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Different Topologies of Efficient Rectifier Circuits for Energy Harvesting: A Review

Reem Fawaz Abdulkareem[1], Asst. Prof. Dr. Shamil H. Hussein Al-Najjar[2*]
[1,2*]*Department of Electrical Engineering, University of Mosul, Mosul, Iraq*
[1]*reem.enp37@student.uomosul.edu.iq*, [2]*shamil_alnajjar1984@uomosul.edu.iq*

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Abstract:
Energy harvesting systems have emerged as a promising solution for powering low-energy wireless devices, eliminating the need for frequent battery replacements in applications such as wireless sensor networks (WSNs), Internet of Things (IoT) devices, biomedical implants, and radio-frequency identification (RFID) systems. The RF energy harvesting (RFEH) system is an exception among energy harvesting techniques due to ambient RF signals from Wi-Fi, cellular networks, and other communication systems being readily available. The rectifier circuit is an important component of the RFEH systems which converts RF signals into usable DC power and operates at 5G frequency bands. This paper presents a comprehensive review of state-of-the-art rectifier topologies such as voltage doubler rectifier (VDR), reconfigurable rectifiers, differential drive rectifiers (DDR), and CMOS/Schottky diode-based designs. Different key challenges are discussed including power conversion efficiency (PCE%), adaptability to low input power environments, sensitivity, and broadband operation. Additionally, this paper describes the consideration of antenna structures and the impedance matching methods for maximizing energy harvesting and transferring. Finally, this review provides helpful guidance for researchers of future RFEH systems and organizes the path for battery-less, sustainable wireless technology.

Keywords: *Rectifier circuit topologies, Energy harvesting systems, Power conversion harvesting, Impedance matching networks, and 5G bands.*

1 Introduction

Triggered by the development of sensor technologies and the need for smaller devices, the search for new energy solutions for powering such devices and to decrease the dependency on traditional batteries while using and harvesting a variety of environmental energy sources has become a necessity. This requirement is what gave rise to energy harvesting, a technology that captures and converts energy from the environment into electrical power, which is then used to operate electronic devices without external power sources as in today's systems. This technology is particularly useful for small, standalone devices, wireless sensors, and Internet of Things (IoT) applications, reducing maintenance costs and improving sustainability (Sanislav et al., 2021).

Many new reports have reported that circular energy systems rely on various sources, including: Solar energy (optical energy) provides a constant amount of energy that varies depending on the availability and intensity of light. Thermal energy generated from industrial processes works efficiently in industrial applications, but its applications in the Internet of Things are limited. Kinetic energy converts pressure and continuous movement into electrical energy. Each of the different sources has its own advantages and limitations (Sanislav et al., 2021).

The final and most important type of energy harvesting system is harvesting energy from electrical waves generated by surrounding communications networks and converting it into electrical energy. This technology enables low-power electronic devices to be operated wirelessly without the need for batteries. Compared to traditional energy sources and many other alternatives, RFEH stands out with several key features that make it a focal point of modern research and wireless energy applications. One of its most significant advantages is its availability everywhere, as RF energy is abundant in modern environments due to the widespread use of wireless communication systems such as Wi-Fi, cellular networks, and radio transmitters, providing a continuous and easily accessible energy source (Odiamenhi et al., 2024).

In addition, one of the most important features of radio frequency energy harvesting systems is their versatility, as they can be used across a wide range of input power. This feature gives them the ability to adapt to provide effective solutions to meet the needs of different applications. Based on these features, previous research has focused on developing more sustainable solutions, such as smart home applications, health and security monitoring systems, and industrial applications, as these solutions increase device lifespan and autonomy due to the widespread availability of RF energy (Halimi et al., 2022).

The energy harvesting system consists of three main parts: the antenna, which is responsible for collecting the surrounding electrical waves, the rectifier circuit, and the matching circuit. Most systems end with the last part, which is the load to be operated by Fig. 1. An antenna captures radio frequency energy, which occurs in the form of electromagnetic waves, from surrounding sources (communication systems and Wi-Fi networks). The efficiency of radio frequency energy harvesting systems depends largely on antenna design, as each design has specific operating frequency ranges that achieve maximum energy capture efficiency. High efficiency is particularly important in harvesting energy from weak signals.(Muhammad et al., 2020).

To achieve these features, a balance between antenna size and performance is required, as good performance requires a larger size, which poses a particular difficulty for applications that require a small size. For example, in the design of broadband RFEH antennas, careful consideration is given to antenna parameters to optimize performance. The rectifying circuit is the main component of EH systems that transform radiofrequency energy from existing sources into DC power. The purpose of the impedance matching network is to match the input impedance of the rectifier to the antenna for maximum power transfer.

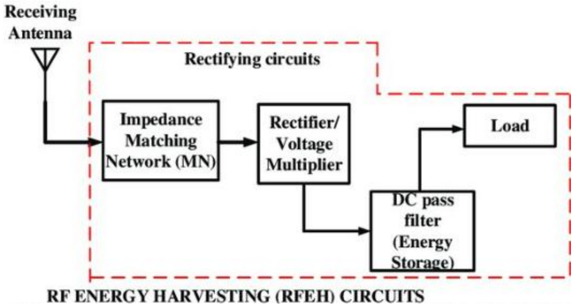

Figure 1: Schematic diagram of the radio-frequency energy harvesting systems (Muhammad et al., 2020)

The conversion of radio frequency signals into direct current (DC) used to power low-power devices is one of the most important features of RF energy harvesting systems. Input power, load size and requirements, required conversion efficiency, small size, and device complexity are the most important criteria for selecting the rectifier circuit design, the most important component of RF energy harvesting systems. Traditional diode-based rectifier circuits such as series, shunt diode rectifiers, Dickson rectifiers, half and full wave rectifiers, suffer from low power conversion efficiency with poor sensitivity at ultra-low input power due to high drop-voltage. Therefore, different topologies of rectifier circuit design have been used such as single band, multiband rectifiers, broadband rectifiers, voltage multipliers, differential drive rectifiers, reconfigurable rectifiers, CMOS, and Schottky diode rectifier circuits (Odiamenhi et al., 2024).

The operation and performance of a rectifier are significantly influenced by the selected operating frequency range (0.9 GHz, 1.8 GHz, and millimeter wave). Due to the good balance between switching efficiency and threshold voltage, Schottky diode-based designs are typically used at lower frequencies (0.9–2.4 GHz). However, millimeter wave frequencies require specialized CMOS applications to address parasitic effects and impedance matching issues. Schottky diodes also offer a significant advantage in switching time compared to conventional diodes because they do not rely on recombination of electrons and holes as they move through parallel. Therefore, they are ideal for energy harvesting circuits that require high switching speed and operate at very high frequencies (Reddaf et al., 2024a).

Recent studies highlight tunnel diodes as particularly promising for mm-wave rectification, offering superior high-frequency performance compared to conventional Schottky diodes. For instance, Asymmetric Spacer Layer Tunnel Diode (ASPAT) tunnel diode as demonstrated in (Muttlak et al., 2022) by Muttlak, Saad G., et al. in 2022. They proposed a new completely integrated rectenna system design that uses an ASPAT as the active rectifier for implantable medical devices (IMDs) because of its high non-linearity and temperature insensitivity. The rectenna has a Cockcroft-Walton rectifier built into its compact (1×5 mm^2) architecture and an L-shaped planar folded antenna that operates at the ISM frequency band of 2.4GHz. For a 5 cm transmission distance, experimental results showed an output voltage of 0.8 V at 20 dBm transmit power.

Other enhancements are anticipated for multistage designs, which will achieve 0.24 mW output power at 23 dBm. The study demonstrates the possibility of wireless power transfer in implantable devices, backed by comparisons with cutting-edge technologies and experimental confirmation.

This article provides a comprehensive review of the latest advances in practical RF-DC rectifier development over the years, as well as providing an overview of the RFEH front-end circuit, which consists of the antenna, impedance matching network, and rectifier. In section II, the review covers different antenna structures that operate at 5G bands and are used for RF energy harvesting applications. Section III, provides a brief overview of the different topologies for RF-DC rectifier circuits design. Section IV presents a comprehensive review of the future design aspects that contribute to a more efficient RFEH front-end system. Finally in section V, concludes this review article.

2 Antenna Design for RFEH System

Antennas in RF energy harvesting systems play an important role in capturing ambient RF signals to be converted into electrical energy. The efficiency of this energy capture greatly affects the overall performance of the system. RF energy harvesting antennas are typically designed in low-profile, multi-band, circularly polarized or array configurations, and are designed to optimize energy capture from various ambient sources. Important factors to consider when designing an antenna are impedance matching, bandwidth matching, and polarization matching to ensure maximum power transfer to the rectifier circuit. The efficiency of the receive antenna that is used in the RFEH systems in a specific direction is measured by antenna gain. Although they are necessary for RFEH, high-gain antennas work best when the energy source is well-maintained.

Unidirectional antennas are suitable for long-distance transmission, while the omni-directional antennas are used when the direction of incoming waves is unknown. Dual linearly polarized antennas reduce polarization mismatch for improved reception, while circularly polarized antennas absorb energy from several polarizations. Wearable and mobile applications, where compact form factors are essential, continue to face significant challenges in terms of miniaturization. Although high-gain antennas work well for harvesting RF energy, their size may restrict their application in portable systems. Table 1 shows a survey of some recent research in the field of antenna manufacturing in RF energy harvesting systems, reviewing the types used and an analysis of the results of each type (Ullah et al., 2022).

For the basic RFEH applications, dipole antennas are widely used due to providing high frequency response (Niamien, 2022). Microstrip patch antennas are the most commonly used for their low profile and ease of fabrication that achieve circular polarization to improve conversion efficiency. For mobile communications and RFID systems, monopole antennas are used and adaptable for circular polarization. The Yagi-Uda antenna is used for point-to-point communication systems and suitable for RFEH systems due to providing high gain and directivity. The slot antennas are compact design and suitable for high RFEH and RFID systems. To further improve antenna performance, the incorporation of metamaterials has been explored. Metamaterial antennas can behave as if they are larger than their physical size, effectively storing and re-radiating energy, which is useful for capturing weak RF signals in energy harvesting applications (Behera et al., 2023).

For compact electronic low power devices such as wireless and biomedical devices, small antennas were used and developed to address miniaturization challenges. One of the broadband antennas that have been performed to enhance the efficiency of RFEH systems is the self-complementary slot and patch structures which are operate at 2.45GHz resonant frequency (Smyth et al., 2024). The differential antenna based on triple-band frequency achieves maximum efficiency over 59% at -10dBm input power with a range from 2.1GHz to 3.8GHz (Bakytbekov et al., 2022a),. The fractal technique of antennas has up to 78% conversion efficiency and its suitable for compact RFEH systems.

3 RF-DC Rectifying Circuit Design

The main component of RF energy harvesting systems is the rectifier circuit, which converts the RF energy harvested from the environment into DC power used to power the load. Achieving high conversion efficiency is one of the most important goals of this circuit, especially in certain applications such as energy harvesting for wireless sensors and wireless power transmission. The basic component of rectifier circuits is the diode.

These circuits may consist of one or more diodes, and they are responsible for rectifying the alternating current coming from the antenna into DC power. The matching network, input power, and diode characteristics are among the most important factors on which the efficiency of rectifiers depends. Rectifier circuits operate in low-power environments, especially in sensitive devices, where semiconductors operate close to their lower activation thresholds. These thresholds vary depending on the diode type. The operating voltage for Schottky diodes ranges from 0.15 to 0.45 V, while for MOSFET transistors, it is slightly above the threshold voltage (V_TH). This provides effective rectification of weak RF signals (from -30 to -20 dBm), but as usual, this comes at the expense of manufacturing efficiency, as it requires careful design to eliminate the increased sensitivity to temperature and the resulting losses. Several fabrication topologies have been used to achieve this precision, including multi-stage and adaptive biasing (Xu et al., 2022) which have contributed to maintaining conversion efficiencies of over 20% even under the most severe operating conditions.

Recent research in rectifier design development focuses on improving conversion efficiency, increasing bandwidth, and compactness, making them more efficient in diverse applications and operating under varying conditions. Broadband rectifiers have been developed for small sizes, diverse radio frequency signal environments, and various power requirements, such as medical devices, microsensors, and the Internet of Things. Many rectifiers have also been developed to operate in multiple bands or at dual frequencies. In general, a balance must be struck between the conversion efficiency of a rectifier and its ability to operate effectively across a wide range of frequencies and input power levels, along with compactness, to ensure they are operational and deliver satisfactory results in diverse operating environments and practical applications. (Ibrahim et al., 2022).

Table 1: Performance comparison of different advanced antenna structures for RF energy harvesting applications

Ref. Year	*Operating Frequency [GHz]*	*Antenna Structure*	*Gain [dBi]*	*Radiation Efficiency [%]*	*Power Radiated (Pin) [dBm]*	*Applications*
(Zhang et al., 2021)	0.915	Dual-Antenna Energy Harvesting	3.1	----	----	IoT/WSN
(Eltresy et al., 2021)	5.8	ITO Transparent Antenna Array	5	70.8	-10	IoT/ 5G
(Bakytbekov et al., 2022b)	0.9	Dual-Function Triple-Band Heatsink Antenna	3.8	80	----	Self-powered IoT
	1.8		4			
	2.1		5.3			
(Morsy and Saleh, 2022)	0.35 – 0.65	Integrated Solar Mesh Dipole antenna	---	83	----	Solar and RFEH System for IoT, Smart Devices.
(Muttlak et al., 2022)	2.4	Folded Dipole Antenna (FDA)	-26.9	15	-30	RFEH for powering of IMDs
(Kim et al., 2023)	1.2	Broadband Stepped Bow-Tie Antenna	0.96	80	-21.1 to 10.6	RF Energy Harvesting powering of IoT sensors
	2.6		4.74			
(Das et al., 2023)	2.57	Magnetoelectric (ME) Antenna	---	----	−1	Implantable devices
	6.363					
(Derbal and Nedil, 2023)	5.8	CP Hexagonal Antenna Array with FSS technique	12.7	97.2	−10	RF Energy Harvesting for powering of Wireless Sensor Networks (WSNs)
(Nadali et al., 2024)	0.603-0.930	Dual-Band Dual-Polarized Printed Antenna	3.5	85	−15	RF Energy Harvesting in Cellular and Digital Terrestrial Television Bands
	1.64 - 1.89			63		
(Gimenez-Guzman et al., 2024)	0.915	Dual-Band Patch Antenna with EBG	7.1	94.3	5	Energy Autonomous RFID-Based Real-Time Battery Level Monitoring
	2.48		9.2	83.8		

3.1 Diode Rectifiers for RF Energy Harvesting

In RF energy harvesting rectifier circuits, diode selection significantly impacts efficiency and performance, particularly in low-voltage and low-power applications. Schottky diodes are widely preferred due to their low forward voltage drop (typically between 0.15V and 0.45V) and fast switching speeds, making them ideal for both low-voltage and high-frequency scenarios, such as wireless sensor networks (WSNs) and IoT applications. In contrast, silicon diodes, with a higher forward voltage drop (around 0.7V), are more suitable for higher-voltage applications. Germanium diodes offer lower forward voltage drops compared to silicon-based diodes, providing improved efficiency in low-power applications, though their higher reverse leakage currents limit their use in high-efficiency systems (Roy et al., 2021).

P-N junction diodes, despite their higher voltage drop, are cost-effective and commonly utilized in multi-stage rectifiers to enhance DC output voltage in energy harvesting systems, particularly in higher-power applications. Additionally, specialized diodes such as tunnel diodes, with their negative resistance properties, are occasionally used in high-frequency applications but have a narrow operating range, limiting their versatility (Halimi et al., 2022).

PIN diodes, featuring an intrinsic layer between the p-type and n-type materials, are employed in high-frequency rectifiers where high linearity and power-handling capabilities are required, making them suitable for medium to high-power RF energy harvesting systems. The RF-DC rectifier circuits are a core component in the RFEH systems which are used for converting RF energy harvested by antennas to usable DC current for powering of low power electronic devices, the performances of these circuits can be evaluated based on the following points (Xu et al., 2022).

Various diode types are utilized in RF energy harvesting, each with its own unique features. Low turn on voltage (0.15-0.45V) and wide power range (-30 to 20 dBm), Schottky diodes (e.g. SMS7630) are available for most applications. Faster switching is better achieved with PIN diodes, but they have a high turn-on voltage (~0.7V). Commonly used varactor diodes allow for tunability but come with high losses. Tunnel diodes (such as ASPAT) perform well at mm-Wave frequencies, providing high nonlinearity; however, matching is critical! At very low power (−40 dBm) zero-bias Schottky diodes (for example, HSMS-2850 devices) exhibit good performance, but performance falls off at higher signal levels. Which to choose depends on frequencies, power levels, and required applications (Xu et al., 2022).

Schottky diodes, such as the SMS7630, offer the best trade-off when it comes to performance, with low Vth (0.15–0.45V), a large dynamic range (-30 to 20 dBm), and compatibility with frequencies ranging from 0.9 to 5.8 GHz. While SiC diodes support high-power applications, they are inefficient for weak RF signals. In comparison, GaAs diodes extend operation to 100 GHz but have a higher Vth (~0.7V). Tunnel diodes perform better for mm-Wave harvesting than traditional Schottky devices, although integration is still difficult. In order to maximize efficiency across a range of power and frequency, future rectifier designs may make use of hybrid diode combinations.

3.1.1 Sensitivity of the Rectifiers

The sensitivity of a rectifier is the minimum amount of input power required to produce a 1 V DC output at the desired output load. To ensure that the RFEH system is operational and can operate reliably in a real-world environment, this metric is critical. The rectifier sensitivity can be expressed as follows (Pozar, 2012).

$$P(dBm) = 10log_{10}P(mw) \qquad (1)$$

Where P(mw) is the power received by the rectifier, expressed in milliwatts, and P(dBm) is the rectifier's sensitivity, expressed in dBm.

3.1.2 Power Conversion Efficiency (PCE%)

The power conversion efficiency (PCE) of an RF rectifier, denoted η_{REC} (%), represents the ratio of the output DC power (P_{DC}) to the input RF power (P_{RF}), expressed as η_{REC} (%) in Equation 2. This key performance measure determines how effectively a rectifier converts the output RF power into usable DC power in low-power electronic devices. Power conversion efficiency (PCE) depends on factors including input power level, operating frequency, diode characteristics, and impedance matching; higher values indicate more efficient power conversion (Muttlak et al., 2022).

$$\eta_{RF}(\%) = \frac{P_{DC}(dBm)}{P_{RF}(dBm)} * 100\% \qquad (2)$$

3.1.3 Power Dynamic Range (PDR)

The power dynamic range (PDR) of the rectifier circuits is the range of input power at which it maintains a PCE above 20%. According to the definition, the relationship between the rectifier's PDR and PCE is as follows (Pozar, 2012)

$$PDR(dB) = 100\% \geq \eta_{RF} \geq 20\% \qquad (3)$$

Where η_{RF} is a PCE% of the rectifier, and PDR is the power dynamic range in dB. The RFEH is more reliable in an RF ambient with different power densities when performance maintains a wide PDR.

An efficient rectifier design is shown below that combines a Schottky diode for low-voltage DC rectification with MOSFETs that use pulse-width modulation (PWM)-controlled active switching to improve output smoothing and reduce power loss. By better controlling power and reducing voltage drops, this method maximizes power conversion efficiency. The implementation of this design is illustrated in the following circuit diagram as shown in Fig. 2, which shows how the use of pulse-width modulated MOSFETs and Schottky diodes improves rectification performance while maintaining a constant DC output (Dai et al., 2015).

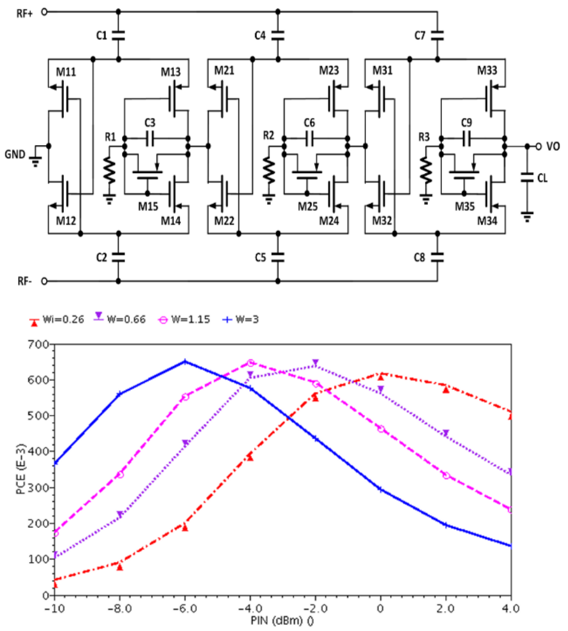

Figure 2: Three stage rectifier circuit designed based on cross-coupled (CC) NMOS switches integrated with two PMOS diodes (Dai et al., 2015): (a) Schematic diagram, (b) simulated PCE% as a function of input power for different widths of PMOS transistors.

3.2 Rectifier Topologies for RF Energy Harvesting

Improving the performance of RF energy harvesting circuits depends primarily on selecting the appropriate rectifier topology, as it is the main component in converting RF energy present in the environment into direct current and using it to operate the required devices and loads. This makes it suitable for operating devices used in applications that require low power, as well as in environments that contain low input power, such as Internet of Things devices, sensors, medical monitoring devices, and biomedical implants.(Xu et al., 2022). The efficiency of RF energy harvesting circuits is mainly influenced by the characteristics of the rectifier and its ability to operate in diverse environments with different input power levels and varying operating frequencies depending on the distance from the RF source.

Balancing component optimization, maximizing power recovery, managing losses, and, most importantly, circuit topology is among the most important factors involved in selecting the right rectifier. Proper rectifier design ensures stable and reliable power harvesting in variable environments by overcoming the challenges of low input power, a wide operating frequency range, and the minimum required conversion efficiency. Half-wave rectifiers are simpler but less efficient because they use half of the AC cycle. Full-wave rectifiers overcome this problem by using the full AC wave. Polar bridge rectifiers are more complex due to the additional diodes they contain, but they are best suited for harvesting energy from small AC signals, as they convert the AC current to DC. Diode-based rectifiers, including Schottky diode-based designs, are widely used due to their lower threshold voltages, making them ideal for low-power applications. Dickson rectifiers, commonly found in voltage multiplier circuits, achieve higher output voltages but suffer from poor sensitivity and lower power conversion efficiency (PCE) at low input levels (Ibrahim et al., 2022).

Cross-Coupled Differential-Drive (CCDD) rectifiers improve efficiency and sensitivity compared to Dickson rectifiers through differential drive and cross-coupling techniques, though they are limited by reverse leakage currents that affect power dynamic range (PDR) (Chun et al., 2022) as shown in Fig. 3. Class-E/F rectifiers minimize harmonic distortion and enhance PCE, making them particularly useful for low-power RF energy harvesting applications such as IoT and wireless sensor networks (WSNs) (Mansour and Mansour, 2025a).

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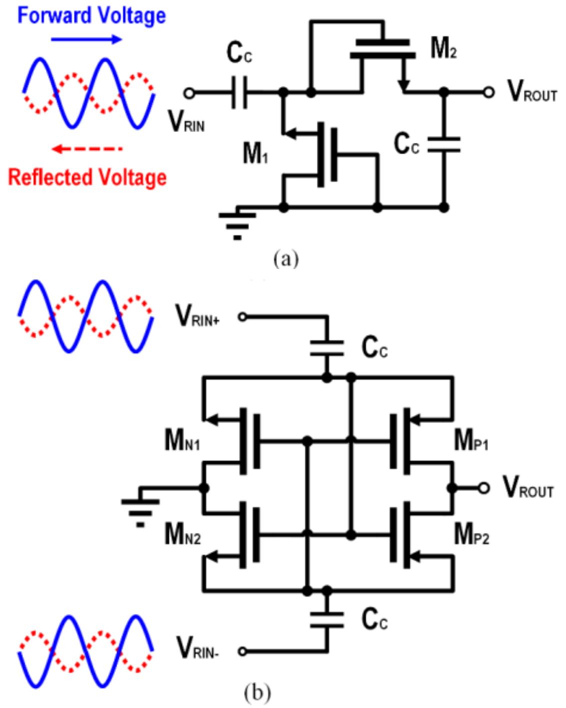

Figure 3: RF-DC rectifier circuits topology (Chun et al., 2022): (a) Dickson charge pump rectifier, (b) Cross-coupled differential drive (CCDD) rectifier

Broadband and multi-band rectifiers have gained popularity for their ability to operate over a wide frequency range, leveraging advanced impedance matching techniques and multi-stage designs to enhance adaptability in dynamic environments. High-efficiency CMOS rectifiers are increasingly favoured for their low cost and integration capabilities, particularly in applications requiring a wide PDR and minimal power consumption. Recent advancements have focused on improving efficiency and extending PDR for reliable RFEH performance in real-world conditions (Bui et al., 2024a).

Voltage doublers and multipliers play a crucial role in increasing DC output voltage, especially for low-power input signals, often being integrated with other rectifier designs to enhance efficiency, though their performance is highly dependent on input power levels and frequency stability. While traditional rectifiers such as Dickson and diode-connected MOSFET rectifiers widely used, advancements in multi-stage, broadband, and CMOS-based rectifiers offer improved performance across a wider range of input powers and frequencies, each presenting trade-offs in sensitivity, power conversion efficiency, and operational complexity (Bui et al., 2024a).

Rectifier topologies and power management techniques significantly influence overall system performance. Diode-connected MOSFETs are employed in high-frequency applications to create rectifiers with minimal power loss, leveraging their low on-resistance and fast switching capabilities. Active rectifiers, replacing traditional diodes with transistors or MOSFETs, can further reduce voltage drops and improve efficiency, even at lower input voltages. Pulse-width modulation (PWM) control for MOSFETs in active rectifiers helps maintain high efficiency by minimizing switching losses. Efficient rectifiers must also operate effectively at low input voltages, often below 1 Volt, necessitating the use of low-threshold voltage devices such as MOSFET-based rectifiers or optimized Schottky diodes. Operating MOSFETs in the subthreshold region enables rectification of low-voltage signals, which is particularly beneficial for ultra-low-power applications (Ballo et al., 2023).

The rectifying circuit converts the RF power signal received by the antenna into a usable DC voltage for battery-powered wireless devices. The diode is the most crucial parameter in the circuit. Therefore, choosing the correct diode is imperative. The overall rectenna's performance is influenced by the rectifier's performance (Abdulwali et al., 2023). a voltage doubler rectifier (VDR) is used to investigate the harmonic rectifier circuit. It's difficult to design a rectifier with higher rectification efficiency when the input power is low (Shin and Oh, 2024).

The RF to DC conversion efficiency is the main performance metric in the rectifier analysis. Schottky diodes are used to construct rectifier circuits at range of input RF power because they have a low threshold voltage (V_{th}), low series resistance (R_s), low junction capacitance (C_{jo}), and large breakdown voltage (V_{br}). Different Schottky diodes families have been investigated in the literature for energy harvesting application. These diodes are the most common microwave detector diode which has been used since 1940. It has been discovered that the SMS 7630 and HSMS 28xx diode families are suitable for both low and high RF input power. But, the drawback of SBD diodes is the transmission of the charge carriers by thermionic emission is dominant and the current transmission mechanism is highly influenced by temperature (Da Paz et al., 2023).

To achieve high efficiency in rectifier circuits for energy harvesting applications, selecting the right topology is crucial. The efficiency of a rectifier circuit directly impacts the overall performance of the energy harvesting system. Bandwidth and operating frequency are the most important factors influencing this selection. Broadband or multi-band rectifiers are preferred in variable environments to ensure continuous energy harvesting, (Pandey et al., 2024). while single-band rectifiers are suitable for environments with a fixed ISM frequency of 2.4 GHz. (Du et al., 2024),

Schottky rectifiers based on Schottky diodes are commonly used due to their low threshold voltage and high efficiency. Power conversion efficiency (PCE) is a key factor, as the harvested RF power is often less than milliwatts. For wireless sensor networks (WSNs) and IoT applications, advanced architectures, such as class E/F rectifiers, incorporate harmonic suppression to reduce power losses, making them ideal for such applications. (Mouapi et al., 2019). Since RF power levels are affected by distance, obstacles, and interference, wide power dynamic range (PDR) rectifiers, such as CMOS-based designs, are of critical importance, maintaining high efficiency despite variations in input power (Chun et al., 2022).

There are many researches published in the rectifier circuits design which is used in the RFEH applications. The work in Ref. (DeLong et al., 2018)developed by Daasari, et al. in 2021 through increased PCE and output voltage. They proposed a VDR circuit based on the SMS7630 Schottky barrier diode to be applied for the transfer of delivered RF-energy by the antennas. Figure. 4 depicts the proposed diode model's equivalent circuit. The rectifier circuit is designed by using ADS simulation with dimension is [27.5×19.75×1.6] mm^3 and operates at 2.4 GHz. It is insensitive to a broad range of RF-input power levels between (-30dBm to 20dBm). At a 0dBm input-power, the max. measured PCE of 47.7%, with output voltages of 1.68V.

To ensure the RFEH system operates efficiently in a highly dynamic RF environment, this paper explores advanced rectifier topologies have been carried out to extend the PDR, achieving a high PCE and good sensitivity such as differential-drive and feedback-enhanced architectures (CMOS RF-DC rectifier and self-biasing technique), and reconfigurable rectifiers (wide dynamic range designs) (Chun et al., 2022).

Lu, Yan, et al. in 2016 (Lu et al., 2016) proposed a five stage Cross-coupled Differential drive (CCDD) rectifier circuit based dual-path structure using 65nm CMOS process for RF energy harvesting and operating at the frequency of 900MHz. The proposed circuit achieves a PDR of 11 dB and driving a load resistance of 147kΩ. The measured PCE% about 20% and sensitivity of -17.7dBm when the RF input power is -16 to -5 dBm and output voltage of 1V.

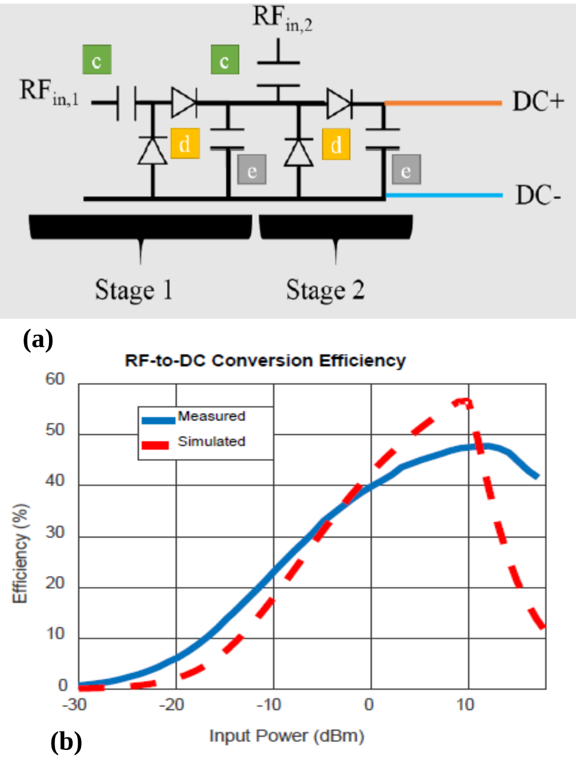

Figure 4: Two stages of the voltage doubler rectifier based on SBD diodes (DeLong et al., 2018): (a) Schematic circuit design, (b) measured power conversion efficiency

Moreover, a reconfigurable rectifier described in (Khan et al., 2020) maximizes the operating range of the RFEH system by adaptively switching between a series path and a parallel path during low power operation and a wide PDR during high power operation, as shown in Fig. 5(a). Feedback diode-connected transistors, which are positioned to be reverse-biased for RF input and forward-biased of DC output, are used in (Aboulsaad et al., 2020) to replace the feedback resistors. This allows the RF signal to pass from the input to the output as seen in Fig. 5(b).

System size and integration are essential, particularly for miniaturized applications like IoT devices and biomedical implants (Dawood Butt et al., 2022), where the rectifiers with seamless integration into matching networks and antennas are preferred.

The rectifier's ability to provide higher output voltages in smaller float designs makes CMOS-based AC rectifiers and multi-stage configurations the preferred choice for battery-free systems (La Rosa et al., 2024). The rectifier is selected based on the application-specific requirements. For example,

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advanced designs such as CCD rectifiers and voltage doubler rectifiers are used in wireless power transfer (WPT) applications and medical implants where they must maintain high efficiency in harsh environments. Rectifiers with high sensitivity to weak RF signals are widely used in remote applications, such as agriculture or environmental sensing (Noghabaei et al., 2021).

Schottky diode and multistage rectifiers are typically used to maximize power conversion in conditions where input power is low. Rectifiers must operate efficiently even under low ambient RF power, as efficiency is one of the most important factors in such conditions.(Reddaf et al., 2024b). Therefore, the operating environment, frequency range, power requirements, system size, and efficiency goals all influence the selection of rectifier topology, and a comprehensive understanding of these aspects is essential to ensure sustainable and efficient RF energy harvesting across various applications.

Table 2 shows the latest technologies used in rectifier circuits for RF energy harvesting applications and their respective performance.

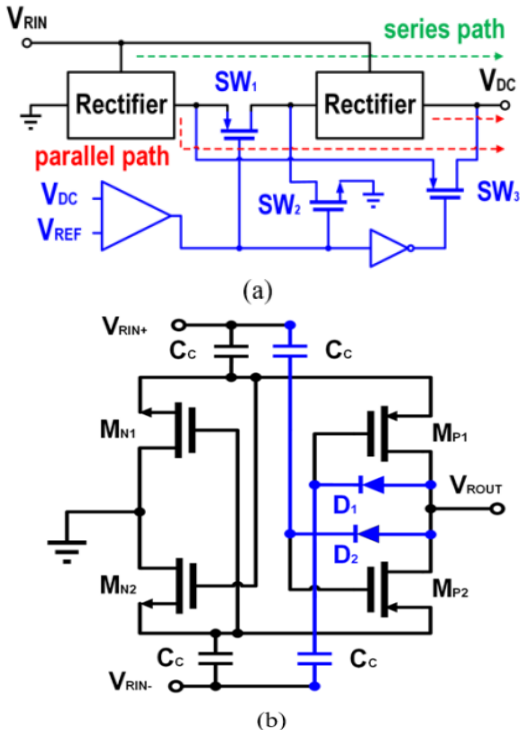

Figure 5: RF-DC CCDD rectifier circuits with wide PDR based on (Khan et al., 2020) (Aboulsaad et al., 2020): (a) Reconfigurable rectifier, (b) self-biased technique

Table 2: Performances comparison of recent published works on rectifier circuits design for RFEH applications

Ref. Year	***Freq. [GHz]***	***Rectifier Topology***	***Diode Type***	***RF to DC Efficiency [%]***	***RL [kΩ]***	***Input Power [dBm]***	***Application***
(Keshavarz and Shariati, 2022)	5.8	Voltage-Doubler Rectifier (VDR)	Schottky HSMS2850	70	11	-10	RFEH for powering of IoT and WSNs
(Muttlak et al., 2022)	2.4	Single and Multi-stages Voltage-Doubler Rectifier (VDR)	ASPAT tunnel diodes	15	10	-30	RFEH for powering of IMDs
(Roy et al., 2022)	0.9	Voltage-Doubler Rectifier (VDR)	Schottky HSMS286C	52	6.18	-20	RFEH for powering of IoT and WSNs
	2.12			55	-7.5		
(Nam et al., 2023)	0.91	Dual-Band Inverse Doherty rectifier	Schottky BAT15-03W	79.95	0.5	13	RFEH for powering of wireless sensors
	2.4			77.67		12.5	
(Paz et al., 2023)	2.4	Series RF rectifier	Schottky SMS7630	25.33	---	-20	RFEH for powering of temperature sensor
(Lian et al., 2023)	1.9	Adaptive Dual-Band Dickson charge pump (DCP) rectifier	CMOS-based Diodes	40	80	-25 to 2	RFEH for powering of wireless medical sensors
	2.4			32			

(Eshaghi and Rashidzadeh, 2024)	5.2	Dickson charge pump (DCP) rectifier	Schottky BAT1504W, HSMS286C	73.46	0.5	-25	RFEH for powering of IoT sensors in 5G systems
				49.12	1000	15	
(Bui et al., 2024b)	1.64 - 3.18	shunt-diode half wave rectifier configuration	Schottky BAT15-03W	70	0.51	13	WPT and EH
(Diniz et al., 2024)	2.4	series-diode half wave rectifier configuration	Schottky SMS7630	16.93	2.9	−20	low-power applications
(Mansour and Mansour, 2025b)	0.9	Class-E/F2 shunt rectifier	Schottky HSMS2850	50	4.3	0	RFEH for powering of IoT sensors in GSM and LTE systems
				56		-10	
(Huang et al., 2024)	5.8	single-stage rectifier	Schottky HSMS-286C	59.6	0.6	16.7	WSN, RFID, Medical devices

4 Advanced RF Energy Harvesting Systems

Radio frequency energy harvesting systems have become the ideal solution for powering low-power devices, which in turn has provided significant progress in manufacturing small-sized devices that can be worn or injected into the body, establishing independent wireless sensor networks, and the great development in self-sustaining and self-sufficient Internet of Things devices. Accordingly, this article presents a study of the latest developments in radio frequency energy harvesting systems, reviewing design challenges and new developments.(Younis and Hussein, 2024).

The diverse uses of radio frequency energy harvesting (RFEH) and how it can be integrated with other energy sources are also discussed in this article. Advanced radio frequency energy harvesting (RFEH) systems have played a crucial role in enabling the sustainable operation of Internet of Things (IoT) devices and sensors without the need for batteries. Ambient energy harvesting, which results in low power levels, or dedicated transmission, which results in high power, are two distinct methods for energy transfer.(Chun et al., 2022).

A receiving antenna, an impedance matching network, a rectifier circuit, and a load terminal are the main components that make up RFEH systems, specifically the rectenna. Selecting the best diode, designing a suitable impedance matching network, and selecting the best topology for the energy harvesting circuit are the steps in the design process.(Hussein and Mohammed, 2023).

Impedance matching networks (IMNs) improve power transfer between rectifiers and antennas in RF energy harvesting systems. L-type or π-type core networks, used in single-band rectifiers, are tuned to a specific frequency of 2.4 GHz. Multi-band systems combine multiple discrete frequencies using cascaded or tunable networks (such as varactor networks). Wideband rectifiers use multiple methods to cover a continuous frequency range (1–5 GHz), such as multi-section transformers or tapered transmission lines. To maintain efficiency over a range of input power levels and frequencies, advanced IMNs can use adaptive tuning, ensuring maximum performance under real-time RF conditions.

A simple matching circuit consists of a capacitor, an inductor, and a resistor. The actual resistance component is the resistor, while the reactive components are the inductor and the capacitor. Using only resistors to match the resistance results in power loss. Increasing the RF input voltage level of the rectifier and improving the power transfer from the receiving antenna to the rectifier circuit are the main objectives of the impedance matching network. L-type, π-type, and T-type networks are the three basic types of matching networks for RFEH as shown in Figure 6 (Bougas et al., 2021).

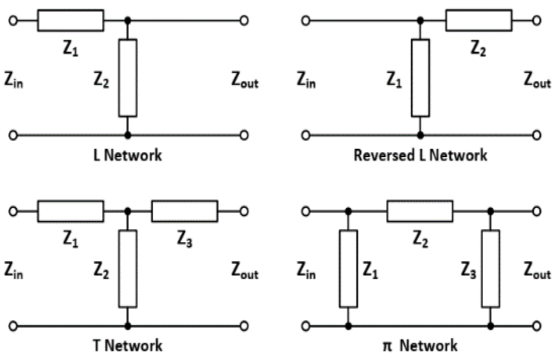

Figure 6: Different topologies of an impedance matching networks (IMNs) used for rectifier RFEH systems (Bougas et al., 2021): L-matched network, Reversed L-matched network, T-type and π matched network

The L-matching network must increase the load impedance when it is smaller than the antenna impedance; conversely, it must lower it. Consequently, it aids in the uphill and downward load impedances, as illustrated in Figure 7 (Lee et al., 2023). Inductors carry low-frequency signals, while capacitors carry high-frequency ones. Consequently, in an L-matching network, a low-pass and high-pass L-matching transfer function are realized once the capacitor and inductor are flipped.

π type networks are superior to L type networks due to their bigger resonance amplitude and extra degree of freedom. π and T-shaped networks are two popular three-element networks that fall into low- and high-pass categories. A good match minimizes the reflection of harvested input RF signals. The reflection coefficient, S_{11} in dB, which is determined by.

$$S_{11} = \Gamma = (Z_{rect}-Z_{ant}*) /(Z_{rect}+Z_{ant}*) \ldots \ldots \ldots (4)$$

The L-matching is the simplest IMN network that has been used and researched for RFEH systems, where Z_{ant} is the impedance of the antenna, Z_{rect} is the impedance of the rectifier, and Γ is the reflection coefficient.

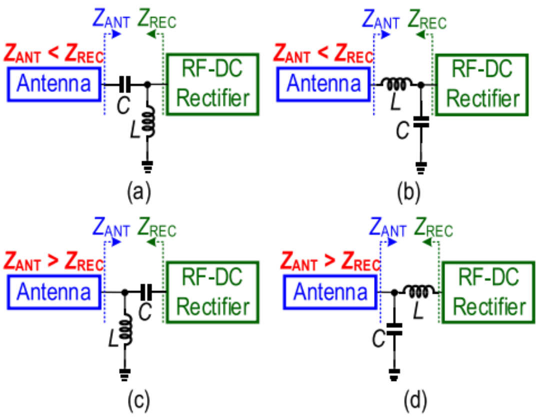

Figure 7: L-type IMNs for RFEH systems (Lee et al., 2023): (a), (b) High pass and Low-pass upward load transformation of impedance, (c), and (d) High and low pass downward load transformation of an impedances

RFEH wireless node power sources, conversion stages, and typical uses in industrial, scientific, and medical (ISM) fields are all represented in the straight antenna system design. This energy then goes through several conversion processes to generate the appropriate voltage levels to operate the node. As shown in Figure 9, sensor networks are frequently used in ISM applications for industrial monitoring, scientific data collection, and medical device connectivity (Wagih et al., 2020).

An example of such a system is the Flexible Meta-Patch Rectenna Array designed for wearable medical sensors. This rectenna array, constructed using a textile-based meta-surface, offers high efficiency (77%) and a broad bandwidth of 120 MHz, making it ideal for low-power applications. The system achieves power conversion efficiencies (PCE) of 52%, 53%, and 56% in single-element, 2 × 1, and 2 × 2 array configurations respectively, under continuous RF power. Another notable example is the broadband circularly polarized rectenna, which integrates a coplanar waveguide-fed circularly polarized antenna with an artificial magnetic conductor (AMC). This design boosts gains from 0.5-0.8dBi to 5-6.5dBi and achieves a peak PCE of 65% for a 7 dBm input power as shown in Fig. 8 (Bairappaka et al., 2024).

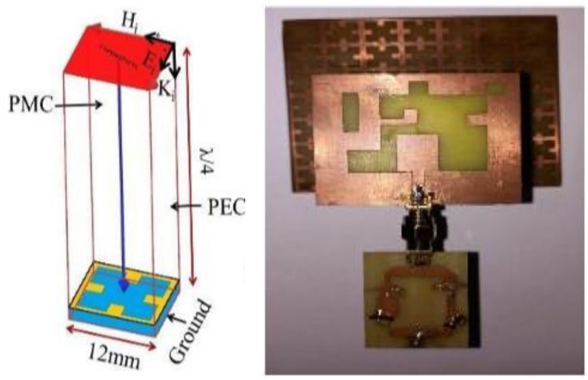

Figure 8: Circularly polarized CP rectenna systems based on AMC metamaterials at the frequency of 2.4GHz

Additionally, the Class-F Harmonic Rectenna uses a dual-band rectifier structure to maximize efficiency at low RF input power levels, demonstrating a PCE of 71% at 868 MHz and 64% at 915 MHz (Moloudian et al., 2023). A versatile RF energy harvester has been developed for IoT sensors in 5G networks, utilizing power splitting techniques to balance harvested power and data rate. This approach addresses the challenge of interference caused by wide bandwidth signals, enhancing the reliability and efficiency of energy harvesting in dynamic 5G environments.

Lastly, the Flat-Panel Rectenna for wireless-powered sensors ensures broad RF energy harvesting coverage, with a half-power coverage of 144.6° and a peak RF-to-DC conversion efficiency of 51.8% (Han et al., 2024). The receiving antenna is fully integrated with the rectifying circuits based on Schottky diodes (SBDs) using proper IMNs. Different RFEH systems for many applications have been reported in Table 3. This review provides valuable insights to guide researchers in designing efficient rectenna systems for RF energy harvesting applications.

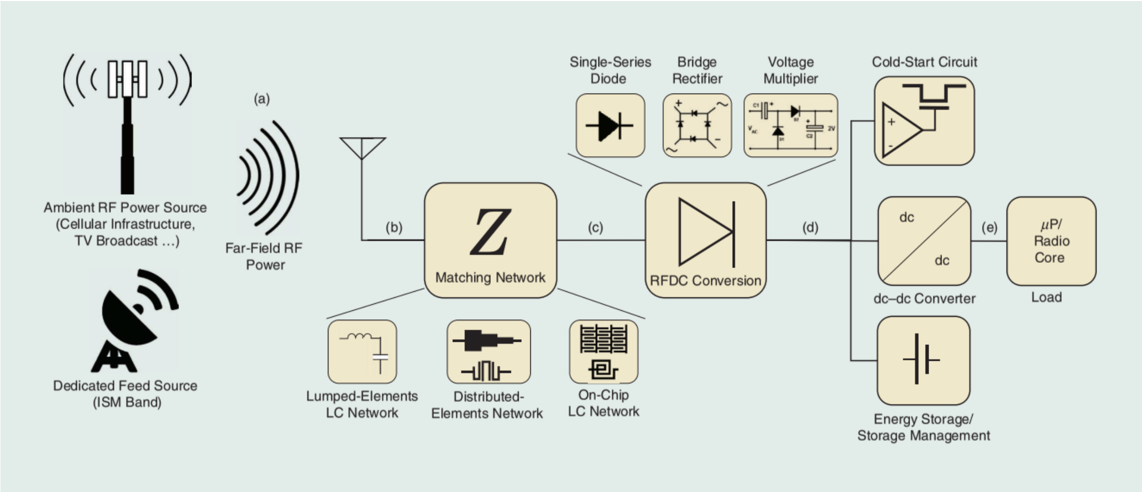

Figure 9: Full architecture diagram of a RFEH system for wireless sensor nodes [62]

Table 3 Performance comparison of advanced RF energy harvesting systems for powering of wireless sensors

Ref. year	***Rectenna (RFEH) structure***	***Operating frequency [GHz]***	***Conversion Efficiency [%]***	***V_{out} [Volt]***	***Pin [dBm] @ R_L [KΩ]***	***Applications***
(Kumar Bairappaka et al., 2024)	Broadband circularly polarized (CP) rectenna	2.3 - 2.8	65	2.55	(-10 to 12) @ 2	RFEH for indoor IoT
(Moloudian et al., 2024)	Dual-Band Class-F Harmonic Rectenna	0.868, 0.915	71	2.84	(-30 to 10) @ 7	RFEH for low-power devices
(Keshavarz, Shariati, 2022)	Highly Sensitive and Compact Quad-Band Rectenna	5.8	55	0.2	(-50 to -10) @ 11	RFEH for IoT Devices
(Ha et al., 2024)	Low-Profile, Wide-Angle, Bandwidth-Enhanced Rectenna	11.5-12.5	45	1.8	--- @ 0.388	Wireless Power Transmission
(Wagih et al., 2021)	E-Textile Coplanar Waveguide Rectenna	0.915	80	1.8	10 @ 4.5	RFEH for powering of wearable medical device
(Muttlak et al., 2022)	Folded antenna with multi-stages VDR	2.4	15	1.6	-30@ 10	RFEH for powering of IMDs
(Prashad et al., 2023)	Compact Circular Rectenna	2.45	52	2.17	0 @ 10	RFEH for powering of WSNs
(Han et al., 2025)	Flat-Panel Rectenna with Broad RF Energy Harvesting Coverage	5.8	51.8	1.915	(-20 to 15) @ 1	RFEH for powering of WSNs
(Khan et al., 2022)	Dual-Band Inverted F-Shaped Patch Rectenna	2.4 5.8	71 51.9	3.6	10 @ 1.25	RFEH for powering of wireless sensors

5 Conclusions

This review has examined recent advancements in RF-DC rectifier circuits, focusing on Schottky diodes and MOSFET-based designs for RF energy harvesting (RFEH) systems. The integration of optimized antennas, rectifiers, and load matching is crucial for developing efficient energy harvesters capable of powering ultra-low-power devices, including IoT sensors, medical implants, RFID tags, and 5G modules. As demonstrated, rectifier efficiency remains the key determinant of overall system performance in these applications.

Different rectifier topologies offer varying advantages depending on factors like input voltage, frequency, power levels, and the characteristics of the energy source. Advanced rectifier topologies have significantly improved the viability of RFEH. Innovations in adaptive reconfiguration, differential-drive architectures, and hybrid systems address critical limitations in efficiency and dynamic range.

This paper examines advanced rectifier topologies designed to address critical challenges such as low input power sensitivity, broadband operation, and high-power conversion efficiency (PCE%). By synthesizing recent innovations in voltage multipliers, differential-drive architectures, adaptive reconfigurable techniques, and hybrid systems.

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Biography

Shamil H. Hussein Alnajjar was born in 1984 in Mosul / Iraq, he received the B.Sc. degree from the University of Mosul / Electrical Engineering Department at electronic & communication. He finished his M.Sc. in Electronics from Mosul University / Iraq in 2012. He finished his PhD in Electronics from Mosul University / Iraq in 2023. His research interest in Microelectronic, IC Design, RF power amplifier design, and Intelligent Systems. He is now a lecturer in Electrical Engineering Department in Mosul university / Iraq.

Reem Fawaz Abdulkareem was born in Mosul / Iraq, she received the B.Sc. degree from the University of Mosul / Mechatronics Engineering Department at in 2018, High Diploma degree from University of Mosul / Electrical Engineering department in 2022, She is now a M.Eng. student in Electronics field at the Electrical Engineering Department / Mosul University / Iraq.