of an active radio frequency powered multi-hop wireless sensor network," in 2012 7th IEEE Conference on Industrial Electronics and Applications (ICIEA), July 2012, pp. 1721–1726. [Online]. Available: https://doi.org/10.1109/ICIEA.2012.6361003
82. W. K. G. Seah and J. P. Olds, "Data delivery scheme for wireless sensor network powered by rf energy harvesting," in 2013 IEEE Wireless Communications and Networking Conference (WCNC), April 2013, pp. 1498–1503. [Online]. Available: https://doi.org/10.1109/WCNC.2013.6554785
83. X. Zhang, H. Jiang, L. Zhang, C. Zhang, Z. Wang, and X. Chen, "An energy-efficient asic for wireless body sensor networks in medical applications," IEEE Transactions on Biomedical Circuits and Systems, vol. 4, no. 1, pp. 11–18, Feb 2010. [Online]. Available: https://doi.org/10.1109/TBCAS.2009.2031627
84. U. Olgun, C. . Chen, and J. L. Volakis, "Design of an efficient ambient wifi energy harvesting system," IET Microwaves, Antennas Propagation, vol. 6, no. 11, pp. 1200–1206, August 2012. [Online]. Available: https://doi.org/10.1049/iet-map.2012.0129
85. U. Olgun, C. Chen, and J. L. Volakis, "Efficient ambient wifi energy harvesting technology and its applications," in Proceedings of the 2012 IEEE International Symposium on Antennas and Propagation, July 2012, pp. 1–2. [Online]. Available: https://doi.org/10.1109/APS.2012.6349384
86. M. Arrawatia, M. S. Baghini, and G. Kumar, "Rf energy harvesting system from cell towers in 900mhz band," in 2011 National Conference on Communications (NCC), Jan 2011, pp. 1–5.
87. U. Batool, A. Rehman, N. Khalil, M. Islam, M. U. Afzal, and T. Tauqeer, "Energy extraction from rf/ microwave signal," in 2012 15th International Multitopic Conference (INMIC), Dec 2012, pp. 165–170. [Online]. Available: https: //doi.org/10.1109/INMIC.2012.6511489A
88. P. Nintanavongsa, M. Y. Naderi, and K. R. Chowdhury, "A dual-band wireless energy transfer protocol for heterogeneous sensor networks powered by rf energy harvesting," in 2013 International Computer Science and Engineering Conference (ICSEC), Sep. 2013, pp. 387–392. [Online]. Available: https://doi.org/10.1109/ICSEC.2013.6694814
89. S. Kitazawa, H. Ban, and K. Kobayashi, "Energy harvesting from ambient rf sources," in 2012 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications, May 2012, pp. 39–42. [Online]. Available: https://doi.org/10.1109/IMWS.2012.6215815