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A REVIEW OF ENERGY HARVESTING SYSTEM FOR WIRELESS SENSOR NETWORK APPLICATIONS

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Abstract:

Recent years have observed different techniques in Wireless Sensor Networks (WSNs), but energy is still a vital resource. The main limitations imposed are the cost and size, therefore, these sensor nodes are provided with a constrained amount of energy. So, there is a pressing requirement for energy harvesting. This paper presents a comprehensive overview of the energy harvesting systems for powered-battery wireless sensor nodes. These systems operated at 5G frequency bands such as 2.4GHz, 5.8GHz, and 6GHz, which included receiving antenna, rectifier circuit, impedance matching network, and load. The RF energy harvested from the surrounding environment by antenna, and converted to usable DC current using microwave Schottky rectifier diodes. There are different challenges presented in this study such as antenna structure design with resonant frequency bands, rectifier topologies with choosing diodes, and impedance matching for full integration of low power rectenna. The most important key parameters for these systems in order to evaluate are conversion efficiency and output voltage and power at the optimum load resistor. This review article summarizes the recent advances and the most important challenges in the 5G band energy harvesting systems for WSNs applications at the structures and topologies.

Keywords: *Energy harvesting (EH), Rectifier topology, Schottky diodes, Antenna, Conversion efficiency, DC output voltage.*

1 INTRODUCTION

In response to rapid developments in smart technologies and the Internet of Things, low-energy harvesting (EH) systems have emerged to provide uninterrupted power supply, adapting to the evolving technological landscape. These systems use minimal energy to operate devices sustainably, ensuring continuous operation in the face of increasing demands (Calautit et al., 2021). EH technologies have evolved as an alternative to batteries to power wireless sensors as energy is extracted from sources in the surrounding environment. Figure 1 shows the energy sources present in the environment, including thermal energy (Xia et al., 2020), solar energy (Antony et al., 2020), radio frequency (Sidhu et al., 2019), and vibrational energy (Khan et al., 2020).

There has been a lot of interest in using ambient RFEH in urban and suburban environments as a substitute power source for low-power devices such as Wireless Sensor Nodes (WSNs) (Lee et al., 2023). Due to the widespread use of wireless communication devices like laptops, tablets, and cell phones (Ma et al., 2020). There is an excess of RF energy in the surrounding air that may be used for a number of purposes (Ramalingam et al., 2021). Research carried out in various urban settings and environs has yielded encouraging findings about the viability of utilizing ambient RF energy to power wireless sensor networks (AbdelGhany et al., 2019).

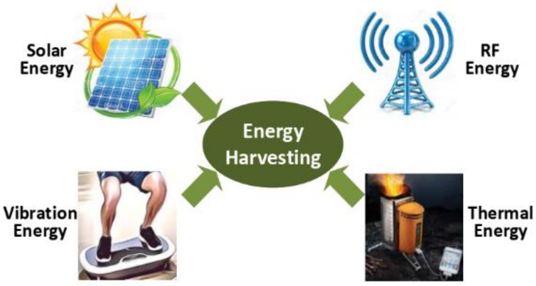


Figure 1: Different types of sources for energy harvesting (Khan et al., 2020)

For WSNs deployed at scale, this residual RF energy emissions-basically, the remains of wireless device transmissions-offer a feasible energy source, especially for applications like industrial manufacturing (Younan et al., 2020). and environmental monitoring in smart cities(Santos et al., 2019). There has been a lot of interest in RFEH in the past little years (Samir et al., 2019). The capacity to capture ambient RF energy offers a compelling substitute for conventional power sources such as Li-ion batteries, which have drawbacks related to size, dependability, and upkeep, particularly in large-scale applications where battery longevity is a problem (Li et al., 2021). But creating effective ambient radio frequency energy harvesters is still difficult, especially when incorporating them into system-on-a-chip (SoC) applications (Karim et al., 2019). Power conversion efficiency (PCE) of rectifiers is limited by the difference between the threshold voltage (Vth) of transistor and low-power density of RF energy (Zareianjahromi et al., 2022). Figure 2 shows an ideal RFEH that includes an antenna to capture RF energy, matching network for maximum power transfer, and a power manager to regulate the output of loads (Karami and Moez, 2021).

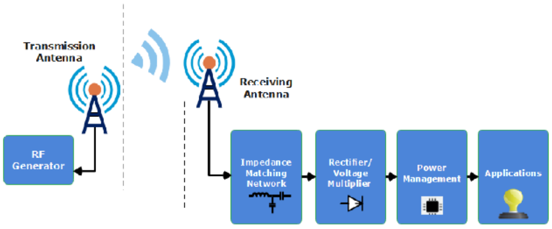


Figure 2: Block diagram of RFEH systems (Karami and Moez, 2021)

Different topology has been reviewed comprehensively of energy harvesting systems for wireless charging WSNs. This study seeks to direct research and developement activities towards IC integration. In order to provide a better solution for RF harvesting for low-power devices, we have comprehensively reviewed every part of the harvesting, including received antenna, impedance matching network and rectifier circuit. Section II deals with the design of antennas and their specifications, while the impedance matching network, the RF-DC rectifier circuit and rectenna system are clarified in the III and IV sections, respectively. The full integrated of the rectifier with antenna as explored by section V, while discussion and our analysis's conclusions in VI section followed by a list of references.

2 ANTENNA DESIGN

In order to effectively capture and transform radio frequency energy into useable electrical power, there are a number of factors to take into account while designing an antenna for radio frequency harvesting devices, the main considerations are frequency range, polarity, radiation pattern, efficiency optimization and size, return loss and gain (Pandey et al., 2020). In order to perform RFEH applications use a variety of conventional antenna types with varied structures, including as microstrip antennas, monopole antennas, dipole antennas, and ring-slot antennas (Amer et al., 2020).

Numerous structures, such as microstrip or patch antennas, have been presented as ways to reduce the size of the antennas (Assogba et al., 2020). The simplest method reported in the literature is to use the basic microstrip patch antennas integrated with rectifier elements on the same printed circuit board. This will result in a drastic increase in received power. Additionally, the matching elements will be increased for array designs. To have more power received, the receiving antenna design should follow an array pattern (Sethi, n.d.). Although utilizing multiple antennas can boost power harvesting and improve the efficiency of RF-DC conversion, but increases the cost and size of the circuit (Cansiz et al., 2019).

2.1 Compact Antenna Techniques

Researchers and antenna engineers are able to develop small antennas with today's tiny electronic gadgets (Ullah et al., 2022). In 2020, DucDung and others presented pin antenna array with an enhanced gain 14.4 dBi, ISM frequency band of 5.8GHz with return loss -25 dBm (Nguyen et al., 2020). In (Zhang et al., 2020), PEI ZHANG and others presented back-to-back microstrip antenna which provides gain 3.96 dBi, resonant frequency 2.4GHz, 5.8GHz with return loss of -14dBm and -24 dBm respectively.

In the same year 2020, Mohhamed Derbal and Nedil presented multilayer substrate structure excited by a perture coupling feed which resonant frequencies 3.5, 5.8 GHz, provides gain 10.2, 8.94 dBi respectively and the return losses are lower than -10 dBm (Derbal and Nedil, 2020). In 2021, Sharma and Kumar presented slotted symmetrical M-shape microstrip patch antenna at 5.8 GHz provides 2.04dBi with return loss -25 dBm (Sharma and Singh, 2021).

In (Cai et al., 2021), Xiao and others showed antenna array consisting of six elements with flat top radiation pattern receiving resonant frequency 5.8 GHz and provides 4.7 dBi for each element by return loss lower than -25 dBm, that was in 2021. In 2022, Wajid Khan and others tested inverted F-shaped patch antenna which receiving dual resonant frequencies 2.4, 5.8 GHz, provides 3.6, 3.3 dBi by return loss -24, -26 dBm respectively (Khan et al., 2022). In (Derbal and Nedil, 2023), Mohammed Cherif and Mourad Nedil presented 3-layer circularly polarized antenna array at 5.8 GHz resonant frequency which provides 12.7 dBi per each element, by return loss -20 dBm, was in 2023.

Table 1. shows the antennas used for the above purpose along with some important specifications of the antennas.

Table 1: An Overview of RFEH Low-Profile Antennas

Ref. Year	**Proposed Antenna structure**	**Resonant Frequency [GHz]**	**Input Power [dBm]**	**Return Loss [dBm]**	**Gain [dBi]**
(Samir et al., 2019)	Multi band U-Slot MPA	2 3.7 5.8	NR	-15.75 -15.21 -15.73	11.86
(Pandey et al., 2020)	TNP multiband antenna	1.42 to 5.8	NR	-15 to -31.34	4.45
(Nguyen et al., 2020)	2×2 array MPA with shorting pin	5.8	12	-25	14.4
(Zhang et al., 2020)	MPA with back-to-back technique	2.4 5.8	-8.5 -8.9	-14 -24	3.96
(Derbal and Nedil, 2020)	Multiband antenna with multilayer substrates	3.5 5.8	0	≤ -10	10.2 8.94
(Sharma and Singh, 2021)	MPA with M-shape slotted	5.8	-26.79	≤ -25	2.04
(Cai et al., 2021)	1×6 MPA antenna array	5.8	-34.17	≤ -25	4.7 per element
(Khan et al., 2022)	MPA with Inverted F-shaped	2.4 5.8	-20 - 30	-24 -26	3.6 3.3
(Derbal and Nedil, 2023)	CP patch antenna array	5.8	-7 to -18	-20	12.7 per element
(Aboualalaa et al., 2020)	RSR antenna	0.7 1.4	-6.5 -4.5	≤ -30 ≤ -15	3.5 4.2
(Zhao et al., 2020)	CPW antenna with folded slot technique	2.4 5.2	13 13	≤ -10 ≤ -20	NR
(Pandey et al., 2021)	MPA with octagonal shape	1.975 to 4.744	-10 to 20	≤ -10	4.3
(Vu et al., 2020)	Bow-tie antenna with slits	0.84 - 2.4	-25 to -5	≤ -10	NR
(Mirzababaee et al., 2021)	MPA with Octagonal and rectangular slot	0.84 - 5.49	0	≤ -10	NR
(Sakai et al., 2021)	Short-stub connected high-impedance dipole antenna	5.8	30	NR	2.3
(Li et al., 2024)	Loop shaped antenna	2.45 5.8	9 11	-36.3 -45.3	NR
(Kiran et al., 2020)	CP textile antenna	2.45	NR	-22	4.25
(Ullah et al., 2021)	CPW-fed antenna with Hexagonal-shaped	2.1, 2.45, 3.2, 3.5	NR	-33.16, -35.33, -42.17, -35.16	1.31 1.63 1.97 2.2

MPA: Microstrip Patch Antenna, RSR: Rectangylar Split Ring, CPW: Coplanar Wave Guide,
CP: Circular Polarized, TNP: Triangular Nested Patch and NR: Not Reported.

2.2 Antenna Radiation Properties

The primary factor that allows for the distinction of ambient RFEH is the properties of antenna radiation (directivity, gain and polarization). Higher directivity does not equate to higher harvested power in ambient RFEH, assuming a 3D random incident field, according to an analysis of the number of antenna elements and ports. This finding has been confirmed by field measurements conducted in an urban setting (Shen et al., 2019).

For RFEH applications, high gain directional antennas and arrays have received a lot of attention. They are meant to increase the harvesting efficiency from low RF power densities or to compensate for propagation losses. When space allows, scalable rectenna arrays for optimizing the incident power density included bow-tie arrays, CPW CP arrays, spiral arrays, tightly-coupled Vivaldi arrays, Yagi-Uda rectenna array, and wide-area patch arrays (Wagih et al., 2020a).

Figure 3. shows some designs of array antenna, The ability of a circularly polarized (CP) antenna to receive electromagnetic energy from different polarizations makes it valuable. Therefore, for RFEH in particular, a wideband CP may be useful for obtaining energy from random polarization (Ullah et al., 2022). CP antennas have a tendency to be extra favorable for electricity harvesting structures as they mitigate the orientation dependence of receiving antennas (Kiran et al., 2020). The random-ness of RF in the surrounding environment makes omnidirectional radiation (Wang et al., 2022).

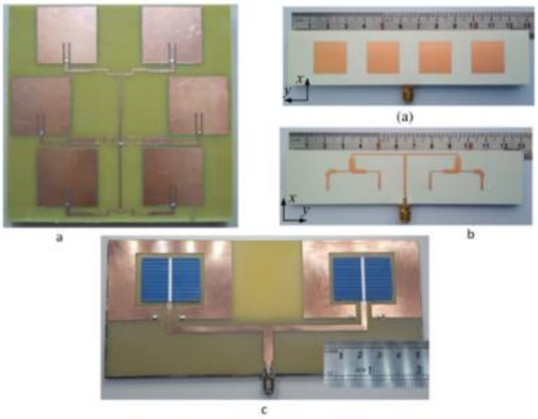


Figure 3: Array antennas design for RFEHs (Ullah et al., 2022)

2.3 Frequency and Bandwidth of Antennas

The range of electromagnetic frequencies that an antenna is intended to transmit or receive is known as its operation frequency. It's critical to the antenna's operation since it establishes how well-suited it is to various communication devices and systems. Antennas are designed to send and receive signals within a certain range by efficiently resonating at particular frequencies. The best communication performance is ensured by matching the operating frequency of antenna with the intended signal frequency (Ullah et al., 2021).

The chosen harvesting frequency must be chosen before beginning to develop a multiband RF energy harvester. With reference to Fig. 3, the four most often harvested center frequencies are (0.433, 0.9, 1.8, and 2.4) GHz because of their high signal strength resulting from their density of use (Lee et al., 2023). Measurements were made of the power density levels at 36 distinct places, some of which were outside and others of which were within (Cansiz et al., 2019). The majority of antennas are made up of wide radiators that produce surface current distributions that match each frequency in order to provide a wide bandwidth for the RFEH (Kim et al., 2023). A reduced efficiency at the higher frequency range is the key disadvantage (Mansour et al., 2021).

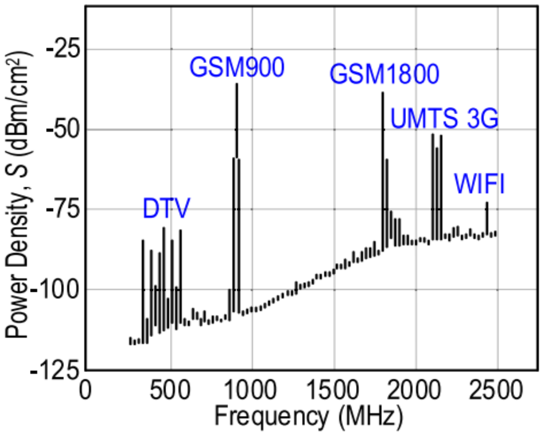


Figure 4: Measured input radio frequency power density outside of Northfields London Underground Station (Lee et al., 2023).

2.4 Effectiveness and Size of Antennas

Antenna efficiency is influenced by several factors, including shape, size, antenna construction material, frequency, and antenna impedance. When the physical size of the antenna decreases, efficiency also does (Thal, 2018). Due to decreased radiation efficiency and greater losses, which are mostly brought on by higher resistance in smaller conductors and a smaller radiation aperture, antenna efficiency declines as physical size decreases. This leads to a reduced capacity to efficiently transform input power into electromagnetic waves that are radiated (Geyi, 2021). Low efficiency in RF-based WPT still needs improvement. These methods include the use of reconfigurable intelligent surfaces, high-gain antenna design, and high-efficiency rectifier design (Amri and Sabila, 2023). Larger sizes cause reduced efficiency in microstrip, monopole, slot, dielectric resonator, and other types of antennas. Metasurface /metamaterial structures are employed as EH collectors in order to get beyond the aforementioned limitations and improve efficiency with reduced size (Amer et al., 2020).

Table 2 shows the key parameters of the receiving antennas in the energy harvesting system for more than 20 studies.

Table 2: A Performance comparison of Antenna for RFEH System Applications

Ref. Year	**Antenna structure**	**Dimension [mm^3]**	**B.W [MHz]**	**Dielectric Materials**	**Applications**
(Samir et al., 2019)	Multi band U-Slot MPA	65×70×1.6	179 278 298	FR-4, ε_r=4.3	Wireless powering of WSN
(Pandey et al., 2020)	TNP multiband antenna	45×41×1.67	50 100 200	FR-4, ε_r=4.3	Battery powered of wireless sensor nodes
(Zhang et al., 2020)	MPA with back-to-back technique	42.6×32.6×8	250	F4-B, ε_r=4	Wireless power transfer of sensor nodes
(Derbal and Nedil, 2020)	Multiband antenna with multilayer substrates	95×65×4.91	250 400	Rogers RT 5880, ε_r=2.2	Battery powered of wireless sensor nodes
(Sharma and Singh, 2021)	MPA with M-shape slotted	25×30×1.6	240	Rogers RT 5880, ε_r=2.2	Wireless powering of WSN
(Khan et al., 2022)	MPA with Inverted F-shaped	35× 40 × 1.6	230 620	Rogers RT 5880, ε_r=2.2	Wireless power transfer of sensor nodes
(Zhao et al., 2020)	CPW antenna with folded slot technique	55×30×0.78	250 400	FR-4, ε_r=4.3	Battery powered of wireless sensor and IoT devices
(Mirzababaee et al., 2021)	MPA with Octagonal and rectangular slot	60×60×1.57	484 450 5593	Rogers RT 5880, ε_r=2.2	Wireless powering of WSN
(Li et al., 2024)	Loop shaped antenna	67.5×71.5×1	500 800	FR-4, ε_r=4.3	Wireless powering of WSN
(Kiran et al., 2020)	CP textile antenna with L-shape technique	60× 60 × 1	400	Jeans	Wireless power transfer of sensor nodes
(Ullah et al., 2021)	CPW-fed antenna with Hexagonal-shaped	37×35×1.6	204 740 923	FR-4, ε_r=4.3	Battery powered of wireless sensor and 5G devices
(Shen et al., 2019)	Inverted F-antenna PIFA	240×240×1.6	25 50	FR-4, ε_r=4.3	Battery powered of wireless sensor and wearable devices
(Kim et al., 2023)	Broadband stepped bow-tie antenna	68×107 ×1.01	124	FR-4, ε_r=4.3	Battery powered of wireless sensor and IoT devices
(Afify et al., 2022)	Small size monopole antenna	21×21×0.5	800	Rogers RT 5880, ε_r=2.2	Battery powered of indoor wireless sensor
(Chandravanshi et al., 2021)	Dual-ring shaped monopole antenna	92×70	100	polyimide	Battery powered of wireless sensor and wearable devices
(Le et al., 2021)	Dual-band ring antenna	50×35	400 800	RO4003C	Energy Harvesting System for powering of WSNs

(Vinnakota et al., 2019)	Aperture-coupled patch antenna	150×150	100	FR-4, ε_r=4.3	Wireless power transfer of sensor nodes
(Muhammad et al., 2021)	Circular-slot wideband antenna	50×56×1.6	1500	FR-4, ε_r=4.3	Battery powered of wireless sensor and IoT devices
(Jan et al., 2022)	MPA with microstrip line feeding	40×35×1.6	1540	FR-4, ε_r=4.3	WPT for WSNs and remote portable devices.
(Saravanan and Priya, 2022)	Tri-band patch antenna	60×60×1.6	100 150	FR-4, ε_r=4.3	Wireless power transfer of sensor nodes
(Geran et al., 2021)	broadband monopole antenna	43× 44 ×1.57	7148	RT/duroid 5880, ε_r=2.2	Battery powered of wireless sensor and IoT devices

MCPA: Multiband Circular Polarised Antenna, WCSs: Wireless Communicaton Systems, WPTS: Wireless Power Transfer System, MWCs: Modren wireless communications, CWCSA: compact wide band circular slot antenna.

3 IMPEDANCE MATCHING NETWORK

A basic matching circuit is a combine of resistance, an inductor, and a capacitor. The reactive components of the impedance are the inductor and the capacitor, while the actual component is the resistor. Power loss results by using just resistors in the impedance matching (Cansiz et al., 2019). Maximizing power transfer from the receiving antenna to the rectifier circuit and raising the rectifier's RF input voltage level are the main goals of the impedance matching network, For RF energy harvesting, there are three main kinds of matching networks: L-type, π-type, and T-type networks as shown in Fig. 5 (Khan et al., 2020).

When the load impedance is less than the antenna impedance, the L-matching network is responsible for increasing it, oppisite that, it must be decreased. As a result, it helps with the downward and upward load impedances as seen in Fig. 6(Lee et al., 2023). High-frequency signals are carried by capacitors, and low-frequency signals are carried by inductors. therfore, in an L-matching network, flipping the positions of the capacitor and inductor results in the realization of a low-pass and high-pass L-matching transfer function, respectively.

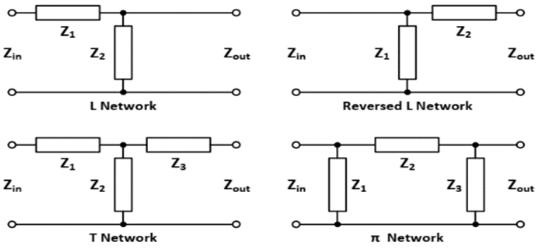


Figure 5: Impedance matching network (IMN) design circuits (Khan et al., 2020)

π type networks are better than L type networks because they offer an additional degree of freedom and a larger resonance amplitude (Divakaran et al., 2019). Fig. 7 shows the two common three-element networks that are divided into low- and high-pass categories: π and T-shaped networks (Wang et al., 2020). A good match reduces the harvested input RF signals reflection, and the IMN performance is measured by the reflection coefficient, S_{11} in dB which is given by:

$$S_{11} = \Gamma = \frac{Z_{rect}-Z_{ant}^*}{Z_{rect}+Z_{ant}^*} \qquad \dots\dots\dots(1)$$

Where Z_{ant} is the antenna's impedance, Z_{rect} is the rectifier's impedance, and Γ is the reflection coefficient, the most basic IMN network that has been implementedand studied for RFEH system is the L-matching (Chong et al., 2018).

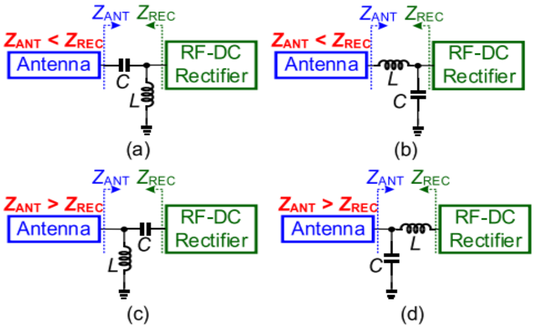
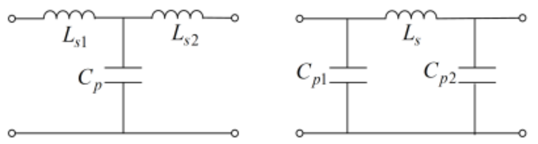
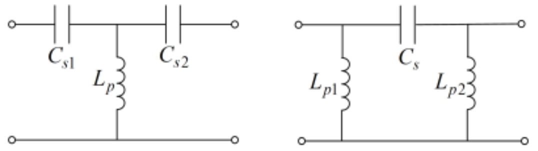


Figure 6: Types of L-matching network: (a) High-pass, (b) low-pass upward load impedance transformation, (c), and (d) High-pass, low pass downward load impedance respectivily (Lee et al., 2023).



(a) Low-pass T-shaped (b) Low-pass ∏-shaped



(c) High-pass T-shaped (d) High-pass ∏-shaped

Figure 7: Standard matching networks: (a, b) Low-pass T-shaped, π-shaped respectivily. (c, d) High-pass T-shaped, π-shaped respectivily (Wang et al., 2020)

4 RF-DC RECTIFIER CIRCUIT

The main part of an RF energy harvesting system, an RF-DC rectifier transforms the RF power which the receiving antenna collects into useful DC power, a rectifier can be configured in three basic ways, diode-based, diode bridge and voltage multiplier (Khan et al., 2020). the Schottky diode is recommended, because of its quick switching times and lower turn-on voltage (Li et al., 2021).

Several prototype Schottky diodes in use include HSMS 2820, HSMS 2850, HSMS 2852, HSMS 2860, HSMS 2862, Schottky SMS 7630 (Assogba et al., 2020). Compared to a full-wave rectifier (FWR), a half-wave rectifier (HWR) gives poorer efficiency. On the flip side, there are three varieties of full-wave rectifiers: the cross-coupled differential-drive (CCDD) rectifier, the Dickson-type rectifier, and the Cockcroft-Walton rectifier (Lee et al., 2023). A single diode is used, offering high efficiency at low input power, this setup avoids losses associated with multiple diode configurations, most of published research focused on single band rectifier operations; multiband harvesting was less common and requires more research to determine the best rectifying (Mansour et al., 2021).

The HWR is not suitable for high-power applications due to its low efficiency. To address this, more complex rectifier structures like voltage doublers and multistage rectifiers are employed. While these configurations provide higher output voltages, they involve additional diodes, which increase power losses and reduce efficiency. Therefore, the choice of rectifier structure depends on the specific power requirement and efficiency consideration of the application (Le et al., 2021).

4.1 Selection of Rectifier Topology

To choose a suitable rectifier configuration, consider HWR, FWR, multistage rectifier circuits utilizing the same load and incident power level. Half-wave configuration provides the maximum conversion efficiency in the input power range of -10dBm to 0dBm, but voltage doublers can produce better output voltage, which is important for powering electronic equipment. Figure 8 shows common voltage multiplier configurations (Tran et al., 2017). Power conversion efficiency (PCE) is an essential factor in circuit applications for power harvesting. Theoretical RF to DC conversion efficiency is expressed by (Vinnakota et al., 2019):

$$\eta_{RF-DC} = \frac{P_{DC}}{P_{RF}} \times 100\% \qquad \dots\dots\dots(2)$$

Where P_{RF} is the input RF power from the antenna and P_{DC} is the output DC power across load.

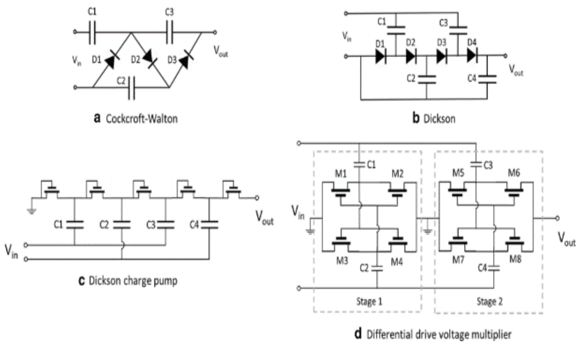


Figure 8: Voltage multiplier configurations (Tran et al., 2017)

4.2 Shunt and Series Single Diode Rectifier

In shunt-diode rectifier topology, the diode is connected in parallel with the load, allowing RF input to directly influence the diode, while DC output is extracted from load. In series-diode rectifier topology, the diode is connected in series with the load, separating the RF and DC, with the RF choke preventing RF signal from reaching the DC load as shown in Fig. 9 (Gao and Zhang, 2019).

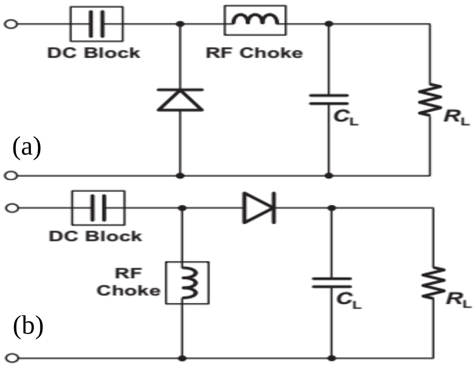


Figure 9: Single diode rectifier circuit topology: (a) Shunt, (b) Series structure (Gao and Zhang, 2019).

4.3 Voltage Doubler Rectifier

Voltage Doubler (VD) rectifiers are the most common type, The Greinacher Voltage Doubler (GVD) and the Delon Voltage Doubler (DVD) are the two main configurations of VD, and they are seen in Fig. 10, Because it enables the fabrication of multistage rectifiers for increasing the voltage, the GVD configuration is the one that is given the most attention, In the case of the GVD, the diode D_1 conducts during the negative half-wave and the capacitor C_1 charges to the value V_{max} when a voltage $v(t)= V_{max} sin(wt)$ is applied to the rectifier's input. The diode D_2 conducts and the capacitor C_2 charges to a maximum of $2V_{max}$ at the positive half of the cycle of the input voltage (Mouapi et al., 2020).

4.4 Efficiency of Rectifier

It's important to know the input power at which the PCE should be optimised when designing rectifier circuits. In Fig. 11, the diode's loss mechanism is shown, the rectifier uses a low turn-on voltage diode for high power conversion efficiency at low input power, but its PCE drops at higher power due to low breakdown voltage. To maintain high PCE, a high-power rectifier with a higher turn-on and breakdown voltage activates when input power exceeds a set threshold. This adaptive method, shown in Fig. 12, is effective for wireless power transfer with known RF power and directional transmission. A commercial WPT receiver achieves PCE% 55% and 62% at low and high power (-6dBm, 3dBm) respectively (Arpanutud et al., 2022).

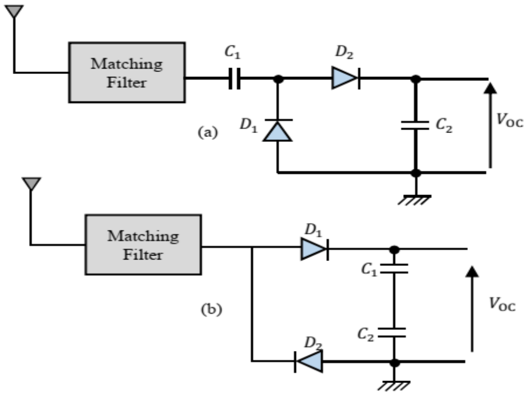


Figure 10: Antenna for receiving using voltage doubler rectifiers: (a) GVD, and (b) DVD (Mouapi et al., 2020)

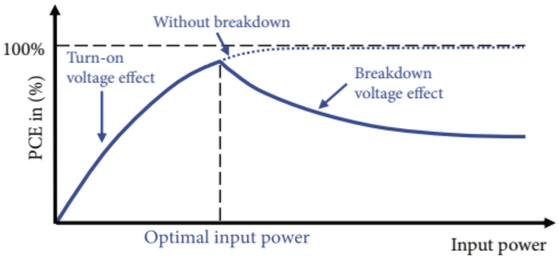


Figure 11: A rectifier circuit's diode's loss mechanism (Arpanutud et al., 2022)

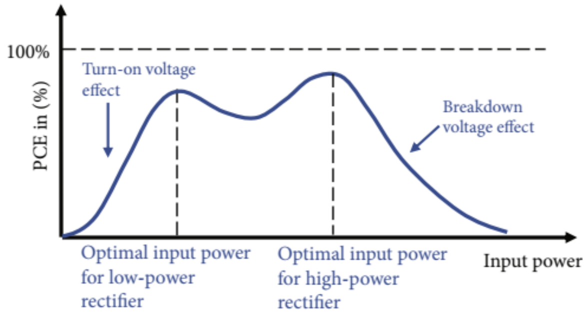


Figure 12: PCE over a rectifier's input power using adaptive path control (Arpanutud et al., 2022)

5 RECTENNA SYSTEM

Rectennas, or rectifying antennas, are crucial for RFEH applications. They combine a rectifier and an antenna into a single structure. The antenna's design significantly affects the radiationto-RF harvesting efficiency, which determines the potential DC output power. To enhance rectenna performance, various antenna designs like fractal, meandering, and slotted antennas are commonly used. Schottky diodes are often paired with rectifiers in these systems due to their advantages (Khan et al., 2022). A key component of RFEH system is the rectenna, depicted above in Fig. 2, it consists of an antenna that receives ambient electromagnetic waves and converts them into AC power, this AC power is then rectified to DC power by a rectifier/diode (Khan et al., 2022).

To ensure maximum power transfer from the antenna to the diode, an impedance matching network is placed between them, a LPF filter follows the diode to remove high order harmonics, delivering smooth DC power to the load, the overall efficiency of the rectenna system depends on the efficiency of its individual components, operating frequency, input power and the attached load (Khan et al., 2022). Table 3 shows the different rectifier topologies and performance were compared with literature review.

The rectenna system is an architecture that embodies an RFEH wireless node, including its sources of power, phases of conversion, and common applications in ISM (Industries, Science, Medicine) domain. It works by collecting radio frequency energy from the surrounding environment and converting RF signals into electrical power, usually with the use of Rectenna. After that, this power is put through a number of conversion steps to produce voltage levels that are appropriate for the node to run on. Sensor networks for medical device communication, scientific data collection, and industrial monitoring are common implementations within ISM applications as shown in Fig. 13 (Wagih et al., 2020b).

Of course, setting up the tools and processes required to guarantee accurately and dependable operation of the manufactured system is known as a calibration setup. The system's readings are compared to known values or preset criteria using calibration software, test devices, and reference standards in this configuration. The purpose of calibration is to guarantee that the system operates within specified tolerances and produces reliable outcomes for the intended uses as indicated in the Fig. 14 (Prashad et al., 2023).

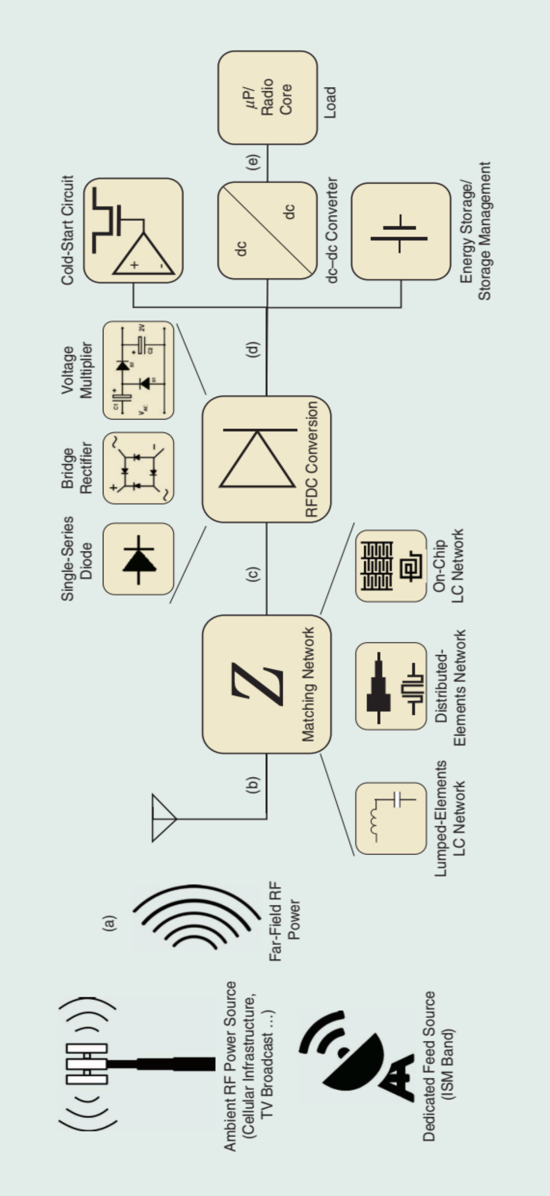


Figure 13: The rectenna system integrates RFEH wireless nodes (Wagih et al., 2020b)

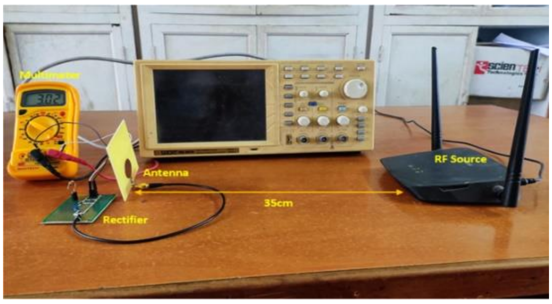


Figure 14: The established apparatus's calibration setup (Prashad et al., 2023)

Table 3: A Performance comparison of rectifier circuit for RFEH System Applications

Ref. Year	RF Band [GHz]	Rectifier Topology	Schottky Diode	Pin [dBm]	Output voltage [V]	Peak conversion efficiency (PCE%) @ load R_L [KΩ]
(Nguyen et al., 2020)	5.8	VDR	HSMS-2860	7	3	75% @ 6.8
(Derbal and Nedil, 2020)	3.5 5.8	Dual band with VDR	SMS-7630	0	0.656	44% @ 0.5 29% @ 0.5
(Cai et al., 2021)	5.8	HWR with one series connect	SMS-7630	-4	1.7	61% @ NR
(Khan et al., 2022)	2.4 5.8	Single stage VDR	HSMS-2850	14 11	1.1	71.0% @ 1.25 51.9% @ 1.25
(Derbal and Nedil, 2023)	5.8	HWR with one series connect	SMS-7630	-10	0.423	44.5 % @ 3.65
(Aboualalaa et al., 2020)	0.7 1.4	HWR with one series connect	SMS-7630	- 6.5 - 4.5	0.7	74% @ 1.9 70% @ 1.9
(Zhao et al., 2020)	2.4 5.2	HWR with one series connect	HSMS-2860	13 13	1.4 1.53	63.38% @ 0.15 65.40% @ 0.15
(Pandey et al., 2021)	3.2	Single satge FWR	HSMS 270B	0 10 20	10.703	88.58% @ 100 34.70% @ 100 53.52% @ 100
(Li et al., 2024)	2.45 5.8	Dual band VDR	HSMS-2852	9 11	2.46 2.57	63.6% @ 1.2 43.8% @ 1.2
(Shen et al., 2019)	0.9 1.8	HWR with one series connect	HSMS-2850	-20 -20	1.05	38.1% @ 7 34.0% @ 7
(Kim et al., 2023)	0.9 1.8	Single stage VDR	SMS-7630	-3	0.21	75.6% @ 12
(Chandravanshi et al., 2021)	1.8 2.45	Single stage VDR	SMS-7630	-12	1.2 0.98	40% @ 2.5 33% @ 2.5
(Le et al., 2021)	2.45 5.8	Single stage VDR	HSMS-2860	-10 to 0	1.36 1.28	47.45% @ 1 42% @ 1
(Vinnakota et al., 2019)	5.8	Single stage VDR	SMS-7630	0	0.6	41% @ 1
(Huang et al., 2024)	5.8	HWR with one shunt connect	HSMS 286C	16.7	3.17	59.6% @ 0.6
(Tafekirt et al., 2020)	0.9 1.8 2.45	Single stage VDR with triple bands	HSMS-2852	0	> 1.3	46.5% @ 3.8
(Liu et al., 2020)	0.915 2.45	Single stage VDR with dual	SMS-7630	-1	1.375	69.2% @ 1.5 64.1% @ 1.5
(Bui et al., 2024)	1.8 3.2	Two parallel diodes with two series TL	BAT15 03W	0	2.18	70% @ 0.501

MSIC: Multi Section Impedance Conversion, VDR: Voltage Doubler Rectifier, FWR: Full Wave Rectifier, HWR: Half Wave Rectifier, TL: Transmission Line

6 CONCLUSION

In this review paper, we presented more than 60 published articles on energy harvesting systems for powered-battery low power electronic devices such as IoT and WSN devices which utilize at the 5G modern communication systems. The energy harvesting system consists of recevied antenna, impedance matching network, rectifier circuit, and band pass filter with load which it's usually named by Rectenna system (Rectifier and Antenna). The Rectenna system can be operated at different frequency bands based on the availability of ambient energy such as WiFi, LTE, and 5G bands.

This paper focuses on overview of the different Rectenna systems for RF energy harvesting applications. Tables 1, 2 shows different geometry structures of the receive antenna designs at different frequency bands which convert ambient RF energy to usable DC current. The most important structure is microstrip patch antenna (MPA) with defected ground structure (DGS) and Artificial Magnetic Conductor (AMC) metamaterial techniques. The efficient antenna design used for WSN application requires compact size, high efficiency with gain.

The other most important part of Rectenna systems is the rectifying circuit to convert RF energy to usable DC current. There are many rectifier topologies such as half and full wave rectifiers and voltage doubler (VDR) circuits based on Schottky tunnel diodes. The VDR is commonly used in this application due to enhancing both the DC output voltage and power conversion efficiency at the optimum load. Table 3 shows a different rectifier topology that can be a candidate for harvested system for WSN nodes.

Different Schottky diodes have been used in the rectifying circuit such as HSMS 28xx and SMS 7630. The maximum RF-DC efficiency was obtained using HSMS 2860 and HSMS 286B is about more than 70% due to have several features likes low threshold voltage (V_{th}), low turn on voltage (V_{on}), low series resistance (R_s) is 6Ω, low junction capacitance (C_j) is 0.75pF, and large breakdown voltage (V_{br}) of 7V. The DC output voltage is about 4V ath the RF power of 20dBm.

The fully integrated receiving antenna with rectifying circuit using better impedance matching network. Table 4 presents a different Rectenna for energy harvesting applications in order to transfer power from the ambient environment to charging a WSN node. In my opinion, this review article will assist many researchers in the Rectenna systems design for RF energy harvesting applications.

Table 4: Performance comparison of the different Rectenna systems for RF energy harvesting applications

Ref. Year	**Rectenna configuration (Antenna, Rectifier)**	**Freq bands [GHz]**	**Pin [dBm]**	**Vout [V]**	**Max PCE [%]**	**R_L [KΩ]**	**Applications**
(Derbal and Nedil, 2020)	Coupled antenna, inductors, stubs and two diodes in parallel are used	3.5 5.8	0	0.656	44% 29%	0.5	Energy harvesting in wireless sensor networks.
(Cai et al., 2021)	Microstrip patch antenna array, TL where SMS 7630 schottky diode used	5.8	0	1.8	60%	1.18	RF energy harvesting from varying time and space sources.
(Khan et al., 2022)	Multiband compact patch antenna, Voltage doubler	2.4 5.8	14 11	3.5 2.2	71% 51.9%	1.25	Wireless power transmission, IoT devices and smart home systems.
(Derbal and Nedil, 2023)	DC combining for the proposed hexagonal rectenna array	5.8	-10	0.42	67.75 %	4	Wireless Power Transfer
(Aboualalaa et al., 2020)	CPW rectifier integrated with a rectangular split ring antenna	0.7 1.4	-20	0.18	47% 36%	1.9	Wireless Sensor Networks, Internet of Things and Smart Cities
(Zhao et al., 2020)	CPW FS antenna, Half wave rectifier	2.4 5.2	13	1.4 1.53	63.38 % 65.4%	0.15	WSNs, Remote and Low Power Electronics and Emergency systems
(Pandey et al., 2021)	Microstrip patch antenna, Voltage doubler rectifier	1.975-4.744	0	10.7	88.58 %	100	RFEH and Battery-less Power Sensors.
(Sakai et al., 2021)	Short-Stub-Connected High-Impedance dipole antenna, Bridge diode rectifier	5.8	30	29	92.8	0.89	Wireless Power Transfer, Energy Harvesting and Medical Devices.
(Li et al., 2024)	RP and defective ground, omnidirectional antenna, Voltage doubler rectifier	2.45 5.8	10	2.96 2.41	65.1% 38.4%	1.2	Efficient energy harvesting to power sensor nodes
(Shen et al., 2019)	Multi port dual band antenna, Series single diode rectifier	0.94 1.84	-20	3.2	38.1% 34.0%	7	Powers remote environment sensors and provides power to network nodes.
(Chandravanshi et al., 2021)	DRSM antenna, Voltage doubler rectifier	1.8 2.45	-12	1.2 0.98	40% 33%	2.5	WSNs, Smart wearable technology and IoT.

(Le et al., 2021)	Dual band ring antenna, Voltage doubler rectifier	2.45 5.8	-10 to 0	1.36 1.28	47.45 % 42%		Autonomous wireless sensor nodes and low-power wireless sensors.
(Vinnakota et al., 2019)	Aperture-Coupled patch antenna, Voltage doubler rectifier	5.8	0	0.7	41%	1	sensors networks, wireless communication systems and IoT devices.
(Saravanan and Priya, 2022)	Tri-band patch antenna, Voltage doubler rectifier	2.45 5.05 4.075	-10	0.298 0.275 0.256	54% 47% 43%	---	wireless sensor devices with low power consumption.
(Duy et al., 2020)	Single antenna element has four ports, full wave rectifier	5.8	0	1.3	57.82 %	0.501	WSNs, environmental monitoring and smart agriculture.

TL: Transmission lines, CPW: Co-Planar Waveguide, FS: Folded Slot, RP: Radiation Patch, DRSM: Dual Ring-Shaped Monopole, IoT: Internet of Things.

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