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SURVEY

Enhancing SWIPT Systems: A Systematic Review of Rectifier Technologies, Efficiency, and Integration Strategies

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ABSTRACT This paper reviews the recent advances in rectifier technology for simultaneous wireless information and power transmission (SWIPT) systems in a systematic way, focused on ways to make them more efficient, scalable, and easier to integrate. It analyzes the outcomes of innovative experiments employing standard techniques to enhance energy harvesting (EH) and data transmission in SWIPT by tackling issues related to size reduction, multi-band functionality, and environmental sustainability. It also examines alternative design methodologies, including metamaterials and sophisticated rectenna designs, capable of attaining higher power conversion efficiencies while minimizing their dimensions. The SWIPT architecture utilized by artificial intelligence (AI)- and Deep Reinforcement Learning (DRL) optimization enhances the performance of SWIPT systems by increasing the reliability of RF-to-dc conversion and communication across varying channel conditions. The results show that flexible and wearable rectifier technologies, when combined with antenna co-design and advanced power management circuits, could enable truly self-powered IoT systems. Such devices would be capable of supporting applications in healthcare monitoring, smart textiles, and industrial sensing, continuous operation without batteries, while also reducing maintenance costs and electronic waste. Finally, we emphasize sustainability and interdisciplinary perspectives, recommending life-cycle assessments to address environmental impact and collaborative approaches that unite circuit, antenna, and protocol design. These reflections identify both the opportunities and bottlenecks that must be addressed for SWIPT rectifiers to enable practical 5G, 6G, and beyond applications.

INDEX TERMS Rectifier, rectenna, SWIPT, energy harvesting, design innovations, integration strategies.

I. INTRODUCTION

SWIPT is a new way of doing things in wireless communication. It lets you send both data and power over the same radio frequency (RF) medium. SWIPT could make wireless devices more independent and long-lasting in sectors like the Internet of Things (IoT), wearable electronics, and industrial monitoring by making them less reliant on traditional power sources [1], [2], [3] as shown in figure 1. In this context, the rectifier plays a critical role by converting the received RF

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signals into usable DC power for EH while simultaneously ensuring reliable information decoding (ID).

For EH applications, the rectifier rapidly and efficiently transforms weak or variable RF signals into a steady DC output, all within small size and low-power. As shown in [3], a well-designed rectifier should have high RF-to-DC efficiency across a range of input power levels, a wide input range or multi-band capability, a low startup voltage, and minimal circuit losses, so it can work with input powers below –10 dBm. The rectifier should be compact for easy integration with antennas, stable performance in changing climatic and load circumstances, which helps keep output reliable over time. In recent years, researchers have been developing novel rectifier designs to address various issues associated with SWIPT systems. Some of these problems are being solved by achieving high RF-to-DC conversion efficiency across a wide range of operating frequencies, managing nonlinear behaviors in rectifiers to maximize harvested energy, and reducing the form factor to enable use in small, wearable, and embedded devices. [2], [4].

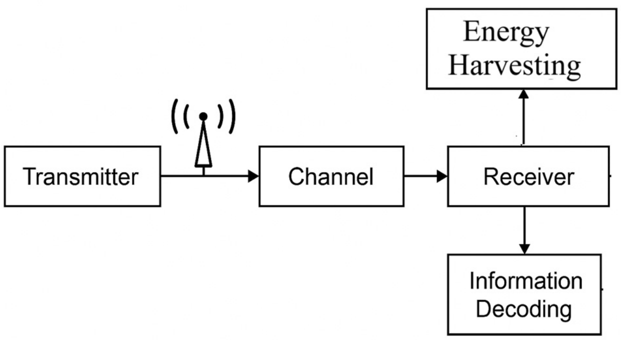

FIGURE 1. Schematic of a basic SWIPT system architecture. The figure is adapted from [4].

The rectifier's performance has a direct effect on how efficient and feasible large-scale SWIPT deployments are, affecting performance metrics such as sensitivity, multi-band operation, and compatibility with different communication protocols [5]. Moreover, it is becoming more important to understand and reduce the negative effects on the environment caused by materials, manufacturing processes, and the final disposal of devices. This has led to the search for greener and more sustainable solutions [6].

Against this backdrop, this paper presents a comprehensive review of recent developments in rectifier technologies applied to Simultaneous Wireless Information and Power Transfer (SWIPT) systems. Unlike previous surveys that may have concentrated solely on certain aspects—such as antenna design, modulation techniques, or beamforming strategies, our study provides a holistic examination encompassing efficiency optimization, scalable architecture, and multi-functional integration techniques [7], [8]. By doing so, we not only present a clearer picture of how recent advancements address existing technical hurdles but also highlight potential pathways for further research and innovation.

In particular, the review will: (1) present a systematic survey of current rectifier technologies to enhance both EH and data transmission; (2) introduce and analyze state-of-the-art design methodologies that tackle size reduction, multi-band capability, and improved conversion efficiency; (3) explore effective integration strategies, including co-design of antennas and rectifiers as well as beamforming and waveform optimization for improved system adaptability; and (4) identify environmental considerations and emerging research directions, such as flexible, wearable rectennas and the incorporation of AI-driven techniques for dynamic optimization [9], [10], [11].

Figure 2 shows the main improvements and areas of focus in SWIPT rectifier technology as discussed in the paper, innovative Rectenna Designs, Strategies for novel designs that solve problems such as size reduction issues, multiple frequency bands and performance enhancement efficiencies. This visual summarizes the technological advances and applications discussed, highlighting how these improvements make it possible to use SWIPT systems in a wide range of fields in a practical and long-lasting way. The study also aims at identifying the current inequities and promising research areas that could be covered in the future on SWIPT rectifier technologies, including incorporation of 5G technologies, development of flexible and wearable rectenna solutions, and use of AI-driven optimization techniques.

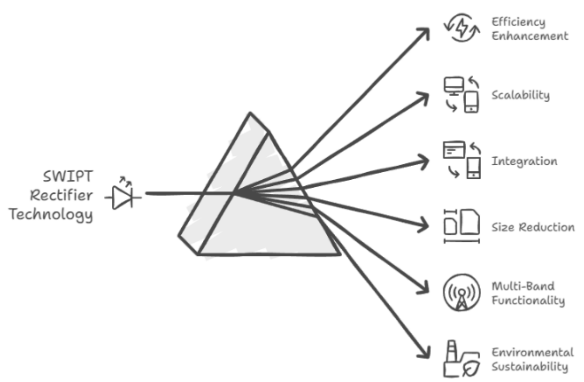

FIGURE 2. Main improvements and research focus areas driving next-generation SWIPT rectifier technology.

The overall organization of the paper is illustrated in figure 3, which maps the flow and structure of the paper. Table 1 contains all the acronyms and abbreviations used throughout the study.

II. SYSTEMATIC REVIEW PROTOCOL

A. METHOD

"SWIPT" and "rectifier" are the most significant keywords in this article, focusing on efficiency improvement, scalable

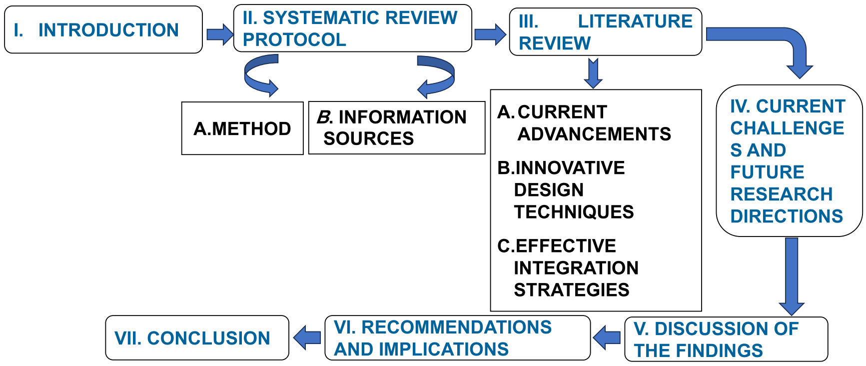

FIGURE 3. Organization of the paper.

design, and integration techniques. The scope of this article is limited to English literature.

B. INFORMATION SOURCES

Three reputable databases—ScienceDirect, IEEE Xplore, and Web of Science—were used to identify relevant research. This selection aims to encompass the domain and criterion literature while providing a global perspective on researchers' efforts.

Figure 4 demonstrates that the conclusive total of publications is 119, derived from comprehensive text analysis, with ScienceDirect, WoS, and IEEE Xplore contributing 32, 53, and 34 articles, respectively.

The methodology consisted of two processes: literature source searching and screening and filtering. These techniques seek to identify articles most pertinent to our domain. The screening and filtration procedure had two phases. The initial step was the removal of duplicates and irrelevant articles by examining the title and abstract of each publication. The second stage involved a comprehensive review of each article filtered from the previous stage. The authors that executed these methods employed identical eligibility criteria.

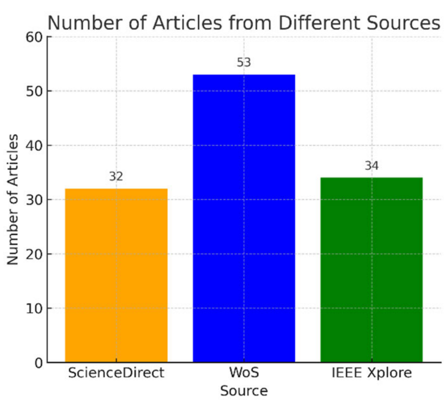

FIGURE 4. Number of articles from different sources.

The inquiry was performed at the beginning of June 2024 using the search functionalities of ScienceDirect, IEEE Xplore, and WoS databases. We employed "SWIPT" and "rectifier". The precise query is displayed at the top of Figure 5. We further utilised the features in each search engine to exclude book chapters and other report formats, focussing just on journal and conference papers. The period included from 2013 to 2025 across all digital libraries.

The investigation identified 152 papers when the search was performed from three databases: ScienceDirect, IEEE Xplore, and WOS. The distribution is 45 from ScienceDirect, 38 from IEEE Xplore, and 80 from WOS. All these articles date from 2013 to 2025. Across the three databases, 32 duplicate datasets were identified and excluded from further analysis to avoid redundancy. A total of 32 items were excluded thereafter. By analyzing their title and abstract, which further refined the totalling 115 items. Ultimately, after reviewing each of the 115 We removed 5 items, resulting in a total of 119 articles. Ultimately, the remaining articles constituted the final compilation of studies included in this review. To ascertain the comprehensive outline for the last series of articles, we executed a comprehensive analysis to ascertain the primary objective of these documents. A limited number of articles (16.8%; 20/119) are reviews and surveys. Figure 6 illustrates a thorough Summary of this trajectory. The predominant category of publications consisted of research papers. 83.19% (99 out of 119).

Figure 7 illustrates the number of papers categorized by publication year. The distribution of papers from 2013 to 2024 is shown as well.

III. LITERATURE REVIEW

This section is divided into three main aspects of rectifier technologies for SWIPT systems a.) Current Advancements, b.) Innovative Design Techniques, and c.) Effective Integration Strategies.

Section III examines multiple techniques, including matching networks, advanced modulation schemes, and load optimization methods. Each approach addresses common rectifier challenges, such as nonlinearity, broadband operation, and miniaturization—especially miniaturization—especially under unpredictable outdoor conditions.

TABLE 1. Abbreviations and acronyms.

Abbreviation /Acronym	Full Form
SWIPT	Simultaneous Wireless Information and Power Transfer
IoT	Internet of Things
MIMO	Multiple Input Multiple Output
RF	Radio Frequency
DC	Direct Current
PMIC	Power Management Integrated Circuit
AI	Artificial Intelligence
WPT	Wireless Power Transfer
RFID	Radio Frequency Identification
PMU	Power Management Unit
MPPT	Maximum Power Point Tracking
QPSK	Quadrature Phase Shift Keying
OFDM	Orthogonal Frequency Division Multiplexing
PAPR	Peak-to-Average Power Ratio
BER	Bit Error Rate
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
ASK	Amplitude Shift Keying
FPGA	Field-Programmable Gate Array
NOMA	Non-Orthogonal Multiple Access
MDP	Markov Decision Process
MaMIMO	Massive Multiple Input Multiple Output
WBAN	Wireless Body Area Network
LPWAN	Low-Power Wide Area Network
UAV	Unmanned Aerial Vehicle
FSK	Frequency Shift Keying
IRS	Intelligent Reflecting Surfaces
ML	Machine Learning
DRL	Deep reinforcement learning
DNNs	Deep neural networks
CSI	Channel State Information
ICT	Information and Communication Technology
PSR	Power-splitting relaying
TSR	time-switching relaying
ID	Information Decoding
EH	Energy Harvesting

A. CURRENT ADVANCEMENTS

In this section advancements in rectifier topologies were discussed, which have been shown to significantly improve system efficiency but require careful consideration of nonlinearity and impedance matching.

The studies conducted by [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], and [12] show appreciable progress in the developments of rectifier systems for SWIPT. These works describe fundamental advancements in system interconnections, advanced modulation techniques, and physical configurations. The primary concern among these studies is the optimization of SWIPT system efficiency across different applications, including wearable technologies and industrial IoT.

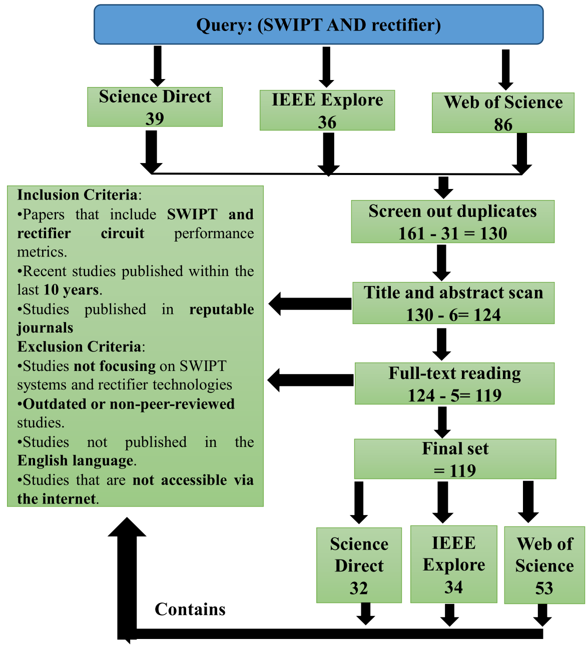

FIGURE 5. Flow chart of the query, selection and inclusion criteria employed in the article.

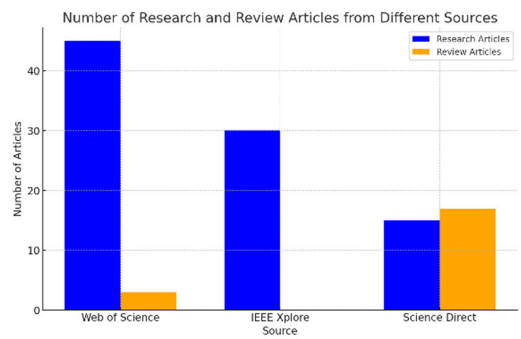

FIGURE 6. Number of research articles compared with review articles.

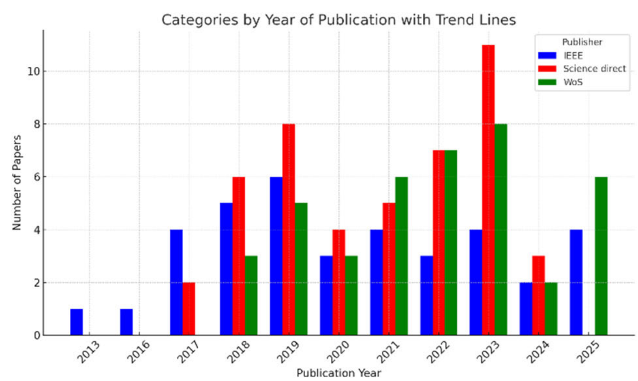

FIGURE 7. Categories by year of publication.

Similarly, by directly integrating rectifier components with the antenna, [2], [3], and [13] helped to simplify SWIPT systems. This method allows for direct impedance optimization, which simplifies the design and enhances matching at the power harvesting ports. Parameters such as impedance levels, frequency tuning, and component selection play a critical role in influencing rectifier performance, as they maximizing RF-to-DC conversion efficiency and reducing reflection losses, thereby eliminating the need for separate matching networks.

Similarly [7], [12], and [14] share the design of advanced rectifiers intended to expand the range of use of SWIPT in complicated circumstances such as industrial IoT and diverse communication systems. These designs are especially effective in managing multiple external variations, which will subsequently improve the system reliability.

The works carried out by [12] and [15] propose a multi polarization rectenna system with a two-port antenna and an orthogonal hybrid coupler that allows switching between different modes of operation, thus its goal was to enhance power distribution and isolation of communication from power ports to increase application scope of this system to a wide range of practical situations.

Studies by [16], [17], [18], [19], [20], [21], [22], [23], [24], and [25] generalize the significant trends in the development of SWIPT technologies, in particular, which improvements in rectifier technology, optimization of the SWIPT system and the integration of Green Information and Communication Technology (ICT) have led to more modern and green communication structures.

Nonlinear diode characteristics play a crucial role in SWIPT receivers by shaping how efficiently the incoming RF signal is converted into DC power. While simplifications of the diode's I–V equation may omit higher-order terms, recent work indicates that preserving more terms of this nonlinearity can, in some scenarios, enhance rectification efficiency [17]. Specifically, for amplitude shift keying (ASK) signals, the amplified input signal peaks within the diode's nonlinear region can generate higher DC output if the diode's polynomial approximation includes terms beyond the fourth order.

In [24] and [26], the capabilities of SWIPT systems are studied in relation with MaMIMO systems and it is shown that through a directional beamforming, EH efficiency is able to improve. This integration is important in attaining the various goals of the network for instance in maximizing energy efficiency in transmission while at the same time preserving the security of the information that is transmitted.

The studies [27], [28], [29], [30], [31], [32] constitute research of this nature, these innovations demonstrating how SWIPT systems can be integrated into everyday devices without compromising usability. By preserving efficiency, they remain suitable for both low-power and high-performance scenarios.

The studies by [2], [34], [35], [36], [37], [38], [39], [40], and [41] present technological breakthroughs in the design of SWIPT systems that combine more complex receiver architectures, antennas, and rectifiers to improve EH and ID performance.

The studies [2] and [43] use a proposal of textile antenna including a high-impedance rectenna and microstrip antenna, where no separate rectifying circuit is required. This simplification enhances the antenna design and significantly improves the RF to DC efficiency, many folds, which is a great improvement for the wearable SWIPT technology. Such innovations show how SWIPT systems can be easily integrated into everyday devices without affecting their usability. The aim is to meet practical needs without compromising on the efficiency SWIPT system offers.

Figure 8. shows a schematic of a voltage-doubler rectifier topology. Recent developments in rectifier technologies have resulted in more efficient SWIPT networks [40]. This advancement has been achieved through an intensive chain of studies that optimize rectifier architecture, refine modulation techniques and integrate sophisticated system designs to address concerns associated with efficiency, complexity, and sustainability. The need for design simplicity and operational efficiency, particularly in highly mobile applications like wearable technologies necessitate SWIPT system architectures such as integrating antennas with rectifier components.

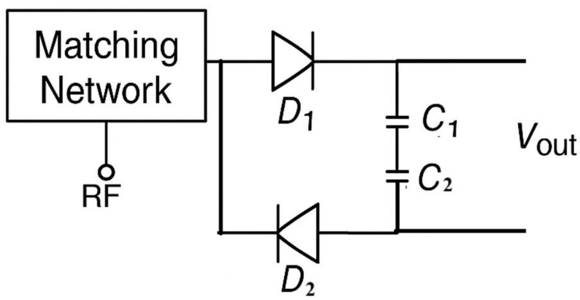

FIGURE 8. Schematic of a voltage-doubler rectifier topology. The figure is adapted from [41].

Furthermore, these advanced modulation strategies reflect both the limitations of traditional SWIPT systems and their adaptability to innovative hardware designs in multi-tier network architectures like 5G environments that can reduce power consumption while supporting high data throughput. Integration of advanced technological frameworks for dynamic environment optimization of systems architectures as well as new modulation schemes for communication systems still providing energy efficiency will be the focus of further research. Table 2 provides a concise representation of some key studies within SWIPT through summarizing SWIPT and Rectifier Technology Advancements.

B. INNOVATIVE DESIGN TECHNIQUES

This section discusses advanced rectifier configurations, power management integration strategies, metamaterial-

TABLE 2. Summary of SWIPT and rectifier technology advancements.

Ref.	Year	Advancement	Limitations	Description	Benefits	Applications
[2]	2021	Textile Antenna with High-Impedance Rectenna	**Limited durability under repeated bending/washing**; **efficiency reduction at off-design frequencies**; max transmitted power of 15 dBm restricted experimental validation	Integrated rectifying circuit in antenna design	Improved RF-to-DC efficiency, simplified design	Wearable SWIPT technology
[3]	2020	Dynamic Signal Routing in MIMO	**High control complexity for large-scale MIMO**; **additional switching losses**; reduced robustness under rapid channel fading	Dynamically routes multiple RF signals to different rectifier pathways	Maximized RF-to-DC energy conversion	MIMO systems, complex communication networks
[4]	2019	Multi-tone Amplitude Modulation	**Increased insertion loss and phase noise** from tunable components; requires precise synchronization to avoid intermodulation distortion	Balances data rate and power efficiency	Reduced symbol error rates, increased EH efficiency	General SWIPT systems
[5]	2023	Multipolarization Rectenna System	**Potential mismatch losses between polarization ports**; increased design complexity for maintaining isolation at multiple frequencies	Two-port antenna with orthogonal hybrid coupler	Enhanced power distribution, isolation of communication from power ports	Wide range of practical situations
[11]	2022	Nonlinear Harvesting Methods	Performance highly dependent on input waveform characteristics; **risk of increased harmonic distortion** impacting co-located communication	Exploiting diode nonlinearities for energy extraction	Improved efficiency in variable environments	Dynamic SWIPT deployments
[12]	2021	μ-law Companding Technique	Requires additional signal processing hardware; **potential distortion if companding/expanding stages are not perfectly matched**	Reduction of PAPR effect	Optimized balance between power efficiency and data transmission	Power amplifiers, rectifier systems
[13]	2023	High-Gain Antenna in RFID	**Narrow beamwidth limits coverage**; alignment sensitivity may reduce efficiency in mobile applications	Strategic design improvements	Enhanced power efficiency and strong communication	RFID modules in SWIPT systems
[14]	2018	Iterative Water-Filling Algorithm	**Computationally intensive for real-time adaptation**; sensitive to Channel State Information (CSI) estimation errors	Channel capacity and power delivery optimization	Improved system performance in real-world conditions	Real-world SWIPT deployments
[15]	2019	Discrete-Component Matching Network	**Increased PCB area**; frequency drift due to component tolerances; limited reconfigurability	Fine-tuning of RF EH	Strengthened power harvesting across wide power spans	IoT smart sensors
[16]	2023	SWIPT in MaMIMO	**High computational complexity in optimal beamforming**; performance degradation with imperfect CSI	Integration with MaMIMO systems	Improved EH efficiency via directional beamforming	5G networks, secure information transmission

TABLE 2. *(Continued.)* **Summary of SWIPT and rectifier technology advancements.**

[17]	2022	Underwater Communication Networks	**High path loss in underwater RF channels**; limited operational range due to conductive seawater	Energy-scavenger protocols for marine conditions	Enhanced operation in critical underwater environments	Marine ecosystem monitorin g
[27]	2019	Asymmetric Phase-Shift Keying	**Reduced spectral efficiency**; higher complexity in demodulator design	Imbalanced modulation schemes	High power conversion efficiency	Energy harvesters in SWIPT systems
[29]	2020	Compact Rectenna Systems	**Reduced gain due to small form factor**; efficiency drops sharply at low input power levels	Efficient harvesting from ambient RF signals	Enables batteryless device operation	IoT applicatio ns
[35]	2021	Ambient Backscatter Communication	**Limited range**; performance sensitive to interference and ambient signal availability	Low-power device communicati on	Overcomes battery limitations, fosters sustainable solutions	IoT ecosystem s
[39]	2022	Coherent Soft Techniques	**Requires precise synchronization**; sensitive to phase noise and channel estimation inaccuracies	Integration with detection methods	Increased power-harvesting performance and data reliability	Advanced SWIPT receivers
[41]	2020	Dual-Output Quasi-Yagi Antenna	**Bandwidth is limited by element spacing and design geometry**; efficiency varies with frequency separation	Operates at separate frequency ranges for communicati on and EH	Increased efficiency without performance degradation	Mobile communic ation, EH
[42]	2019	Dual Polarized Communication Rectenna Array	**Complex matching network design**; performance degrades with polarization misalignment	Voltage doubler topology for high conversion efficiencies	Minimized cross-polarization and mutual interference	Advanced rectenna technolog y

inspired antennas, multi-band rectifier topologies, and AI/DRL Enabled SWIPT Systems as shown in figure 9.

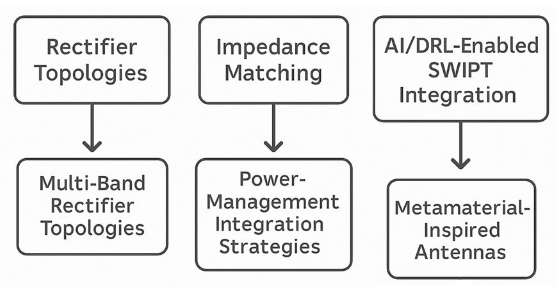

FIGURE 9. **Thematic flow representation of SWIPT research domains.**

Recent progress in SWIPT systems reveal a collaborative drive towards incorporating innovative design techniques that enhance performance, efficiency and utility of compact multifunctional devices. Each study provides unique contribution to this evolving field through highlighting the sophistication behind them along with a practical approach.

For example, [41] and [44] both examine dual-polarized designs but apply different methodologies to improve rectification performances. Although [44] microstrip design manages many bands effectively maintaining its small size, yet the achievement of high conversion efficiencies between RF and DC powers across the bands addressed issues related to shrinking sizes are resolved by [41] who utilized voltage doubler topology as it helped by reducing interference while keeping isolation at optimum levels, hence attaining a trade-off balance between power extraction functions on one side versus communication tasks on the other side.

Another approach used by [13], [46], and [47] involved creating a small Huygens antenna with metamaterial-inspired elements that combine WPT with communication functionalities. In addition to having a high conversion efficiency, it is also capable of being manufactured quite economically since its fabrication process involves nothing more than standard PCB technologies.

Similarly, [51], [56], and [57] propose designing a SWIPT rectifier using biased amplitude shift keying. This approach maximizes the device's sensitivity to input signals, reducing its external power requirements. As a result, the system sustains highly efficient at low power levels while robustly maintaining performance across various environmental conditions.

Other studies by [43], [49], [50], [51], and [55] introduce novel rectifier designs and efficiency improvements in SWIPT systems through contemporary technology. For instance, [43] have proposed an antenna that acts as both a wireless data transfer device and a conducting feed for a single-layer low-cost dual band patch antenna to power IoT sensors that uses dielectric resonance power transfer through proximity coupling and electronic circuits to convert power from wireless IoT networks with Schottky diode capacitive coupling to DC power components.

TABLE 3 shows a Comparison of Rectifier Key Performance Parameters (Efficiency, Output Power, Sensitivity) for some studies.

Moreover, [51], [56], and [57] propose an improved methodology of designing SWIPT system rectifier using biased amplitude shift keying. A unique one is ASK modulation-based power supply circuit which maximizes the sensitivity of the device to input signal strengths thereby reducing the need for powering it hence making it more efficient at low powers while still guaranteeing excellent performance in different environmental conditions.

Besides, [52] introduce a new model of rectifier which considers receiver non-linearity in the design of SWIPT systems. The use of such models as envelope detectors and quadratic detectors helps understand how different detection methods work when they are being used to support efficient EH with good data integrity, without affecting SWIPT networks' reliability. The studies carried out by [15], [55], [58], [59], [60], [61], [62], and [63] have significantly expanded the scope of SWIPT system designs with innovative rectenna configurations, rectifier technologies, integration strategies that improve efficiency, reduce size while increasing performance in various operational environments.

Studies by [15], [58], [60], [62], [63], and [102] has accomplished remarkable developments in the design paradigms of SWIPT systems by exploiting novel rectenna structures, upgrading the rectification technologies, and diverse integration methodologies, which maximized the efficiency, reduced physical footprints, and optimized performance under diverse operational scenarios. Ja'Ffar et al. [102] propose a frequency-reconfigurable rectenna, which combines switchable shorting pins and tunable capacitors and supports multi-frequency operation without the need for any matching network. Such an invention facilitates easy and cost-effective antenna design and overall system performance improvement, which finds significant value in the smart living space.

To systematically analyze the performance of rectifier designs in SWIPT systems, Table 4 summarizes key metrics, equations, and their relevance to system optimization. These include conventional performance indicators such as efficiency and voltage conversion ratio, as well as diode-specific nonlinear characteristics such as junction capacitance and series resistance, which significantly affect high-frequency rectification behavior.''

Wang et al. [58] and Gu et al. [60] utilise a Field-Programmable Gate Array (FPGA)-controlled jointly modulated amplifying programmable metasurface (APM) that enhances electromagnetic wave control with superior power transfer attributes.

Rajabi et al. [61] propose a hybrid rectifier-receiver using two-tone stimulation of signals to boost the effectiveness of electromagnetic EH by better demodulating data at baseband frequencies. These developments do away with superfluous components, like extra power splitters and down-conversion circuitry.

Han and Li [62] investigate different receiver architectures for combined wireless communication and power transmission using time-switching, power-splitting, and antenna-switching techniques as shown in figure 10 to optimize system performance and resource allocation.

Makhetha et al. [63] examine the application of SWIPT systems in the field of IoT by Low-Power Wide Area Networks (LPWANs), while highlighting advanced EH methods like resonant inductive and capacitive coupling. Their study advocates for deployment of multi-band operations as well as use of innovative materials to improve flexibility and enhance efficiency of SWIPT systems implying transformational implications on how power and data are managed in smart devices.

The recent developments in SWIPT systems by [14], [47], [65], [66], [67], [68], and [69] have brought together various innovative design approaches to enhance the performance, efficiency, and integration of these technologies in complex environments such as the IoT networks. A joint survey of some of the most recent SWIPT researches is covered by this paper, including [14] who discussed beamforming techniques with novel rectifier structures that are not only enhancing its efficiency but also making it more functional. The study investigates segregated and consolidated receiver architectures regarding power management and EH targets, which are critical to enabling the widescale deployment of Internet of Things devices.

In this research, Park and Hong [66] examine the time-reversal method, which focuses energy at the receiving end utilizing multipath environments, unlike conventional beamforming approaches, thus attaining effective rectification.

Yue et al. [67] advocate for the implementation of intelligent reflecting surfaces (IRS) that demonstrate substantial enhancement in RF-to-DC conversion by passive beamforming employing sophisticated algorithmic control, leading to negligible energy transfer loss.

Ur Rehman et al. [68] use LabVIEW simulations to build a model of a SWIPT system to improve the efficiency of a

TABLE 3. Comparison of rectifier key performance parameters (Efficiency, Output Power, Sensitivity).

Ref.	Year	Rectifier Design / Type	Compactness	Peak Efficiency (%)	Output Power (dBm) @ Input Condition	Sensitivity (dBm)	Notable Features / Outcomes
[2]	2021	Textile High-Impedance Rectenna	Flexible, wearable	~60% @ –5 dBm	–10 dBm @ –5 dBm	–20 dBm	Wearable design, moderate efficiency under low input
[12]	2021	µ-law Companding-Based Rectifier	Moderate	~65% @ 0 dBm	–5 dBm @ 0 dBm	–18 dBm	Balanced efficiency and data reliability
[15]	2019	Discrete-Component Matching Network	Moderate	~70% @ –10 dBm	–8 dBm @ –10 dBm	–22 dBm	High sensitivity and efficiency over wide power range
[29]	2020	Compact Ambient RF Rectenna	Very compact	~55% @ –15 dBm	–15 dBm @ –15 dBm	–25 dBm	Batteryless IoT operation at very low input power
[41]	2020	Dual-Output Quasi-Yagi Rectifier	Moderate (antenna–rectifier combo)	~53.6% @ 0 dBm (measured ~51.1%)	–0.7 dBm (~0.85 mW) @ 0 dBm	–15 dBm (PMU start-up)	Optimized antenna–rectifier integration; PMU enables low-power usability

TABLE 4. Fundamental equations and parameters in SWIPT rectifier design.

Design metrics	Equation	Description	Application
Rectifier Efficiency (η)	$\eta = \frac{P_{DC}}{P_{RF}} * 100\%$	Ratio of DC to RF input power	General performance
Voltage Conversion Ratio (VCR)	$VCR = \frac{V_{out}}{V_{in}}$	RF-DC voltage gain	Rectifier sizing
Ripple Voltage	$V_{ripple} = \frac{I_{out}}{2fC}$	Output DC ripple	Stability filtering
PAPR	$A = \frac{P_{peak}}{P_{avg}}$	Peak-to-average ratio in modulated signals	EH waveform design
Junction Capacitance	$C_j(V) = \frac{C_{j0}}{(1+\frac{V}{V_b})m}$	Voltage-dependent capacitance of the diode's junction depletion layer	Impacts high-frequency performance and matching in SWIPT rectifiers
Internal Series Resistance (Rs)	$V = IR_s + nV_T \ln(\frac{I}{I_s}+1)$	Represents conduction and contact losses in diode material	Reduces power conversion efficiency at higher currents

rectifier at varying power-splitting ratios and in noisy environments, thus allowing optimal system parameter tuning. Shanin et al. [69] provide a learning framework based on Markov Decision Processes (MDP), specifically designed for energy-harvesting circuits, to enhance input signal allocation by maximizing power reception through mutual information between the transmitter and receiver.

Moreover, academic research [51], [70], [71], [72], and [73] provide detailed assessments of the complex architectures of SWIPT systems. The research stresses improvements in efficiency, functionality, and integration through new rectifier technologies covering multiple modulation methods and energy-harvesting strategies.

Hou et al. [70] simulate to evaluate rectifier configurations that optimize for DC-to-RF efficiency. Dhull et al. [73] demonstrate that changes in the quantities of phase shift for various tones increase ripple voltage, leading to greater BER and higher power conversion efficiency, thus showing suitability for low-power IoT devices.

Research carried out by [73], [75], [76], [77], and [78] offers new frameworks and approaches that greatly boost the technological development and system effectiveness of the SWIPT system, especially in IoT environments. Dhull et al. [73] propose a new multitone PSK modulation method that utilizes the nonlinear properties of integrated receiver-rectifier structures to enhance power conversion efficiency and reduce the BER. This system synchronizes EH with information transmission effectively through ripple voltage reduction and modulation parameter adjustment, which are optimized for low-power sensing networks in IoT scenarios.

Alevizos and Bletsas [76] underscore the need of accurate modelling for nonlinearities in RF EH to enhance rectifier efficacy. Analyzing numerous models, from linear to intricate polynomial forms, enhances comprehension of rectifier performance, which is crucial for improving efficiency in SWIPT systems.

Quddious et al. [78] provide an adjustable power splitter for a SWIPT system that employs varactor diodes to regulate the equilibrium between EH and ID. This design facilitates the alteration of power ratios, enhancing system flexibility to varying channel conditions, and enhancing both energy-harvesting efficiency and signal integrity.

Recent advancements in rectification technology for SWIPT systems demonstrate significant improvement in the dual optimisation of EH and wireless ID. Research conducted by Wagih et al. [79], Zhu et al. [41], Kim et al. [45], Lin and Ziolkowski [13], and Dhull et al. [14] presents novel designs that enhance efficiency, integration, and operating capacity. This research highlights dual-polarized, multifunctional antenna designs, sophisticated receiver combinations, and innovative materials for RF applications.

Wagih et al. [44] and Zhu et al. [41] focuses on optimising rectifier architectures to enhance multi-band functionality, reduce interference, and enhance communication reliability and energy efficiency. Kim et al. [45] streamline the SWIPT system architecture by combining direct RF signal rectification with amplitude-based modulation techniques, improving power consumption efficiency and rendering it suitable for IoT applications without increasing design complexity.

The integration methods utilised by Lin and Ziolkowski [13], Xu et al. [22], Dhull et al. [14], and Sanislav et al. [31] utilize contemporary technology such as metamaterials and beamforming techniques to enhance system efficiency and reduce energy loss. This method facilitates the necessary compactness and resolves miniaturisation issues, which are crucial for practical growth into many application domains.

In conclusion, several researchers have achieved significant advancements to optimize SWIPT systems for practical use. These developments demonstrate prospective opportunities and lay the groundwork for future research that will explore innovative materials, integration techniques, and optimisation tactics to improve the performance and efficiency of SWIPT applications across several industries. Table 5 provides Summary of Innovative Design Techniques in SWIPT Systems and Rectifier Technology.

The integration of power-management circuitry into rectifier modules has been thoroughly examined. Table 6 lists some common strategies that focus on co-design, optimizing impedance, and AI-enabled management frameworks.

Table 7 shows that several studies use metamaterial and metasurface-based antennas to get over problems with size and efficiency

Table 8 shows how new dual-band and multi-frequency rectifier topologies work. These designs can change frequency and work with a wide range of frequencies, which makes SWIPT more useful.

Tables 6 to 8 show three trends that work together to shape the current state of SWIPT rectifier research.

First, PMU solutions show that designing rectifiers with PMUs and adaptive matching circuits together greatly improves the efficiency of converting RF to DC and the stability of the output when the load changes. More and more, these systems use nonlinear modeling and AI-based optimization to manage impedance and harvested power in real time.

Second, antenna constructions based on metamaterials open up new possibilities to make them smaller, more directional, and able to do two things at once. Recent efforts have achieved high efficiency and a smaller physical footprint for rectennas by incorporating metasurfaces and magneto-dielectric substrates. This is an essential feature for wearable, IoT, and energy-autonomous applications.

The third, multi-band and reconfigurable rectifier topologies allow SWIPT to operate across a wide range of frequencies, which makes it possible for it to operate with 5G and 6G systems and adapt to different loads. These systems address the age-old issue of balancing bandwidth and efficiency by using adjustable parts and networks that only operate on certain frequencies.

All these changes are aimed at a clear shift from improving individual circuits to designing intelligent SWIPT systems at the system level, where rectification, power management, and antenna behavior are all integrated. Future research is anticipated to focus on AI-driven, metamaterial-enhanced, multi-band SWIPT platforms that optimize efficiency, compactness, and dynamic adaptability for next-generation wireless energy-information systems as shown in figure 11.

Emerging research challenges and AI/DRL-based opportunities for next-generation SWIPT systems are summarized in Table 9.

C. EFFECTIVE INTEGRATION STRATEGIES

Rectifiers within SWIPT systems integrating are addressed by the studies of [8], [69], [80], [81], and [82] have focused on strategies to enhance the seamless operation of rectifiers with other system components. These strategies include analytical approaches, system-level optimization, communication-power component co-design, and waveform optimization.

For example, [80] optimize load resistance to maximize RF-to-DC conversion efficiency by integrating antennas with

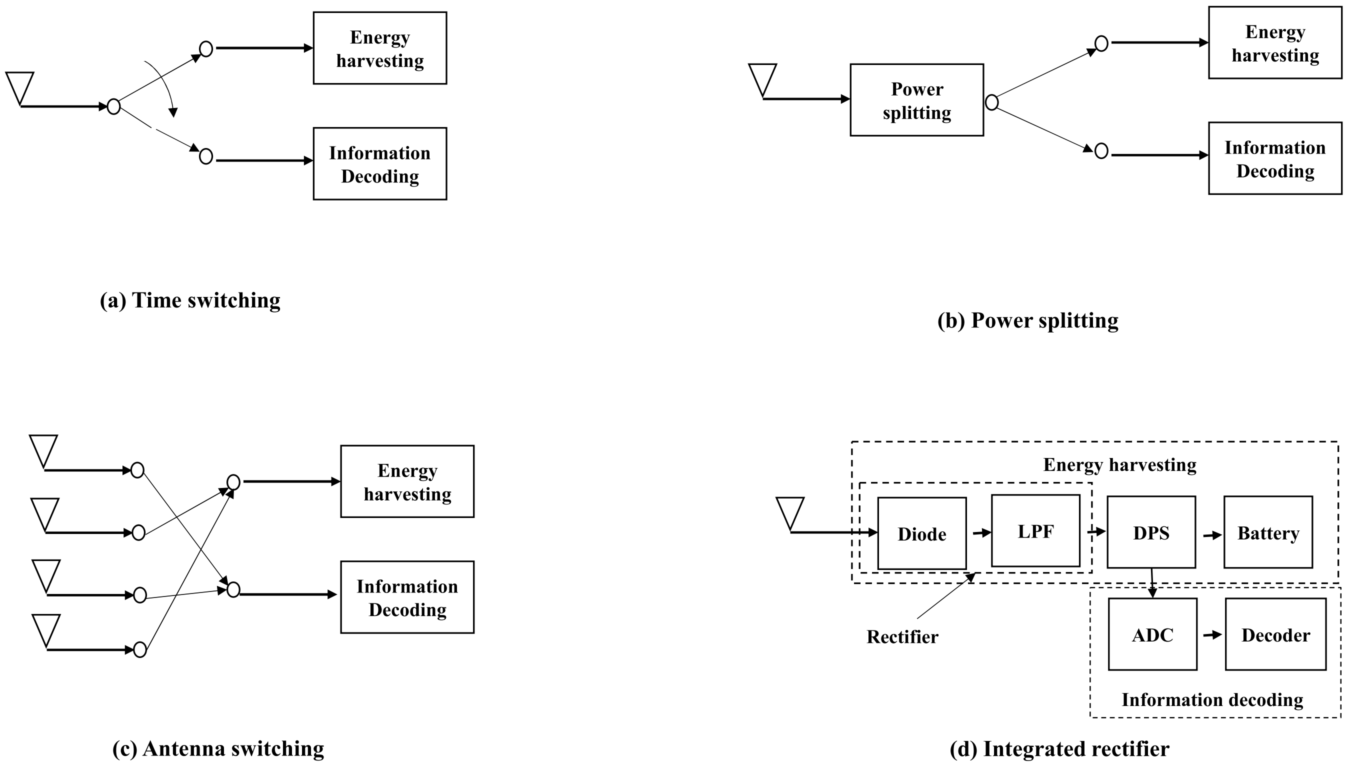

FIGURE 10. Practical SWIPT receiver structures. The figure is adapted from [62].

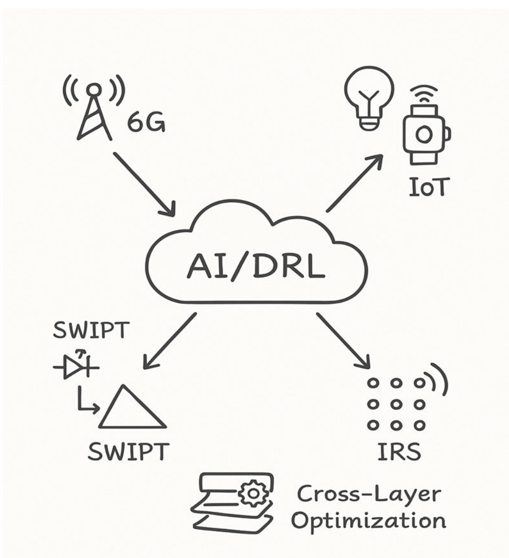

FIGURE 11. A simplified schematic depicting AI/DRL-assisted SWIPT architecture.

rectifiers. They provide closed-form solutions for determining optimal parasitic effects as well as packaging effects resulting from matching networks and PMU which could be integrated with them smoothly to ensure this rectifier is working at its peak performance when integrated upon other SWIPT system parts as shown in figure 12.

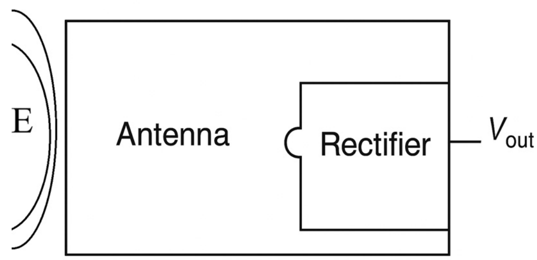

FIGURE 12. Integrated antenna–rectifier rectenna structure. The figure is adapted from [71].

In a multi-user MIMO WPT system, the study [81] investigates multiple antenna integration with rectifiers. Multiple rectifiers could be used to capture more power by using maximum ratio transmission (MRT) beamforming along with scalar symbols. Such an approach stresses the importance of such global tactics as energy beamforming and optimal transmit power allocation for making a better performing integrated rectifier in SWIPT systems.

Debels and Moeneclaey [82] address issues associated with communication-component co-designing using linear precoding (LP) and Tomlinson-Harashima pre-

TABLE 5. Summary of innovative design techniques in SWIPT systems and rectifier technology.

Ref.	Year	Innovation	Description	Benefits	Applications
[41]	2019	Dual-Polarized Communication Rectenna Array	Voltage doubler topology to minimize interference	High conversion efficiencies, reduced cross-polarization	Advanced rectenna technology
[44]	2021	Dual-Band Dual-Mode Microstrip Design	Handles multiple bands effectively with compact size	High RF-to-DC conversion efficiency across bands	Wearable devices, IoT applications
[45]	2019	Integrated Receiver Architecture with Amplitude Modulation	Direct RF signal rectification using amplitude-based modulation schemes	Streamlined components, enhanced ID and EH, suitable for low power	IoT devices, low-power applications
[46]	2022	Electrically Small Huygens Rectennas	High-performance rectennas for IoT sensing	Enhanced wirelessly powered IoT devices	IoT sensing applications
[47]	2022	Energy-Autonomous SWIPT RFID Tag	RFID tag integrating a rectifier for communication and power	Battery-less operation, enhanced EH and communication	RFID systems, IoT applications
[51]	2018	Biased ASK Modulation and Dual-Purpose Hardware	Enhanced rectifier design using biased ASK modulation	Maximizes device sensitivity, reduces power needs	Low-power IoT applications, SWIPT networks
[55]	2017	Advanced Antenna Arrays Combining Power and Spatial Division	Hybrid design merging energy capture and data exchange	Improved gain, minimized interference	Antenna design for SWIPT systems
[58]	2023	FPGA-Controlled Amplifying Programmable Metasurface	Optimizes electromagnetic wave control	Excellent power transfer characteristics	Future wireless networks, SWIPT applications
[62]	2017	Receiver Architectures for Integrated Wireless Communication and Power	Time-switching, power-splitting, and antenna-switching techniques	Optimized system performance and resource allocation	Combined wireless communication and power systems
[63]	2024	Integration of SWIPT in LPWANs	Advanced EH techniques with multi-band operations	Improved flexibility and efficiency in smart devices	IoT applications, smart devices
[65]	2018	X-band MMIC Amplifiers in SWIPT	Compared with traditional rectifiers for modulated signals	Higher RF-to-DC conversion efficiency	SWIPT systems handling modulated signals
[66]	2020	Time-Reversal Based Far-Field WPT	Concentrates energy using multipath conditions	Efficient rectification, reduced energy loss	WPT systems in complex environments
[67]	2023	IRS for WPT	Passive beamforming with advanced control	Significant improvement in RF-to-DC conversion	IRS-aided WPT systems
[68]	2018	LabVIEW Simulation for SWIPT Systems	Modeling SWIPT performance under different conditions	Optimal system parameter fine-tuning	SWIPT system design and optimization
[69]	2021	MDP-Based Learning Model for Energy Harvesters	Optimizes input signals based on mutual information	Maximizes power harvesting, enhances system adaptability	Energy harvester circuits in SWIPT systems
[71]	2019	Multitone FSK Modulation for SWIPT	Improves rectifier performance using nonlinear properties	Optimizes rate–energy tradeoff, preserves information rates	SWIPT systems with advanced modulation schemes
[73]	2024	Multitone PSK Modulation Technique	Balance EH with data transmission	Reduced ripple voltage, improved power conversion efficiency	Low-power IoT devices, sensing networks
[75]	2016	Multisine Waveforms with Different PAPRs	Efficient data transfer with RF-to-DC conversion	Reduced power consumption and complexity	Battery-less IoT devices

TABLE 5. ***(Continued.)*** **Summary of innovative design techniques in SWIPT systems and rectifier technology.**

[78]	2018	Tunable Power Splitter for SWIPT Receivers	Varactor diodes to control EH and ID balance	Flexible power ratio adjustment, optimized EH efficiency	SWIPT systems adaptable to channel conditions

TABLE 6. **Representative studies on PMU strategies in SWIPT systems.**

Focus Area	Representative References	Key Contributions
Antenna–Rectifier–PMU Co-Design	[2], [13], [22], [41], [42], [55], [60], [62], [80]–[82]	Integration of rectifier stages with antennas and power management units (PMUs) for improved impedance matching and efficient RF-to-DC conversion. Xu *et al.* [22] and Lin & Ziolkowski [13] demonstrate seamless antenna-rectifier-PMU designs that enhance energy flow and system compactness.
Analytical Optimization & Matching Integration	[11], [39], [80], [83], [84]	Introduce analytical optimization of load resistance, impedance matching, and parasitic reduction to maximize RF-DC efficiency under real-world conditions. Niotaki *et al.* [83] and Shanin *et al.* [84] propose improved matching and multi-rectifier cooperation frameworks.
Multi-Rectifier / Multi-Input Architectures	[4], [81], [82], [84], [85], [86]	Explore multi-input and MIMO rectifier structures integrated with beamforming and linear precoding. Debels & Moeneclaey [82] use Tomlinson–Harashima precoding for joint EH and ID optimization.
Nonlinear Rectifier Integration and Modeling	[8], [69], [76], [84], [110]	Integrate nonlinear behavior of rectifiers within the system model to improve waveform design, EH efficiency, and joint communication–power optimization through ML and DRL frameworks.
PMU-Based Energy Harvesting Systems	[21], [41], [47], [63], [85]	Incorporate DC storage, boost converters, and MPPT circuits for continuous EH operation and self-sustainability in IoT devices. Energy-autonomous RFID tags [47] and dual-output rectifiers with PMUs [41] exemplify this approach.
Wideband & Multi-Band Integration	[11], [39], [41], [42], [80]	Combine broadband antennas with optimized matching networks to maintain efficiency across multi-band frequencies. Adaptive LC and transmission-line elements are integrated to maintain stable impedance response.
System-Level Co-Design and Beamforming Integration	[55], [61], [67], [70], [81]	Integrate power-management strategies with MIMO beamforming and IRS-aided WPT; Shanin *et al.* [84] and Wang *et al.* [58] highlight cooperative power management for improved transmission efficiency.

coding techniques. They handle the EH versus ID trade-off under multiuser SWIPT scenarios. By integrating non-linear rectification, they clarify how EH can perform ID based on co-design, ensuring efficient system functioning.

The study [8] focuses on integrating the rectifier's non-linear behavior into the system model by considering the average harvested DC power as a function of the incident RF waveform's power distribution. Optimizing this side of the transmitter will enable improved integration of the rectifier in the SWIPT system to improve both EH and communication performances.

Furthermore, studies such as [1], [69], [71], [77], [83], and [84] emphasize optimizing EH, communication efficiency, and system integration, providing holistic approach on how to integrate rectifiers within SWIPT systems. These studies handle different technical challenges facing these devices while suggesting innovative approaches that can enhance the functionality and efficacy of SWIPTs, especially in IoT and WSNs.

According to [69], it is vital for nonlinear energy harvester circuits with memory effects including Markov reward chains and deep neural networks. (DNNs) Thus, this progresses rate-power tradeoffs as well as eases integration with other parts of the entire system, augmenting overall performance and efficiency of such systems.

Recent advancements in wideband rectifier design have demonstrated that combining broadband antenna architectures with optimized impedance-matching networks can sustain high RF-to-DC conversion efficiency across multi-bands frequencies [41], [42]. Adopting carefully tuned LC or transmission-line segments within the matching circuitry helps maintain a favorable power transfer, even though the input signal frequency is varying.

TABLE 7. Representative studies on metamaterial-inspired antennas in SWIPT.

Focus Area	Representative References	Key Contributions
Huygens and Electrically Small Antennas	[13], [46], [47], [64], [79]	Lin & Ziolkowski [13] introduced electrically small Huygens antennas operating at 915 MHz that merge power transfer and communication while maintaining high isolation. Follow-up designs [46], [47], [79] apply metamaterial-inspired structures to enhance directivity, efficiency, and compactness for IoT sensing and SWIPT.
Metamaterial-Integrated Rectennas	[46], [47], [49], [50], [64], [110]	These studies utilize metamaterial unit cells, magneto-dielectric substrates, and metasurfaces to improve RF focusing, impedance matching, and miniaturization. Alamu et al. [49] and Ojukwu et al. [110] emphasizes the use of programmable metasurfaces for energy harvesting and WPT optimization.
Dual-Polarized and Multi-Band Metamaterial Designs	[41], [44], [107]	Zhu et al. [41] propose a dual-polarized quasi-Yagi rectenna with metamaterial elements to achieve high isolation and broadband operation. Wagih et al. [44] and Zhang et al. [107] extend these concepts to dual-band, dual-mode, and dual-circular-polarized configurations for multi-frequency SWIPT.
Metasurface-Enabled Beamforming and Energy Focusing	[58], [60], [67], [110]	FPGA-controlled programmable metasurfaces and IRS are utilized to enhance beamforming, electromagnetic focusing, and adaptive energy redirection—improving RF-to-DC conversion efficiency and link reliability.
Compact and Flexible Implementations	[2], [43], [46], [49], [64]	These works emphasize flexible or textile metamaterial rectennas suitable for wearable and conformal SWIPT applications, combining high efficiency with structural adaptability.

TABLE 8. Representative studies on multi-band rectifier topologies in SWIPT systems.

Focus Area	Representative References	Key Contributions
Dual-Band / Multi-Band Rectifier Designs	[2], [13], [41], [44], [46], [47], [63], [64], [102], [107]	Works by Wagih *et al.* [2] and Lin & Ziolkowski [13] integrate dual-band rectennas for simultaneous 900 MHz and 2.4 GHz operation. Zhu *et al.* [41] and Wagih *et al.* [44] demonstrate dual-polarized and dual-mode rectifiers achieving high isolation and conversion efficiency. Ja'Ffar *et al.* [102] propose frequency-reconfigurable rectennas supporting multi-band operation without matching networks.
Wideband and Broadband Rectifiers	[11], [39], [41], [42], [80]	Studies emphasize broadband antenna–rectifier integration with tuned LC or transmission-line networks to maintain high RF-to-DC efficiency across multiple frequency bands. [11] and [39] model diode capacitance and resistance for maintaining impedance stability under frequency variation.
Multi-Frequency and Tunable Rectification	[46], [47], [49], [50], [64], [107]	Electrically small Huygens and metamaterial-based rectifiers provide multi-resonant operation, high gain, and flexibility for IoT applications. [107] specifically uses dual-circular-polarized antennas optimized for reduced interference in multi-band SWIPT.
Reconfigurable and Adaptive Rectifiers	[67], [102], [110], [114]	Frequency-reconfigurable rectennas and adaptive matching architectures dynamically adjust resonance or load for sustained efficiency. IRS [67] and metasurface-enabled designs [110], [114] extend these to adaptive beam-steering and energy focusing.
Multi-Input Multi-Output (MIMO) and Hybrid Multi-Band Systems	[4], [24], [55], [61], [62]	These explore multi-band signal routing and hybrid MIMO architectures that allocate frequency resources across multiple rectification channels for improved EH and ID performance.

The diode technology itself is a key factor in such wideband performance. Schottky diodes are preferred for SWIPT rectifiers due to their lower forward voltage and faster switching response compared to conventional PN diodes [11], [39]. However, their nonlinear I–V characteristic can increase signal distortion and reduce overall rectifier efficiency, particularly at higher input power levels or in multi-frequency environments. In [11], for instance, the authors highlight how

TABLE 9. Emerging research trends, key challenges, and future directions in AI/DRL-enabled SWIPT systems.

Theme	Emerging Research Trend	Key Challenge	AI/DRL Role	Future Direction	Refs.
Waveform & Nonlinearity-Aware Design	Co-designing multisine waveforms with rectifier nonlinearity for adaptive EH	Joint modeling of EH nonlinearity and channel variations	AI learns nonlinear mapping between incident waveform and rectifier DC output for real-time adaptation	Closed-loop learning frameworks integrating predictive waveform optimization	[1], [69], [84], [110], [111]
Resource Allocation in SWIPT	AI-based joint optimization of power splitting, scheduling, and beamforming	Nondeterministic Polynomial time (NP)-hard and non-convex optimization under partial CSI	DRL dynamically allocates resources and power for EH/ID users under stochastic conditions	Multi-agent DRL for distributed energy-information balancing	[2], [3], [115], [116], [117]
IRS-Aided Energy Transfer	IRS-assisted SWIPT for improved energy focusing	Joint phase shift optimization and channel estimation	Deep learning models optimize IRS phase configuration for real-time adaptation	Hierarchical DRL for multi-IRS cooperative control	[4], [76], [94], [110], [111]
Cross-Layer Optimization	AI integration across Physical Layer (PHY)–Medium Access Control (MAC)–Network layers	Maintaining rate–energy trade-offs across layers	DRL for joint beamforming, EH/ID mode switching, and link adaptation	Cross-layer learning architectures with multi-objective policies	[3],[69], [84], [110], [115]
Security and Robustness	Deep learning–enabled physical layer security for SWIPT	Eavesdropping risk in energy-carrying signals	DNN optimizes secure power allocation and waveform design to maximize secrecy rate	Adversarial DRL for robust and secure SWIPT architectures	[2], [117], [118],]
Energy-Harvesting Cognitive Networks	Cognitive radio with EH-enabled SWIPT	Balancing interference mitigation with EH demands	DRL agents manage spectrum sensing and energy cooperation under uncertainty	Safe DRL and federated learning for dynamic spectrum–energy management	[3], [115], [116],
Nonlinear Modeling & Circuit Optimization	AI-assisted modeling of diode and impedance behavior	Complex nonlinear rectifier equations	ML surrogate models emulate circuit-level RF–DC conversion	Hybrid simulation–learning pipelines for hardware co-design	[76], [84], [110], [111]
Green and Sustainable Design	AI-driven energy-efficient SWIPT for IoT and 6G	Energy loss and hardware inefficiency	DRL minimizes wasted power and optimizes EH efficiency	Sustainable AI–SWIPT integration for 6G and IoT	[1], [5], [93], [104], [115],

exploiting diode nonlinearities can enhance energy extraction under certain conditions, while [39] emphasizes the importance of carefully accounting for diode capacitances and resistances to handle dynamic variations.

By incorporating wideband antenna designs [41], specialized matching circuits [42], and detailed diode modeling [11], [39], researchers can reduce adverse nonlinear effects. This approach simultaneously maintains stable high-efficiency response while improving the rectifier's resilience against frequency and input power variations, key factors for SWIPT deployments where devices often operate under unpredictable real-world conditions.

Additionally, the studies conducted by [1], [8], [85], [86], and [81] advance the field of SWIPT and RF EH by focusing on optimizing transmission strategies, integrating EH with communication protocols, and enhancing the modeling of energy harvesters to improve system performance and efficiency.

For instance, Ayir et al. [8] propose a comprehensive approach to optimize transmit waveforms for RF WPT systems. This is done using novel nonlinear rectifier model that facilitates power prediction and optimization from different waveform types thereby enhancing energy efficiency through tailoring waveforms that match the specific linear characteristics as well as impedance mismatches of harvest circuits. Proving this optimization framework through stringent simulations together with experimental setups shows significant enhancement in EH efficiency.

The study by [81] tackles nonlinearity based memory effects in SWIPT systems using complex nonlinearities, Markov reward chain models, non-instantaneous response of rectifier components; DNNs for memory effect equalization; input signal distribution optimization; modelling through DNNs; information rate improvement via optimizing input signal distribution among other pertinent issues which usually change into better things via applying some efforts to them directly on these problems.

The study [85] propounds amplitude-modulated Orthogonal Frequency Division Multiplexing (OFDM) signals for integrating rectifiers along with information receivers without local oscillators. This technique minimizes power consumption thereby simplifying receiver architecture, making it suitable for low-power IoT applications where space efficiency is critical.

The study [86] proposes more realistic models compared to traditional linear-based strategies that consider even bigger nonlinearity and monotonicity of harvested power. In other words, their piecewise linear approximations better predict what happens under real-world conditions than Newton's laws do providing important insights into system design and operation under energy constraints.

Moreover, studies like [87], [88] [26], and [89] advance the technology of SWIPT by coming up with different approaches to improving energy efficiency and optimizing signal integrity for both power transfer and information transmission. Indeed, these studies give important insights and techniques that can improve performance as well as effectiveness of SWIPT systems, especially in IoT applications.

Buckley and Heath [87] examine a new transmitter architecture in OFDM system that enables optimization of both EH capacity together with information transmission through conditioning both cyclic prefix and part of the OFDM signal. Their system integrates a selective switching mechanism capable of alternating dynamically between modes used for EH or decoding information which results in efficient conversion process that supports self-sustainability at system level, while still providing an effective rate-energy trade-off. On their part.

Kim et al. [88] propose an innovative SWIPT scheme consisting of high-power continuous wave combined with weak modulated signals meant for low interference as well as increased power amplifier efficiency in IoT devices. The receiver circuit is simplified using this method whereby the received signal is rectified before separating the power component from the information one thereby reducing complexity as well as minimizing power consumption.

The study carried by [90] also addresses advanced waveform designs and modulation techniques to enhance efficiency and functionality of SWIPT systems, respectively, focusing on reducing interferences, optimizing EH, managing the dual needs of power and information transfers in various wireless networks applications.

For example, [90] present a novel way to include highly rectangular power pulses into the cyclic prefix of CP-OFDM systems with high PAPR. Within the same frequency and time resources, this technique superimposes EH signals over data signals for maximum communication integrity while minimizing external interference during data transmission. In fact, through making sure that all the energy in a pulse is contained within a cycle prefix which is discarded at receiver side as far as communication is concerned means that they minimally interfere with OFDM symbols hence enabling rectifier optimization with minimal communication integrity losses.

Studies like [90] and [91] suggest biased ASK modulations for SWIPT in IoT where hardware complexity needs to be minimized. The study proposes flexible hardware architecture which can switch between rectifying and envelope detecting functionalities depending on modulation rate and filter settings.

The work in [82] looks at regarding co-design strategies for communication and power components. As per [8] explanation concerning waveform optimization, the study indicates how far these technologies have come in terms of development showing how crucial it is to understand well about integrating rectifiers properly for use within SWIPT systems such that these devices become more efficient and user friendly than ever before.

For instance, [80] and [92] list out some ways through which load resistance can be optimized to ensure efficient RF-DC conversion within the system. Jiang et al.'s technique uses a rat-race coupler to split non-information carrying components in the received signal for rectification while directing information-carrying components towards data recovery. This technique improves conversion efficiency, enables high efficiency at small input powers and is particularly suitable for WPAN applications. This compactly designed dual-purpose system has been practically measured under various network conditions, validating its operational efficacy in concurrent data/power transmission.

In conclusion, effective integration strategies are essential for optimizing the performance of rectifiers within SWIPT systems. By employing analytical approaches, system-level optimizations, communication-power component co-design, and waveform optimization, researchers have developed techniques that enhance both EH and ID capabilities. These strategies ensure that rectifiers operate efficiently within SWIPT systems, contributing to the advancement of WPT and communication technologies. TABLE 10 Organized a comprehensive overview of integrated strategies used in SWIPT systems and Rectifier Technology, including key innovations, benefits, and corresponding references.

IV. CURRENT CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Various challenges facing rectifier technologies have been approached in studies by [21], [42], [93], and [95]. This has led to critical areas for future research and improvement that

TABLE 10. A comprehensive overview of integrated strategies used in SWIPT systems and rectifier technology.

Focus Area	Key Innovations	Benefits	References
Antenna Design and Integration	- Dual-Polarized Designs - Shared Aperture Antennas - Microstrip Designs - Huygens Antenna with Metamaterial-Inspired Elements - Frequency Reconfigurable Rectenna - Multipolarization and Wideband Antennas - Dual-Output Antennas - Textile Antenna/Rectenna Integration - Dual-Band, Dual-Mode Antennas	- Improved rectification performance - Reduced complexity compared to multi-antenna systems - Enhanced multi-band operation - Size reduction and miniaturization - Enhanced isolation between EH and ID paths - Efficient EH over a broad frequency range - Effective ID capabilities - Enhanced versatility in wearable devices	[2], [7], [13], [36], [44], [46], [47], [50], [54], [64], [79]
Rectifier Technology and Component Co-Design	- Voltage Doubler Topology - Class-F Rectifiers - Hybrid Rectifier-Receiver (HRR) - Monolithic Microwave Integrated Circuit (MMIC) Amplifiers - Hybrid Rectifier-Receiver Nodes - EH and ID Block Integration Using Intermodulation	- Reduced interference - Optimized power conversion efficiency - Enhanced EH - Minimized losses associated with separate components - Improved sensitivity - Reduced hardware complexity	[9], [32], [42], [57], [60], [61]
Modulation Schemes and Integration	- Amplitude-Based Modulation - Biased ASK - Multi-Tone PSK Modulation - Asymmetric Modulation - Biased ASK Modulation - Multitone PSK Modulation	- Improved ID - Enhanced sensitivity - Balanced EH and data transmission - Simplified system architecture - Improved EH efficiency while maintaining acceptable ID performance - Rectifier serves dual functions (EH and ID)	[17], [28], [46], [52], [57], [69], [73]
System Architecture and Shared Hardware Integration	- Integrated Receiver Architecture - Time-Switching, Power-Splitting, Antenna-Switching Techniques - Integrated Receiver Design - Dual-Purpose Rectifiers	- Streamlined component use - Optimized system performance - Eliminated need for fixed power splitters - Reduced area requirements - Simplified receiver design - Enhanced overall efficiency	[46], [56], [57], [58], [71], [74]
Advanced Materials and Metamaterial Integration	- Magneto-Dielectric Substrates - Metamaterials - Electrically Small Antennas - Metasurfaces for Energy Conversion	- Improved multi-band operation - Enhanced miniaturization and size reduction - Achieved compactness and efficiency suitable for IoT applications - Enhanced EH capabilities without adversely affecting ID performance	[13], [46], [50], [64]
EH Techniques	- Dielectric Resonance Power Transfer - Triboelectric/Piezoelectric Transducers - Resonant Inductive/Capacitive Coupling	- Improved efficiency in underwater communication - Enhanced flexibility in device design - Enabled efficient WPT over various coupling methods	[43], [59]
Beamforming and Signal Processing	- Time Reversal (TR) Method - (IRS) - MaMIMO Technology - Joint Beamforming Design - Hybrid Beamforming in IoT Networks	- Improved energy concentration - Enhanced RF-to-DC conversion efficiency - Reduced environmental energy loss - Optimized transmission and reflection of signals for both EH and ID - Achieved efficient power transfer and reliable information delivery	[14], [61], [62], [67], [70]
Modeling and Simulation	- Non-Linear Rectifier Models - LabVIEW Simulation - MDP-Based Learning Model	- Optimized system parameters through accurate modeling - Improved understanding of rectifier behavior	[53], [63], [64], [73]

TABLE 10. *(Continued.)* **A comprehensive overview of integrated strategies used in SWIPT systems and rectifier technology.**

		under various conditions - Developed strategies for system design considering practical constraints	
Integration Strategies	- Low-Power Operation Management Units - Smart Building Technologies - Integration with LPWANs for IoT - Integration in Wearable and Textile Devices - Power Splitters and Couplers in Receiver Architecture	- Minimized energy wastage - Improved overall system efficiency - Enhanced versatility and efficiency in wearable applications - Optimized balance between EH and ID - Reduced system complexity and cost	[2], [12], [14], [44], [51], [59], [78]
Novel Configurations	- Power-Optimized Waveforms (POW) - Tunable Power Splitter	- Enhanced rectifier efficiency - Flexible adjustment of power ratios between EH and ID - Improved adaptability to varying system requirements	[74], [78]
Integrated Circuit Design	- CMOS Rectifiers with Matching Networks - High Conversion Gain Envelope Detectors	- Enhanced EH efficiency - Compatibility with existing semiconductor technologies for easy integration - Efficient conversion of RF signals to baseband - Suitability for low-power applications and IoT devices	[3], [22]

will enhance the efficiency, integration, and environmental sustainability of these systems.

For example, [93] vividly delineated on some of the environmental impacts as well as technical hurdles relating to rectifier technologies including inefficiency in power transmission over long distances among others, suggesting life cycle assessments tools are used for understanding and mitigating their ecological consequences of SWIPT systems. In this regard, they advocate for further studies aimed at increasing power transfer efficiency while minimizing its impact on the environment through use of new materials or even system architectures which incorporate green technology development strategies. The need for effective integration strategies such as advanced beamforming techniques and innovative system designs is also stressed here since they extend operational range and improve system efficiency. However, high rectifying efficiency may not be easily maintained amidst different operating conditions such as duty cycle variations and changing input power levels if developing better materials have failed to act on it is a recommendation provided by [42]. It then becomes necessary to consider alternative designs that can adapt to different situations without rendering them inefficient while ensuring maintainability of the existing levels of performance. They argue further that advanced beamforming techniques should be employed so as to extend coverage area thereby enhancing overall network coverage quality besides simplifying RF front-end design procedures within wireless communication systems transmitting information wirelessly from one device into another without plugging cables between them all the time; other elements include envelope tracking circuits based amplifiers or differential amplifiers plus power-efficient envelope detector capable transceivers.

Additionally, [21] and [96] discussed more specifically on how wearables SWIPT happen with the use of rectifier technology. A design is presented that integrates a Self-Injection Locked Oscillator with a dual-polarized patch antenna and a passive receiving subsystem for efficient energy transfer. This means of achieving energy autonomy in wearable devices would further refine the rectifying and system integration processes so that it can be used to develop effective EH capabilities. Through this, one will have made an effort towards making use of the available potential energy resources in order to provide power requirements necessary for low-power IoT nodes presently on the rise as far as market demands are concerned.

In [95], the researchers proposed optimization of non-linear rectifiers using multisine signals plus balanced pre-equalization strategy to improve SNR and power conversion efficiency. Furthermore, PAPR affects rectifier efficiency in terms of its average input signal power thus such transmission strategies should be designed in such ways that they optimize PAPR leading into better overall system performance among others which emphasize how much more work still needs to be done before full information transmission while maximizing power transfer efficiencies is achieved using non-linear rectifiers in order to meet our expectations about future penetration levels across different areas where wireless sensors or mobile smartphones will dominate various sectors such as healthcare delivery systems services like monitoring patients' condition overtime wherever they are at any time through internet-based technology communication protocols between them even without visiting hospitals physically too often since according latest statistics from the world bank over 75% population has access cellular networks globally but only 49% people own smart phones today these figures reveal just fewer than half human beings possess handset capable connecting said computer networks based upon recommendations early intervention program recommendations conducted within health ministry guidelines set forth regarding treatment severe cases management underlying diseases associated adults children below eighteenth birthday old age group; other features could include transceivers having similar architecture but different tuning ranges driver stages can change impedance matching consequently changing their behavior during operation reconfigurable antennas for providing beamforming.

Rectifier technologies for SWIPT systems are at the heart of these research papers. The works of [51], [59], [97], and [98] represent the most significant challenges in the field, and possible solutions that can be used to optimize both power transfer efficiency and data communication. Reference [51] discuss a novel two-tone frequency shift keying (FSK) modulation scheme which uses rectifiers' non-linear characteristics to improve both power and data transfer efficiencies within single hardware architectures. This study examines modulation optimization for improved energy and spectral efficiency in SWIPT systems by treating information versus power trade-offs including transmitter distortion due to PAPR of waveforms as well as other factors. On the other hand, [97] take a look at dynamic power splitting techniques such as dynamic PS algorithms to deal with hybrids in such devices as mobile phones or low-power sensors among others so that there is always optimal signaling going on.

In trying to make receivers more efficient, [98] came up with pulse position modulation instead of conventional ASK; this enhances energy use for instance in wearable devices powered by harvested RF energy. A new kind of pulse position modulation has been developed by [98], which helps reduce consumed energy significantly for many low-power IoT applications without compromising accuracy too much through use of high amplitude pulses encoded into pulse positions. This paper therefore argues why it is necessary to have better receiver designs that can meet both needs stated above, thereby improving overall performance of these applications. The article introduces an innovative method called Pulse Position Modulation that combines rectification process with ID thus boosting energy efficiency especially on low-energy devices. This paper presents a new pulse position modulation (PPM) method that enhances energy efficiency for ultra-low-power devices by combining the rectification process with ID.

Four studies, [5], [99], [100], and [101] cover different aspects and problems of integrating rectifier technology in SWIPT systems, with each one addressing diverse applications and the optimization of overall system performance across various environments. For instance, [99] explain about the integration of SWIPT technologies in Wireless Body Area Network (WBANs) especially for medical monitoring purposes; they underline that it would be important to improve efficiency of these rectifiers and build networks that are more sturdy for better performance and user experience in the area of healthcare applications through a variety of ways such as improved power management techniques or by designing suitable power electronics suitable for wearable health monitors. Their study raises awareness on inadequate power supply as well as inefficient systems, thereby future work should center on innovation of materials and devices that can fit seamlessly into user-centric healthcare applications.

On the other hand, [100] discuss architectural, operationalization, and optimizing issues related to melding wireless energy transfer systems with drones. This research calls attention to the necessity of increasing WPT effectiveness, adapting designs to dynamic operating environments as well as improving energy management capabilities for Unmanned Aerial Vehicle (UAVs). It also emphasizes the need for eco-friendly, yet flexible WPT solutions which can vary depending on conditions and types of application used for UAVs.

In a similar vein, [101], have developed an innovative dual-port fully-textile antenna designed towards SWIPT applications within BANs. They take advantage of this opportunity by using co-designing a rectifier with an antenna thus eliminating any further need for matching network enabling both communication and EH to be enhanced simultaneously. This design improves the efficiency of power conversion at its output while reducing system complexity making it ideal for wearable health/fitness monitors and IoTs where sustainability and efficiency dominate. Another example is [5] who introduced a multi-tone amplitude modulation (MAM) approach that ensures optimum in symbol error rate (SER) and EH efficiency, making it suitable for any IoT application. It serves as a strategic advantage since the scheme improves SWIPT system's performance through enhanced energy conversion via using high PAPR signals.

The work of [12], [28], [30], and [64] looks into novel ways for integrating and enhancing rectifier technologies in SWIPT systems, with applications to different communication environments such as IoT. In their research, [12] propose a multi polarization rectenna system employing an orthogonal hybrid coupler to have significant isolation between ports with reduced signal interference and improved adaptability towards several communication environments. This design is focused on improvements in the integration of rectifying circuitry so that efficiency and impedance matching can be better handled over various modes of operation. According to this research, it is essential to optimize these systems for complex environmental interactions so as to achieve high efficiency of power conversion as well as communication integrity too.

The [28] introduces asymmetric phase-shift keying (PSK) modulation that promotes a trade-off between rate-energy in SWIPT systems by exploiting nonlinearities embedded in rectifiers' devices. The authors demonstrate that asymmetric PSK outperforms traditional symmetric PSK by improving EH effectiveness without compromising transmission rates considerably. This study reveals numerous promising directions for future research regarding modulations designed explicitly for EH applications and system architectures optimization aimed at more efficient exploitation of nonlinearity in energy harvesters.

The study [30] examined the merging of EH technologies with SWIPT technology necessary to solve power hunger issues common among Internet-of-Things devices. It proposes integrating innovative techniques like backscatter communication, WPT, EH etc., into IoT deployments so that their sustainability could be enhanced together with efficiency at all costs possible according to their viewpoint expressed therein. It suggests moving forward with greater alignment among these technologies such that power efficiency within them shall be boosted while bringing about efficient system performance that is essential for resilient IoT architectures capable of sustained operation without considerable energy resources.

In addition, [42], [51], [62], [67], and [102] have all focused on the ongoing development and optimization of rectifier technologies for SWIPT systems with an interest in increasing efficiency, adaptability, and integration in order to meet demands of IoTs, smart living and other wider ranging wireless networks. Besides indicating the difficulties associated with parasitic capacitance in high-frequency RF energy harvesters; [22] also points out the key importance of effective matching networks and MPPT towards optimizing rectifier performance; which is often achieved by minimizing parasitic effects as well as improving rectifier efficiency at low powers for power limited IoT domains. The researchers call for innovative design techniques that enhance overall system performance in SWIPT applications like this one.

According to [102], they describe a frequency reconfigurable rectenna designed especially for self-sustaining low-power wireless sensor networks, aiming to improve on frequency tunability enhancement without using a matching network; hence varying the distance of shorting pins so that resonant frequencies can be changed brings a flexible answer capable of being modified easily over various IoT infrastructures to let antenna impedance integrate with that of the rectifier.

Literature such as [62] give a comprehensive review on challenges encountered in developing SWIPT systems/WPT-radiated communication networks focusing on balancing EH with information transmission within these frameworks. The future research areas envisaged by them are aimed at enhancing energy transfer efficiency; optimizing system designs considering better integration; improving communications network performance based on SWIPT technology.

Moreover, [67] examine how transmit beam formers, passive beam formers, power splitters, energy combiners can be jointly optimized when dealing with energy receivers in IRS-aided WPT systems and this is aimed at addressing complex interactions that exist within the system while these algorithms are refined to enhance energy efficiency and system performance.

The authors of [51] have explored how MaMIMO could be used to improve the efficiency of both WPT and WIT in SWIPT systems. Their research shows how rectifier output voltage can be greatly increased by MaMIMO, which provides a scalable way for improving energy transfer efficiency. Future research is encouraged to perfect precoding strategies, as well as broaden their applicability to increase the effectiveness of SWIPTs in different cases.

Finally, TABLE 11 Shows a comprehensive evaluation of practical future insights, critical challenges, and advancements in SWIPT systems and Rectifier Technology. highlighted persistent challenges have been discussed for rectifier technologies for deployed SWIPT systems, targeting better efficiencies, integration, environmental impacts. Advanced beamforming techniques should be adopted as well as communication-power co-designs so that there are extended operational ranges with high system efficiency. All these together establish an agenda for further technological advances aiming at overcoming present limitations and exploring new potentials of them in SWIPT applications.

V. DISCUSSION OF THE FINDINGS

Rectifier technology for SWIPT systems is experiencing a transformational era, deeply impacting wireless communication and power transfer. One of the key innovations is the integration of antennas with rectifiers, which simplifies SWIPT system topologies and enhances operating efficiency [2], [104]. Such integration is particularly beneficial in dynamic environments like wearable devices, where efficiency and flexibility are paramount. Wagih et al. [2] demonstrated a 2.4 GHz wearable textile antenna/rectenna for simultaneous information and power transfer, highlighting the possibility of optimized designs in wearable technologies.

Sophisticated modulation schemes combined with advanced EH circuits have improved information conversion rates as well as communication reliability. Schemes such as QAM and PSK, designed specifically for SWIPT systems, improve the trade-off between EH and data transmission efficiency [105], [108]. Morsi et al. [105] examined conditional capacity and transmit signal design for SWIPT systems with multiple nonlinear EH receivers, addressing the challenges posed by nonlinearities in energy harvesters and optimizing system performance.

Advanced design techniques have successfully met the impediments related to miniaturization and multi-

TABLE 11. Comprehensive evaluation of practical future insights, critical challenges, and advancements in SWIPT systems.

Aspect	Description / Future Directions and Approaches	Ref.
Efficiency Optimization at Low Input Powers	- **Advanced Rectifier Design**: Enhance performance at low power levels through improved PCB designs, reduced parasitic capacitance, and optimal load resistance. - **Materials and Technologies**: Explore new semiconductor materials and nanotechnology for higher sensitivity and lower threshold voltages. - **Circuit Optimization**: Minimize power losses via impedance matching and advanced circuit techniques.	[22], [23], [104], [106]
Integration with Emerging Wireless Technologies	- **Standardization and Protocol Development**: Develop industry standards for integrating SWIPT with MaMIMO, 6G, and IoT systems. - **Cross-Layer Optimization**: Jointly design radio and computing resources for enhanced energy efficiency. - **Zero-Energy Devices**: Create efficient circuits and artificial intelligent (AI)-driven power management for sustainability in 6G and Cellular IoT (CIoT).	[1], [24], [27], [94]
Practical Implementation and Prototyping	- **Experimental Validation**: Validate theoretical models through experiments with rectenna arrays and wearable devices. - **Hardware Integration and Miniaturization**: Develop compact SWIPT components integrated into IoT devices and wearables while maintaining high efficiency. - **Integration Challenges**: Balance miniaturization with performance, especially in dynamic environments.	[2], [13], [38], [107], [106]
Advanced Modulation and Waveform Design	- **Nonlinear and Adaptive Modulation Schemes**: Design modulation techniques like ASK and multitone FSK tailored for SWIPT to improve EH and adapt to channel conditions. - **Integration with Advanced Modulation**: Incorporate complex modulations (e.g., Quadrature Amplitude Modulation (QAM) to enhance information rate and power efficiency.	[17], [28], [71], [108]
Nonlinear modeling and AI discussions	- **Accurate Circuit Modeling**: Develop analytical and simulation models capturing nonlinear diode behavior, junction capacitance variation, and dynamic characteristics of rectifiers under varying RF input conditions. Such models improve prediction accuracy for RF-to-DC conversion efficiency. - **Algorithm Development**: Apply advanced optimization algorithms, including Markov Decision Processes (MDPs), reinforcement learning (RL), and deep learning (DL), to dynamically manage nonlinear effects and optimize rectifier performance in real time. - **Simulation Tools**: Design and implement software platforms that integrate nonlinear device models with full SWIPT system simulations, enabling co-optimization of circuit, antenna, and resource allocation strategies.	[69], [76], [84], [110], [111], [115], [116], [117].
Multi-Band and High-Frequency/Nonlinear Diode Challenges	- **Broadband Antennas & Matching:** Use multi-resonant antennas with tuned LC or transmission-line matching elements to extend operational frequency range and maintain efficiency across multiple bands. - **Adaptive Impedance Tuning:** Dynamically match impedance under changing frequency and power conditions. - **High-Frequency Schottky Diodes:** Utilize low forward voltage and fast switching; refine modeling to include Rs, Cj and nonlinear effects. - **Nonlinear Behavior Mitigation:** Balance beneficial nonlinear effects with distortion control through harmonic-balance simulations, prototyping, and optimization. - **Multi-Stage Rectification:** Improve efficiency across diverse frequencies and input levels. - **Adaptive Architectures:** Implement dynamic load/bias control with	[11], [39], [41], [42]

TABLE 11. *(Continued.)* **Comprehensive evaluation of practical future insights, critical challenges, and advancements in SWIPT systems.**

	sensing loops for real-time optimization. - **Outcomes:** Stable high efficiency, reduced distortion, and robust multi-band operation for real-world SWIPT scenarios.	
Multi-Antenna and MIMO Techniques	- **Beamforming and Antenna Design**: Design optimized beamforming algorithms and antenna configurations for efficient energy and information delivery. - **Diversity Techniques**: Employ spatial diversity to mitigate fading and enhance reliability. - **Challenges**: Managing complexity without increasing system cost significantly.	[4], [24], [55]
CSI and Realistic Channel Modeling	- **Robust Transceiver Design**: Develop architectures that perform well under CSI uncertainty and in dynamic environments. - **Enhanced Channel Estimation**: Improve methods suitable for energy-constrained systems to acquire accurate CSI. - **Incorporating Fast-Fading Effects**: Model fast-fading channels for realistic performance evaluation.	[24], [69], [83]
Security and Privacy Concerns	- **Physical Layer Security**: Implement measures to protect against eavesdropping and jamming. - **Resource Allocation for Security**: Balance EH efficiency with security requirements. - **Secure Protocols**: Develop lightweight protocols suitable for energy-constrained SWIPT devices.	[37], [77], [99]
Energy Management and Optimization	- **Dynamic Power Control**: Implement adaptive mechanisms responsive to energy availability and QoS needs. - **Energy-Efficient Routing**: Design protocols considering nodes' EH capabilities; incorporate AI for optimization. - **Battery and Storage Management**: Investigate hybrid systems combining harvesting with storage for stability.	[31], [33],[50], [53], [69],[84],[110]
Environmental Impact and Sustainability	- **Eco-Friendly Designs**: Use green materials such as recyclable metals, lead-free soldering compounds.and sustainable practices in device manufacturing. - **Harvesting Ambient Energy**: Expand research on harvesting from ambient RF and other sources. - **Safety and Health Regulations**: Address safety concerns, especially for high-power and far-field applications.	[30], [93], [105], [110]
Standardization and Interoperability	- **Industry Collaboration**: Work with standardization bodies to develop common protocols. - **Interoperable Systems**: Ensure compatibility with existing standards and devices, including LPWANs. - **Regulatory Compliance**: Navigate spectrum usage regulations and power transmission limits.	[24], [63], [100]
Advanced Antenna and Rectenna Technologies	- **Broadband and Multi-Band Designs**: Create rectennas capable of harvesting across wide frequency ranges. - **Polarization Diversity**: Utilize dual-polarized and reconfigurable antennas to maximize energy capture. - **Metasurface Integration**: Incorporate metasurfaces for enhanced performance and adaptability. - **Challenges**: include managing design complexity and striking a balance between efficiency and miniaturisation.	[7], [44], [64], [107], [110], [106]
Mobility and UAV-Based WPT Systems	- **Trajectory and Energy Optimisation:** Strategies UAV routes for maximal energy transmission and communication efficacy. - **Real-Time Adaptation:** Create systems that adjust to evolving settings and user locations. - **Applications:** Investigate dynamic charging for electric cars and portable electronics. - **Challenges:** Constraints of battery technology and adherence to regulatory standards for UAV operations.	[47], [100], [101], [110]

TABLE 11. *(Continued.)* Comprehensive evaluation of practical future insights, critical challenges, and advancements in SWIPT systems.

Integration with Other Technologies	- **Hybrid Systems:** Combine SWIPT with NOMA, IRS, AI, and programmable metasurfaces to augment system capacity and efficiency. - **Algorithm Development:** Formulate algorithms to address the intricacies of merging various technologies. - **Practical Implementations:** Develop and evaluate integrated systems in real-world contexts.	[26], [39], [47], [110]
Prototyping and Real-World Deployment	- **Pilot Projects and User Studies:** Evaluate SWIPT systems under realistic situations and collect user input. - **Adaptability:** Guarantee that systems sustain performance under fluctuating surroundings and power circumstances. - **Challenges:** Transitioning from prototypes to broad deployments while ensuring dependability.	[2], [30], [98], [11]
Micro EH for IoT Platforms	- **Efficiency and Miniaturisation:** Enhance Micro EH systems for increased effectiveness and IoT device integration. - **Adaptive Models and Storage:** Create EH models that adjust to fluctuating surroundings and enhance storage efficiency. - **Challenges:** Reconciling dimensions, efficacy, and compatibility across many applications.	[11]
Advancements in WPT and Future Applications	- **Efficiency Enhancement:** Concentrate on augmenting WPT efficiency, particularly over extended distances. - **Emerging Applications:** Examine space-based wireless power transfer, dynamic charging for electric vehicles, and integration with Internet of Things devices. - **Safety and Regulations:** Mitigate health risks and adhere to safety regulations in high-power applications. - **Challenges:** Technical obstacles in increasing gearbox distances and guaranteeing user safety.	[6], [110], [94]
Underwater applications	- **Effective Underwater Channel estimate**: Employ trained DNNs in conjunction with pilot signals to get effective channel estimate in aquatic settings. - **Development of Specialized Protocols**: Develop protocols that tackle the specific challenges of underwater communication, including elevated water pressure, restricted bandwidth, propagation delay, and increased error rates. - **Techniques for EH**: Employ EH techniques appropriate for underwater sensors to extend operating longevity and minimize battery replacement requirements. - **Challenges**: Addressing environmental challenges such as water currents, signal degradation, and multipath propagation necessitates new solutions specifically designed for underwater SWIPT systems.	[6],[17], [43], [25], [49], [59]
General Challenges in SWIPT Systems	- **EH Efficiency:** Enhance rectification operations and reduce power loss, particularly at low input power levels. - **Concurrent transmission Balance:** Facilitate energy and information transmission without considerable compromises; mitigate the constraints of time-switching and power-splitting techniques. - **System Complexity:** Handle the growing complexity of modern SWIPT systems while guaranteeing their scalability and dependability. - **Health and Safety Regulations:** Guarantee adherence to regulations and safety standards in high RF power transfer systems as they expand.	[107], [108], [109], [110]

band operation. The use of metamaterials combined with sophisticated microfabrication methods facilitates designing high-performance rectennas with a combination of compactness and multi-band operation [46], [106], [107].

Rosaline et al. [106] designed and optimized a miniaturized dual band rectenna for wireless power transfer, obtaining performance improvements through size minimization and efficiency enhancement.

Zhang et al. [107] also developed a highly efficient and compact rectenna with dual circular polarization and reversed Wilkinson power divider to increase its efficacy for wireless power and information transmission.

System-level optimizations have enabled effective integration strategies like energy beamforming and concurrent communication and power component design, thus enhancing system-level efficiency [80], [81], [110].

In their research, Ojukwu et al. [110] discussed the use of metasurface-enabled WPT and energy harvests in future wireless networks, highlighting the ability of metasurfaces to improve the efficiency of energy transfer and adapt the system for increased flexibility.

The effective mapping of transmitted waveforms to match the non-linear rectifier characteristics successfully solves the typical impedance mismatch between antennas and rectifiers, ensuring maximum power delivering and enhancing the efficiency of SWIPT schemes [8], [105], [109]. Claessens et al. [109] presented the WiLO-OFDM transmission strategy for SWIPT that utilizes waveform optimization to optimize EH while ensuring communication effectiveness.

It is critical to identify the key issues and possible directions of research into the development of rectifier technology in the scope of SWIPT devices. The ecological consequences and the losses of long-distance transmission are the matters of great concern [93], [94]. Broad-based life-cycle analysis and the development of environment-friendly technologies are recommended to reduce the ecological impact. Abbas et al. [94] discussed the future of 6G technology and the Cellular Internet of Things, highlighting the need to adopt the technology of zero-energy devices and environment-friendly practices.

The integration of SWIPT with upcoming technologies like 5G, 6G, and IoT offers the potential to leverage greater speeds and lower latencies, hence enhancing resilience and effectiveness [1], [24], [94]. Jaiswal et al. [1] considered green computing in IoT using time-slotted SWIPT, highlighting the necessity for power efficiency in IoT networks. The evolution of flexible wearable rectenna technology for IoT devices enhances their use in smart devices [2], [106]. AI-based optimization techniques offer significant potential for optimizing the design and operation of SWIPT systems, resulting in smarter and more flexible configurations [69], [84], [110].

Furthermore, higher-level rectifier structures are tackling issues concerning nonlinearities of EH devices. The research conducted by Morsi et al. [105] and Shanin et al. [69] explored nonlinear EH models and optimization techniques, like the MDP, designed to boost system performance. The literature highlights the need for precise modeling and algorithm development in suppressing nonlinearities and enhancing the performance of SWIPT systems.

Wu et al. [108] introduced an integrated rectifying-mixer circuit for SWIPT, enhancing efficiency through the amalgamation of rectification and mixing processes in the realm of modulation and waveform creation. These advancements facilitate the advancement of low-power and small receiver designs appropriate for IoT applications.

Current research highlights the significance of collectively devised components and the use of new materials in integration techniques. Metamaterials offer the possibility of designing electrically compact antennas with improved performance and thus play a vital role in overcoming miniaturization and multi-band requirements, as evident from work by Lin and Ziolkowski [46], and Ojukwu et al. [110] facilitate the development of electrically tiny antennas with improved performance, essential for applications necessitating miniaturization and multi-band functionality.

Experimental tests and practical demonstrations are used to prove theoretical concepts and determine the feasibility of high-end SWIPT systems [2], [103], [106], [107]. Experimental approaches by Chang et al. [103] involved using wideband rectennas that allow multi-polarization and thus proved to be pertinent in the case of industrial IoT applications, including manufacturing industries. The experimental verification process provides valuable information concerning operational effectiveness and related challenges, thus determining the direction of future developments. These environments are characterized by complex operating conditions where higher reliability is of utmost significance. Therefore, this has identified challenges and potential research areas that have driven technological advancements in rectifier technology in SWIPT systems.

Recent studies show that SWIPT systems have made significant progress in rectifier performance, integration techniques, and application-specific improvements. For example, advanced approaches of nonlinear optimization have been utilized to represent rectifier nonlinearity and make the system more efficient [111]. At the hardware level, tiny mmWave receiver modules that combine rectifiers with sensing and communication capabilities have shown high RF-to-DC efficiency and are good for IoT applications [112].

PCB-based SWIPT solutions have successfully addressed parasitic and matching problems by making realistic design decisions, including split capacitors and load isolation [113]. Furthermore, nonharmonic dual-band architectures and circularly polarized antennas have enabled multi-bands operation while maintaining strong isolation between the EH and ID paths [114]. On the modulation strategies, optimized pulse energy modulation has significantly improved the energy–information trade-off in integrated receiver designs [115].

From a system integration perspective hybrid harmonic beamforming rectennas offer a multifunctional platform by combining EH, RF sensing, and communication [116]. The idea of "Versatile Rectifiers 2.0" makes rectifiers useful in more areas, such as backscatter and ambient RF sensing [117]. New antennas, including octa-port dual-polarized MIMO rectennas, show good isolation, minimal envelope correlation, and great efficiency in complicated IoT settings [118].

Finally, co-designed rectifying metantennas-antennas based on metamaterials combine the antenna and rectifier into one structure, which gives them great gain and efficiency in very small, battery-free IoT deployments [119].

Furthermore, there are serious concerns about the environmental impact of large-scale deployment of these systems as well as their inefficiency over long distances. There is therefore a need for future research in order to address this through green technologies and sustainable practices that will mitigate these impacts Consequently, exploration AI-driven optimization techniques provide opportunities for better system performances with more intelligent and adaptive designs. These emerging trends include integration of SWIPT systems into 5G technologies, flexible and wearable rectennas which can be explored further for further research. The technical scope of these applications offers additional dimensions to the use of SWIPT systems, thereby making them easily integrated with everyday technological requirements. As such, this research provides an important roadmap for advancing rectifier technology used in SWIPT systems where it starts from basic improvement towards designing and integration then to broader challenges dealing with futuristic application on the horizon. Further development is leading to more efficient, reliable, and sustainable development hereunder.

VI. RECOMMENDATIONS AND IMPLICATIONS

Extensive analysis of the rectifier technology used in the SWIPT system presents worthwhile lessons and practical suggestions toward the development of this technology. Increasing the challenges related to the operationalization of new technologies could boost the effectiveness and viability of the SWIPT system.

The potential ecological impacts resulting from the wide-scale application of SWIPT technology are an area of great concern [93], [104], [111]. Thus, it becomes critical to perform stringent life-cycle analyses to minimize and mitigate the environmental issues resulting from these systems. Future research should concentrate on developing environmentally friendly technologies and the enhancement of sustainable behaviors, which include the use of energy-efficient technologies and system structures designed to minimize carbon emissions during both the production and usage periods of the systems [93], [104]. Enhancing transmission power efficiency, particularly under long-distance conditions, can result in the reduction of the overall wireless network energy consumption and thus the achievement of global sustainability objectives.

Furthermore, the incorporation of SWIPT with nascent technologies such as 5G, 6G, and the IOT offers substantial prospects [1], [24], [94]. Integrating SWIPT with 5G networks facilitates the use of high speeds and low latencies, thus enhancing the robustness and performance of SWIPT systems. Research is required to enhance SWIPT in 5G and 6G contexts to enhance efficiency and efficiency for concurrent data and power transfer [94]. Creating adaptable, wearable rectenna technologies suitable for various IoT devices can enhance their use in smartphones, tablets, and wearables, providing more opportunities for EH and data transmission [2], [106], [107].

The use of AI-enabled optimization has been a promising approach to enhancing the adaptability, effectiveness, and overall performance of SWIPT systems.

Using machine learning (ML) and advanced signal processing methods, researchers are now more able to address the intricacies related to nonlinear rectifier behaviors, time-varying channel conditions, and issues regarding resource allocation. ML-based systems can predict environmental conditions, the mobility of the user, and potential interferences, thus enabling real-time adjustments of the transmit waveform, beamforming directions, or power splitting ratios [69], [84]. Such adaptive control methodologies can result in higher EH efficiency, reduced system losses, and better data transmission quality.

DRL methods have demonstrated promise to enhance the rate-energy tradeoff by learning dynamically from the environment and making optimal decisions under uncertainty [110]. Incorporating DRL within SWIPT system enables dynamic rectifier operating parameter control, modulation scheme switching, as well as optimal antenna configuration selection based on changing conditions. Furthermore, these AI-based methods accelerate the design process by reducing computational complexity and enabling system engineers to find solutions that are more efficient and less labor-intensive.

Optimization platforms that utilize AI far surpass classical rule-based technologies due to their advanced predictive analytics and superior decision-making capabilities. Additionally, SWIPT systems possess superior intelligence, robustness, and effectiveness in numerous dynamic operating environments.

Ultimately, a focus on ecological sustainability, the integration of new technologies, AI-driven optimization, and interdisciplinary collaborations are poised to transform the effectiveness and applicability of SWIPT systems into myriad areas of investigation in the future.

VII. CONCLUSION

This extensive study has systematically considered progressions, integration strategies, challenges, and upcoming directions in SWIPT Systems' rectifiers' technology through an analysis spanning many years. The examination also reveals various examples of advanced innovations on architecture designs as well as discussions on how these may impact future developments within SWIPT environment's domain. The examination discovered significant improvements in power transducers within space. Thus, antennas directly connected to rectifiers simplified designs resulting in increased energy efficiency required for wearable devices like smart watches or medical implants. In addition, new modulation techniques combined with efficient harvesting processes have enhanced communications reliability across different environments. New design concepts have successfully resolved issues involving miniaturization while supporting multi-band operations. Metamaterials-based materials enable enhanced performance from uncomplicated circuits and antennas that are smaller, yet more efficient. They are particularly valuable for IoT and industrial applications where qualities such as resilience and environmental tolerance are paramount. Research into integration approaches has revealed the value of system-level interactions like energy beamforming, communication/power components co-design.

Further, smooth running of rectifiers within SWIPT systems is ensured by employing these techniques, improving their efficiency and functionality. Thus, identifying current hurdles and future research focus areas were important to understand the limitations and potential growth avenues for rectifier technologies. This implies that there is a need for further research on environmental impacts, inefficiency towards distant locations, and merging with new technologies.

Additionally, it is interesting to mention that wearable devices with flexibility can be created through AI-driven optimization techniques to enhance the utility and practicality of energy receivers among others.

This comprehensive study has examined the development, integration methods, issues, and future opportunities in rectifier technology for SWIPT systems over the past several years. The study examines significant changes in architectural designs and examines their potential impact on future development in the SWIPT field.

The direct integration of antennas with rectifiers has improved system designs, enhancing energy efficiency for wearable devices such as smartwatches and medical implants [2], [104], [111].

The integration of new modulation schemes with effective EH methods has increased the effectiveness of communication in various environments [105], [108], [112].

'Innovative design approaches have effectively tackled miniaturization issues while facilitating multi-band operations. Metamaterials have enhanced the performance of smaller and more efficient circuits and antennas [46], [106], [107], [113]. These materials are especially advantageous for industrial and IoT applications where characteristics like durability and environmental adaptation are essential.

The search for solutions of integration has highlighted the system-level interconnections, including energy beamforming and the simultaneous design of the communication and power devices [80], [81], [110], [114]. The use of these methodologies guarantees the smooth functioning of the rectifiers in the SWIPT system, thus increasing their efficiency and overall performance.

Understanding the limitations and future opportunities of rectifier technology requires an identification of the existing issues and future directions of research. It is also essential to investigate the ecological consequences, the losses related to long-range transmission, and compatibility with future technologies like 5G, 6G, and AI-optimization techniques [93], [94], [110], [115], [116], [117], [118], [119]. The development of multimodal wearable technologies enabled by AI-optimization also holds the possibility of enhancing the effectiveness and utility of energy receivers in a range of uses.

In summary, the development of rectifier technology in SWIPT systems calls for ongoing interdisciplinary study and collaborative efforts. As the challenges are solved and novel ideas are investigated, future SWIPT systems can potentially attain higher efficiency, reliability, and sustainability in many applications.

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In this article, ChatGPT is used for improving writing quality.

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