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REVIEW ARTICLE

Key Components of Rectenna System: A Comprehensive Survey

Daasari Surender[1], Taimoor Khan[1], Fazal A. Talukdar[1], Asok De[2], Yahia M.M. Antar[3] and Al. P. Freundorfer[4]

[1]Department of Electronics and Communication Engineering, National Institute of Technology, Silchar, India; [2]Department of Electronics and Communication Engineering, Delhi Technological University, Delhi, India; [3]Department of Electrical and Computer Engineering, Royal Military College of Canada/Queen University, Kingston, Canada; [4]Department of Electrical and Computer Engineering, Queen University, Kingston, Canada

ABSTRACT
In this paper, a comprehensive survey on the key components of a rectenna system, including antenna configurations, rectifier configurations, impedance matching networks, and RF filter, is outlined. Due to increased applications, the rectenna has occupied a unique place in the RF and microwave engineering. For the last few decades, the research on the rectenna design is focused-on to improve the power conversion efficiency, compatibility and to reduce the design complexity. The main objective of the proposed paper is (i) to accommodate the key design requirements of the rectenna; (ii) highlight the specifications and the possible configurations of the rectenna elements as diode, rectifier, and input source; and (iii) present an inclusive survey of the remarkable research carried out and obtained results.

KEYWORDS
Full-wave rectifier; Gain; Half-wave rectifier; Power conversion efficiency; Rectenna; Rectifier; Voltage multiplier

1. INTRODUCTION

Advancements in the field of wireless technologies have led to the development of various wireless technologies such as internet of things (IoT), 5G systems, RFID Tags, wearable/ portable devices, which demand efficient electronic devices for their effective implementation. These technologies involve sensors that are deployed at remote places with the capacity of interacting with each other through wireless media. However, it is difficult to provide endless power to these devices with conventional approaches like by a battery or through wired cables [1]. Also, the lifetime of the battery is limited, so the frequent replacements of the battery is needed. This increases the additional expenditure on the system and may cause environmental pollution. Sometimes, replacing the battery placed at an inaccessible place, becomes impossible. To overcome these limitations, energy harvesting (EH) techniques have grabbed significant attention globally [1]. Different energy harvesting approaches available, based on type of sources, are as follows: solar EH, wind EH, acoustic EH, thermal EH, mechanical EH, radio frequency (RF) EH, etc. Among all energy harvesting techniques, radio-frequency energy harvesting (RFEH) is a more prominent technique due to an increasing availability of RF energy emanating from different widely available radio transmitters. Besides, by virtue of limited space requirement for installing the harvesting system, RFEH systems can be operated efficiently in the indoor atmosphere. However, low power density is the main limitation in the RFEH approach. The rectenna is an essential component for converting ambient electromagnetic radiation into a usable form of electrical direct current (DC). In 1960′s, the concept of the rectenna was initially proposed by William C. Brown for wireless power transfer applications [2]. Wireless transmission is useful to power electrical devices in cases where interconnecting wires are inconvenient, hazardous, or are not feasible. Finally, a rectenna device was implemented in 1964 and patented in 1969 by William C. Brown [3]. At that time, the size of the rectenna was very large. Since the invention of rectenna, tremendous research has been carried out to improve the rectenna performance by reducing the size. Later on, applications of rectenna are extended to wireless energy harvesting (WEH), wireless sensor networks (WSN) and implantable devices. However, rectennas are suffering from larger dimensions and low rectenna efficiency.

The overall efficiency of the rectenna is an important parameter. The rectenna efficiency largely depends on the efficiency of individual elements connected to the rectenna system. The crucial stages in implementing the rectenna are designing an efficient antenna and a rectifier circuit. The performance of the rectenna usually relies on the performances of both the harvesting ability of the antenna and power conversion efficiency (PCE) of the rectifier circuit. In general, the PCE of the rectifying circuit is directly proportional to the power captured by the antenna. The PCE is defined as the ratio of the output DC power to the input RF power to the rectifier circuit. As the power received by the antenna is more, the power supplied to the rectifying circuit increases which in turn increase the available power to be delivered to the load. Various techniques for increasing the receiving power by the antenna followed by the PCE of the rectifier circuit have been analysed in this review article. As far as, the literature on rectenna review articles is concerned, many review works have been reported in the existing literature, however, their scope has been very much limited [4–9]. Hamid *et al.* [4] have reviewed primarily about different rectifier topologies for energy harvesting applications. Antwi *et al.* [5] have reviewed the design issues of the rectenna with an emphasis on the impedance matching network. Zahriladha *et al.* [6] have reviewed various antenna and rectifier topologies and their comparisons. However, they did not consider different techniques that are useful for increasing the rectenna performance such as gain, miniaturization, etc. Evgeniy *et al.* [7] have reviewed the progress in the rectenna but only with various diode components and their fabrication techniques. Sleebi *et al.* [8] have reviewed the present design challenges of rectenna including various rectifier topologies. Cansiz *et al.* [9] have reviewed the harvesting system components, especially focusing efficiency performance of the rectenna. Thus, a review article by simultaneously considering the design aspects and performance evaluation of different configurations of a rectenna circuit has not been reported till date to the best of the authors' knowledge. The comprehensive discussion on key modules of the rectenna includes the type, specifications, and configurations of an antenna, a brief overview of the antenna miniaturization techniques, type of diodes, rectifier configurations, are made in the proposed review article. In Section 2, an overview of RFEH systems has been made. In Section 3, various antenna configurations [10–85], and their performances are discussed. Types of rectifiers and their topologies are then discussed in Section 4. Section 5 discusses the Filter and matching networks. Applications of rectenna are discussed in Section 6. Section 7 illustrates the summary of the reviewing process. Finally, Section 8 discusses the concluding remarks followed by references.

2. AN OVERVIEW OF REEH SYSTEMS

As described in Section 1, radio-frequency energy harvesting (RFEH) is one of the common techniques used for harvesting the energy especially to energize low power electronic devices. The RFEH approach employs harvesting electrical form of energy of ambient or dedicated RF sources present in the surrounding atmosphere and processing the signal according to the desired manner of energizing low power electronic devices. The available power density from the different RF sources is varying from 0.1 μW/cm^2 (ambient source) to 1000 μW/cm^2 (dedicated source). The device used for capturing the EM signal, is a rectifying antenna which is basically an integrated form of antenna circuit and rectifier circuit. This rectifying antenna, commonly known as rectenna, has achieved maximum attention among the researchers in recent years. The basic block diagram of a rectenna system is shown in Figure 1.

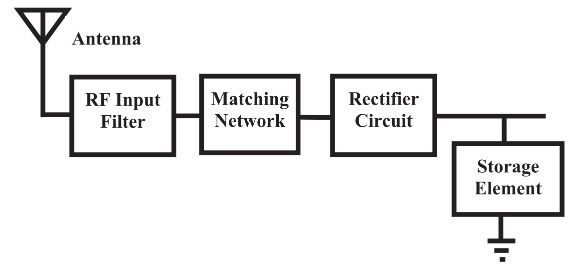

Figure 1: Basic block diagram of a rectenna

In general, the rectenna system consists of an antenna, rectifier, impedance matching network and RF filter. The antenna is to sense and receive the RF energy and the rectifier then converts the RF signal into DC signal. An RF input filter, known as "pre-rectifier," is basically a filter used to suppress harmonics generated by a non-linear component in the rectifier. The matching network is required between the filter and rectifier circuit for maximum power transfer. Irrespective of the application, the basic functioning of a rectenna system remains the same. A flow-diagram, showing various components and applications of the rectenna system, is shown in Figure 2.

Various energy sources radiating energy in the RF bands are as: frequency modulation (FM), digital television (DTV), Global System for Mobile Communications (GSM), Global Positioning System (GPS), Long Term Evolution (LTE), Universal Mobile Telecommunications System (UMTS), Wireless Fidelity (Wi-Fi), Worldwide Interoperability for Microwave Access (Wi-Max), and 5G etc. Energy from these sources can be utilized for RFEH systems. Frequency bands of some of the sources are listed out in the Table 1, as shown below.

3. ANTENNA CONFIGURATIONS

The antenna is one of the crucial components deployed in the front-end of a rectenna system. The antenna is used to

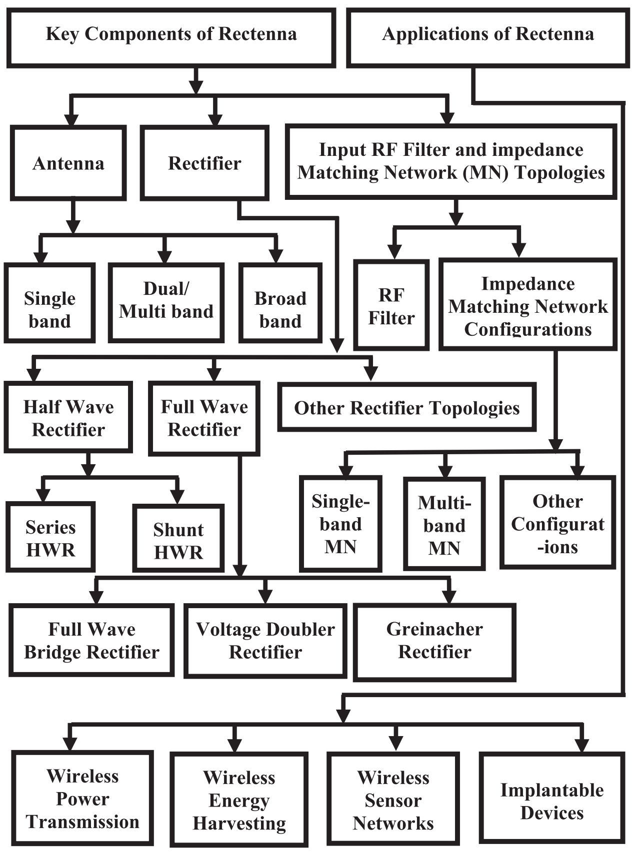

Figure 2: Flow-diagram of various components of rectenna

Table 1: Frequency bands and ranges

S. No.	Frequency band	Range of frequencies (GHz)
1.	FM	0.088–0.108
2.	DTV	0.470–0.862
3.	GSM900	0.890–0.960
4.	GSM1800	1.710–1.880
5.	UMTS2100	1.920–2.170
6.	LTE2500	2.500–2.690
7.	Wi-Fi	2.400–2.483 5.725–5.870
8.	Wi-Max	3.300–3.500
9.	5G	3.400–3.600 3.700–4.200 4.800–4.990 24.250 -29.500

receive the incoming RF power and convert it to DC signal through the subsequent stages of the rectenna system. The performance, size, and complexity of a rectenna system are highly governed by the efficiency of the selected antenna. An antenna structure is desired to have broad operating frequency range, high gain, omnidirectional radiation pattern, circular polarization, compact dimensions, low-profile, etc. In this section, the performance of several antenna configurations available in open literature [10–85], are studied in detail. For ease of understanding, the existing literature is classified into different subsections based on their frequency of operation as single-band [10–52], broad-band [53–63], and dual-/multi-band [64–85], respectively.

3.1 Single-Band Antennas

In rectenna systems, single-band antennas are designed to operate in a single narrow frequency band. From a performance point of view, different parameters are considered while designing single-band antennas. Circular polarization (CP) is one such key parameter that is intended to obtain a stable output power from the antenna. A stable output helps in increasing the overall rectenna output power. Further, the ability of CP antennas to receive RF energy in any plane with minimum loss makes them an important candidate for improving the overall efficiencies in rectennas systems. Several configurations of single-band antennas are investigated in the open literature to achieve CP. Terminated gaps in a dual-rhombic loop antenna provide the CP characteristics [10–12]. A radiating patch embedded with two unbalanced slots yields CP properties [13]. In addition to the CP, the antenna also holds harmonic rejection property with reduced antenna size. A dual-port antenna is investigated in which two cross-slots are etched in the ground plane for generating CP [14]. Two small triangular-shaped cuts on to the periphery of a circular microstrip patch antenna help in achieving CP characteristics [15]. In [16], the CP is achieved by optimizing the lengths of four symmetrically integrated strips diagonally with a square patch. Saswati [17] has obtained CP features with a shorted section embedded on to a square ring slot antenna. An aperture coupling with an isosceles right triangle slot offers CP [18]. The CP characteristics are observed with an embedded U-shaped slot in addition to truncated corners of a radiating patch [19]. A dual-fed by two slot-lines with transverse ends is implemented for CP in [20]. The implemented antenna design with a coplanar waveguide (CPW) back-feeding technique is used to improve the antenna bandwidth. A circular radiating patch with an embedding E-shaped slot with four notches is investigated for CP [21]. Shabnam *et al.* [22] have proposed a technique with multiple microstrip patches oriented orthogonally and excited with 90° phase difference to provide CP. A substrate integrated waveguide (SIW) cavity-backed technique is further used to improve the axial ratio performance.

However, a circularly polarized (CP) antenna unable to detect a reversely circularly polarized wave. Thus, the harvesting ability of a CP antenna deteriorates from the mismatch loss due to polarization inequality. To overcome this limitation, antennas with dual polarized (dual linearly or dual circularly) configuration has been proposed. A dual polarized antenna receives any polarized wave from the surrounding environment. Sun *et al.* [23] have implemented a dual port dual linearly polarized antenna. The two ports (H-port and V-port) of the antenna are used to receive all polarized signals. Besides this, a dual port rectifier circuit is designed for obtaining better conversion efficiency. Chou *et al.* [24] have designed a dual circularly polarized (DCP) antenna. A T-shaped slot in the ground plane in addition to the perpendicular feed-lines are helps in receiving all polarized waves. The antenna also holds the harmonic rejection property. Two cross-slots etched in the ground plane which is placed between two substrate materials helps in achieving dual circular polarization characteristics is discussed in [25]. A dual-polarized EM energy harvester is implemented using an array of 16 Electric Inductive-Capacitive (ELC) resonator cells which forms a metamaterial medium in [26]. In [27], an aperture coupled microstrip patch antenna is implemented for dual-polarization characteristics. Two H-shaped orthogonal slots are introduced in the ground plane excites two orthogonal modes. Two non-uniform superstrate layers are placed one over the other to form a Febry-Perot antenna. These layers help in increasing the gain of the antenna. However, all these proposed designs suffer either from an adjustment of feeding ports at an appropriate place or with large antenna dimension due to an array of elements.

Another important characteristic parameter is the antenna gain. An antenna with a high gain is able to collect more RF energy from the ambient environment since the gain of the antenna is directly proportional to the electrical aperture area of the antenna. Antennas are required to have a high gain when the incident direction of a receiving signal is known. In addition to a high gain, omnidirectional features of the antenna helps in receiving more RF energy from the receiver even if the incident direction is unknown. Besides these, dual polarization characteristics are additional benefit of an antenna for further increasing the harvesting power. A high gain antenna is suitable for achieving more received power and better power conversion efficiency (PCE) with high output voltage. In the literature, various techniques have been adapted to increase the antenna gain. A stacked antenna configuration is implemented to achieve a large gain as referenced in [28–30]. In [29], it is further investigated that by introducing an air-gap in a stacked dielectric resonator antenna (DRA), the performances of antenna such as gain and impedance bandwidth improve, as shown in Figure 3. In [30], introducing the aluminium cavity along with metallic vias in a stacked DRA structure enhances both gain and impedance bandwidth performances. The

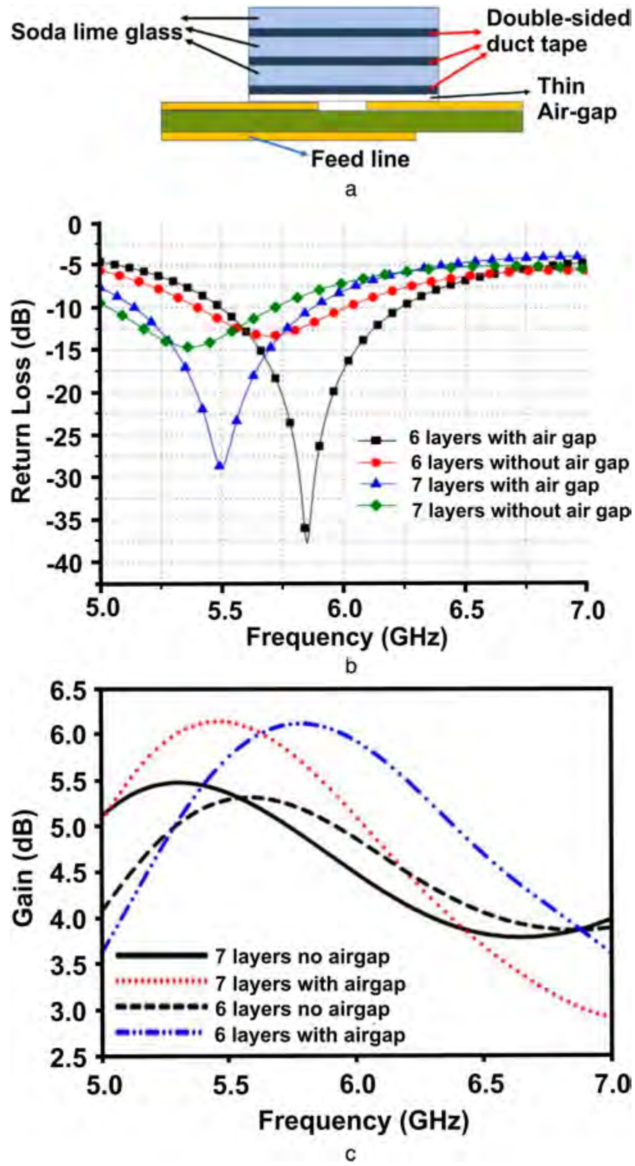

Figure 3: (a) DR antenna (b) simulated return loss performance (c) simulated gain performance [29]

gain of an antenna can also be increased by placing a reflecting plane behind an antenna [31]. A dual-probe feeding technique is investigated to enhance gain performance [32]. In addition, the impedance bandwidth is increased by introducing an air-gap.

The use of differential feeding techniques to increase the antenna gain is noticed in [33, 34]. In [33], microstrip antennas adopted differential feed operation that reduces the cross-polarization. Besides this, higher-order modes also suppressed with differential feeding. Thus, the radiation efficiency of the antenna can be increased and the resultant gain can be improved. Two ports are to be adjusted properly for feeding the antenna in a differential feeding case to achieve sufficient gain, as shown

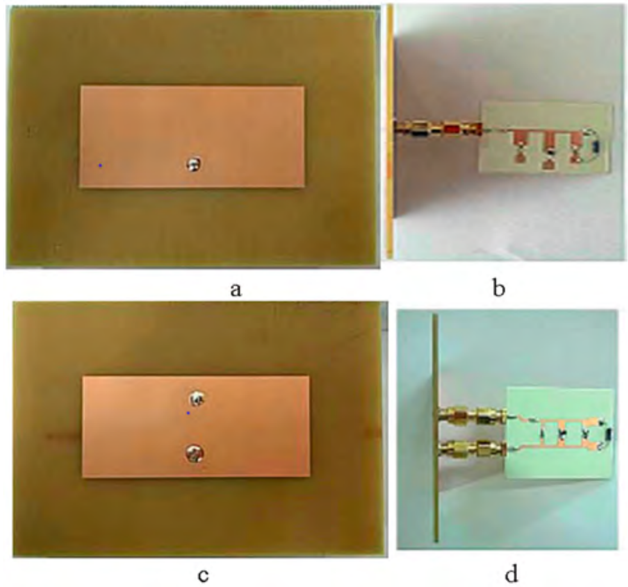

Figure 4: Two Configurations (a) Rectenna #1 top-view, (b) Rectenna #1 side-view, (c) Rectenna #2 top-view, (d) Rectenna #2 side-view [33]

in Figure 4. Here the Rectenna #1 is implemented in a single-feed configuration and Rectenna #2 is implemented with a differential feeding provided by two feed probes. However, the use of two different sources for differential feeding increases the system complexity. In [35], it is noticed that the gain of the antenna is increased by loading two perfect electric conductor (PEC) sidewalls on to the chosen Rogers Duroid 5880 substrate. Two sidewalls are perpendicular to the plane of the substrate.

The antenna gain, increased with an array configuration of antennas in a single band rectenna, is investigated in [12, 36]. An array of dual-rhombic-loop antennas (DRLAs) helps in achieving large antenna gain [12]. Ren *et al.* [36] have investigated that the array of antenna elements increases the antenna gain further. A special technique like aperture coupled patch antenna array is studied in [37]. The proposed aperture coupled antenna array helps in increasing the receiving power above 0 dBm with increased gain. Sethi *et al.* [38] have implemented an equilateral triangular DR antenna array for improving the directivity and bandwidth. An antenna array operating at a cellular GSM 900 band is investigated [39]. The proposed antenna array is composed of two T-shaped monopole antennas. The implemented array enhances the antenna gain, as shown in Figure 5. A stub introduced in the ground plane, makes the antenna size compact.

To increase the beamwidth, an array of four antennas including two auxiliary antennas, has been implemented

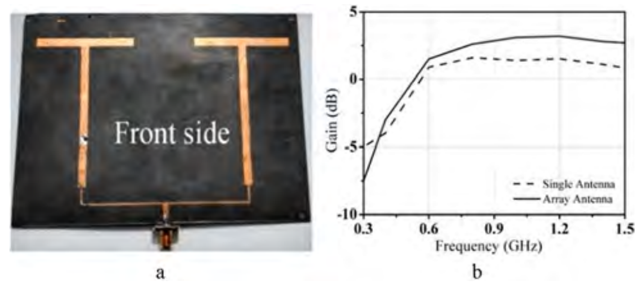

Figure 5: Array design and the performance [39]

in [40]. In [41], an enhancement in the received power is observed by increasing the number of feeding lines in the array design. The techniques that are reported in the literature for increasing gain are found to increase the antenna size and complexity. Moreover, it is noticed that the antenna array narrows the bandwidth thereby the capturing ability is reduced. Hu *et al.* [42] have proposed a multiport approach for wide angle coverage in addition to have high gain of the antenna. A grid array antenna with tilted beams have been implemented to realize a multiport antenna. An RF balanced characteristic incorporated two-branch rectifier circuit is presented to add the rectified DC power. Various techniques are thereby adopted to achieve antenna miniaturization. Shabnam *et al.* [43] have proposed a technique in which the antenna radiator is folded to obtain compactness. The fractal geometries are also investigated in [44–46] to reduce the antenna size. Slots-loaded microstrip radiating patch antenna [47] and meandered line technique [48] helps in minimizing the antenna size. A rectangular ring printed around the flat dipole antenna (FDA) is investigated in [49]. The antenna with a circinal geometry makes the antenna size compact [50]. The circinal geometry is realized by expanding the folding curves. A spiral planar inverted-F antenna (SPIFA) is proposed in [51] to design a compact antenna. The planar inverted-F antennas (PIFAs) are resonating at less than quarter-wavelength due to shorting pin at the end. A modified form of Hilbert fractal geometry is proposed to implement a rectenna with a tiny-size antenna [52]. Thus, the single band antenna configuration receives a large amount of power either with a large aperture area of a radiating patch or with a large antenna gain. A large aperture area is possible by an array of antennas, which increases the size of the antenna and hence the size of the rectenna too. Thus, a single band antenna with high gain is suitable for the rectenna design. The techniques that are reported for increasing the gain [28, 30–35] increase the rectenna dimension or the design complexity. In the reported literature [29], a multi-layer structure is the most favorable technique to achieve high gain. To extend rectenna applications, the antenna size following the rectenna size must be small. A fractal-based geometry is the most useful technique to make the antenna size compact. The main limitation with a single band antenna in the rectenna system is their compatibility in all geographical areas due to their unique frequency of operation.

3.2 Broad-Band Antennas

The broadband antennas are designed to operate over a broad range of frequencies. The antenna can collect energy from multiple sources covered over the broad range of frequencies. Multiple works of literature are reported on broadband antennas. In [53], a grounded coplanar waveguide (GCPW) antenna is proposed to achieve wide impedance bandwidth. Arrawatia *et al.* [54] have proposed broadband bent triangular antenna in which introducing gradual flaring at each bend in the proposed antenna enhances the impedance bandwidth of the antenna. The broadband characteristics are achieved by introducing a slot in the ground plane [55, 56]. In [55], a combination of DRA and an underlying slot with a narrow rectangular notch in the ground plane broadens the antenna bandwidth. Whereas, in addition to a slot in the ground plane, a patch is also loaded in the ground plane for further improvement in the bandwidth [56]. A fractal antenna with CPW feeding is investigated in [57]. A CPW-fed slotted microstrip patch antenna is implemented in [58] to achieve broadband characteristics. Slots embedded in the microstrip patch antenna are optimized to obtain the desired response. A log-periodic dipole array (LPDA) antenna is implemented to achieve an increase in gain over the entire operating band of the designed antenna [59]. In addition to having a high gain, the CP property is achieved with an array of patch antennas by employing sequential rotation technique in [60]. Compact broadband antennas are desirable to meet the trend of miniaturized and light-weight rectenna designs. A Vivaldi antenna is proposed to have broadband characteristics with compact antenna size [61]. By introducing rectangular and annular slots on the radiating surface, antenna bandwidth is enhanced by Shi *et al.* [62]. Further improvement in bandwidth is obtained by embedding symmetrical slots on either side to the feed-line in the ground plane. A CPW monopole antenna is investigated in [63]. The broadband antennas, thus discussed, operate over a wide range of frequencies. Hence, it is difficult to achieve the proper impedance matching between antenna and rectifier circuit. The mismatching in the impedance may result in reducing the RF-to-DC conversion efficiency of the rectenna system. From the literature, it is noticed that a slot-loaded ground structure is a widely adopted technique to obtain broadband characteristics of an antenna.

3.3 Dual-/Multi-Band Antennas

The multi-band antenna covers many desired frequencies that are useful for rectenna applications. Thus, the antenna receives more power from the ambient environment. A limited literature on multi-band antennas [64–85] for designing a rectenna is available. A meandered line integrated planar inverted-F antenna (PIFA) structure is proposed to obtain triple-band characteristics in [64]. A slot-loaded folded antenna operating at two frequencies is studied in [65]. In [66], it is observed that the performance of the multi-band antenna is better than that of a single band antenna, as shown in Figure 6. A pentagon-shaped DRA with a rectangular slot in the ground plane is implemented in [67] for achieving a wider impedance bandwidth with an increase in gain. A dual-port L-probe triple-band microstrip patch antenna is investigated in [68]. The proposed patch antenna is implemented by stacking two single-port patch antennas back-to-back. Miaowang *et al.* [69] have proposed a monopole antenna with two arms. The longer arm with fractal geometry produced a lower frequency band and a shorter arm generates a higher frequency band. The antenna with multi-band characteristics is implemented with two annular slots nested one inside the other [70]. Slots-loaded antennas are investigated to achieve multi-band characteristics in [71–72]. A multi-band antenna with high gain characteristics increases the antenna receiving power. Various techniques such as differential-feeding [73], air-gap technique [74], antenna array [75–76], and aperture-coupled feeding technique [77]. These reported techniques are suffering either from large antenna size or design complexity. A multi-band rectenna with small antenna size increases rectenna applications. Different techniques such as Fractal geometry [78], meandered lines concept [79], Sierpinski fractal technique [80] and multi-bending curves method [81] have been adopted to make the antenna size compact. A multi-band antenna with circular polarization (CP) characteristics is an added advantage to receive more and stable power. Neeta *et al.* [82] have presented a dual-polarized antenna. The designed antenna provided CP at three resonant bands. The CP at three bands is achieved by truncating the corners of the square patch radiator and loaded with some circular slots and L-slots surrounded by a U-shaped slot.

A spiral antenna with asymmetrical cross slots loaded in the patch is implemented in [83]. Truncated corners in the proposed antenna design help in achieving

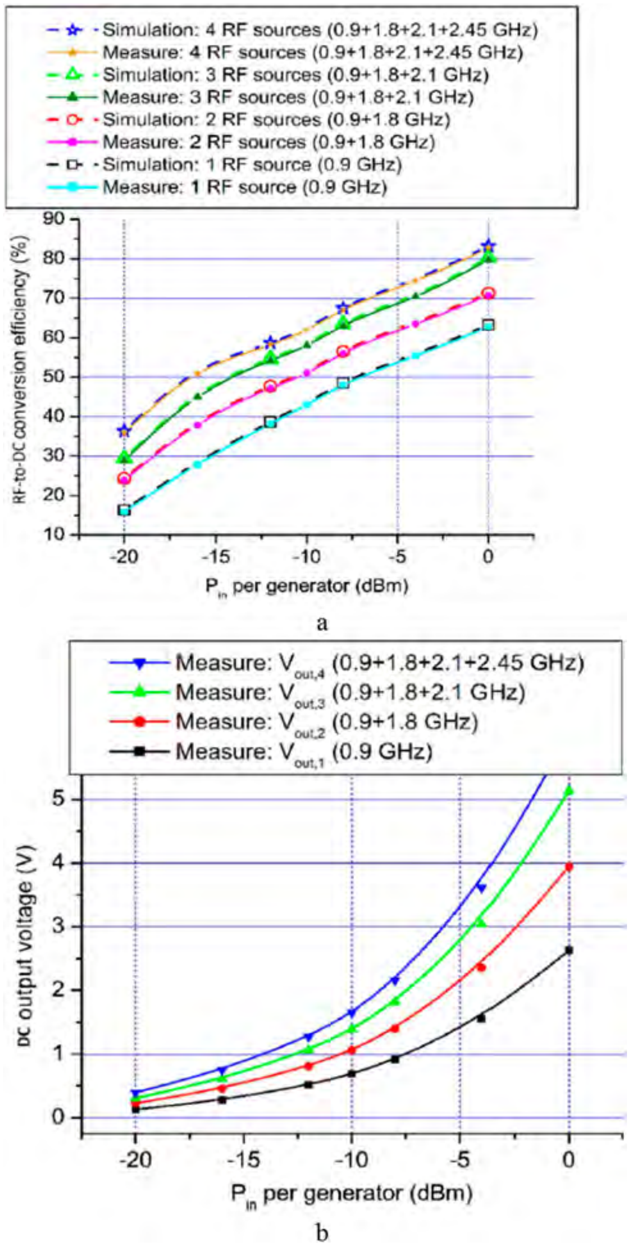

Figure 6: Performance comparison of Rectenna (a) RF-to-DC conversion efficiency, (b) DC output voltage performance [66].

CP characteristics. A fractal geometry with few truncations provides CP at two frequencies in a six-band antenna is studied in [84]. Enhanced performance is noticed with a multi-band rectenna implemented with an array of antennas compared to a single band circularly polarized rectenna [85]. The multiband antennas, discussed here, operate over multiple frequencies and capture the EM energy from all its operating bands. Hence, the receiving power by them is more. Achieving proper impedance matching is comparatively better than a broadband antenna. A slot-loaded radiating patch is the most suitable technique to obtain multiple band characteristics. Most of the multi-band designs reported in the literature [73–77] are suffered from large dimensions. Multi-band antennas with compact sizes are desirable for an increasing number of rectenna applications.

Table 2: Operating frequencies of rectenna applications

S. No.	Frequency (GHz)	Ref.
1.	0.402	[64]
2.	0.433	[64]
3.	0.9	[17, 28, 39, 43, 49, 52, 65, 66–70, 79, 84]
4.	1.8	[41, 44, 66–71, 74–76, 79, 84]
5.	2.1	[41, 66, 68, 70, 71, 73, 75–76, 80]
6.	2.3	[62]
7.	2.4	[21, 26, 32, 48, 72, 74, 83]
8.	2.45	[13–15, 18, 19, 23–25, 31, 33, 35, 41,42, 45–47, 50, 53, 64–66, 73, 77, 78, 81]
9.	2.5	[62, 84]
10.	2.6	[16, 41, 70]
11.	3.5	[73, 81, 83, 84]
12.	4.75	[82]
13.	5.0	[29, 77]
14.	5.2	[83]
15.	5.5	[82, 84]
16.	5.8	[10–12, 20, 27, 34, 36, 37, 40, 58, 72, 78, 80, 82]
17.	6.2	[27]
18.	6.4	[82]
19.	6.9	[82]
20.	7.35	[84]
21.	7.61	[82]
22.	24.0	[22]

Various antenna configurations that are used different frequency bands for rectenna applications are presented in a Tabular form, as presented in the Table 2. From Table 2, it is observed that frequencies which are most suitable for radio frequency energy harvesting applications are 0.9 GHz, 1.8 GHz, 2.1 GHz, 2.4 GHz, 2.45 GHz, 3.5 GHz, and 5.8 GHz frequencies.

4. RECTIFIER CONFIGURATIONS

The rectifier is another integral part of a rectenna system which converts the received RF power into DC power. Designing a rectifier with increased rectification efficiency is a challenging task. The efficiency of a rectifier circuit is usually represented in terms of the parameter known as power conversion efficiency (PCE) which is numerically defined as:

$$\eta_{\mathbf{RF-DC}} = \frac{\mathbf{P_{dc}}}{\mathbf{P_{RF}}} = \frac{\mathbf{V_{dc} \times I_{dc}}}{\mathbf{P_{RF}}} = \frac{\mathbf{V_{dc}^2}}{\mathbf{P_{RF} \times R_L}} \quad (1)$$

here, "V_{dc}" and "I_{dc}" denotes the DC output voltage and DC output current, respectively across load resistance (R_L). The diode is an essential component of the rectifying circuit that is used for RF-to-DC conversion process. In general, diodes with a low threshold voltage (V_{th}) or low turn-on voltage, low series resistance (Rs), low junction capacitance (C_{jo}), and large breakdown voltage (V_{br}) are used for designing rectifier circuits [43]. A diode with a low turn-on or threshold (V_{Th}) voltage and high

Table 3: Characteristic parameters of Schottky diode models

Diode Model	Manufacturer	V_{th} (V)	R_s (Ω)	C_{jo} (pF)	V_{br} (V)	I_s (μA)	Ref.
SMS7630	Sky Works	0.09	20	0.14	2.0	5.0	[65, 76]
MA4E1317	M/A COM	0.7	4.0	0.02	7.0	0.1	[10, 12]
HSMS2852	Avago	0.15	25.0	–	3.8	3.0	[82]
HSMS2860	Avago	0.25	6.0	–	7.0	0.05	[91]
HSMS2850	Avago	0.15	25.0	0.18	3.8	3.0	[92]
HSMS286B	Avago	0.69	6.0	0.18	7.0	0.05	[74]
HSMS2820	Avago	0.15	6.0	0.7	15.0	0.022	[90, 93]

breakdown voltage is desirable for the rectifier design. However, it is difficult to realize both the characteristics in the same diode. In addition to these, reverse saturation current (I_s) of a diode is also one of the important characteristic parameters. The saturation current of the diode changes the diode parallel resistance. For larger values of "I_s", the diode parallel resistance reduces which is more effective at low frequencies [86]. Further, the diode resistance also reduces, hence the diode allows to start the conduction at low input power levels. The "I_s" rely on the diode barrier width. The diode having low barrier height possesses low forward voltage drop and large amount of reverse leakage current across the diode junction barrier. The turn-on voltage of the diode becomes low. Thus, the application of low power levels desires the diode with large reverse saturation current (I_s) to turn-on the diode easily at low power signals. The diode with more saturation current offers better conversion efficiency comparatively. The conventional diodes are not suitable for use at radio frequencies. Therefore, a special class of diodes such as Schottky diodes is used that satisfy the requirements of a rectifier circuit at RF levels. In the literature, various Schottky diode families for rectenna applications have been studied. The most frequently used diodes are HSMS28xx, MA4E1317, and SMS7630. Because of its low threshold voltage, the diode SMS7630 is usually chosen for designing rectifiers with weak RF input signal (< -40 dBm) [65, 76, 87]. The HSMS28xx diode families have a range of breakdown voltages from 3.8V to 15 V [88, 74, 13]. This diode family is, therefore, suitable to operate at both low and high input power levels (> -40 dBm). The diode MA4E1317 has a breakdown voltage of 7 V [10, 12, 89], which is best suited where the input power level is greater than 0dBm. A detailed experimental study to analyse the performances of SMS7630 and HSMS28xx diodes families at various power levels has also been performed in [90]. The diode SMS7630 performance is found better for power levels below 13 dBm (between the ranges of RF values −50 dBm to 13 dBm). The output from the rectenna is limited to a maximum of half of the breakdown voltage. Thus, the diode with a large breakdown voltage provides a better output voltage. SMS7630 diode family is found to be suitable for low RF input power levels and HSMS28xx family is suitable for large input power levels. Table 3 lists the electrical characteristics of some of the frequently used Schottky diode models for increasing PCE in rectenna applications.

Diode based rectifier configurations are generally used in rectenna circuits due to its low turn on or threshold voltage compared with CMOS circuits. However, CMOS rectifiers using "three-terminal" MOS transistor, have unique characteristics that cannot be realized by rectifiers composed of "two-terminal" diode. When bias voltage is applied to MOS gate electrode, turn-on voltage of diode-connected MOS transistor can be varied. Some V_{Th}-cancelation high efficiency rectifiers with reduced forward voltage drop have been presented so far. In [94], a CMOS half wave rectifier (HWR) circuit is implemented for RFID tags. No external biasing circuit is needed for "V_{Th}" cancelation. The proposed CMOS HWR circuit achieves two properties such as, primarily it holds an internal "V_{th}" cancelation circuit, and secondly, the decoupling of parasitic capacitances is possible in the internal "V_{Th}" cancelation circuit from the input terminals. A differential "V_{Th}" cancelation approach is investigated in [95]. The gate of the transistor is actively biased by a differential mode signal. A multi-stage configuration is realized for large output voltage without degrading the PCE. In [96], an enhancement in rectenna performance in terms of output voltage is observed with a RF multi-stage CMOS rectifier. Here, self-compensation of "V_{Th}" is achieved by increasing the gate bias offset with increasing number of cascaded doubler stages. A cross-coupled differential rectifier approach is implemented for "V_{Th}" self-cancelation in [97]. Here, the output and common mode gate voltages are generated during rectification, provides an additional biasing and reduces the required turn-on voltage, effectively. A multi-stage rectifier further is employed to enhance the rectifier output voltage performance. The better performance of a voltage multiplier circuit with PMOS in terms of both PCE and output voltage is observed in [98].

The performance comparison of various diodes has been observed in [99]. The CMOS rectifier provides better conversion efficiency than all other components at low input power levels. However, the performance of a Spin

Diode is found to be suitable for rectification at ultra-low RF input power levels due to its low zero bias resistance (ZBR). The ZBR is a directly proportional to the area of the tunnel junction in the Spin Diode. However, the Spin Diode doesn't have enough non-linearity for demonstrating as a practical rectifier.

However, the limitation of Schottky diode using circuit-based approach is its higher production costs compared with the standard CMOS technology comparatively. But, the turn on voltage of CMOS rectifiers is large compared with Schottky diodes. Various approaches have been discussed to reduce the turn on voltage of the CMOS rectifier. Conversely, the drawback of these approaches involves additional circuitry to make the "V_{Th}" of the CMOS transistors low, which increases the chip fabrication cost and circuit complexity too. Besides, these CMOS transistors are more prone to thermal runaway. As an alternative to use Schottky diodes with CMOS technologies for minimizing the fabrication cost by maintaining low "V_{Th}", and these are used to enhance the performance of RF energy harvesters.

4.1 Classification of Rectifiers Configurations

Based on configuration topology, rectifiers can broadly be classified as half-wave rectifiers (HWRs) and full-wave rectifiers (FWRs). In this section, a detailed study of different configurations of rectifier circuits presented to achieve high RF-to-DC power conversion efficiency has been performed.

4.1.1 Half-Wave Rectifiers

In case of the HWR circuit, only half cycle of the input wave is considered for converting into DC. The HWRs are again classified as series HWR and shunt HWR depending on the connection of a diode with respect to the load resistance. A simple half-wave configuration is shown in Figure 7. Due to a single diode operation, an HWR configuration consumes less power which makes it suitable for low-power applications.

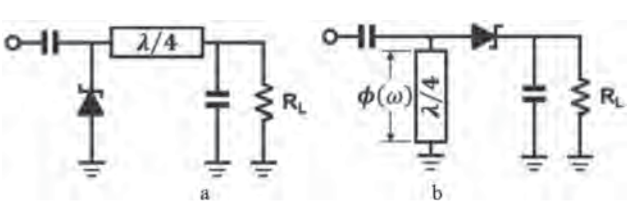

Figure 7: Half-wave rectifier (a) with shunt configuration (b) with series configuration [100]

Implementation of the HWR circuit for RF-to-DC conversion has been successfully investigated in [101]. A Wilkinson power divider with two half-wave rectifier circuits is used to enhance the rectifier performance [102]. The proposed technique is insensitive to the angle of incidence. A similar approach of power splitting and combining is investigated in [103]. This technique helps-in increasing the performance of the rectifier by avoiding power handling problems with improved sensitivity. Traditionally, the PCE of the rectifier reduces with increase in operating frequency. At higher frequencies, receiving power by the antenna reduces with small antenna dimension. The received small amount of RF power is input to the rectifier after passing through a suitable filter. However, better in rectifier performance in terms of PCE using a shunt diode HWR is observed at 35 GHz frequency in [104]. A microstrip line is connected to the rectifying diode that helps in removing the diode's imaginary impedance, thus impedance matching is easily achieved. Further, enhancement in rectifier PCE at 35 GHz frequency is noticed with a series diode HWR circuit in [105], here the proposed HWR is designed using MA4E1317 diode for conversion purpose. The maximum PCE of 81% is achieved at an input power density of 30 mW/cm^2.

In case of RFEH, when RF(AC) power is injected to the HWR, some amount of power flows to the output load (or to the output smoothing capacitor) during only half cycle (positive cycle) of RF signal due to the diode function. During the other half cycle (negative cycle), incident RF power is blocked and reflected back. However, reflected power is once absorbed by the impedance matching circuit and then released and injected again to the HWR. Impedance matching circuit and rectifier compose LC tank circuit in this case. Therefore, PCE higher than 50% can be achieved even by HWRs [106, 107]. Although, the HWR configuration consumes low-power by virtue of a single-diode operation, the power handling capability of the HWR is low. This is one of the major drawbacks of HWRs. The limitations of HWRs are overcome by using FWRs (full-wave rectifiers).

4.1.2 Full-Wave Rectifiers

In FWR, both positive and negative cycles of the input wave are considered completely for conversion into DC signals. The existing configurations of FWR circuits can be primarily categorized as a full-wave bridge rectifier, voltage doubler rectifier, Greinacher rectifier, etc. A full-wave bridge rectifier comprising of four diodes arranged in "series pairs". During each half-cycle, only two diodes are supporting for conducting current. A full-wave (FW) bridge is implemented between two dipole antennas in

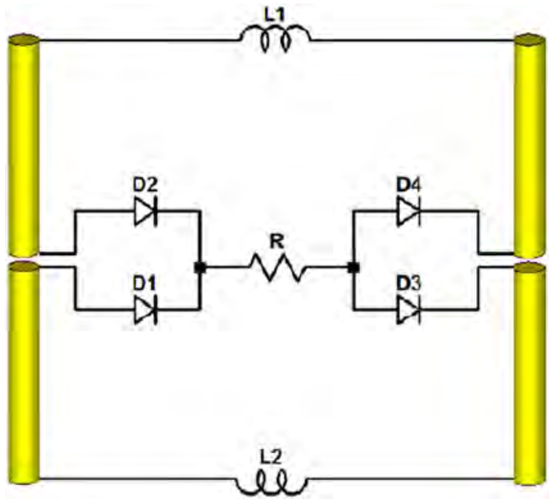

Figure 8: Full-wave rectifier configuration [108]

[108]. The corresponding circuit arrangement has been presented in Figure 8. In this FW bridge configuration, the diode pairs are fed differentially with a pair of dipole antennas, thereby, exhibiting better efficiency than an HWR configuration. Similarly, in [109], the performance of a full-wave rectifier (FWR) circuit is observed.

A full-wave bridge rectifier configuration requires four diodes which increases diode counts and associated loss. The resultant output may reduce by considering losses associated with diodes. Thus, FWR is found to be suitable at large input power density levels. Further, to satisfy biasing conditions of the FWBR rectifier, the minimum input voltage (turn-on voltage or V_{Th}) required is twice than that of an HWR due to two of its four diodes are connected in each branch of FWBR circuit [110]. By using a proper low loss impedance matching network, the minimum input voltage required can be reduces. To overcome this issue, a voltage doubler configuration is reported in the literature. A voltage doubler rectifier (VDR) is an electronic circuit that charges capacitors from the input voltage and switches these charges in a proper way to produce output voltage almost twice than that of the input.

Assume "V_{amp}" is the input signal amplitude given to the VDR circuit as shown in Figure 9. For the negative input peak, the voltage drop across C1 is "V_{amp}-V_{Th1}". Where "V_{Th1}" is the turn-on voltage of diode D1. For the positive input peak, current passes along diode D2 while diode D1 is cut-off. The voltage developed across C1 remains constant as the previous negative input signal. At the positive peak, the voltage developed across diode D1 is "$2V_{amp}$-V_{Th1}" and the voltage across the capacitor C2 is "$2V_{amp}$-V_{Th1}-V_{Th2}", where "V_{Th2}" is the turn-on

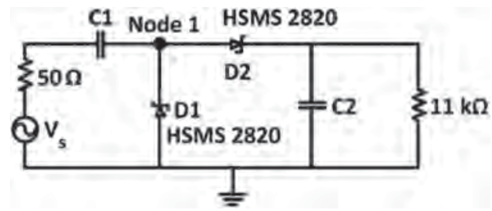

Figure 9: General voltage doubler rectifier configuration [111]

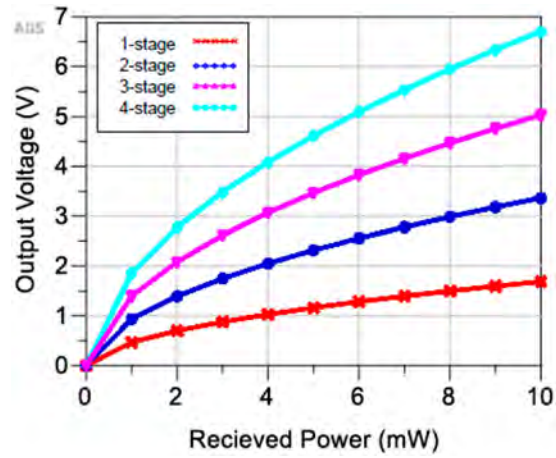

Figure 10: Effect of number of stages on to the output performance [72]

voltage of diode D2. Thus, the voltage across output of the VDR is $V_{out} = 2V_{amp}$-V_{Th1}-V_{Th2}.

Vth2 Shariati *et al.* [111] have proposed a voltage doubler rectifier circuit suitable for a dual-band rectenna system in which the designed rectifier circuit is tuned over two frequency bands such as 478–496 MHz and 852–869 MHz. The general voltage doubler topology is shown in Figure 9. A voltage doubler (VD) configuration is investigated over the broad frequency range in [54]. Jouko *et al.* [112] have implemented a VDR circuit to integrate with a dual-band antenna to achieve better rectification efficiency performance. The voltage doubler (VD) configuration provides better performance than HWR [113].

A coplanar waveguide (CPW) configuration for the rectifier design has been adopted to increase the conversion efficiency in [114]. In [95], it is observed that as the number of voltage multiplier circuits in a cascaded connection increases, the overall output voltage increased. A similar type of result is observed in [72], as shown in Figure 10.

A rectifier circuit is designed in [41] to operate over a wide range of frequencies. The wideband characteristics are obtained by four rectifier circuits that are designed

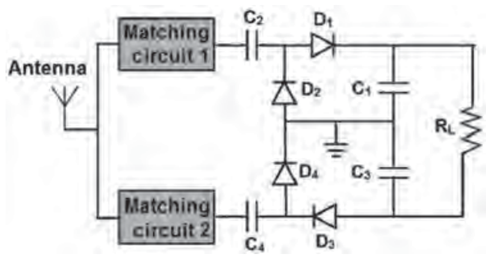

Figure 11: Greinacher rectifier configuration [116]

with non-uniform transmission lines. A differential configuration is designed using a voltage doubler rectifier to improve the conversion efficiency in addition to a stable balanced output voltage [115]. Enhancement in rectenna performance is further noticed with a Greinacher rectifier circuit (GCR) [82, 116–118]. Basically, a Greinacher rectifier circuit is equivalent to a two-stage VDR circuit arranged in a bridge formation. The equivalent circuit arrangement of a GCR is given in Figure 11. The GCR comprising of two branches with two diodes in each branch. The biasing voltage of each diode can be partially produced by the output of the previous diode. In [116], the designed rectifier circuit is suitable to operate over a wide range of frequencies (1.8–2.5 GHz). Whereas in [117], a hybrid rat-race coupler is used to provide the phase difference of 180° to the proposed Greinacher rectifier circuit.

In [119], a rectifier-booster regulator (RBR) topology is implemented. The designed RBR topology evolved from a Greinacher rectifier and a Cockcroft-Walton charge pump. This topology helps in rectifying the RF energy into DC and boosts the output voltage. The output from a Greinacher rectifier is sufficient to operate a boost converter.

4.1.3 Other Rectifier Topologies

The performance of the rectifier circuit in any type of configuration is generally depicted by the PCE of the rectifier circuit. Various techniques such as resistance compression network (RCN), adaptive rectifier circuits, etc. are adopted to decrease the sensitivity to loading conditions and hence reduces the impedance variations. One of the techniques is a resistance compression network (RCN) [120]. The compression network allows the rectifier system to appear as an approximately constant-resistance load independent of AC drive power or DC-side conditions. A dual-band RCN with reduced sensitivity is implemented in [121]. However, it is more sensitive to an impedance variation at the rectifier input compared to the RF input. The limitations in RCN are overcome by the transmission line resistance compression network (TLRCN). In the TLRCN, the input power is distributed equally into several rectifier circuits. This is advantageous in the case of a rectifier with limited power handling capability [122].

The limitation in Schottky diode is the diode switching speed which is overcome by MOSFET technology. However, the turn-on voltage required for the MOSFET device is more than the Schottky diode and also MOSFET devices are sensitive to thermal runaway.

A diode connected MOSFET configuration is investigated to for the rectenna design in [123]. Here, it is studied that the turn-on voltage of the rectifier is reduced with proposed configuration. A full-wave rectifier is implemented using this configuration for further increasing the conversion efficiency. In [124], the performance of the adaptive MOSFET is studied for wide input power range levels. An enhancement in conversion efficiency over the expanded range is observed with adaptive rectifier circuit. An adaptive rectifier circuit is designed to operate over two band of frequencies with better conversion efficiency in [125]. Besides these, it is also noticed that low turn-on voltage and large break-down voltage is also possible with an adaptive rectifier. Further, enhancement in operating range of the rectifier with suitable performance at low power levels is noticed with adaptive rectifier in [126]. A field-effect transistor (FET) is used for switching into four different modes based on the input RF power level. A rectifier with wide bandwidth is possible by an adaptive power distribution technique [127]. An enhancement in rectenna performance is noticed with a novel Graphene FET (GFET) based rectifier in [128]. Here, the proposed GFET rectifier exhibits wide impedance bandwidth in the millimeter wave range, and also provides a better conversion efficiency over high frequency ranges. A maximum conversion efficiency of 80.32% is possible for the rectenna at an input power of 2dBm. A new type of rectifier topology is implemented to achieve a low- threshold voltage and a large breakdown-voltage in [92], as shown in Figure 12. This technique reduces early breakdown problems. A single-stage Cockcroft-Walton rectifier is implemented for better performance in [47].

4.2 Performance Comparison of Rectifier Configurations

The performance of the rectifier is analysed based on its PCE. Different topologies are compared based on the existing literature. From [93], it is noticed that a single series diode (SSD) rectifier provides better results at low input power levels (< 0 dBm) and a full-wave bridge

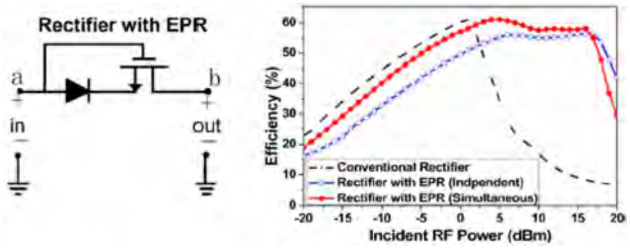

Figure 12: Modified rectifier topology for extended power range [92]

rectifier topology is suitable at high RF input power levels (> 15 dBm). Whereas the shunt diode topology is suitable for mid-range of values (between 0 and 15 dBm). In [129], it is noticed that a voltage doubler rectifier (VDR) is suitable to operate at low RF input power levels above −21 dBm. The single series topology composing of SMS7630 diode is suitable to operate above −50 dBm. The performance of SMS7630 and HSMS2860 in a single diode rectifier configuration is studied in [130]. The results show that the SMS7630 diode achieved better conversion efficiency from the input power level of −40 dBm to 5 dBm at a single band of frequency. The dual-band rectifier performance is better at power levels above −5 dBm. In [131], it is observed that less amount of input power is required to get the sufficient output power in case of a VDR configuration associated with an HSMS2850 diode compared that with an SMS7630 diode. In [132], it is noticed that more PCE is possible with the HWR circuit and more DC output voltage is possible with voltage multiplier circuits. The PCE can be enhanced by a hybrid power harvesting technique as investigated in [133]. Here, both mechanical vibration and microwave radiation are considered for harvesting purposes. Similarly, a cooperative harvesting technique is implemented by integrating two uncorrelated energy sources for increasing the rectifier PCE at low input power levels in [134]. System complexity increases with integrating uncorrelated energy sources. In [135], it is noticed that a multi-stage rectifier circuit is useful only when the applied input power to the rectifier circuit is large, as shown in Figure 13.

From Figure 13, at an input power level of −20 dB, maximum conversion efficiency and output DC voltages obtained with a single-stage rectifier circuit. As the input power level increases, the performance of both the rectifier circuit and the rectenna system increases with increasing number of rectifier stages. At 10 dBm input power level, both conversion efficiency and output voltage are maximum with a 9-stage rectifier circuit. If the input power level is low, some amount of the harvested power is absorbed by passive components in the circuit, thus the rectifier performance is inefficient with more number of rectifier stages at low input power levels. Besides this, a considerable reduction in rectifier efficiency has been noticed if the load value is too low or too high. It is also observed that a rectenna in a low-power design performs well with the minimum number of antenna elements. However, high-power design performance is good for the maximum number of antenna elements. A similar response with a multi-stage rectifier circuit is also observed with a dual-band rectenna system in [72]. In addition to the power required to be more, component losses also increase as the number of voltage multiplier stages increases [136].

The output from the rectenna using single-stage HWR is limited to a maximum of half of the breakdown voltage. Thus, the diode with a large breakdown voltage provides a better output voltage. The HWR circuit associated with SMS7630 diode achieves better results than all possible combinations at low input RF power levels. The power handling capability and complete power utilization are done by FWR circuits such as bridge rectifier, voltage doubler rectifier (VDR) and Greinacher rectifier (GRC). The VDR is suitable at a low and mid-range of RF input power levels. The VDR utilizes a complete RF input cycle and losses associated with the rectifier are low due to a limited number of diodes used for conversion.

5. INPUT RF FILTER AND IMPEDANCE MATCHING NETWORK (IMN) TOPOLOGIES

5.1 RF Filter Configurations

The functioning of the input RF filter is to block the harmonics created by a diode in the rectifying circuit and provides matching between antenna and rectifier. In a multi-band or broadband case, the input RF filter is used to allow desired frequencies through a stacked configuration. Limited literature has been reported on input RF filters in the rectenna design. In [137], a low-pass filter is integrated with two additional band stop filters (BSF) to block the second-order harmonics effectively at both frequencies. A balanced bandpass filter is designed in [138], as shown in Figure 14.

5.2 Impedance Matching Network (IMN) Configurations

5.2.1 Single-Band Matching Network

The impedance matching network (IMN) is connected between the antenna and a rectifier circuit to transfer maximum collected RF power by the antenna to the

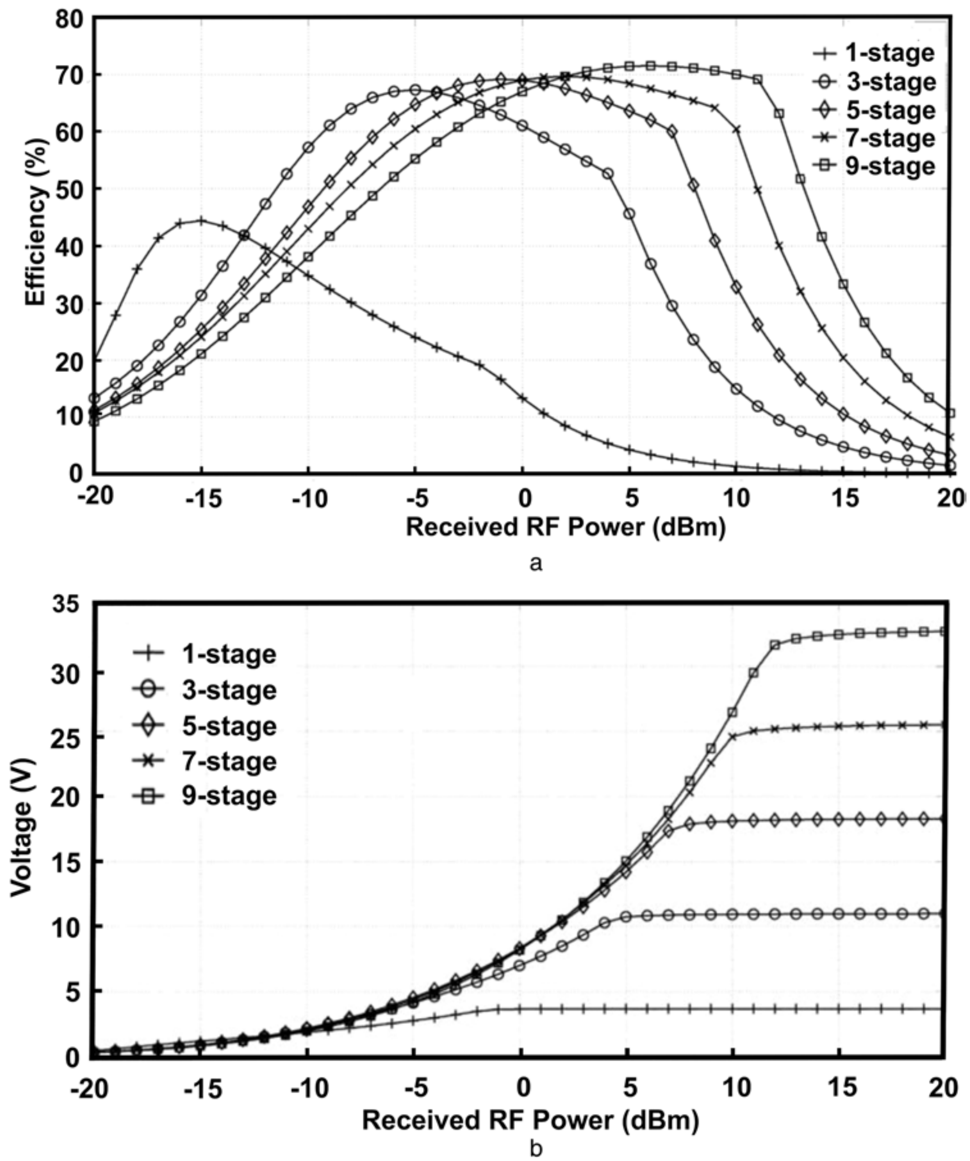

Figure 13: Performance comparison with multiple numbers of stages (a) conversion efficiency performance (b) output voltage performances [135]

rectifying circuit. Various IMN topologies have been investigated. The performance of the rectenna with a matching network (MN) shows better results as compared to rectenna without MN in [139] and this is illustrated in Figure 15 where the performance of π-type MN is observed better than L-type MN. An L-section network is implemented to achieve proper impedance matching in [140, 141]. It is easier to achieve the proper impedance matching in the case of a single band rectenna. However, it is difficult to achieve in the case of either in multi-band or broadband rectenna.

5.2.2 Multi-Band Matching Network

A multi-section dual-band matching network composed of the designed rectifier circuit is implemented in [111]. Stack of several rectennas, each one with a single band MN and associated rectifier topology is implemented to a multi-band rectenna in [66]. Stacked rectennas, in which each one with a three dual-band bandpass IMN and associated rectifier circuit is implemented for a six-band rectenna in [82, 84, 142]. A 4th order dual-band IMN is implemented using a series and parallel combination of the LC pair in [143]. A triple-band IMN is implemented using two stubs in [144]. A quad-band matching network is implemented with a series of matching networks in [145]. Each matching network is tuned to a particular resonant frequency. The performances of common matching (CM) and two-branch matching networks associated independently with a voltage octuple rectifier are investigated in [146]. In CM techniques,

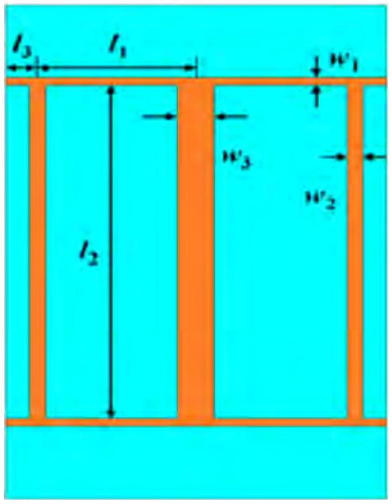

Figure 14: Band Pass Filter [138]

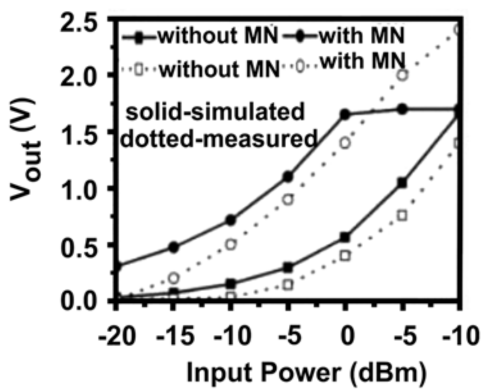

Figure 15: Measured and simulated output voltage [139]

the MN is connected between the input port and the 2-stage rectifier circuit. Whereas in TBM techniques, the total feed-line impedance of 50-Ohms is divided into two branches of 100-Ohms equally. Thus, the impedance of the two-stage rectifier circuit is matched to 100-Ohms. Better impedance matching is obtained with the TBM technique compared to the CM technique. The performance of the rectenna with a two-branch matching network shows better results as compared to a common matching network, as shown in Figure 16.

With an input RF filter, the rectenna-size gets increased which limits their applications. The rectenna holding harmonic rejection property, is well suited for the design. In [147], the rectenna itself holds harmonic rejection property. In [148], Yang *et al.* have proposed a rectenna design using the combination of aperture coupled dual-polarized patch antenna and a matching network comprises of open stub, short stub and $\lambda/4$ transmission lines avoids the usage of a filter to reject harmonic components generated from the diode. In [149], two novel feeding approaches of compact microstrip resonant cell-U

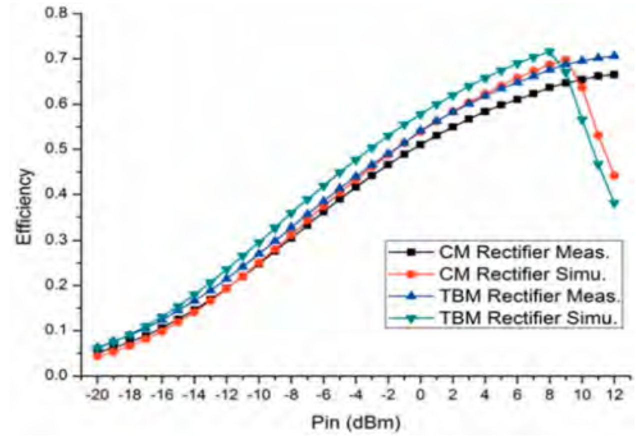

Figure 16: Performance comparison of a rectifier with two different matching topologies [146]

slot (CMRC-U) and double compact microstrip resonant cell (DCMRC) have been investigated for holding harmonic rejection features in a CPW monopole antenna. By the first approach only the third harmonic frequency is removed, and both second and third harmonics are rejected with the second approach. But, impedance bandwidth of the antenna reduces with introducing the proposed approaches.

5.3 Other Configurations

Chaoyun *et al.* [150] have implemented a broadband rectenna without MN. The proper impedance matching is achieved between the antenna and the rectifier by adjusting the feed position of the off-centre-fed-dipole (OCFD) antenna. Later on, Chaoyun *et al.* [131] have proposed a new off-centre-fed patch (OCFP) antenna design with a similar technique. In the implemented broadband design, two pairs of identical shorting pins are symmetrically loaded on the OCFP with the aim to achieve electable/flexible impedance matching for the rectenna design. A favorable matching is obtained with a short-circuit stub, a transmission line segment, and an exponential taper transformer in [151].

The impedance matching is easy to achieve in the case of a single band rectenna. However, it is difficult to realize a proper IMN in the case of a multiband rectenna. Stack of several rectennas, each rectenna is associated with an MN and the associated rectifier is found to be a suitable technique to realize a multiband rectenna.

The DC output power from the rectenna can also be increased with two techniques; RF power combining and DC power combining techniques, as shown in Figure 17 [152]. The RF power combining technique is suitable

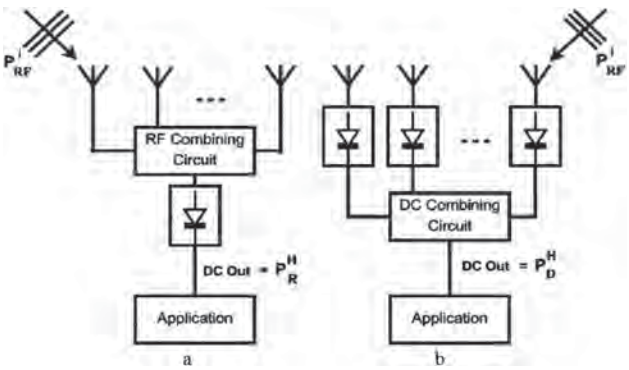

Figure 17: (a) RF power combining circuit, (b) DC combining circuit [152]

when the RF energy to be harvested by an individual antenna is low, and the combined signal can able to turn-on the diode to be used for conversion. If large power levels, received by an individual antenna, are applied to an RF power combiner, impedance-matching problems occurs. In such cases, the DC power combining technique is found suitable to combine the receiving ambient power level. In the DC power combining technique, on the other hand, the series associated rectenna array yields better performance in terms of the output voltage. However, the conversion efficiency of such series-associated rectenna array is noted to be lower than that of parallel-associated rectenna array [153]. The beamwidth is wider in case of a DC power combining approach as compared to RF power combining method.

The performance of DC combining method is observed in [154]. Here, a triple-port pixel rectenna comprising of triple-port pixel antenna and a triple-port rectifier circuit is implemented. For DC combining, three single series diode rectifier circuits are designed to connect a triple-port rectifier circuit. A comparison has been made between triple-port pixel rectenna and a single-port monopole rectenna for a comparison purpose. It is observed that by the proposed approach, an improvement in output DC power of nearly twice that of the single port monopole rectenna. The harvested ambient RF power is less at higher frequencies using a single port antenna. A frequency-dependent multi-port rectenna is implemented in [155]. Here in this, number of ports in the antenna increases with the operating frequency utilizing the same area. A single series diode rectifier is chosen for rectification. The performance of the proposed method is investigated to two frequency bands such as 900 MHz and 1800 MHz bands, simultaneously. From the performance results, it concludes that DC combing approaches enhances the overall rectenna performance. The drawback with RF combining method is narrow beamwidth, and the drawback with DC combining approach is low RF-to-DC conversion efficiency. The drawbacks in both approaches is overcome by a wideband hybrid power combing approach discussed in [156]. In the proposed approach, hybrid combining is performed to increase the antenna gain for allowing RF energy of lower power density with good RF-to-DC efficiency while broader the beamwidth for wide space coverage.

6. SOME APPLICATIONS OF RECTENNAS

The rectenna was initially designed for wireless power transmission (WPT) applications. As discussed in the introduction section, the concept of wireless energy transmission was initiated by Brown in the 1960s by integrating the antenna and rectifier in order to collect a high-frequency electromagnetic beam. Later on, applications of rectenna has been extended to wireless energy harvesting (WEH) applications. With the motivation of power transmission, rectenna applications also find in wireless sensor networks (WSN) such as in RFID Tags [157], monitoring the health condition of structures and buildings [158], etc. The rectenna also find in wearable applications [159–161].

Many of the human beings are suffering from various organ related issues in their body. For continuous monitoring the condition of these organs, sensing elements are wearing inside the human body. Due to the limitations of a conventional batteries, rectennas have now been attracted for endless powering to the sensing elements. Applications of rectenna includes to operate Head-Mountable Deep Brain Stimulation Device [162], Deep-Body Implantable Devices [163], Dosimeter Tags [164], Pacemakers [165], Skin Mimicking Gels for Continuous Glucose Monitoring [166], Deep-Tissue Implants [167], etc.

The applications of rectenna has also been expanded to many fields with increasing availability of frequency spectrum. Smart cities are the dreams of all countries in the world, and the dream of smart cities is becoming reality with the increasing high data rates, which is possible with 5G technologies. Various applications are performed in the smart city such as smart buildings, smart lightening, smart transportation, smart parking, smart agriculture, etc. In the smart cities, sensors play a key role to make the things easy to the dwellers. Now-a-days, most of the rectenna applications are found in smart cities for continuous operation of various sensors connected through internet of things (IoT).

7. SUMMARY

The detailed review of the existing literature reveals that the antenna designed for use in rectenna systems must resonate at frequencies that are mostly available in the surrounding environment. It has been observed that a single band antenna can be easily designed to achieve better impedance matching with the rectifier circuit. However, the limitation with a single band antenna is its compatibility in all geographical areas due to their unique frequency of operation and less capturing power by the antenna. On the other hand, broadband antennas tend to cover all the frequencies available in the band of resonating frequencies. However, due to their wide impedance bandwidth, the gain of the antenna is low. Besides this, it is difficult to achieve proper impedance matching between the antenna and the rectifying circuit due to the wide impedance bandwidth. Thus, the conversion efficiency of the antenna reduces. Broadband antennas mostly suffer from either low gain or minimal power conversion efficiency. The limitations in single and broadband antennas have been overcome by a multi-band antenna. The multi-band antennas comparatively achieve better RF-to-DC power conversion efficiency and high gain, but at the cost of larger antenna dimensions.

In the case of rectifiers, Schottky diodes have been preferred for the rectification of RF signals to DC power. Usually, SMS7630 diode families are chosen when the received RF signal has low power levels. Similarly, HSMS28xx family diodes are used for high input RF power levels.

Out of different rectifier topologies, the half-wave rectifiers (series or shunt) circuit consumes less power. However, due to the single diode operation of the half-wave rectifier (HWR), the power handling capability is low. For this reason, HWR is best suited for low input RF power levels. The limitation of HWR is overcome by an FW bridge rectifier. The bridge rectifier utilizes a complete cycle of the input RF power. However, a large input RF power is required to satisfy the biasing conditions of the bridge rectifier circuit. Additionally, the use of multiple diodes introduces losses in the bridge rectifier. Greinacher rectifier (GR) circuits improve the power handling capability of the rectifier unit. Additionally, they require comparatively low biasing voltage. However, losses introduced are more since they involve four diodes as in the case of a bridge rectifier. On the other hand, the voltage doubler rectifier (VDR) circuit is mostly adopted rectifying circuit, operated efficiently at low as well as for moderate input RF power levels.

Another technique found to be used in designing rectifiers is the voltage multiplier circuits. In this technique, multiple stages of rectifier circuits are designed to increase the overall rectenna output voltage. The circuit topology can be used efficiently for both low as well high input power levels. The voltage multiplier configuration is effective for low input power level operation when output load resistance of the rectifier (voltage multiplier) is high. Generally, when output loading resistance of the rectifier is high, input impedance of the rectifier also becomes high and impedance matching with antenna having low characteristic impedance becomes difficult. Because RF input terminals of each stage of the voltage multiplier are connected in parallel, input impedance of the voltage multiplier is effectively lowered as compared with the single stage rectifier. This results in the ease of the impedance matching. Thus, overall efficiency can be improved.

In recent years, several configurations of rectennas are designed where the antenna circuits have been equipped with harmonic rejection property as well as impedance tuning property. This technique helps in avoiding the usage of a separate RF filter and matching networks.

The most adopted technique to increase the gain of the antenna is by introducing multi-layer circuit topology. A VDR circuit is useful to achieve high conversion efficiency and output voltage. Fractal based geometries are best suited for achieving antenna miniaturization.

Two techniques that are adopted to increase the rectenna performance, they are RF power combining and DC power combining techniques. The RF power combining technique is efficient when the input RF power levels low in density. The DC power combining technique is useful when the RF input power levels high in density.

Various techniques that are used to achieve CP are compared in Table 4. A wide AR bandwidth is noticed in [15, 74]. However, in [15] aperture feeding technique is used which increases the design complexity. A truncated corner technique is found to be a suitable technique to achieve CP characteristics.

Various techniques they are associated with an air gap are compared in Table 5. The minimal variation in gain is noticed in all techniques. However, the impedance bandwidth is varied considerably. In [46], a wide impedance bandwidth is achieved with a reflecting surface associated with an air-gap. It is concluded that a multi-layer structure is suitable to obtain high gain in antenna design.

Table 4: Comparison of various techniques to achieve circular polarization (CP) characteristics

Technique	AR bandwidth (GHz)	Ref.
Termination Gap	5.58–5.98	[10]
	5.58–5.98	[11]
	5.58–5.98	[12]
Unbalanced circular slots	2.445–2.475	[13]
Dual-feeding	2.025–2.75	[14]
Peripheral cuts	2.431–2.460	[15]
Symmetric-strips along the diagonal directions	2.54–2.605	[16]
Shorted section	0.87–0.97	[17]
Square patch with a triangle slot etched on the ground plane	2.0–3.0	[18]
U-slot and truncated corners	2.44–2.46	[19]
CPW back-fed	5.775–5.825	[20]
Truncated corners with rotated L-slots	5.3–5.7	[82]
	6.65–6.95	
	7.0–7.4	
Truncated Corners	2.18–2.56	[83]
	3.21–3.6	
	4.77–5.35	
	1.25–2.15	[84]
	2.35–2.95	

Table 5: Comparison of various techniques for improving the antenna gain and bandwidth performance

Technique	Maximum Gain (dBi)	Bandwidth(GHz)	Ref.
Air-gap with aperture coupling	7.70	2.25–2.75	[18]
Air-gap with aperture coupling	7.82	1.762–1.878	[74]
		2.348–2.493	
Air-gap with stacked Configuration	9.1	0.877–0.988	[28]
	6.69	5.15–5.90	[29]
Air-gap with Dual probes	8.4	2.35–2.55	[32]
Stacked configuration	9.2	2.9–5.2	[30]
Air gap with a Reflecting Plane	8.6	2.4–2.5	[31]
	10.0	2.2–2.6	[53]
	8.7	1.67–6.7	[55]
Differential Feeding with a Reflector	9.2	1.99–2.08	[73]
		2.36–2.65	
		3.5–3.8	
Differential Feeding	5.47	4.3–5.0	[33]
Differential fed antenna array	14.29	5.77–5.84	[34]
Perfect electric conductor wallswith parasitic patches	8.1	2.37–2.53	[35]

Different miniaturization techniques are listed and compared in Table 6. As the size reduces, the gain of the antenna reduced with Meandered line techniques is noticed. The low gain is observed with Hilbert geometry. Sierpinski fractal geometry provides the better gain performance of the antenna with a small dimension in [71]. Fractal based geometry is the most adopted technique to achieve compactness.

The performance of different rectifier topologies is compared in Table 7. The HWR circuit shows better performance with a single band of operation. The VDR configuration is appropriate for multiband of operation.

The performance of different impedance matching network (IMN) topologies is compared in Table 8. It is easy to achieve impedance matching at a single band operating frequency. A π-section IMN is found to be suitable at a single band operating frequency. From the reported literature, it is summarized that a multi-band IMN is suitable at multi-band frequencies than multiple single-band IMNs. But, it is difficult to realize a multi-band IM network with proper impedance matching. A stack of several branch rectennas is the most adopted IMN technique. In this, each branch comprises of dual-band impedance matching network and a VD rectifier.

Table 6: Various antenna miniaturization techniques

Technique	Dimension (mm)	Volume (mm^3)	Max. Gain (dBi)	Ref.
Koch-Fractal Geometry	$45\times45\times0.8$	1620.0	3.9	[44]
Fractal geometry	$35\times35\times2.5$	3062.5	−0.19	[45]
Fractal geometry	$38\times38\times3.2$	4620.8	3.1	[46]
Sierpinski fractal	$46.676\times53.038\times1.6$	3960.9	2.7	[78]
Hilbert Fractal	$80\times82\times1.52$	9971.2	2.17	[52]
Sierpinski fractal	$40\times40\times1.6$	2560.0	6.5	[80]
Meandered Line	$60\times60\times4.6$	16560.0	3.78	[48]
	$40\times30\times0.8$	960.0	1.91	[79]
PIFA	$3.14\times5.2\times3.1$	243.35	−15.37	[51]
PIFA Meandering strips	$10\times10\times2.54$	254	−7.0	[64]
Circinal geometry	$37\times35\times1.6$	2072.0	1.85	[50]
Multi-bending Curve	$35\times37\times1.6$	2072.0	2.13	[81]
Oscillating tapered slot	$55\times40\times1.6$	2240.0	3.0	[61]
Slotted patch and ground	$35\times50\times1.5$	2625.0	3.6	[62]
Monopole antenna with two L-shaped stubs	$47\times46.75\times0.76$	1669.9	4.2	[63]

Table 7: Comparison of different rectifier topologies

Topology	Max. RF-to-DC conversion efficiency $<$ 50%	Max. RF-to-DC conversion efficiency $>$ 50%
HWR	[65] [74] [87]	[10] [12] [76] [88]
Bridge Rectifier	–	[108] [109]
VDR	[41]	[13] [54] [112]
GRC	–	[69] [81] [116]
Differential Rectifier	[115]	–
Voltage Multiplier	[72]	–

Table 8: Comparison of different IMN topologies

Technique	Frequency bands	Ref.
L-section and π-section	Single	[139]
L-section	Single	[140]
L-section	Single	[141]
Dual-band IMN with series and parallel combination of the LC pair	Dual-band	[143]
Multi-section dual-band	Dual-band	[111]
Stack of several rectennas	Quad-band	[66]
	Six-band	[82]
	Six-band	[84]
	Six-band	[142]

8. CONCLUSION

The research on rectenna targeting to CP, gain, miniaturization, RF-to-DC power conversion efficiency and impedance matching are reviewed and analysed chronologically. The primary aim of this review is to illustrate the novel research that has been carried out since invention in these above specific areas. This article helps current/future researchers who are involving with Rectenna to find auspicious attentiveness by finding out the research gap.

It is clear that the rectenna has the ability to take up CP, gain, antenna miniaturization, RF-to-DC power conversion efficiency, and impedance matching by means of different approaches. Generally it can be concluded that (i) the circular polarization is mainly controlled by feeding approaches (single mode or dual mode), truncated corners of radiator, slot-loaded radiator; (ii) the gain of the antenna used in designing a rectenna usually rely on dimension of the antenna, type of feeding technique, and type of antenna configuration; (iii) the miniaturization is possible for the antenna with different Fractal based geometries, meandered line concepts, etc. (iv) usually the RF-to-DC power conversion efficiency depends on the RF input power level and a rectifier circuit with a suitable diode is considered and (v) research on impedance matching network is very less, which need to be improved for broadband rectenna especially.

From a perspective point of view, the authors recommendations are (i) for CP, truncated corners and slotted radiators could be a better alternative, (ii) for gain, reflector/ multi-layer techniques are best possible ways for increasing the gain, (iii) modified form of Hilbert shapes and meander line approaches are utilized in antenna miniaturization, (iv) power distributed to multiple paths could be useful in the case of multi-band and broadband approaches, (v) a voltage doubler rectifier could be the better alternative in power conversion.

In the RFEH approach, the direction of the incident wave is unknown that is the position of the source is not clear or multiple number of transmitters exists at various locations. Only few works have been reported on rectennas with wide angular coverage and high gain antenna for increasing the harvesting power at low input power levels. There is a need to find an effective solution in a better way for collecting the RF wave incident from any of its direction.

Most of the rectennas reported in the existing literature have tested in the anechoic chamber using dedicated source. Only limited number of rectenna system configurations have been tested in the realistic environment. The performance of the rectenna is studied for static RF input power levels most of the time. But in the realistic environment, ambient energy is not stable. There is a necessity to demonstrate the rectennas in the realistic environment, where the exact performance can be known with changing input power levels.

The authors have reviewed this article to the best of their level in incorporating novel contributions, still, the authors do make an apology to the researcher community if any relevant article(s) is missed unknowingly.

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REFERENCES

1. W. Saeed, N. Shoaib, H. M. Cheema, and M. U. Khan, “RF energy harvesting for ubiquitous, zero power wireless sensors,” *Int. J. Antennas Prop*, Vol. 2018, pp. 16, 2018. Article ID 8903139.
2. W. C. Brown, “The microwave powered helicopter,” *J. Microw. Power*, Vol. 1, no. 1, pp. 1–20, Jun. 2016. doi:10.1080/00222739.1966.11688626
3. W. C. Brown, *et al.* “Microwave to dc converter,” US Patent US3434678A, filed 05 May 1965 and issued 25 March 1969.
4. H. Jabbar, Y. S. Song, and T. T. Jeong, “RF energy harvesting system and circuits for charging of mobile devices,” *IEEE Trans. Consumer Electron*, Vol. 56, no. 1, pp. 247–253, 2010. doi:10.1109/TCE.2010.5439152
5. A. Nimo, D. Grgic, and L. M. Reindl, “Optimization of passive low power wireless electromagnetic energy harvesters,” *Sensors*, Vol. 12, pp. 13636–13663, 2012. doi:10.3390/s121013636
6. Z. Zakaria, *et al.*, “Current developments of RF energy harvesting system for wireless sensor networks,” *Advances in Information Sciences and Service Sciences (AISS*, Vol. 5, no. 11, pp. 328–339, June 2013. doi:10.4156/aiss.vol5.issue11.39
7. E. Donchev, *et al.*, “The rectenna device: from theory to practice (a review),” *MRS Energy & Sustainability*, Vol. 1, pp. 1–34, 2014. doi:10.1557/mre.2014.6
8. L. K. Divakaran, D. D. Krishna, and Nasimuddin, “RF energy harvesting systems: an overview and design

issues," *Int J RF Microw Comput Aided Eng*, Vol. 29, no. 1, pp. 1–15, 2019. doi:10.1002/mmce.21633

9. M. Cansiz, D. Altinel, and G. K. Kurt, "Efficiency in RF energy harvesting systems: a comprehensive review," *Energy*, Vol. 174, pp. 292–309, May 2019. doi:10.1016/j.energy.2019.02.100
10. B. Strassner, and K. Chang, "5.8-GHz circularly polarized rectifying antenna for wireless microwave power transmission," *IEEE Trans. Microw. Theory Techn*, Vol. 50, no. 8, pp. 1870–1876, Aug. 2002. doi:10.1109/TMTT.2002.801312
11. B. Strassner, and K. Chang, "5.8-GHz circularly polarized dual-rhombic-loop traveling-wave rectifying antenna for low power-density wireless power transmission applications," *IEEE Trans. Microw. Theory Techn*, Vol. 51, no. 5, pp. 1548–1155, 2003. doi:10.1109/TMTT.2003.810137
12. B. Strassner, and K. Chang, "Highly efficient C-band circularly polarized rectifying antenna array for wireless microwave power transmission," *IEEE Trans. Antennas Propag*, Vol. 51, no. 6, pp. 1347–1356, June 2003. doi:10.1109/TAP.2003.812252
13. T. C. Yo, C. M. Lee, C. M. Hsu, and C. H. Luo, "Compact circularly polarized rectenna with unbalanced circular slots," *IEEE Trans. Antennas Propag*, Vol. 56, pp. 882–886, 2008. doi:10.1109/TAP.2008.916956
14. Z. Harouni, L. Cirio, L. Osman, A. Gharsallah, and O. Picon, "A dual circularly polarized 2.45-ghz rectenna for wireless power transmission," *IEEE Antennas Wireless Propag. Lett*, Vol. 10, pp. 306–309, Apr. 2011. doi:10.1109/LAWP.2011.2141973
15. F. J. Huang, T. C. Yo, C. M. Lee, and C. H. Luo, "Design of circular polarization antenna with harmonic suppression for rectenna application," *IEEE Antennas Wireless Propag. Lett*, Vol. 11, pp. 592–595, May 2012. doi:10.1109/LAWP.2012.2201437
16. S. B. Vignesh, Nasimuddin, and A.Alphones, "Circularly polarized strips integrated microstrip antenna for energy harvesting applications," *Microw. Opt. Technol. Lett*, Vol. 58, no. 5, pp. 1044–1049, May 2016. doi:10.1002/mop.29721
17. S. Ghosh, "Design and testing of rectifying antenna for RF energy scavenging in GSM 900 band," *Int. J. Comp. Appli*, Vol. 39, no. 1, pp. 36–44, Jan. 2017.
18. S. Ahmed, Z. Zakaria, M. N. Husain, I. M. Ibrahim, and A. Alhegazi, "Efficient feeding geometries for rectenna design at 2.45 GHz," *Electron. Lett*, Vol. 53, pp. 1585–1587, Nov. 2017. doi:10.1049/el.2017.2657
19. N. Zainol, Z. Zakaria, M. Abu, and M. M. Yunus, "A 2.45 GHz harmonic suppression rectangular patch antenna with circular polarization for wireless power transfer application," IETE J," *Research*, Vol. 64, no. 3, pp. 310–316, Jan. 2018.
20. Y. Liu, K. Huang, Y. Yang, and B. Zhang, "A low-profile lightweight circularly polarized rectenna array based on coplanar waveguide," *IEEE Antennas Wireless Propag. Lett*, Vol. 17, no. 9, pp. 1659–1663, Sept. 2018. doi:10.1109/LAWP.2018.2861938
21. K. T. Chandrasekaran, N. Nasimuddin, A. Alphones, and M. F. Karim, "Compact circularly polarized beam-switching wireless power transfer system for ambient energy harvesting applications," *Int J RF Microw Comput Aided Eng*, Vol. 29, no. 1, pp. 1–10, 2019. doi:10.1002/mmce.21642
22. S. Ladan, A. B. Guntupalli, and K. Wu, "A high-efficiency 24 GHz rectenna development towards millimeter-wave energy harvesting and wireless power transmission," *IEEE Trans. Circuits Syst. I, Reg. Papers.*, Vol. 61, pp. 3358–3366, 2014. doi:10.1109/TCSI.2014.2338616
23. H. Sun, and W. Geyi, "A new rectenna with all-polarization-receiving capability for wireless power transmission," *IEEE Antennas Wireless Propag. Lett*, Vol. 15, pp. 814–817, 2016. doi:10.1109/LAWP.2015.2476345
24. J. H. Chou, D. B. Lin, K. L. Weng, and H. J. Li, "All polarization receiving rectenna with harmonic rejection property for wireless power transmission," *IEEE Trans. Antennas Propag*, Vol. 62, no. 10, pp. 5242–5249, Oct. 2014. doi:10.1109/TAP.2014.2340895
25. W. Haboubi, "An efficient dual-circularly polarized rectenna for RF energy harvesting in the 2.45 GHz ISM band," *Progress In Electromagnetics Research*, Vol. 148, pp. 31–39, 2014. doi:10.2528/PIER14031103
26. T. S. Almoneef, F. Erkmen, and O. M. Ramahi, "Harvesting the energy of multi-polarized electromagnetic waves," *Scientific Reports*, Vol. 7, no. 1, pp. 1–14, Nov. 2017.
27. S. S. Vinnakota, R. Kumari, and B. Majumder, "Dual-polarized high gain resonant cavity antenna for radio frequency energy harvesting," *Int J RFMiCAE*, Vol. 29, no. 12, pp. 1–12, Dec. 2019.
28. M. Arrawatia, M.S. Baghini, G. Kumar, "RF energy harvesting system from cell towers in 900 MHz band," 2011, pp. 1–5.
29. A. A. Masius, Y. C. Wong, and K. T. Lau, "Miniature high gain slot-fed rectangular dielectric resonator antenna for IoT RF energy harvesting," *AEU-Int. J. Electron. C*, Vol. 85, pp. 39–46, 2018. doi:10.1016/j.aeue.2017.12.023
30. W. J. Sun, W. W. Yang, P. Chu, and J. X. Chen, "A wideband stacked dielectric resonator antenna for 5G applications," *Int J RF Microw Comput Aided Eng*, Vol. 29, no. 10, pp. 1–6, 2019.

31. H. Sun, Y. X. Guo, M. He, and Z. Zhong, "Design of a high-efficiency 2.45-GHz rectenna for low-input-power energy harvesting," *IEEE Antennas Wireless Propag. Lett*, Vol. 11, pp. 929–932, 2012. doi:10.1109/LAWP.2012.2212232

32. C. Phongcharoenpanich, and K. Boonying, "A 2.4-GHz dual polarized suspended square plate rectenna with inserted annular rectangular ring slot," *Int J RF Microw Comput Aided Eng*, Vol. 26, no. 1, pp. 164–173, Oct. 2015.

33. H. Sun, "An enhanced rectenna using differentially-fed rectifier for wireless power transmission," *IEEE Antennas Wireless Propag. Lett*, Vol. 15, pp. 32–35, 2016.

34. D. Kumar, and K. Chaudhary, "Design of an improved differentially fed antenna array for rf energy harvesting," *IETE J. Research*, 1–7, 2018. doi:10.1080/03772063.2018.1488628

35. G. Zheng, K. Dang, B. Sun, and J. Zhang, "Design of perfect electrical conductor wall-loaded 2.45 GHz high-efficiency rectenna," *Int J RF Microw Comput Aided Eng*, Vol. 29, no. 3, pp. 1–8, Mar. 2019. doi:10.1002/mmce.21604

36. Y. J. Ren, and K. Chang, "5.8-GHz circularly polarized dual-diode rectenna and rectenna array for microwave power transmission," *IEEE Trans. Microw. Theory Techn*, Vol. 54, no. 4, pp. 1495–1502, Apr. 2006. doi:10.1109/TMTT.2006.871362

37. C. Yu, F. Tan, and C. Liu, "A C-band microwave rectenna using aperture-coupled antenna array and novel class-F rectifier with cavity," *J. Electromagn. Waves Appl*, Vol. 29, pp. 977–991, 2015. doi:10.1080/09205071.2015.1018394

38. W. T. Sethi, H. Vettikalladi, H. Fathallah, and M. Himdi, "Optimising an antenna array at 1550 nm band," *Micro & Nano Lett*, Vol. 11, no. 11, pp. 779–782, 2016. doi:10.1049/mnl.2016.0493

39. M. Singh, S. Agrawal, and M. S. Parihar, "Design of a rectenna system for GSM-900 band using novel broadside 2×1 array antenna," *J. Engg*, Vol. 2017, no. 6, pp. 232–236, 2017.

40. H. Sun, and W. Geyi, "A new rectenna using beamwidth-enhanced antenna array for RF power harvesting applications," *IEEE Antennas Wireless Propag. Lett*, Vol. 16, pp. 1451–1454, 2017. doi:10.1109/LAWP.2016.2642124

41. H. Mahfoudi, M. Tellache, and H. Takhedmit, "A wide-band rectifier array on dual-polarized differential-feed fractal slotted ground antenna for RF energy harvesting," *Int J RF Microw Comput Aided Engg*, Vol. 29, no. 8, pp. 1–9, Aug. 2019.

42. Y. Y. Hu, S. Sun, H. Xu, and H. Sun, "Grid-array rectenna with wide angle coverage for effectively harvesting RF energy of low power density," *IEEE Trans. Microw. Theory Techn*, Vol. 67, no. 1, pp. 402–413, Jan. 2019.

43. S. Ladan, N. Ghassemi, A. Ghiotto, and K. Wu, "Highly efficient compact rectenna for wireless energy harvesting application," *IEEE Microw. Mag*, Vol. 14, pp. 117–122, 2013. doi:10.1109/MMM.2012.2226629

44. M. Zeng, A. S. Andrenko, X. Liu, Z. Li, and H. Z. Tan, "A compact fractal loop rectenna for RF energy harvesting," *IEEE Antennas Wireless Propag. Lett*, Vol. 16, pp. 2424–2427, 2017. doi:10.1109/LAWP.2017.2722460

45. E. L. Chuma, L. D. L. T. Rodriguez, Y. Iano, L. L. B. Roger, and M. A. Sanchez-Soriano, "Compact rectenna based on a fractal geometry with a high conversion energy efficiency per area," *IET Microw. Antennas Propag*, Vol. 12, pp. 173–178, 2018. doi:10.1049/iet-map.2016.1150

46. Y. Shi, J. Jing, Y. Fan, L. Yang, and M. Wang, "Design of a novel compact and efficient rectenna for Wi-Fi energy harvesting," *Progr. Electromagn. Res. C*, Vol. 83, pp. 57–70, 2018. doi:10.2528/PIERC18012803

47. 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. 35857–35866, 2018. doi:10.1109/ACCESS.2018.2848907

48. K. Celik, and E. Kurt, "A novel meander line integrated E-shaped rectenna for energy harvesting applications," *Int J RF Microw Comput Aided Eng*, Vol. 29, no. 1, pp. 1–10, Jan. 2019. doi:10.1002/mmce.21627

49. A. Okba, A. Takacs, and H. Aubert, "Compact flat dipole rectenna for IoT applications," *Progr. Electromagn. Res. C*, Vol. 87, pp. 39–49, 2018. doi:10.2528/PIERC18071604

50. M. Wang, L. Yang, Y. Fan, M. Shen, Y. Li, and Y. Shi, "A compact omnidirectional dual-circinal rectenna for 2.45 GHz wireless power transfer," *Int J RF Microw Comput Aided Eng*, Vol. 29, no. 1, pp. 1–7, Jan. 2019.

51. A. Abdi, and H. Aliakbarian, ""A miniaturized UHF-band rectenna for power transmission to deep-body implantable devices," Cardiovascular devices and systems," *IEEE J. Translational Eng. in Health and Medicine*, Vol. 7, pp. 1–11, 2019. doi:10.1109/JTEHM.2019.2910102

52. M. Palandoken, and C. Gocen, "A modified Hilbert fractal resonator based rectenna design for GSM900 band RF energy harvesting applications," *Int J RF Microw Comput Aided Eng*, Vol. 29, no. 1, pp. 1–8, Jan. 2019.

53. M. J. Nie, X. X. Yang, G. N. Tan, and B. Han, "A compact 2.45-GHz broadband rectenna using grounded coplanar waveguide," *IEEE Antennas Wireless Propag. Lett*, Vol. 14, pp. 986–989, Apr. 2015. doi:10.1109/LAWP.2015.2388789

54. M. Arrawatia, M. S. Baghini, and G. Kumar, "Broadband bent triangular omnidirectional antenna for RF energy

harvesting," *IEEE Antennas Wireless Propag. Lett*, Vol. 15, pp. 36–39, 2016.

55. S. Agrawal, R. D. Gupta, M. S. Parihar, and P. N. Kondekar, "Wideband high gain dielectric resonator antenna for RF energy harvesting application," *AEU-Int. J. Electron. C*, Vol. 78, pp. 24–31, May 2017. doi:10.1016/j.aeue.2017.05.018

56. S. Agrawal, M. S. Parihar, and P. N. Kondekar, "Broadband rectenna for radio frequency energy harvesting application," IETE J," *Research*, Vol. 64, no. 3, pp. 347–353, Jan. 2018.

57. X. Bai, J. W. Zhang, L. J. Xu, and B. H. Zhao, "A broadband CPW fractal antenna for RF energy harvesting," *ACES J*, Vol. 33, no. 5, pp. 482–487, May 2018.

58. N. Saranya, and T. Kesavamurthy, "Design and performance analysis of broadband rectenna for an efficient RF energy harvesting application," *Int J RF Microw Comput Aided Eng*, Vol. 29, no. 21628, pp. 1–12, 2019.

59. H. Kumar, M. Arrawatia, and G. Kumar, "Broadband planar log-periodic dipole array antenna based RF-energy harvesting system," IETE J," *Research*, Vol. 65, no. 1, pp. 39–43, Dec. 2017.

60. N. H. Nguyen, *et al*., "A novel wideband circularly polarized antenna for RF energy harvesting in wireless sensor nodes," *Int. J. Antennas Propag*, Vol. 2018, pp. 1–9, 2018. ID 1692018. doi:10.1155/2018/1692018

61. Y. Shi, J. Jing, Y. Fan, L. Yang, J. Pang, and M. Wang, "Efficient RF energy harvest with a novel broadband Vivaldi rectenna," *Microw. Opt. Technol. Lett*, Vol. 60, pp. 2420–2425, 2018.

62. Y. Shi, Y. Fan, Y. Li, L. Yang, and M. Wang, "An efficient broadband slotted rectenna for wireless power transfer at LTE band," *IEEE Trans. Antennas Propag*, Vol. 67, no. 2, pp. 814–822, Feb. 2019. doi:10.1109/TAP.2018.2882632

63. O. M. A. Dardeer, H. A. Elsadek, and E. A. Abdallah. "Compact broadband rectenna for harvesting RF energy in WLAN and WiMAX applications," 2019 Int. Conf. on Innovative Trends in Comp. Eng. (ITCE'2019), Aswan, Egypt, 2019, pp. 292-296.

64. F. J. Huang, C. M. Lee, C. L. Chang, L. K. Chen, T. C. Yo, and C. H. Luo, "Rectenna application of miniaturized implantable antenna design for triple-band biotelemetry communication," *IEEE Trans. Antennas Propag*, Vol. 59, pp. 2646–2653, 2011. doi:10.1109/TAP.2011.2152317

65. K. Niotaki, S. Kim, S. Jeong, A. Collado, A. Georgiadis, and M. M. Tentzeris, "A compact dual-band rectenna using slot-loaded dual band folded dipole antenna," *IEEE Antennas Wireless Propag. Lett*, Vol. 12, pp. 1634–1637, 2013. doi:10.1109/LAWP.2013.2294200

66. V. Kuhn, C. Lahuec, F. Seguin, and C. Person, "A multi-band stacked RF energy harvester with RF-to-DC efficiency up to 84%," *IEEE Trans. Microw. Theory Techn*, Vol. 63, no. 5, pp. 1768–1778, May 2015. doi:10.1109/TMTT.2015.2416233

67. S. Agrawal, M. S. Parihar, and P. N. Kondekar, "A dual-band rectenna using broadband DRA loaded with slot," *Int. J. Microw. Wireless Technologies*, 59–66, February 2018. doi:10.1017/S1759078717001234

68. S. Shen, C. Y. Chiu, and R. D. Murch, "A dual-port triple-band L-probe microstrip patch rectenna for ambient RF energy harvesting," *IEEE Antennas Wireless Propag. Lett*, Vol. 16, pp. 3071–3074, 2017. doi:10.1109/LAWP.2017.2761397

69. M. Zeng, Z. Li, A. S. Andrenko, Y. Zeng, and H. Z. Tan, "A compact dual-band rectenna for GSM 900 and GSM 1800 energy harvesting," *Int. J. Antennas Propag*, Vol. 2018, pp. 1–9, 2018. Article ID 4781465. doi:10.1155/2018/4781465

70. V. Palazzi, *et al*., "A novel ultra-light weight multiband rectenna on paper for RF energy harvesting in the next generation LTE bands," *IEEE Trans. Microw. Theory Techn*, Vol. 66, no. 1, pp. 366–379, Jan. 2018. doi:10.1109/TMTT.2017.2721399

71. A. Khemar, A. Kacha, H. Takhedmit, and G. Abib, "Design and experiments of a dual-band rectenna for ambient RF energy harvesting in urban environments," *IET Microw. Antennas Propag*, Vol. 12, no. 1, pp. 49–55, 2018. doi:10.1049/iet-map.2016.1040

72. O. Amjad, S. W. Munir, S. T. Imeci, and A. O. Ercan, "Design and implementation of dual band microstrip patch antenna for WLAN energy harvesting system," *ACES J*, Vol. 33, no. 7, pp. 746–751, Jul. 2018.

73. S. Chandravanshi, S. S. Sarma, and M. J. Akhtar, "Design of triple band differential rectenna for RF energy harvesting," *IEEE Trans. Antennas Propag*, Vol. 66, no. 6, pp. 2716–2726, Jun. 2018. doi:10.1109/TAP.2018.2819699

74. N. Hassan, *et al*., "Design of dual-band microstrip patch antenna with right-angle triangular aperture slot for energy transfer application," *Int J RF Microw Comput Aided Eng*, Vol. 29, no. 1, pp. 1–11, Jan. 2019. doi:10.1002/mmce.21666

75. H. Sun, Y. X. Guo, M. He, and Z. Zhong, "A dual-band rectenna using broadband Yagi antenna array for ambient RF power harvesting," *IEEE Antennas Wireless Propag. Lett*, Vol. 12, pp. 918–921, 2013. doi:10.1109/LAWP.2013.2272873

76. L. Zhu, J. Zhang, W. Han, L. Xu, and X. Bai, "A novel RF energy harvesting cube based on air dielectric antenna arrays," *Int J RF Microw Comput Aided Eng*, Vol. 29, no. 1, pp. 1–7, Jan. 2019.

77. F. S. M. Noor, Z. Zakaria, H. Lago, and M. A. M. Said, "Dual-band aperture-coupled rectenna for radio frequency energy harvesting," *Int J RF Microw Comput Aided Eng*, Vol. 29, no. 1, pp. 1–9, Jan. 2019.

78. S. Shrestha, S. R. Lee, and D. Y. Choi, "A new fractal-based miniaturized dual band patch antenna for RF energy harvesting," *Int. J. Antennas Propag*, Vol. 2014, pp. 1–9, 2014, Article ID 805052. doi:10.1155/2014/805052

79. D. K. Ho, V. D. Ngo, I. Kharrat, T. P. Vuong, Q. C. Nguyen, and M. T. Le, "A novel dual-band rectenna for ambient RF energy harvesting at GSM 900 MHz and 1800MHz," *Advances in Science, Technology and Engineering Systems Journal*, Vol. 2, no. 3, pp. 612–616, 2017. doi:10.25046/aj020378

80. N. Singh, B. K. Kanaujia, M. T. Beg, M. Siddique, S. Kumar, and M. K. Khandelwal, "A dual band rectifying antenna for RF energy harvesting," *J. Computational Electron*, Vol. 17, pp. 1748–1755, 2018. doi:10.1007/s10825-018-1241-6

81. M. Wang, Y. Fan, L. Yang, Y. Li, J. Feng, and Y. Shi, "Compact dual-band rectenna for RF energy harvest based on a tree-like antenna," *IET Microw. Antennas Propag*, Vol. 13, no. 9, pp. 1350–1357, 2019. doi:10.1049/iet-map.2018.5704

82. N. Singh, B. K. Kanaujia, M. T. Beg, M. Siddique, T. Khan, and S. Kumar, "A dual polarized multiband rectenna for RF energy harvesting," *AEU-Int. J. Electron. C*, Vol. 93, pp. 123–131, 2018. doi:10.1016/j.aeue.2018.06.020

83. N. Singh, B. K. Kanaujia, M. T. Beg, M. Siddique, and S. Kumar, "A triple band circularly polarized rectenna for RF energy harvesting," *Electromag*, 1–10, Aug. 2019.

84. N. Singh, B. K. Kanaujia, M. T. Beg, M. Siddique, S. Kumar, H. C. Choi, and K. W. Kim, "Low profile multiband rectenna for efficient energy harvesting at microwave frequencies," *Int. J. Electron*, Vol. 106, no. 12, pp. 2057–2071, Jul. 2019. doi:10.1080/00207217.2019.1636302

85. I. Adam, M. N. M. Yasin, H. A. Rahim, P. J. Soh, and M. F. Abdulmalek, "A compact dual-band rectenna for ambient RF energy harvesting," *Microw. Opt. Technol. Lett*, Vol. 60, no. 11, pp. 1–9, Nov. 2018.

86. A. Nimo, T. Beckedahl, T. Ostertag, and L. Reindl, "Analysis of passive RF-DC power rectification and harvesting wireless RF energy for Micro-watt sensors," *AIMS Energy*, Vol. 3, no. 2, pp. 184–200, Apr. 2015. doi:10.3934/energy.2015.2.184

87. A. Okba, A. Takacs, H. Aubert, S. Charlot, and P. F. Calmon, "Multi-band rectenna for microwave applications," *Comptes Rendus Physique*, Vol. 18, pp. 107–117, 2017. doi:10.1016/j.crhy.2016.12.002

88. H. Takhedmit, L. Cirio, S. Bellal, D. Delcroix, and O. Picon, "Compact and efficient 2.45 GHz circularly polarized shorted ring-slot rectenna," *Electron. Lett*, Vol. 48, no. 5, pp. 1–2, 2012. doi:10.1049/el.2011.3890

89. A. Mavaddat, S. H. M. Armaki, and A. R. Erfanian, "Millimeter wave energy harvesting using 4×4 microstrip patch antenna array," *IEEE Antennas Wireless Propag. Lett*, Vol. 14, pp. 515–518, 2015. doi:10.1109/LAWP.2014.2370103

90. A. Mouapi, N. Hakem, and G. V. Kamani. "A selective rectifier for RF energy harvesting under non-stationary propagation conditions," 2018 IEEE Int. Conf. Environm. Electr. Eng. and 2018.

91. K. W. Lui, A. Vilches, and C. Toumazou, "Ultra-efficient microwave harvesting system for battery-less micropower microcontroller platform," *IET Microw. Antennas Propag*, Vol. 5, no. 7, pp. 811–817, 2011. doi:10.1049/iet-map.2010.0250

92. Z. Liu, Z. Zhong, and Y. X. Guo, "Enhanced dual-band ambient RF energy harvesting with ultra-wide power range," *IEEE Microw. Wireless Compon. Lett*, Vol. 25, pp. 630–632, 2015. doi:10.1109/LMWC.2015.2451397

93. V. Marian, B. Allard, C. Vollaire, and J. Verdier, "Strategy for microwave energy harvesting from ambient field or a feeding source," *IEEE Trans. Power Electron*, Vol. 27, no. 11, pp. 4481–4491, Nov. 2012. doi:10.1109/TPEL.2012.2185249

94. H. Nakamoto, D. Yamazaki, T. Yamamoto, H. Kurata, S. Yamada, K. Mukaida, T. Ninomiya, T. Ohkawa, S. Masui, and K. Gotoh, "A passive UHF RF identification CMOS tag IC using ferroelectric RAM in 0.35-um technology," *IEEE J. Solid-State Circuits*, Vol. 42, no. 1, pp. 101–110, Jan. 2007. doi:10.1109/JSSC.2006.886523

95. K. Kotani, A. Sasaki, and T. Ito, "High-efficiency differential-drive CMOS rectifier for UHF RFIDs," *IEEE J. Solid-State Circuits*, Vol. 44, no. 11, pp. 3011–3018, Nov. 2009. doi:10.1109/JSSC.2009.2028955

96. G. Papotto, F. Carrara, and G. Palmisano, "A 90-nm CMOS threshold-compensated RF energy harvester," *IEEE J. Solid-State Circuits*, Vol. 46, no. 9, pp. 1985–1997, Sep. 2011. doi:10.1109/JSSC.2011.2157010

97. 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 J. Solid-State Circuits*, Vol. 49, no. 3, pp. 622–634, Mar. 2014. doi:10.1109/JSSC.2014.2302793

98. Z. Hameed, and K. Moez, "Hybrid forward and backward threshold- compensated rf-dc power converter for RF energy harvesting," *IEEE J. Emerg. Sel. Topics*

Circuits Syst, Vol. 4, no. 3, pp. 335–343, Sept. 2014. doi:10.1109/JETCAS.2014.2337211

99. S. Hemour, Y. Zhao, C. H. P. Lorenz, D. Houssameddine, Y. Gui, C. M. Hu, and K. Wu, "Towards low-power high-efficiency RF and microwave energy harvesting," *IEEE Trans. Microw. Theory Techn*, Vol. 62, no. 4, pp. 965–976, Apr. 2014. doi:10.1109/TMTT.2014.2305134

100. T. Oka, T. Ogata, K. Saito, and S. Tanaka. "Triple-band single-diode microwave rectifier using CRLH transmission line," Proc. 2014 Asia-Pacific Microw. Conf., 2014, pp. 1013–1015.

101. S. Joshi, and G. Moddel, "Simple figure of merit for diodes in optical rectennas," *IEEE J. Photovoltaics*, Vol. 6, pp. 668–672, 2016. doi:10.1109/JPHOTOV.2016.2541460

102. S. N. Daskalakis, A. Georgiadis, G. Goussetis, and M. M. Tentzeris, "A rectifier circuit insensitive to the angle of incidence of incoming waves based on a wilkinson power combiner," *IEEE Trans. Microw. Theory Techn*, Vol. 67, no. 7, pp. 3210–3218, Jul. 2019. doi:10.1109/TMTT.2019.2912192

103. M. Abdallah, J. Costantine, A. H. Ramadan, and Y. Tawk, "Enhanced radio frequency rectifier with a power splitting/combining topology for wireless energy transfer and harvesting," *IET Microw. Antennas Propag*, Vol. 13, no. 9, pp. 1280–1286, 2019. doi:10.1049/iet-map.2018.5222

104. H. Mei, X. Yang, G. Tan, and B. Han, "High-efficiency microstrip rectenna for Microwave power transmission at Ka bandwidth with Low cost," *IET Microw. Antennas Propag*, Vol. 10, no. 15, pp. 1648–1655, Dec. 2016. doi:10.1049/iet-map.2016.0025

105. Y. Q. Wang, and X. X. Yang. Design of a high-efficiency circularly polarized rectenna for 35 GHz microwave power transmission system", 2012 Asia-Pacific Power and Energy Engineering Conference, March 2012, pp. 1-4.

106. W. Storr. Electronic tutorial about power diodes as rectifiers. Technical report, Basic Electronics Tutorials, 2013.

107. F. Losee. *RF systems, components, and circuits handbook, chapter semiconduction diodes and their circuits*. Boston: Artech House, Inc., 1997.

108. F. Erkmen, T. S. Almoneef, and O. M. Ramahi, "Electromagnetic energy harvesting using full-wave rectification," *IEEE Trans. Microw. Theory Techn*, Vol. 65, no. 5, pp. 1843–1851, 2017. doi:10.1109/TMTT.2017.2673821

109. F. Erkmen, and T. S. Alm, "Scalable electromagnetic energy harvesting using frequency-selective surfaces," *IEEE Trans. Microw. Theory Techn*, Vol. 66, no. 5, pp. 2433–2441, 2018. doi:10.1109/TMTT.2018.2804956

110. B. Razavi, *Fundamentals of Microelectronics*, 2nd ed., Los Angeles: Wiley Publications, 2013.

111. N. Shariati, W. S. T. Rowe, J. R. Scott, and K. Ghorbani, "Multi-service highly sensitive rectifier for enhanced RF energy scavenging," *Sci. Rep*, Vol. 5, no. 9655, pp. 1–9, 2015.

112. J. Heikkinen, and M. Kivikoski, "A novel dual-frequency circularly polarized rectenna," *IEEE Antennas Wireless Propag. Lett*, Vol. 2, pp. 330–333, 2003. doi:10.1109/LAWP.2004.824166

113. T. Mitani, S. Kawashima, and T. Nishimura, "Analysis of voltage doubler behavior of 2.45-GHz voltage doubler-type rectenna," *IEEE Trans. Microw. Theory Techn*, Vol. 65, no. 4, pp. 1051–1057, 2017. doi:10.1109/TMTT.2017.2668413

114. M. M. Mansour, and H. Kanaya, "High-efficient broadband cpw RF rectifier for wireless energy harvesting," *IEEE Microw. Wireless Compon. Lett*, Vol. 29, no. 4, pp. 288–290, Apr. 2019. doi:10.1109/LMWC.2019.2902461

115. M. Mansour, X. L. Polozec, and H. Kanaya, "Enhanced broadband RF differential rectifier integrated with archimedean spiral antenna for wireless energy harvesting applications," *Sensors*, Vol. 19, no. 655, pp. 1–13, 2019.

116. C. Song, Y. Huang, J. Zhou, J. Zhang, S. Yuan, and P. Carter, "A high-efficiency broadband rectenna for ambient wireless energy harvesting," *IEEE Trans. Antennas Propag*, Vol. 63, no. 8, pp. 3486–3495, 2015. doi:10.1109/TAP.2015.2431719

117. M. A. Gozel, M. Kahriman, and O. Kasar, "Design of an efficiency-enhanced Greinacher rectifier operating in the GSM 1800 band by using rat-race coupler for RF energy harvesting applications," *Int J RF Microw Comput Aided Eng*, Vol. 29, no. 1, pp. 1–8, Jan. 2019.

118. J. Park, Y. Kim, Y. J. Yoon, J. So, and J. Shin, "Rectifier design using distributed greinacher voltage multiplier for high frequency wireless power transmission," *J. Electrom. Eng. Scie*, Vol. 14, no. 1, pp. 25–30, 2014. doi:10.5515/JKIEES.2014.14.1.25

119. S. Fan, Z. Yuan, W. Gou, Y. Zhao, C. Song, Y. Huang, J. Zhou, and L. Geng, "A 2.45-GHz rectifier-booster regulator with impedance matching converters for wireless energy harvesting," *IEEE Trans. Microw. Theory Techn*, Vol. 67, no. 9, pp. 3833–3843, Sept. 2019. doi:10.1109/TMTT.2019.2910062

120. Y. Han, O. Leitermann, D. A. Jackson, J. M. Rivas, and D. J. Perreault, "Resistance compression networks for radio-frequency power conversion," *IEEE Trans. Power Electron*, Vol. 22, no. 1, pp. 41–53, Jan. 2007. doi:10.1109/TPEL.2006.886601

121. K. Niotaki, A. Georgiadis, A. Collado, and J. S. Vardakas, "Dual-band resistance compression networks for improved rectifier performance," *IEEE Trans. Microw.*

Theory Techn, Vol. 62, no. 12, pp. 3512–3521, Dec. 2014. doi:10.1109/TMTT.2014.2364830

122. T. W. Barton, J. M. Gordonson, and D. J. Perreault, "Transmission line resistance compression networks and applications to wireless power transfer," *IEEE J. Emerg. Sel. Topics Power Electron*, Vol. 3, no. 1, pp. 252–260, Mar. 2015. doi:10.1109/JESTPE.2014.2319056

123. Z. Wang, W. Zhang, D. Jin, H. Xie, and X. Lv. "A full-wave RF energy harvester based on new configurable diode connected MOSFETs", 2016 IEEE Int. Conf. Microw. Millimeter Wave Technology (ICMMT), Jun. 2016, pp. 1-3.

124. H. Sun, Z. Zhong, and Y. X. Guo, "An adaptive reconfigurable rectifier for wireless power transmission," *IEEE Microw. Wireless Components Lett*, Vol. 23, no. 9, pp. 492–494, 2013. doi:10.1109/LMWC.2013.2250272

125. A. M. Almohaimeed, M. C. E. Yagoub, J. A. Lima, and R. E. Amaya. "Dual-band harvester with wide range input power for WPT applications", 2018 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW), Jun. 2018, pp. 1-4.

126. J. J. Lu, X. X. Yang, H. Mei, and C. Tan, "A four-band rectifier with adaptive power for electromagnetic energy harvesting," *IEEE Microw. Wireless Compon. Lett*, Vol. 26, no. 10, pp. 819–821, Oct. 2016.

127. X. Wang, and A. Mortazawi, "Rectifier array with adaptive power distribution for wide dynamic range RF-DC conversion," *IEEE Trans. Microw. Theory Techn*, Vol. 67, no. 1, pp. 392–401, Jan. 2019. doi:10.1109/TMTT.2018.2875959

128. N. Singh, "A compact and efficient graphene FET based RF energy harvester for green communication," *Int. J. Electron. Commun. (AEÜ)*, Vol. 115, pp. 153059–153066, 2020. doi:10.1016/j.aeue.2019.153059

129. A. Mouapi, and N. Hakem, "A selective rectifier for RF energy harvesting for IoT applications," *Antenna Propag. Society-2018*, 2523–2524, 2018. doi:10.1109/APUSNCURSINRSM.2018.8608705

130. N. Eltresy, D. Elsheakh, E. Abdallah, and H. Elhenawy. "RF energy harvesting using efficiency dual band rectifier," Proc. 2018 Asia-Pacific Microw. Conf., pp. 1453-1455, 2018.

131. C. Song, Y. Huang, P. Carter, J. Zhou, S. D. Joseph, and G. Li, "Novel compact and broadband frequency- selectable rectennas for a wide input-power and load impedance range," *IEEE Trans. Antennas Propag*, Vol. 66, no. 7, pp. 3306–3316, 2018. doi:10.1109/TAP.2018.2826568

132. Y. S. Chen, and C. W. Chiu, "Maximum achievable power conversion efficiency obtained through an optimized rectenna structure for RF energy harvesting," *IEEE Trans. Antennas Propag*, Vol. 65, no. 5, pp. 2305–2317, May 2017. doi:10.1109/TAP.2017.2682228

133. C. H. P. Lorenz, S. Hemour, W. Liu, A. Badel, F. Formosa, and K. Wu, "Hybrid power harvesting for increased power conversion efficiency," *IEEE Microw. Wireless Compon. Lett*, Vol. 25, no. 10, pp. 687–689, Oct. 2015. doi:10.1109/LMWC.2015.2463229

134. X. Gu, S. Hemour, L. Guo, and K. Wu, "Integrated cooperative ambient power harvester collecting ubiquitous radio frequency and kinetic energy," *IEEE Trans. Microw. Theory Techn*, Vol. 66, no. 9, pp. 4178–4190, Sept. 2018. doi:10.1109/TMTT.2018.2842723

135. P. Nintanavongsa, U. Muncuk, D. R. Lewis, and K. R. Chowdhury, "Design optimization and implementation for RF energy harvesting circuits," *IEEE J. Emerg. Sel. Topics Circuits Syst*, Vol. 2, no. 1, pp. 24–33, Mar. 2012. doi:10.1109/JETCAS.2012.2187106

136. G. D. Vita, and G. Iannaccone, "Design criteria for the RF section of UHF and microwave passive RFID transponders," *IEEE Trans. Microw. Theory Techn*, Vol. 53, no. 9, pp. 2978–2990, Sep. 2005. doi:10.1109/TMTT.2005.854229

137. Y. H. Suh, and K. Chang, "A high-efficiency dual-frequency rectenna for 2.45- and 5.8-GHz wireless power transmission," *IEEE Trans. Microw. Theory Techn*, Vol. 50, no. 7, pp. 1784, July 2002. doi:10.1109/TMTT.2002.800430

138. Y. Chang, P. Zhang, and L. Wang, "Highly efficient differential rectenna for RF energy harvesting," *Microw. Opt. Technol. Lett*, Vol. 61, no. 12, pp. 2662–2668, Dec. 2019. doi:10.1002/mop.31945

139. S. Agrawal, M. S. Parihar, and P. N. Kondekar, "Exact performance evaluation of RF energy harvesting with different circuit's elements," *IETE Technical Review*, Vol. 35, no. 5, pp. 514–522, 2018. doi:10.1080/02564602.2017.1339577

140. T. Ungan, X. L. Polozecv, W. Walker, and L. Reindl. "RF energy harvesting design using high Q resonators," IEEE MlT-S Int. Microw. Workshop on Wireless Sensing, Local Positioning, and RFIO (IMWS 2009-Croatia), 2009, pp. 1-4.

141. A. Nimo, D. Grgic, and L. M. Reindl. "Impedance optimization of wireless electromagnetic energy harvesters for maximum output efficiency at μW input power," Proc. SPIE, Vol. 8341, no. 83410W, 2012, pp. 1-14.

142. C. Song, Y. Huang, P. Carter, J. Zhou, S. Yuan, Q. Xu, and M. Kod, "A novel six-band dual cp rectenna using improved impedance matching technique for ambient RF energy harvesting," *IEEE Trans. Antennas Propag*, Vol. 64, no. 7, pp. 3160–3171, Jul. 2016. doi:10.1109/TAP.2016.2565697

143. S. Agrawal, M. S. Parihar, and P. N. Kondekar, "A dual-band RF energy harvesting circuit using 4^{th} order dual-band matching network," *Cogent Engineering*,

Vol. 4, pp. 1–10, 2017. doi:10.1080/23311916.2017.1332705

144. J. Liu, and X. Y. Zhang, "Compact triple-band rectifier for ambient RF energy harvesting application," *IEEE Access*, Vol. 6, pp. 19018–19024, 2018. doi:10.1109/ACCESS.2018.2820143

145. C. Y. Hsu, S. C. Lin, and Z. M. Tsai, "Quadband rectifier using resonant matching networks for enhanced harvesting capability," *IEEE Microw. Wireless Compon. Lett*, Vol. 27, no. 7, pp. 669–671, Jul. 2017. doi:10.1109/LMWC.2017.2711578

146. M. Zeng, Z. Li, A. S. Andrenko, X. Liu, and H. Z. Tan, "Differential voltage octuple rectifiers for wireless energy harvesting," *Microw. Opt. Technol. Lett*, Vol. 59, pp. 1574–1578, 2017. doi:10.1002/mop.30586

147. H. Takhedmit, L. Cirio, B. Merabet, B. Allard, F. Costa, C. Vollaire, and O. Picon, "Efficient 2.45 GHz rectenna design including harmonic rejecting rectifier device," *Electron. Lett*, Vol. 46, no. 12, pp. 1–2, June 2010. doi:10.1049/el.2010.1075

148. X. X. Yang, C. Jiang, A. Z. Elsherbeni, F. Yang, and Y. Q. Wang, "A novel compact printed rectenna for data communication systems," *IEEE Trans. Antennas Propag*, Vol. 61, no. 5, pp. 2532–2539, May 2013. doi:10.1109/TAP.2013.2244550

149. Z. Ma, and G. A. E. Vandenbosch, "Wideband harmonic rejection Filtenna for wireless power transfer," *IEEE Trans. Antennas Propag*, Vol. 62, no. 1, pp. 371–377, Jan. 2014. doi:10.1109/TAP.2013.2287009

150. C. Song, Y. Huang, J. Zhou, P. Carter, S. Yuan, Q. Xu, and Z. Fei, "Matching network elimination in broadband rectennas for high-efficiency wireless power transfer and energy harvesting," *IEEE Trans. Industrial Electron*, Vol. 64, pp. 3950–3961, 2017. doi:10.1109/TIE.2016.2645505

151. P. Wu, S. Y. Huang, W. Zhou, W. Yu, Z. Liu, X. Chen, and C. Liu, "Compact high-efficiency broadband rectifier with multi-stage-transmission-line matching," *IEEE Trans. Circuits Syst-II: Express Briefs*, Vol. 66, no. 8, pp. 1316–1320, Aug. 2019. doi:10.1109/TCSII.2018.2886432

152. U. Olgun, C. C. Chen, and J. L. Volakis, "Investigation of rectenna array configurations for enhanced RF power harvesting," *IEEE Antennas Wireless Propag. Lett*, Vol. 10, pp. 262–265, 2011. doi:10.1109/LAWP.2011.2136371

153. E. L. Chuma, Y. Iano, M. S. Costa, L. T. Manera, and L. L. B. Roger, "A compact-integrated reconfigurable rectenna array for RF power harvesting with a practical physical structure," *Progr. Electromagn. Res. M*, Vol. 70, pp. 89–98, 2018.

154. S. Shen, C. Y. Chiu, and R. D. Murch, "Multiport pixel rectenna for ambient RF energy harvesting," *IEEE Trans. Antennas Propag*, Vol. 66, no. 2, pp. 644–656, Feb. 2018. doi:10.1109/TAP.2017.2786320

155. S. Shen, Y. Zhang, C. Y. Chiu, and R. Murch, "An ambient RF energy harvesting system where the number of antenna ports is dependent on frequency," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 67, no. 9, pp. 3821–3832, 2019. doi:10.1109/TMTT.2019.2906598

156. S. Shen, Y. Zhang, C. Y. Chiu, and R. Murch, "A triple-wideband high-gain multibeam ambient RF energy harvesting system utilizing hybrid combining," *IEEE Transactions on Industrial Electronics* 2019. doi:10.1109/TIE.2019.2952819

157. G. Monti, F. Congedo, D. D. Donno, and L. Tarricone, "Monopole-based rectenna for microwave energy harvesting of UHF RFID systems," *Prog. In Electromagn. Research C*, Vol. 31, pp. 109–121, 2012. doi:10.2528/PIERC12061501

158. T. Li, K. Sawada, H. Ogai, and W. Si, "UHF-Band wireless power transfer system for structural health monitoring sensor network," *Smart Materials Research*, Vol. 2013, pp. 7. Article ID 496492, November 2013.

159. G. Monti, L. Corchia, and L. Tarricone, "UHF wearable rectenna on textile materials," *IEEE Trans. Antennas Propag*, Vol. 61, no. 7, pp. 3869–3873, 2013. doi:10.1109/TAP.2013.2254693

160. F. J. Huang, C. M. Lee, C. L. Chang, L. K. Chen, T. C. Yo, and C. H. Luo, "Rectenna application of miniaturized implantable antenna design for triple-band biotelemetry communication," *IEEE Trans. Antennas Propag*, Vol. 59, no. 7, pp. 2646–2653, Jul. 2011. doi:10.1109/TAP.2011.2152317

161. M. Haerinia, and S. Noghanian, "A printed wearable dual-band antenna for wireless power transfer," *Sensors*, Vol. 19, no. 1732, pp. 1–10, 2019.

162. M. K. Hosain, A. Z. Kouzani, M. F. Samad, and S. J. Tye, "A miniature energy harvesting rectenna for operating a head-mountable deep brain stimulation device," *IEEE Access*, Vol. 3, pp. 223–234, 2015. doi:10.1109/ACCESS.2015.2414411

163. A. Abdi, and H. Aliakbarian, "A miniaturized UHF-band rectenna for power transmission to deep-body implantable devices," *Cardiovascular Devices and Systems*, Vol. 7, pp. 1900311–1900321, 2019.

164. O. M. Sanusi, F. A. Ghaffar, A. Shamim, M. Vaseem, Y. Wang, and L. Roy, "Development of a 2.45 GHz antenna for flexible compact radiation Dosimeter tags," *IEEE Trans. Antennas Propagation*, Vol. 67, no. 8, pp. 5063–5072, Aug. 2019. doi:10.1109/TAP.2019.2911647

165. M. Asif, "A novel RF-powered wireless pacing via a rectenna-based pacemaker and a wearable transmit-antenna

array," *IEEE Access*, Vol. 7, pp. 1139–1148, 2019. doi:10.1109/ACCESS.2018.2885620

166. T. Karacolak, A. Z. Hood, and E. Topsakal, "Design of a dual-band implantable antenna and development of skin mimicking gels for continuous glucose monitoring," *IEEE Trans. Microwave Theory Tech*, Vol. 56, no. 4, pp. 1001–1008, 2008. doi:10.1109/TMTT.2008.919373

167. K. Zhang, "Near-field wireless power transfer to deep-tissue implants for biomedical applications," *IEEE Trans. Antennas Propag*, Vol. 68, no. 2, pp. 1098–1106, Feb. 2020. doi:10.1109/TAP.2019.2943424

Authors

Daasari Surender received the Bachelor of Technology degree in Electronics and Communication Engineering from Sree Chaitanya College of Engineering, Affiliated to Jawaharlal Nehru Technological University Hyderabad (JNTUH), Telangana in 2008 and Master of Engineering degree in Microwave and Radar Engineering from University College of Engineering (Autonomous), Osmania University, Telangana in 2011. He worked as an Assistant Professor in Kamala Institute of Technology and Science, Affiliated to JNTU Hyderabad during 2012-2017. Currently, he is working as a full-time Ph.D. research scholar in National Institute of Technology Silchar, India since 2017. His current research interests include planar antenna, dielectric resonator antennas, and energy harvesting systems.

Taimoor Khan is presently an Assistant Professor in the Department of Electronics and Communication Engineering at National Institute of Technology Silchar, India where he serves as a full-time faculty member since 2014. Prior to joining NIT Silchar, he served as an Assistant Professor in Delhi Technological University (Formerly Delhi College of Engineering), Delhi, India. Dr. Khan awarded his Ph.D. Degree in Electronics and Communication Engineering from National Institute of Technology (NIT) Patna, India in 2014. He obtained his M. Tech. Degree in Communication Engineering from Shobhit Institute of Engineering and Technology (A Deemed University), Meerut, Uttar Pradesh, India in 2009; Bachelor Degree in Electronics and Communication Engineering from The Institution of Engineers (India), Kolkata, India in the year 2005. His active research interest includes Printed Microwave and Millimeter Wave Circuits, Electromagnetic Bandgap Structures, Dielectric Resonator Antennas, Computational Electromagnetics and Computational Intelligence Paradigms in Electromagnetics. He has guided two Ph.D. Theses in the area of DRAs and EBG Structures and has published over seventy research papers in international journals and conference proceedings of repute. Dr. Khan is involved in executing three sponsored projects funded by Govt. of India and is also a member of the Editorial Board of RFMiCAE Journal. He is an active senior member IEEE, fellow, IETE (India), life member, IAENG (China), member URSI (Belgium) and life member, ISTE (India).

Corresponding author. Email: ktaimoor@ieee.org

Fazal A. Talukdar obtained his Bachelor of Engineering (Hons.) from Regional Engineering College, Silchar (now, NIT Silchar) in 1987. He obtained his M.Tech. in 1993 and Ph.D. in 2002–03 from Indian Institute of Technology Delhi and Jadavpur University, respectively. He joined Regional Engineering College, Silchar as Lecturer in April 1991, became an Assistant Professor in March 1996 and rose to the level of Professor in May 2006. Prior to joining Regional Engineering College, Silchar, he was a Lecturer at Silchar Polytechnic from August 1988 to March 1991. He was Head of the Department of Electronics and Communication Engineering from August 2006 to April 2006. During July 2004 to June 2009, he was the Registrar of NIT Silchar. During March 2005 to August 2007, he held the post of Deputy Registrar (Accounts), during 2012–13, he was the Dean (Alumni Relations) and during 2013–15, he was the Dean (Academic Affairs) of the Institution. Besides these, he worked in many other Committees of the Institute.

Asok De obtained his Bachelor and Master of Engineering with specialization of Electronics and Communication from Jadavpur University Kolkata in 1978 and 1980, respectively. He was awarded Ph.D. degree from Indian Institute of Technology Kharagpur in the year 1986. He joined Delhi University, Delhi, India as Lecturer in the year 1984 and promoted as Reader in the year 1987. In 1991 he joined Kolkata University, Kolkata, India as Reader and subsequently joined Delhi College of Engineering (presently Delhi Technological University), Delhi, India as Professor in the year 1997 and worked as Professor in Electronics and Communication Engineering Department, Head of Computer Engineering and Head of Information Technology. In 2005, he joined Ambedkar Institute of Advanced Communication Technology and Research Delhi as Principal and continued with this position till July 2012. Then he worked as Director of National Institute of Technology Patna from 2012–2017. At that period of time, he also had an additional charge of Director of National

Institute of Technology Durgapur, India. His area of interest includes Antennas, Transmission Lines, Microwave Circuits, and Computational Electromagnetics. He has published over 120 research articles in international journals and more than 130 research articles in international/national conference proceedings. He has supervised 12 PhD Thesis and four are going on. He is a senior member IEEE (USA), fellow IEI (India), fellow IETE (India), and life member CSI (India).

Yahia M. M. Antar received the B.Sc. (Hons.) degree in electrical engineering from Alexandria University, Egypt in 1966, M.Sc. and Ph. D. degrees in electrical engineering from University of Manitoba, Canada in 1971 and 1975, respectively. In 1979, he joined the Division of Electrical Engineering, National Research Council of Canada. In 1987, he joined the Department of Electrical and Computer Engineering, Royal Military College of Canada, Canada, where he has been a Professor since 1990. He has authored or co-authored more than 200 journal papers, several books, and more than 450 refereed conference papers, holds several patents, has chaired several national and international conferences. He has supervised and co-supervised more than 90 Ph.D. and M.Sc. thesis. He was appointed as a member of the Canadian Defence Advisory Board of the Canadian Department of National Defence in 2011. He is a fellow of the Engineering Institute of Canada, the Electromagnetic Academy, and the International Union of Radio Science. He served as the Chair for Commission B from 1993 to 1999 and for CNC, URSI from 1999 to 2008, and has a cross appointment at Queen's University, Kingston. In 2002, he was awarded a Tier 1 Canada Research Chair in electromagnetic engineering, which has been renewed in 2016. He serves as an Associate Editor for many IEEE and IET journals and as an IEEE-APS Distinguished Lecturer. He was elected by the URSI to the Board as the Vice President in 2008 and 2014 and by the IEEE AP AdCom in 2009.

Al. P. Freundorfer received the B.A.Sc., M.A.Sc. and Ph.D. degree all from the University of Toronto, Ontario, Canada in 1981, 1983 and 1989, respectively. While at University of Toronto, he worked on a unique ground penetrating radar (GPR) for three dimensional imaging of buried objects. For his post doctorate, he worked in the areas of non-linear optics of organic crystals, optical reflectometry and optical signal processing. On joining the Department of Electrical Engineering at Queen's University, he invented a coherent optical vector network analyser, which is an instrument similar to a microwave vector network analyser but at optical frequencies. Currently he is working in the area of Wireless Circuits and recent work is being conducted on fully integrated direct digital transceivers. In addition to radio circuits, he is actively involved in integrated antennae, ceramic materials with application to electronics and automotive radars. He has developed a new low temperature process to deposit Barium Strontium Titanate (BST) in thin film or bulk on ICs to construct filters and antenna.