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A Comprehensive Review of Battery-Free Energy Efficient RF and Microwave Systems

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ABSTRACT

Battery-free radiofrequency (RF) and microwave systems have emerged as a promising solution for enabling long-lifetime, maintenance-free wireless sensing and communication platforms by eliminating conventional battery dependence. These systems operate by harvesting ambient or dedicated electromagnetic energy, converting it to usable electrical power, and utilizing ultralow-power circuit and communication techniques to sustain sensing, processing, and wireless data transmission. This paper presents a comprehensive review of battery-free energy-efficient RF and microwave systems, covering the evolution of the field, energy harvesting and rectenna modeling techniques, power management strategies, ultralow-power communication methods, and energy-aware networking protocols. The review further examines key enabling circuit technologies, including subthreshold microwave integrated circuits, passive and backscatter-based transmitters, and envelope-detection receivers designed for nanowatt-to-microwatt operation. Recent experimental developments in battery-free Internet of Things (IoT) nodes, wearable and implantable platforms, and smart-environment monitoring systems are analyzed to highlight the transition from laboratory prototypes to real-world deployments. Performance evaluation metrics such as RF-to-DC conversion efficiency, communication reliability, scalability, and system lifetime are discussed using representative experimental results from recent literature. The paper also identifies major open challenges, including energy intermittency, miniaturization constraints, and security considerations, and outlines future research directions such as integration with 5G/6G infrastructure, AI-assisted energy management, and advanced materials for flexible and multiband harvesting structures. The review demonstrates that advances in rectenna codesign, ultralow-power circuit architectures, adaptive communication techniques, and network-level coordination are rapidly enabling practical battery-free wireless systems, positioning RF and microwave energy harvesting as a key technology for sustainable massive IoT and long-term autonomous sensing applications.

1 | Introduction

The rapid expansion of wireless networks, Internet of Things (IoT) ecosystems and autonomous sensing platforms has created an urgent demand for devices capable of long-term operation with minimal human intervention. Conventional battery-powered wireless systems suffer from intrinsic limitations, including finite operational lifetime, frequent maintenance requirements, environmental disposal concerns and reduced feasibility in large-scale or hard-to-access deployments. These constraints become particularly severe in dense IoT scenarios, wearable electronics, biomedical implants and distributed sensing infrastructures, where battery replacement is costly or impractical. As wireless technologies evolve toward ultradense connectivity and massive device deployments, reliance on batteries undermines system scalability and sustainability. In response to these challenges, battery-free radiofrequency (RF) and microwave systems have emerged as a promising paradigm for sustainable wireless operation. Battery-free systems are defined as wireless platforms that operate with negligible or no reliance on electrochemical energy storage, instead drawing power from ambient or dedicated electromagnetic sources in the RF and microwave spectrum. These systems exploit techniques such as RF energy harvesting (EH), microwave wireless power transfer (WPT), backscatter communication and ultralow-power circuit operation to enable sensing, computation and data transmission without conventional batteries. Unlike traditional EH systems that supplement batteries, battery-free RF/microwave systems are designed for energy autonomy, often operating intermittently or opportunistically depending on available power. A typical battery-free RF or microwave system consists of several tightly coupled components: (i) an antenna optimized for ambient or directed RF/microwave energy capture, (ii) a matching network and rectifier (rectenna) that converts incident electromagnetic energy into usable DC power, (iii) ultralow-power management circuits that regulate, store and distribute harvested energy, and (iv) an energy-efficient communication module, often based on backscatter or low-duty-cycle transmission. Advances in semiconductor technologies, compact antenna design and low-threshold rectification have enabled these components to operate effectively under extremely low input power levels, making fully battery-free operation increasingly feasible.

Recent studies have demonstrated substantial progress in battery-free RF and microwave systems across multiple dimensions. Backscatter-based communication has gained prominence due to its ability to enable data transmission by modulating reflected RF signals rather than generating new carriers, drastically reducing power consumption. Zhan et al. demonstrated a flexible, wearable, battery-free backscatter system capable of continuous color imaging by integrating RF EH with ultralow-power modulation techniques [1]. In parallel, advances in rectenna and microwave circuit design have produced broadband and low-input-power rectifiers capable of operating efficiently under weak ambient energy conditions. Zhou et al. reported microwave rectennas optimized for submilliwatt power levels, significantly improving RF-to-DC conversion efficiency [2]. Beyond standalone RF harvesting, hybrid energy strategies combining RF with other ambient sources such as solar or thermal energy have been explored to enhance operational stability. Ibrahim et al. provided a comprehensive analysis of such hybrid RF EH systems, highlighting their role in extending battery-free operation under fluctuating energy conditions [3]. Additionally, bio-inspired and adaptive microwave systems have been proposed to improve robustness and efficiency in dynamic environments, particularly for future wireless infrastructures [4]. Despite these advances, battery-free RF and microwave systems face several unresolved challenges. Ambient RF energy is inherently sparse and unpredictable, leading to intermittent device operation and limited quality of service. Achieving high RF-to-DC conversion efficiency at ultralow power levels remains difficult due to nonlinear device behavior and impedance mismatches. Communication reliability is further constrained by the need to balance energy availability with data transmission requirements. Moreover, many existing review articles focus narrowly on individual aspects such as rectenna design, RF EH, or backscatter communication without addressing the system-level integration of EH, circuit design, communication protocols, and application requirements. This fragmentation limits the ability of researchers to design scalable, end-to-end battery-free wireless systems.

This review is aimed at providing a holistic and up-to-date synthesis of battery-free, energy-efficient RF and microwave systems, bridging component-level innovations and system-level considerations. The specific objectives are to:

- Define and contextualize battery-free RF and microwave systems within modern wireless ecosystems.
- Review recent advances in RF and microwave EH, rectenna design, and power management.
- Examine ultralow-power communication techniques, including backscatter and simultaneous wireless information and power transfer (SWIPT) enabled systems.
- Analyze system-level performance metrics, deployment challenges, and scalability issues.
- Identify open research challenges and future opportunities aligned with next-generation (5G/6G) networks.

The key contributions of this review include:

- An integrated analysis of antennas, rectifiers, power management circuits, and communication modules in battery-free RF/microwave systems.
- A critical comparison of recent battery-free system implementations across multiple application domains.
- Identification of research gaps not adequately addressed in prior surveys.
- A forward-looking discussion on AI-assisted energy management and future wireless power-aware network design.

Table 1 summarizes the key differences between this review and other reviews on battery-free RF/microwave systems.

The remainder of this paper is organized as follows: Section 2 describes the literature collection methodology; Section 3 presents fundamental principles; Sections 4 and 5 review EH and communication techniques; Section 6 discusses energy-efficient RF and microwave circuit design; Section 7 reviews state-of-the-art battery-free systems and applications; Section 8 presents performance metrics and evaluation criteria; Section 9 outlines challenges and open research issues; Section 10 highlights future research directions; and Section 11 concludes the paper.

2 | Literature Collection Methodology

To ensure a comprehensive and reproducible review, a systematic literature collection methodology was employed,

TABLE 1 | Comparison with existing reviews on battery-free RF/microwave systems.

Reference	Focus area	Years covered	Systems covered	Strengths	Limitations
[1]	Wearable battery-free systems	Up to 2024	Backscatter + EH	Strong experimental validation	Narrow application scope
[2]	Microwave rectennas	Up to 2025	Rectifier design	Excellent microwave analysis	Communication aspects missing
[3]	RF energy harvesting	Up to 2022	Rectennas, EH	Comprehensive EH review	Not battery-free system-focused
[5]	Foundational wireless power transfer (WPT) and information transfer principles	Up to 2021	WPT, SWIPT fundamentals	Strong theoretical foundations for RF power	Limited discussion on ultralow power backscatter applications
[6]	Ambient backscatter communications and systems	Up to 2021	Ambient backscatter system taxonomy	Comprehensive on backscatter principles and taxonomy	Not specifically integrated with microwave energy harvesting
[7]	Merging backscatter with reconfigurable intelligent surfaces (RIS)	Up to 2024	RIS-enhanced backscatter	Advances communication theory for RF battery-free systems	Not a full survey, more focused on novel paradigm
[8]	Hybrid ambient backscatter and SWIPT systems	Up to 2024	Cooperative SWIPT backscatter	Integrates energy harvesting and communication	More focused on specific architectures, not general survey
[9]	mmWave backscatter communication	Up to 2024	Backscatter systems at mmWave bands	Focused on high-speed and mmWave challenges	Not full battery-free system survey
[10]	Battery-free IoT in LoRa networks	Up to 2021	Long Range Wide Area Network (LoRaWAN) battery-free communications	Practical performance modeling	Focused on one technology (LoRaWAN)
[11]	Backscatter synchronization techniques	Up to 2025	Bluetooth Low Energy (BLE), Long-Term Evolution (LTE), Wireless Fidelity (Wi-Fi) backscatter	Focused on enabling communication stability	Limits to synchronization aspects
This work	Integrated battery-free RF/microwave systems	2020–2026	EH + backscatter / SWIPT + protocols + applications	Holistic and system-level survey	Differences in experimental conditions and evaluation metrics across studies limit direct numerical comparison

encompassing database searches, defined inclusion and exclusion criteria, and a structured classification framework. Relevant literature on battery-free RF and microwave systems, EH, backscatter communication, and ultralow-power wireless operation was retrieved from multiple reputable databases including IEEE Xplore, ScienceDirect, SpringerLink, Web of Science, Scopus, and Google Scholar. Search strings combined controlled vocabulary, keywords, and Boolean operators such as “battery-free” or “batteryless” with “RF” or “microwave” and “energy harvesting,” “rectenna,” “backscatter,” or

"SWIPT," adapted to the syntax of each database. The search was limited to articles published between 2020 and 2026 in English, focusing on peer-reviewed journals and high-quality conference proceedings. Titles, abstracts, and keywords were initially screened for relevance, followed by full-text evaluation to confirm suitability for inclusion. Articles were included if they provided substantive contributions to battery-free RF or microwave systems, EH mechanisms, ultralow-power circuits, or communication protocols supporting battery-free operation. Studies were excluded if they fell outside the target publication window, were not peer-reviewed, were written in languages other than English, or lacked full-text availability. A total of 171 peer-reviewed articles were selected for inclusion in the final review dataset. The temporal distribution of the selected publications reflects the rapid growth of research activity in battery-free RF and microwave systems in recent years. Specifically, three articles were published in 2020, 11 in 2021, 22 in 2022, 32 in 2023, 48 in 2024, 50 in 2025 and five in 2026 at the time of manuscript preparation. This distribution confirms that most analyzed studies originate from the most recent years, ensuring that the review captures the latest technological advances, experimental demonstrations, and system-level developments in battery-free wireless platforms. Selected studies were then organized according to a classification framework that grouped research into key themes including EH and power management, communication techniques such as backscatter and SWIPT, circuit and system design, applications and deployments across IoT, wearables, and biomedical systems, and performance evaluation of efficiency, reliability and scalability. This structured approach enabled the extraction of relevant information including publication year, methodology, contributions, and limitations, facilitating a coherent synthesis of current research trends, emerging technologies, and open challenges in battery-free RF and microwave systems. The methodology followed established guidelines for systematic literature reviews, ensuring transparency, reproducibility and coverage of both theoretical and applied contributions in the field.

3 | Fundamentals of Battery-Free and Energy-Autonomous RF/Microwave Systems

Battery-free RF and microwave systems operate by capturing ambient or dedicated electromagnetic energy, converting it to usable electrical power, and utilizing it to sustain sensing, computation, and communication functions without conventional batteries. These systems rely on advances in ultralow-power circuit design, efficient rectification techniques, and energy-aware communication protocols such as backscatter and SWIPT. Understanding the fundamentals requires a grasp of the principles of energy autonomy, the characteristics and availability of ambient RF and microwave energy sources, and the architecture of integrated battery-free nodes. This section provides a comprehensive overview of these aspects, highlighting how system-level design choices, component selection, and energy management strategies collectively determine the operational reliability and efficiency of battery-free wireless platforms. The subsequent subsections (3.1, 3.2, 3.3) elaborate on energy autonomy principles, ambient energy sources, and node architecture in detail.

3.1 | Principles of Energy Autonomy

Energy autonomy is the defining principle that distinguishes battery-free RF and microwave systems from conventional low-power wireless platforms. An energy-autonomous system can sustain sensing, computation and communication tasks solely through harvested electromagnetic energy, without dependence on electrochemical batteries or long-term energy storage. In RF and microwave systems, this autonomy is achieved by tightly coupling EH, power management and communication functions under strict energy constraints imposed by the ambient or dedicated RF environment. Unlike battery-assisted EH nodes, battery-free RF systems must operate within instantaneous or short-term harvested energy budgets. This constraint fundamentally reshapes system design philosophy, shifting emphasis from continuous operation toward energy-proportional and intermittent computing models, where system activity adapts dynamically to available power. Recent studies have shown that such energy-aware operation enables sustainable long-term deployment in large-scale IoT and sensing scenarios, particularly where maintenance or battery replacement is infeasible [12]. At the physical layer, energy autonomy relies on the efficient capture and conversion of RF or microwave energy using rectifying antennas (rectennas). In a typical energy-autonomous system, an antenna captures RF/microwave signals, which are then rectified into DC power using a rectifier network that often utilizes Schottky diodes or advanced spin-rectifier technologies optimized for low threshold voltages. The harvested energy is then regulated and either stored briefly in supercapacitors or routed directly to ultralow-power circuits for sensing, computation or communication as shown in Figure 1.

Efficient impedance matching between the antenna and rectifier is critical, as mismatches lead to reflection losses that greatly diminish the usable power conversion efficiency (PCE), a central

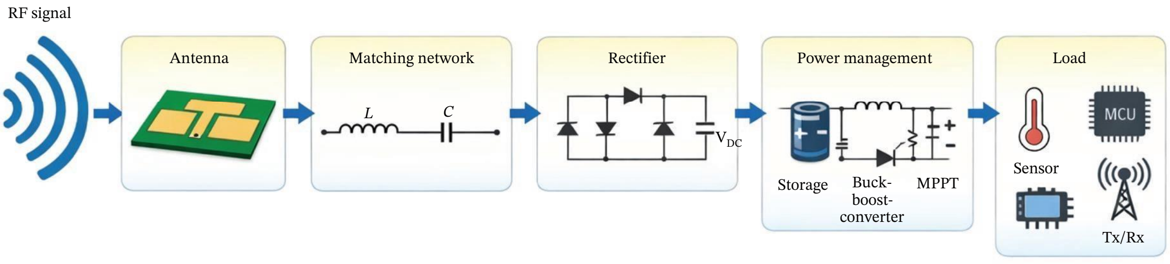


FIGURE 1 | Battery-free RF energy harvesting system.

design challenge in modern rectenna architecture. Recent advances in rectifier and matching network design have achieved high conversion efficiencies even at low input power levels typical of ambient environments, whereas spin-rectifier approaches have shown potential for improved sensitivity at power levels below −20 dBm, enabling operation in environments with sparse RF energy [13, 14]. However, autonomy is not determined solely by RF-to-DC conversion efficiency, it also depends on the minimum operating power of downstream circuits and the ability of the system to tolerate power interruptions. Advances in ultralow-threshold rectifiers, subthreshold CMOS operation, and nanoscale semiconductor devices have reduced the minimum operational power of battery-free nodes to the microwatt and even nanowatt regime, enabling practical autonomy under realistic ambient RF conditions [15]. A central architectural concept supporting energy autonomy is decoupling RF transmission from energy-intensive signal generation. Backscatter-based communication achieves this by modulating incident RF waves instead of actively transmitting carriers, resulting in orders-of-magnitude power savings compared with conventional radios. This paradigm has become foundational to battery-free RF systems, enabling communication at power levels compatible with harvested ambient energy [16]. As a result, energy autonomy in RF systems is increasingly viewed as a codesign problem involving harvesting, computation and communication rather than single-component optimization. Key principles underlying energy autonomy include (i) energy capture sensitivity: ability to extract energy from very weak ambient fields; (ii) conversion efficiency: maximizing energy transformed into DC power; and (iii) power management intelligence: distributing energy for maximum functionality while buffering intermittent supply. The RF-to-DC conversion efficiency is typically influenced by design trade-offs including diode selection, matching network topology, and operating frequency bands. Systems designed for ultralow-power backscatter communications, for instance, can operate with harvested power in the tens of microwatts by exploiting reflected carriers instead of generating new RF transmissions [17]. Other foundational aspects include dynamic energy budgeting mechanisms that adjust device duty cycles based on instantaneous harvested energy estimates and *adaptive frequency selection* that allows systems to tune to spectral bands with higher RF energy densities. These techniques collectively enhance the likelihood of sustained operation under highly variable energy availability [18].

Energy storage, when present, is typically limited to small capacitors or supercapacitors that buffer harvested energy over short time scales. These storage elements support duty-cycled operation, allowing nodes to accumulate energy and execute tasks intermittently. Recent work has explored adaptive energy management strategies that dynamically schedule sensing and communication based on harvested power statistics, improving reliability while preserving autonomy [19]. Such strategies are particularly important in environments where ambient RF energy fluctuates due to mobility, interference, or temporal variations in spectrum usage. From a system perspective, energy autonomy also requires protocols and control mechanisms that explicitly account for power availability. Energy-aware medium access control, wake-up scheduling, and lightweight synchronization mechanisms have been proposed to ensure that communication occurs only when sufficient energy is available, thereby avoiding system failure or data loss [20]. These approaches are increasingly relevant in dense IoT and 6G-oriented deployments, where massive numbers of battery-free devices must coexist efficiently. Recent surveys and experimental demonstrations confirm that true energy autonomy is achievable when RF EH, ultralow-power hardware, and backscatter-based communication are jointly optimized. A comprehensive synthesis of these enabling technologies and their system-level implications has been presented in recent reviews, including Arinze et al. [21], which highlights the transition from battery-assisted harvesting toward fully battery-free RF systems. Nevertheless, continued progress depends on further reductions in circuit power consumption, improved rectenna sensitivity, and adaptive system-level control capable of operating under extreme energy scarcity.

3.2 | Ambient RF and Microwave Energy Sources

Energy autonomy in battery-free RF and microwave systems fundamentally depends on the characteristics of electromagnetic energy available in the surrounding environment. Unlike dedicated WPT systems, which intentionally transmit energy, ambient RF EH relies on the opportunistic capture of existing RF and microwave emissions generated by communication infrastructure, broadcasting services, radar systems, and personal wireless devices. These ambient sources form a heterogeneous and highly dynamic energy landscape, where available power levels vary across frequency bands, locations, and time. Ambient RF energy in urban and semiurban environments primarily originates from cellular base stations, Wi-Fi access points, television broadcast transmitters, and emerging 5G infrastructure. Measurements conducted in modern cities indicate that cellular downlink bands and Wi-Fi frequencies typically contribute the highest average power densities, although values fluctuate significantly depending on user traffic, distance from transmitters, and obstacles in the propagation environment [22, 23]. In dense metropolitan regions, aggregated RF exposure from multiple communication sources can produce ambient power levels in the microwatt-per-square-centimeter range near transmitters, whereas indoor environments generally exhibit lower but still harvestable power densities [24]. The spectral occupancy of ambient RF signals also plays a crucial role; bands with continuous transmission, such as cellular control channels and broadcast services, provide more stable harvesting opportunities compared with bursty or duty-cycled sources. For example, continuous broadcast channels and downlink control channels in cellular networks often provide more stable and predictable ambient power, making them attractive for RF harvesting designs [3, 25]. Figure 2 presents outdoor RF power density measurements obtained using an Aim-TTi PSA6005 6 GHz spectrum analyzer. The GSM-900 and GSM-1800 bands show the highest ambient energy levels, with measured power densities ranging from 36 nW/cm^2 to 84 nW/cm^2, identifying them as dominant contributors to ambient RF harvesting potential.

The microwave portion of the spectrum, particularly frequencies above 2 GHz, is gaining importance due to the proliferation of Wi-Fi, 5G, and future 6G systems. Although free-space path loss increases with frequency, the density of transmitters and beamforming techniques used in modern networks can locally increase available microwave energy. Recent studies highlight that millimeter-wave deployments, although highly directional, can create short-range zones of elevated power density that may be exploited by directional rectennas designed for high-frequency harvesting [27, 28]. However, microwave harvesting introduces additional design constraints, including tighter impedance matching, higher diode switching speeds, and increased propagation sensitivity to blockage. Indoor environments present a distinct ambient RF profile shaped by reflections, multipath fading, and device proximity. Wi-Fi routers, Bluetooth devices, and IoT gateways contribute intermittent yet spatially dense RF emissions, making indoor harvesting feasible when rectennas are optimized for multiband operation and low input power thresholds [29]. Measurement campaigns in residential and office spaces show that spatial variability can be significant, with power levels differing by orders of magnitude within a few meters due to shadowing and interference patterns [30]. Spatial mapping techniques are frequently used to visualize how ambient RF energy varies across real environments. By combining field measurements with geostatistical interpolation methods such as ordinary kriging, researchers can reconstruct continuous power density distributions from discrete sampling points. These maps reveal the strong spatial dependence of RF energy levels, which are influenced by transmitter locations, building density, reflections, and propagation conditions.

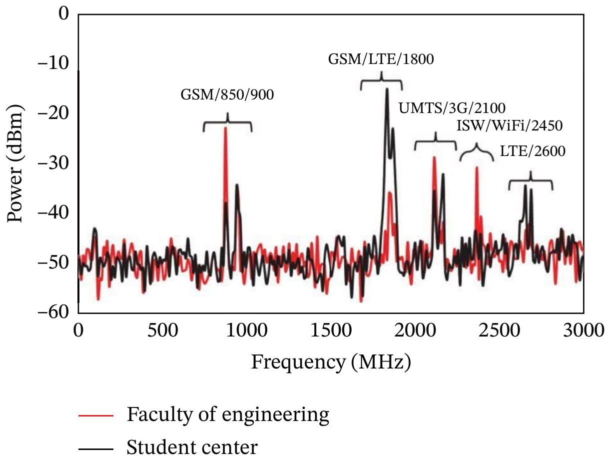


FIGURE 2 | Measured ambient RF power density across frequency bands in an urban environment [26].

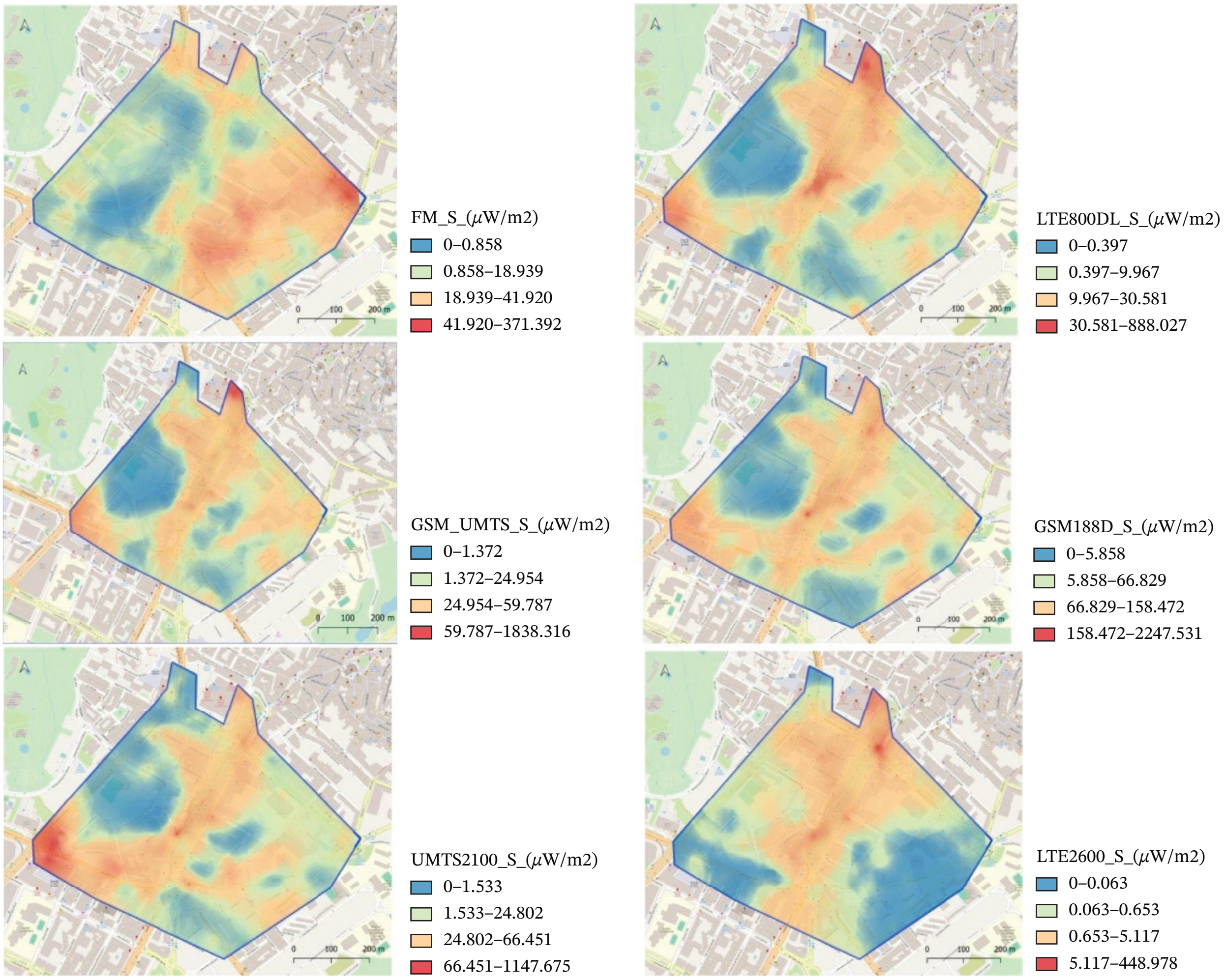


FIGURE 3 | Spatial distribution of measured ambient RF power density for broadcast and mobile telephony downlink bands reconstructed using ordinary kriging interpolation [39].

The spatial and spectral heterogeneity highlighted in Figure 3 demonstrates pronounced variability in ambient RF power density, even within small geographic areas. Higher power levels are generally found in regions with fewer obstructions and stronger line-of-sight exposure to transmitters, whereas lower levels occur in areas affected by building shadowing, multipath fading, or other environmental factors. Differences between broadcast and mobile telephony bands further illustrate that spatial distributions depend on frequency, transmitter deployment patterns, and propagation characteristics. This variability directly impacts the performance of battery-free RF and microwave nodes, as harvested energy availability may fluctuate substantially over short distances. Consequently, adaptive harvesting strategies, multiband rectenna architectures, and energy-aware scheduling are essential to ensure reliable operation. Regions of low ambient energy may limit device duty cycles, whereas localized high-density areas can support more frequent sensing or communication events, highlighting the need for frequency agility and energy-proportional system design. These observations motivate adaptive harvesting strategies and reconfigurable antennas capable of tuning across multiple frequency bands to exploit the strongest available signals at any given moment. Beyond communication infrastructure, other ambient microwave sources include radar systems, satellite downlinks, and industrial microwave equipment. Although less ubiquitous, these sources can provide high peak power densities in specific contexts, offering localized opportunities for EH. For example, harvesting from satellite communication bands has been explored for remote sensing nodes in open environments, where line-of-sight conditions improve energy capture [31]. Similarly, passive harvesting near radar installations or industrial RF heaters has been investigated under controlled conditions, though regulatory and safety considerations limit widespread deployment [32]. Temporal variability is another defining feature of ambient RF energy. Traffic-dependent fluctuations in cellular networks, daily usage patterns in Wi-Fi systems, and mobility of users and devices lead to stochastic energy availability. Statistical models of ambient RF energy demonstrate that harvested power often follows log-normal or Rayleigh-like distributions, reinforcing the need for energy buffering and adaptive duty cycling in battery-free nodes [33, 34]. Consequently, understanding the statistical and spectral characteristics of ambient RF sources is essential for designing rectennas, matching networks, and power management circuits that can operate effectively under realistic energy conditions. From a system design perspective, ambient RF EH requires a trade-off between frequency selectivity and broadband capture. Narrowband designs can achieve higher peak efficiency when tuned to dominant local sources, whereas broadband rectennas increase robustness by collecting energy across multiple services simultaneously [35]. Recent advances in multiband and wideband rectifier architectures, as well as frequency-reconfigurable antennas, have been driven largely by the need to adapt to this diverse and evolving RF environment [36–38]. As wireless networks continue to densify and migrate toward higher frequencies, the ambient electromagnetic landscape will evolve, creating both new opportunities and challenges for battery-free RF and microwave systems.

3.3 | System-Level Architecture of Battery-Free Nodes

Battery-free RF and microwave nodes rely on tightly integrated subsystems to achieve energy autonomy, low-power communication and reliable sensing under variable ambient energy conditions. Unlike conventional battery-assisted devices, these nodes must manage harvested energy efficiently, coordinate sensing and transmission schedules, and maintain operation despite stochastic energy availability. The system-level architecture of battery-free RF and microwave nodes as shown in Figure 1 integrates key subsystems: antennas, impedance matching networks, rectifiers, power management units (PMUs), and communication modules to enable sustainable operation without chemical batteries. This architecture supports adaptive duty-cycling, enabling operation even in energy-sparse environments. Each subsystem plays a critical role in capturing, converting, conditioning, and utilizing the sparse ambient electromagnetic energy available in real environments. At the front end, the antenna subsystem determines the amount and quality of captured energy by defining operating frequency bands, gain, and radiation patterns. Recent multiband and broadband printed rectenna designs demonstrate the potential to harvest energy across critical communication bands (e.g., GSM, WiMAX, and 5G) with robust impedance matching and strong resonance characteristics, supporting efficient energy capture in multiservice environments [37, 40]. Antenna innovations, including circularly polarized (CP) structures and radial arrays, enhance angular coverage, improving energy reception from multiple directions [41]. Once RF energy is received, impedance matching networks minimize reflection losses and maximize power transfer into the rectifier. These circuits are designed using L networks, Pi networks or stub matching techniques, balance trade-offs between bandwidth, insertion loss and parasitic effects, especially at microwave frequencies. The rectifier subsystem converts captured RF/microwave signals into DC power. Rectifier design remains an active research area, with dual-band and multiband topologies enhancing RF-to-DC conversion efficiency under low input power. Voltage-doubler stages and optimized Schottky diodes reduce forward voltage thresholds, making them suitable for energy-limited environments [42]. Surveys also highlight design automation techniques such as artificial intelligence (AI) and machine learning (ML) for co-optimizing antennas, rectifiers, and matching networks [43]. The harvested DC energy is conditioned and regulated by the PMU, often employing maximum power point tracking (MPPT) and energy buffering with supercapacitors or hybrid storage devices. These elements support intermittent operation by providing short bursts of power for sensing or communication when required. PMUs are designed to operate with minimal overhead, balancing storage capacity, leakage losses and load requirements. Communication is typically achieved through backscatter or ultralow-power radio techniques. In backscatter communication, nodes modulate reflected RF carriers rather than actively generating signals, dramatically reducing power consumption and aligning with constrained energy budgets. Some designs integrate SWIPT to further optimize energy use. Energy-aware scheduling, adaptive impedance tuning, and lightweight synchronization protocols are critical to ensure reliable operation under variable RF conditions [44, 45].

Figure 4 presents an advanced multiband rectenna architecture integrated into a battery-free RF node. Unlike the single-path harvesting chain shown in Figure 1, this design employs multiple antenna elements tuned to different ambient frequency bands, each connected to a dedicated rectifier stage. The rectified outputs are combined and managed by a centralized PMU, improving energy availability in spectrally heterogeneous environments. Such architectures enable opportunistic harvesting across cellular, Wi-Fi, and emerging 5G/6G bands, thereby increasing the reliability and duty cycle of battery-free sensing systems. Recent implementations demonstrate that these architectures can achieve tens of microwatts of usable power, sufficient for meaningful sensing and low-data-rate communication in urban, indoor, and industrial environments [46]. Hybrid strategies combining RF with solar or thermal energy further enhance autonomy and reliability [47–49]. The design of battery-free nodes thus represents a holistic codesign problem encompassing EH, storage, power regulation, communication and adaptive control.

3.4 | WPT

WPT refers to the transmission of electrical energy from source to load without the use of physical conductors. Instead of wires, WPT relies on electromagnetic fields to deliver power across an air gap. This technology has gained significant attention due to its ability to provide safe, convenient, and flexible energy delivery in modern electronic and communication systems. The fundamental principle of WPT is based on electromagnetic induction, where a time-varying current in a transmitting coil generates a magnetic field that induces a voltage in a receiving coil. This interaction enables energy transfer without direct electrical contact. The efficiency of this process depends on factors such as coil design, alignment, distance, and operating frequency. WPT systems can be broadly classified into several categories. Inductive coupling is the most common method and operates over short distances, typically used in wireless charging of smartphones and small electronic devices. Resonant inductive coupling extends this concept by tuning both transmitter and receiver coils to the same resonant frequency, thereby improving efficiency and allowing power transfer over relatively longer distances [44]. Capacitive coupling, on the other hand, uses electric fields instead of magnetic fields but is generally limited to low-power applications. For long-range transmission, microwave or RF techniques are employed, where electrical energy is converted into electromagnetic waves and transmitted through space to a receiving antenna. Laser-based WPT is another emerging method, particularly suitable for specialized applications such as space systems. A typical WPT system consists of a power source, a transmitting unit, a transmission medium (usually air), a receiving unit, and a load. The transmitter converts electrical energy into an electromagnetic form, which propagates through space and is captured by the receiver, where it is converted back into usable electrical energy. The advantages of WPT include the elimination of cables, reduced maintenance, enhanced safety in hazardous environments, and improved user convenience. However, the technology also faces challenges such as reduced efficiency over long distances, sensitivity to alignment, electromagnetic interference, and relatively high implementation costs. WPT has found applications in various domains, including consumer electronics, biomedical implants, electric vehicle charging systems, industrial automation, and wireless sensor networks. In the context of next-generation communication systems, WPT plays a crucial role in enabling energy-efficient operation of distributed devices, particularly in IoT and 5G/6G networks. In addition to ambient RF EH, WPT has emerged as an important complementary technique for battery-free systems. It enables controlled energy delivery from dedicated transmitters to receiver nodes, overcoming the limitations of weak ambient RF sources. Techniques such as near-field inductive coupling, far-field microwave power transfer, and beamforming-assisted WPT are widely

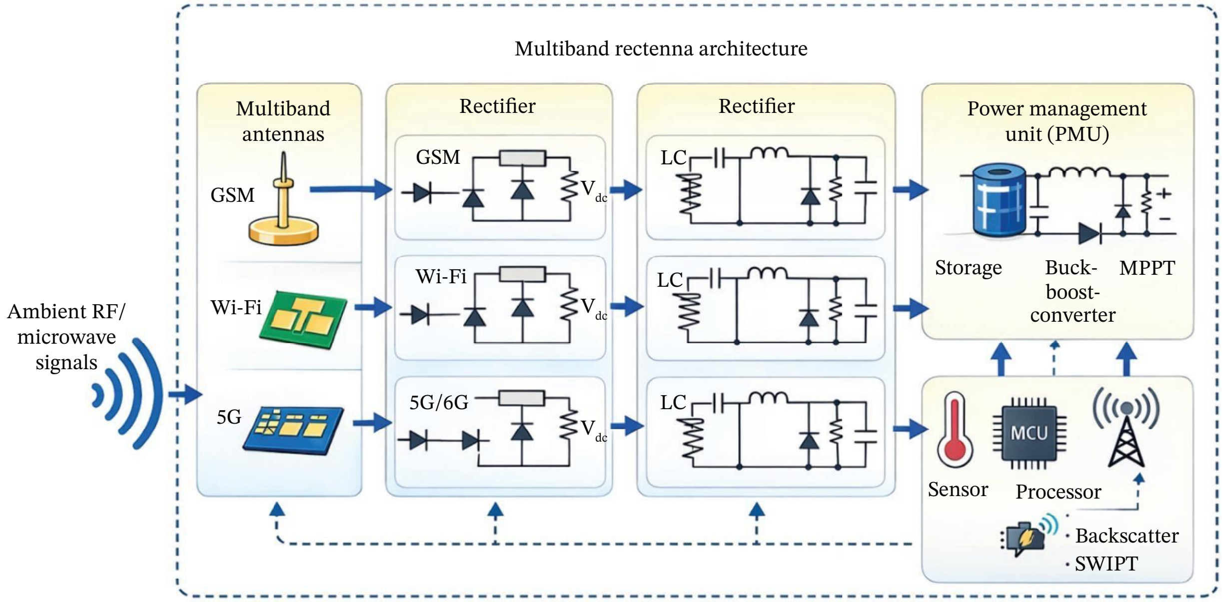


FIGURE 4 | Multiband rectenna architecture for battery-free RF/microwave nodes.

studied for improving energy availability and extending operational range. Hybrid systems that combine ambient harvesting with WPT offer improved reliability and enable more predictable system operation [45].

3.5 | Comparison of Battery-Free Versus Battery-Assisted Low-Power Systems

Low-power wireless systems can broadly be categorized into battery-free and battery-assisted architectures, depending on how energy is sourced, stored, and utilized. Although both approaches are aimed at reducing power consumption and extending operational lifetime, they differ fundamentally in system design philosophy, energy management strategies, and long-term sustainability. Understanding these differences is essential for correctly positioning battery-free RF and microwave systems within the broader landscape of energy-efficient wireless technologies. Battery-assisted low-power systems typically rely on a primary battery supplemented by EH mechanisms such as RF, solar, or vibration-based sources. In these systems, harvested energy is used to extend battery lifetime rather than eliminate the battery entirely. The presence of a battery provides a stable energy reservoir, enabling continuous operation, higher data rates, and predictable performance. However, batteries introduce several limitations, including finite lifespan, capacity degradation over time, maintenance requirements, and environmental concerns related to disposal. These constraints become increasingly problematic in large-scale deployments, wearable electronics, biomedical implants, and inaccessible sensing environments where battery replacement is impractical [11].

In contrast, battery-free RF and microwave systems are designed to operate without long-term electrochemical energy storage, relying solely on harvested electromagnetic energy and, in some cases, short-term buffering using capacitors or supercapacitors. This paradigm enforces strict energy constraints that fundamentally reshape system operation. Battery-free nodes often adopt intermittent and energy-proportional operation, where sensing, computation, and communication tasks are executed only when sufficient energy is available. Rather than guaranteeing continuous functionality, these systems prioritize sustainability and autonomy over long-term deployment horizons. From an architectural perspective, battery-assisted systems can tolerate higher circuit complexity and power overheads, as the battery masks fluctuations in harvested energy. Battery-free systems, however, require tight codesign of EH, power management, and communication subsystems to function reliably under highly variable and often sparse energy conditions. This has led to the adoption of ultralow-power hardware, backscatter-based communication, aggressive duty cycling, and energy-aware control protocols in battery-free designs [10]. Energy storage also represents a key differentiator. Battery-assisted systems use batteries as the primary storage medium, with energy harvesters acting as auxiliary sources. Battery-free systems typically employ only short-term storage elements, such as capacitors or supercapacitors, which buffer energy over limited time scales. Although this reduces system complexity and eliminates battery-aging issues, it also imposes constraints on task scheduling, latency, and achievable throughput. Despite these limitations, battery-free RF and microwave systems offer significant advantages in terms of scalability, maintenance-free operation, and environmental sustainability. They are particularly well suited for massive IoT deployments, disposable sensors, wearable and implantable devices, and long-term monitoring applications where battery replacement is infeasible or undesirable. Battery-assisted systems remain advantageous in scenarios requiring guaranteed quality of service, higher data rates or continuous operation. Battery-assisted systems trade sustainability for performance stability, whereas battery-free systems embrace energy variability to achieve long-term autonomy and minimal maintenance [16]. The growing demand for scalable, sustainable, and maintenance-free wireless infrastructure has positioned battery-free RF and microwave systems as a key enabling technology for next-generation IoT and future wireless networks.

4 | EH and Power Management Techniques

EH and power management form the technological backbone of battery-free RF and microwave systems, directly determining whether harvested electromagnetic energy can be converted into stable, usable power for sensing, processing, and communication tasks. Unlike battery-supported platforms, battery-free nodes must operate under extremely tight and fluctuating energy budgets, making efficient RF-to-DC conversion, intelligent power conditioning, and adaptive energy storage strategies essential for sustained operation. Advances in rectenna design, nonlinear rectifier modeling, and ultralow-power power management circuits have significantly improved the feasibility of harvesting microwatt-level ambient RF energy. At the same time, innovations in MPPT, cold-start circuits, and hybrid storage solutions have enabled reliable operation even under highly intermittent energy conditions. Understanding EH in battery-free systems requires both electromagnetic and circuit-level perspectives, including how RF signals are captured, how nonlinear devices convert them into DC power, and how this energy is regulated and distributed to various subsystems. Equally important are storage and buffering mechanisms that allow nodes to accumulate energy and operate intermittently when instantaneously harvested power is insufficient. This section provides a comprehensive review of RF and microwave EH models, rectenna design and optimization techniques, ultralow-power management circuits, and emerging energy storage alternatives. The following subsections (4.1–4.4) examine these components in detail and highlight recent advances that are pushing battery-free systems toward practical large-scale deployment.

4.1 | RF and Microwave EH Models

RF and microwave EH models describe how ambient electromagnetic energy is captured and converted into usable electrical power, forming a foundational basis for designing efficient battery-free systems. Because ambient RF/microwave energy is generally weak and highly variable in space and time, accurate modeling is essential to predict available power, guide rectenna design, and estimate performance limits of battery-free nodes.

These models span from electromagnetic propagation and antenna reception theory to nonlinear rectifier behavior and statistical distributions of harvested energy across real environments [50]. At the core, RF EH is often conceptualized through a three-stage chain: (i) propagation of RF/microwave signals through space or cluttered environments; (ii) capture of incident power by the antenna subsystem; and (iii) conversion of RF power into DC energy by the rectifier network. Propagation models such as the Friis transmission equation provide a baseline for line-of-sight scenarios [51] by relating transmitted power, antenna gains, and distance, helping bound the maximum harvestable power under free-space conditions:

$$P_r(d) = P_t G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 \tag{1}$$

where $P_r(d)$ is the received power, $P_t$is transmit power, G_t and G_r are antenna gains, λ is wavelength, and d is separation distance. Real environments introduce shadowing and multipath, making the log-distance path loss model more appropriate:

$$PL(d) = PL\left(d_o\right) + 10n log_{10} \left(\frac{d}{d_o} \right) + X_\sigma \tag{2}$$

where PL(d) is the path loss at distanced (dB), $PL\left(d_o\right)$is the reference path loss at distanced$_o$, n is the path loss exponent (environment dependent), X_σ is the zero-mean Gaussian random variable (shadowing, typical $\sigma = 4 - 12\,\text{dB}$) [52]. These models are widely used in urban and indoor RF harvesting studies. Once RF energy reaches an antenna, its effective aperture $\left(A_e\right)$ and radiation properties determine the portion of incident power captured at the terminals of the rectenna. The relationship between power density(S) and received power $\left(P_r\right)$ is as follows:

$$P_r = SA_e \tag{3}$$

$$A_e = \frac{G_r\, \lambda^2}{4\pi} \tag{4}$$

$$P_r = S \frac{G_r \lambda^2}{4\pi} \tag{5}$$

This links the electromagnetic field strength directly to power delivered to the rectifier input [53]. Factors such as polarization mismatch, antenna gain, and impedance match critically affect the amount of usable RF power. Accurate antenna models are therefore necessary to understand how variations in geometry, frequency band, and surrounding scatterers influence harvestable energy. The third stage, RF-to-DC conversion, is inherently nonlinear and usually modeled using diode equations [54]:

$$i_D\left(v_d\right) = i_S\left(e^{v_d/nv_T} - 1\right) \tag{6}$$

where i_D is the diode current, v_d is diode voltage, i_S is saturation current, n is ideality factor, $v_T = kT/q$ =thermal voltage.

For an RF input $V_{RF}(t)$, the diode sees:

$$v_d(t) = V_{RF}(t) - V_{DC} \tag{7}$$

The RF-to-DC conversion efficiency (η) is defined as

$$\eta = \frac{p_{DC}}{P_{RF}, in} = \frac{V^2{}_{DC}}{R_L P_{RF}, in} \tag{8}$$

where V_{DC} is the harvested DC voltage, R_L is load resistance, P_{RF}, in is the RF input power to the rectifier. Conversion efficiency is strongly dependent on the input power level, load impedance, and diode characteristics, with performance typically degrading at very low power levels due to diode threshold voltage and junction capacitance [54]. Recent unified rectifier models capture both high and low power behavior, providing insights into theoretical efficiency bounds and enabling automated rectenna design flows. Emerging research has also emphasized multiband and multisource models, recognizing that ambient RF energy is distributed across multiple frequency bands such as GSM, Wi-Fi, and cellular downlinks. Aggregate modeling techniques estimate total available power by summing contributions from various bands while accounting for spectral occupancy and temporal activity. Total harvestable power can be modeled as follows:

$$P_{total} = \sum_{i=1}^{N} \alpha_i P_i \tag{9}$$

WhereP_i is power in band i andα_i is its occupancy/activity factor (time-dependent). These models help justify multiband rectenna structures that improve overall energy availability in real deployment scenarios [55]. Given the time-varying nature of ambient RF energy, statistical harvesting models are increasingly employed. Measurements in indoor and outdoor environments often show that received RF power follows log-normal, Rayleigh or Rician distributions, depending on the propagation context. Incorporating stochastic models enables analysis of long-term energy availability and informs designs that balance storage, duty cycling, and system longevity under variable energy supply.

Log-normal distribution is often used in shadowing environments [56]:

$$f_R(r) = \frac{1}{r\sigma\sqrt{2\pi}} e^{\left(-(lnr-\mu)^2/2\sigma^2\right)} \tag{10}$$

Where r is the received power, μ is mean of lnr and σ is standard deviation.

Rayleigh distribution is applicable when multiple scattered paths dominate [57]:

$$f_R(r) = \frac{r}{\sigma^2} e^{\left(-r^2/2\sigma^2\right)} \tag{11}$$

Rician distribution is used when there is a dominant line-of-sight component [58]:

$$f_R(r) = \frac{r}{\sigma^2} e^{(-r^2+s^2/2\sigma^2)} I_0\left(\frac{rs}{\sigma^2}\right) \tag{12}$$

where s is the dominant component and I_0 is modified Bessel function.

Many system-level analyses integrate RF EH models with energy queue and energy-neutral operation frameworks, treating harvested RF energy as a stochastic input to a storage buffer. The harvested energy dynamics can be modeled as follows [59]:

$$E(t+1) = \max\{E(t) - C(t), 0\} + H(t) \tag{13}$$

Where is E(t) is the stored energy at time t, C(t) is energy consumed, H(t) is energy harvested. These approaches evaluate whether a node's consumption profile can be sustained by its average harvested energy over time, providing a basis for designing system protocols and scheduling mechanisms that ensure reliable operation in ambient environments where energy is intermittent and unpredictable. The framework supports energy-neutral operation, ensuring long-term sustainability of battery-free nodes.

4.2 | Rectenna Design and Optimization

The rectenna, a portmanteau of rectifier and antenna, is the central building block of RF and microwave EH systems. It captures ambient or dedicated RF energy via an antenna and converts it into DC power through the rectifier network. Because the RF signal levels available in real environments are often extremely low (microwatts or less), rectenna design and optimization are crucial to maximize harvested power, improve conversion efficiency, and ultimately sustain battery-free operation. Rectenna design involves several interdependent subsystems: the antenna, the impedance matching network, and the rectifier. Optimization strategies typically focus on maximizing RF-to-DC conversion efficiency over targeted frequency bands while ensuring good impedance matching under variable input power conditions. Recent research has expanded both theoretical and practical frontiers of rectenna design, embracing multiband operation, wideband harvesting, and novel materials and structures that push performance at low input power levels.

4.2.1 | Antenna Considerations for Rectennas

Antenna design for rectennas must balance several objectives such as high gain, wide bandwidth or multiband coverage, compact size, and stable impedance characteristics suitable for matching the rectifier. Traditional single-band designs have gradually evolved into multiband and wide-band topologies that capture power from multiple ambient sources such as GSM, Wi-Fi, and cellular downlink bands simultaneously, thereby improving total harvested energy [60]. CP antennas also offer advantages in environments with arbitrary signal polarization, reducing polarization mismatch losses and enhancing robustness in complex propagation conditions [61]. Recent research in antenna design has explored metasurface-enhanced radiators and pattern-reconfigurable structures that adapt to changing spectral environments. One prominent example is the reconfigurable varactor-tuned antenna shown in Figure 5, which dynamically shifts its resonant frequencies in response to variations in local RF conditions. This capability improves harvested energy reliability in dense spectral environments by allowing the antenna to continuously tune its operating frequencies toward bands with higher available power. The design illustrated in Figure 5 consists of two substrate layers of RO4003 ($\varepsilon_r = 3.5$, loss tangent $\tan\delta = 0.0027$). The thickness of the upper substrate and the lower substrate are 0.813 and 1.524 mm, respectively. The upper substrate (L1) supports an annular radiator and a circular radiator, whereas the lower substrate comprises the ground plane (L2) with coupling apertures and the feeding

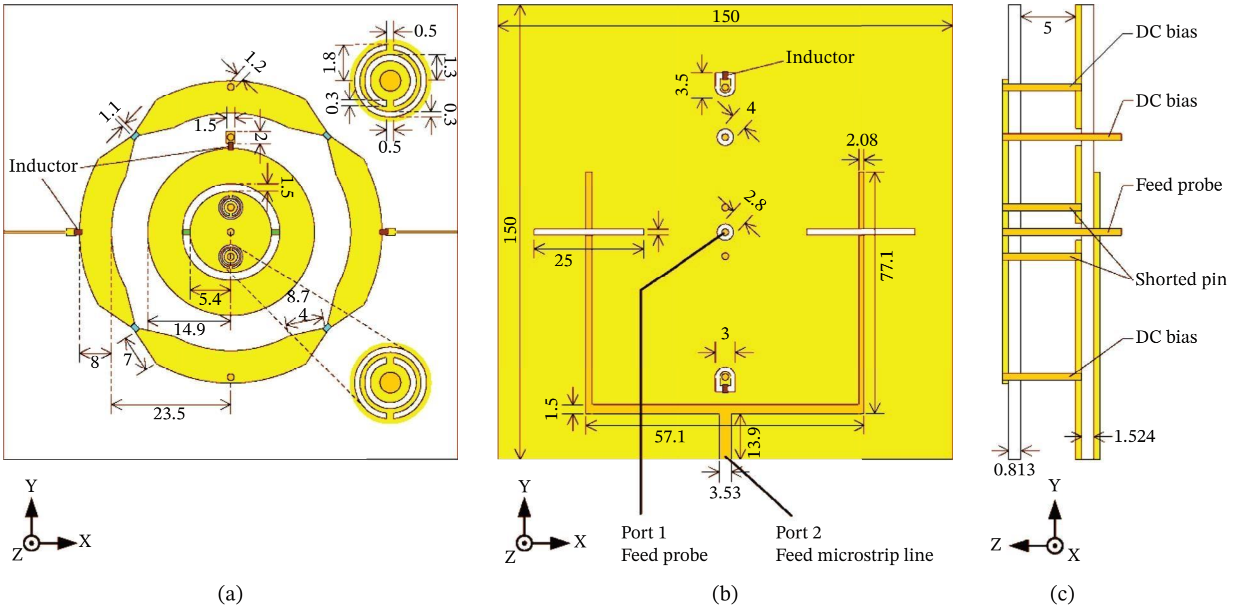
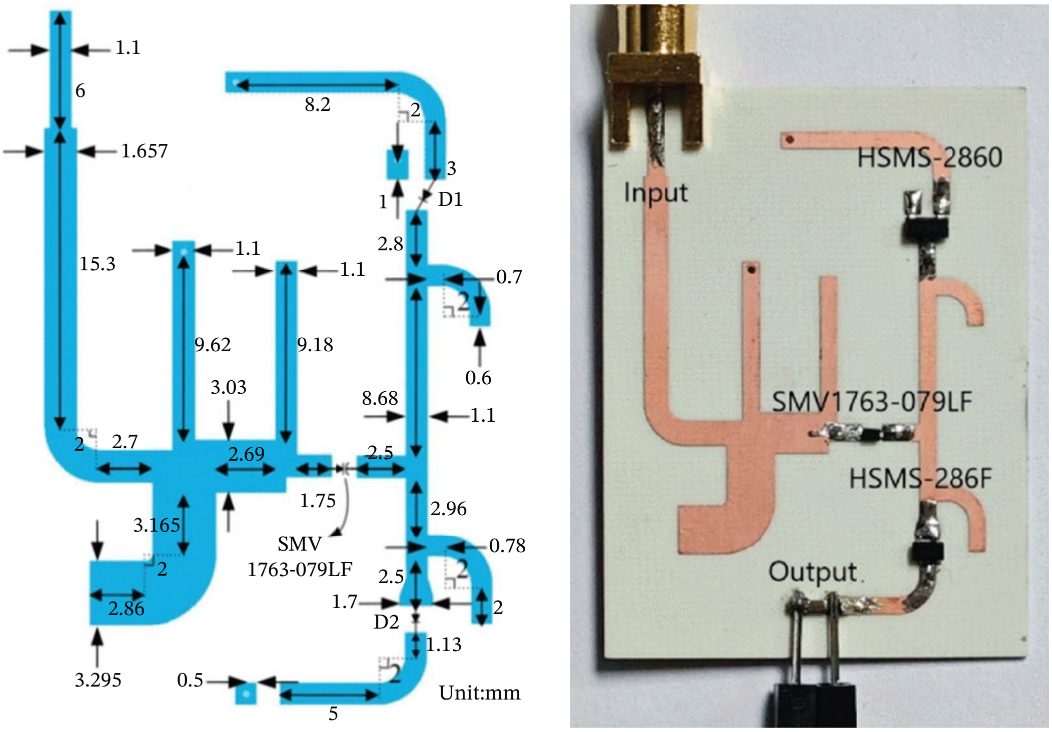


FIGURE 5 | Reconfigurable varactor-tuned antenna topology showing radiator layers, varactor placements, and structural geometry that enable frequency reconfigurability and pattern diversity [62]. (a) L1, (b) L2 and L3, and (c) side view.

structures (L3). The upper and lower substrates are spaced by a 5 mm air gap, which enhances the operational bandwidth of the antenna. Varactor diodes integrated into the radiator enable tuning of the resonant characteristics, allowing the antenna to effectively align with different ambient RF bands as conditions change [62]. By enabling frequency agility and pattern diversity, such reconfigurable antennas are well suited for rectennas in adaptive harvesting systems that must operate in environments with diverse and time-varying spectral occupancy. Materials research, particularly using flexible or wearable substrates, further extends rectenna applications to conformal and IoT form factors, supporting EH in wearable, structural, and embedded deployments [63].

4.2.2 | Impedance Matching and Optimization

Impedance matching between the antenna and the rectifier is essential to minimize reflection losses and ensure maximum power transfer from the captured RF signal into the nonlinear rectifier network. At the very low input power levels typical of harvested RF energy, even small impedance mismatches can result in significant power losses and degraded RF-to-DC conversion efficiency. Classical matching networks such as L-, π-, and T-type configurations are commonly optimized for a single frequency band or operating power level. However, these fixed networks often perform poorly under multiband operation or variable input power conditions, which are characteristic of ambient RF environments. A major challenge in RF EH systems is achieving effective impedance matching due to the nonlinear and input–power-dependent nature of rectifier impedance. This behavior causes significant mismatch losses when operating under varying ambient RF conditions. One effective technique for mitigating this limitation is the use of a resistance compression network (RCN), which stabilizes the effective input impedance of the rectifier across a wide range of input power levels. By compressing impedance variation, RCN-based matching networks reduce sensitivity to load fluctuations and enhance broadband performance. This makes them particularly suitable for ambient RF EH environments, where both frequency and input power levels are highly variable. As a result of fixed network issues, adaptive and broadband impedance matching techniques have gained increasing attention. Wideband transformers, multisection matching networks, and transmission-line stub configurations are widely employed to achieve flatter impedance responses over broader frequency ranges, enabling efficient EH without requiring multiple discrete fixed matching networks [64]. An illustrative example of adaptive impedance matching is presented in Figure 6, adapted from Zhou et al. [2], where low-power varactor diodes are used to dynamically compensate for variations in rectifier input impedance. In this self-adaptive design, the rectified DC output of one subcircuit is utilized as the reverse bias for the varactor diode, enabling automatic capacitance adjustment in response to changing RF input power levels. This approach eliminates the need for external bias circuitry while maintaining optimal impedance matching across a wide operating range. Experimental results demonstrate rectification efficiencies exceeding 50% over an input power range of 2.4–20.9 dBm, highlighting the effectiveness of the technique for low-power EH applications. Such self-biased adaptive matching architectures are particularly attractive for battery-free rectennas, as they enable real-time impedance optimization under fluctuating ambient RF conditions with minimal circuit overhead. Compared with fixed matching



(a)

(b)

FIGURE 6 | Adaptive impedance matching rectifier using varactor-assisted self-biased tuning: (a) circuit layout and (b) photograph of the fabricated prototype [2].

networks, adaptive designs significantly improve RF-to-DC conversion efficiency across wide input power ranges and enhance operational robustness in spectrally dynamic environments. In addition to varactor-based approaches, tunable matching networks employing MEMS switches and other reconfigurable elements have also been explored to enable real-time load tracking and impedance adaptation, further improving harvesting efficiency across diverse spectral conditions [65].

Rectenna design requirements differ significantly depending on the input power regime. For low-power EH (below −10 dBm), the primary challenge is overcoming diode threshold voltage, which necessitates the use of ultralow-barrier diodes, impedance compression techniques, and high-sensitivity matching networks. In contrast, high-power scenarios (above 10 dBm) require designs that can handle higher current levels without efficiency degradation, often involving multistage rectifiers, voltage regulation circuits, and load optimization strategies. These contrasting requirements highlight the need for adaptive and application-specific rectenna design approaches [38].

Load considerations play a critical role in determining the overall RF-to-DC conversion efficiency of rectenna systems, particularly under low–input-power conditions typical of battery-free operation. The rectifier does not operate with a fixed optimal load; instead, the optimal load resistance (R_l) varies with input RF power, frequency, and rectifier topology. As indicated in Equation (8), the harvested DC power is directly dependent on the load, meaning that even small deviations from the optimal load condition can significantly degrade conversion efficiency. At very low input power levels, the rectifier requires a carefully tuned load to maintain sufficient voltage swing across the nonlinear device and overcome diode threshold effects. In practical battery-free systems, the load is not constant but is determined by downstream circuits such as PMUs, sensors, and communication modules. This dynamic interaction creates a strong coupling between the rectifier and the load, necessitating codesign strategies where the rectifier, matching network, and load are optimized jointly. To address this challenge, adaptive load modulation techniques and MPPT schemes are increasingly employed to continuously adjust the effective load seen by the rectifier, ensuring operation near the optimal efficiency point despite variations in ambient RF power. Such approaches are essential for maintaining stable and efficient EH in real-world battery-free RF and microwave systems. [47].

4.2.3 | Rectifier Topologies and Nonlinear Optimization

The rectifier is the core component responsible for converting incident RF or microwave signals into usable DC power. Its operation is inherently nonlinear, making rectifier design a critical bottleneck in achieving high RF-to-DC conversion efficiency, particularly at the ultralow input power levels characteristic of ambient RF EH. Conventional diode-based rectifiers, including single-stage rectifiers, voltage doublers, and Greinacher circuits, are widely used due to their simplicity and compact implementation. However, their efficiency degrades rapidly below approximately −10 dBm input power, primarily due to diode threshold voltages and junction capacitance effects [66]. To address these limitations, extensive research has focused on low-threshold rectifier topologies, including multistage voltage multipliers, optimized Schottky diode stacks, and zero-bias tunnel or backward diodes with reduced turn-on voltages. These designs improve sensitivity at low input power but introduce additional nonlinear interactions between the rectifier, matching network, and load. As a result, rectifier optimization is commonly performed using equivalent circuit models and harmonic balance simulations, which enable joint optimization of diode biasing, load impedance, and matching network parameters to maximize DC output under realistic excitation conditions [67]. As operating frequency increases, RF-to-DC conversion efficiency typically degrades due to increased parasitic capacitances, diode-switching losses, and reduced rectifier conduction efficiency. To mitigate these effects, several design strategies are employed, including the use of low-barrier Schottky diodes or advanced diode technologies, optimized impedance matching networks, harmonic termination techniques, and distributed rectifier architectures. Additionally, careful layout design and minimization of parasitic elements become increasingly important at microwave and millimeter-wave frequencies. Beyond circuit topology optimization, recent studies have demonstrated that input waveform engineering can significantly enhance rectifier performance by exploiting its nonlinear characteristics. Multisine excitation and peak-to-average power ratio (PAPR) shaping techniques concentrate RF energy into high-amplitude peaks that more effectively overcome diode turn-on thresholds. El Moussati et al. demonstrated that properly designed multisine waveforms can substantially increase harvested DC power compared with single-tone excitation at the same average input power, especially in the low-power regime relevant to battery-free systems [68]. These results highlight the importance of treating the rectifier not as a linear load, but as a nonlinear energy conversion element whose efficiency depends strongly on the statistical properties of the incident RF waveform. Consequently, modern rectenna design increasingly adopts a codesign philosophy, where the antenna, impedance matching network, rectifier topology, and excitation waveform are optimized jointly rather than as isolated subsystems. This holistic approach has been shown to improve RF-to-DC conversion efficiency, extend operational sensitivity, and enhance the feasibility of battery-free RF and microwave systems operating under weak and fluctuating ambient energy conditions [69].

4.2.4 | Multiband and Wideband Rectenna Strategies

Harvesting energy from multiple frequency bands increases the total available power, particularly in environments characterized by heterogeneous and time-varying RF sources. Multiband rectennas employ multiple resonant structures or frequency-selective surfaces (FSS) to capture energy across distinct bands such as cellular, Wi-Fi, and broadcast services, using either dedicated matching and rectification paths or aggregated network designs. Several multiband rectenna topologies utilize stacked antennas, fractal geometries, slot-based radiators, or hybrid structures to achieve resonance at multiple frequencies without a significant increase in physical size. Complementary to these approaches, wideband rectennas exploit tapered slot antennas, log-periodic structures, or broadband monopoles to enable continuous energy capture over wide frequency ranges, trading peak efficiency at a single band for increased aggregate harvested power across the spectrum [70]. In addition to slot-based and fractal multiband topologies, FSS have recently been investigated as a means to achieve selective and enhanced multiband energy capture. FSS structures act as spatial filters, enabling selective enhancement or suppression of specific frequency bands within the incident electromagnetic spectrum. As demonstrated in a dual-passband FSS design with high angular stability and polarization insensitivity, distinct passbands can be engineered to target multiple frequency ranges with minimal loss over wide incident angles [71]. Such frequency-selective behavior can be leveraged in rectenna systems to preferentially couple energy from ambient sources (e.g., GSM, Wi-Fi, and LTE) into the rectifier, improving effective multiband harvesting without excessive circuit complexity. Similarly, wideband rectenna architectures incorporating FSS reflectors have been shown to tailor impedance response and electromagnetic field distribution, enhancing harvested power across broad frequency ranges in indoor environments [72]. In addition, FSS-based harmonic suppression techniques can improve rectifier stability and efficiency in multiband rectennas by isolating desired frequency components and mitigating nonlinear distortion effects. By combining multiband reception with FSS-assisted impedance shaping and harmonic control, these designs significantly enhance robustness against spectral variability in real deployment environments [73]. Such strategies are particularly attractive for battery-free RF and microwave systems, where maximizing harvested energy across diverse and fluctuating spectra is essential for sustaining autonomous operation.

4.3 | Power Management Circuits for Ultralow Power Systems

Power management circuits play a pivotal role in enabling battery-free RF and microwave systems by conditioning harvested energy into a stable and usable form for sensing, computation, and communication. Because ambient RF energy is typically intermittent, weak, and highly variable, PMUs for battery-free nodes must operate efficiently at ultralow input power levels while introducing minimal overhead. Unlike conventional power converters designed for milliwatt or watt-level operation, PMUs for battery-free systems are often required to function reliably with input powers in the microwatt or nanowatt range, placing stringent constraints on circuit design, leakage current, and startup behavior. As shown in Figure 7, the PMU integrates cold-start circuitry, energy regulation, MPPT, energy buffering, and load management into a tightly coupled architecture optimized for ultralow-power operation. The cold-start block enables system initialization from near-zero harvested energy, whereas the DC–DC converter and MPPT controller regulate and optimize power extraction from the rectifier. Temporary energy storage in capacitors or supercapacitors supports intermittent operation, and energy-aware load management ensures that sensing and communication tasks are activated only when sufficient energy is available.

A fundamental challenge in battery-free power management is cold-start operation, where the system must bootstrap itself from zero stored energy. Cold-start circuits are responsible for initiating PMU operation directly from the rectifier output without external bias. Recent PMU designs have demonstrated cold-start capabilities at input voltages below 300 mV, enabling operation under weak ambient RF conditions typical of indoor and urban environments. Achieving such low startup thresholds requires careful transistor sizing, subthreshold operation, and the elimination of static bias paths that contribute to leakage losses [74]. Once operational, PMUs must efficiently regulate the harvested DC voltage to levels compatible with ultralow-power loads. Low-dropout regulators (LDOs) are commonly employed due to their simplicity and low noise characteristics; however, their efficiency degrades when the voltage difference between input and output is large. To address this, switched-capacitor DC–DC converters and charge pumps have been widely adopted in battery-free systems, as they can achieve high efficiency at low power levels without requiring bulky inductors. Recent designs

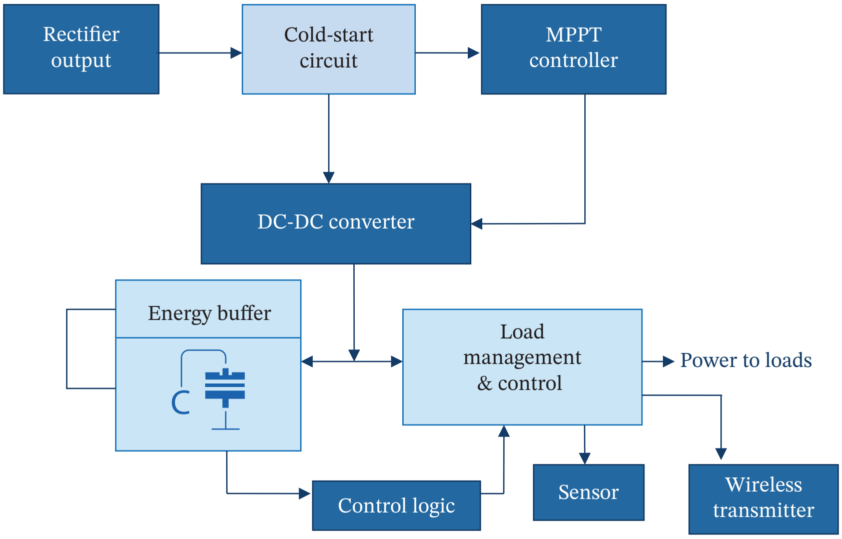


FIGURE 7 | Conceptual block-level architecture of an ultralow-power power management unit (PMU) for battery-free RF energy harvesting systems.

demonstrate conversion efficiencies exceeding 80% at power levels below 10μW, making them suitable for RF EH applications [75].

Another critical function of the PMU is MPPT, which ensures that the rectifier operates near its optimal load condition despite variations in input power and frequency. In RF EH, the maximum power point is highly sensitive to input amplitude, impedance matching, and rectifier nonlinearity. Conventional MPPT techniques used in photovoltaic systems are often too complex or power-hungry for battery-free operation. As a result, simplified MPPT schemes such as fractional open-circuit voltage tracking, perturb-and-observe with ultralow duty cycling, and self-biased adaptive load techniques have been proposed. These approaches minimize control overhead while significantly improving net harvested energy [76]. Energy buffering is another essential aspect of power management in battery-free systems. Because harvested RF energy is intermittent, PMUs typically interface with small storage elements such as capacitors or supercapacitors rather than conventional batteries. These storage components accumulate energy over time and release it in short bursts to support sensing or communication tasks. The PMU must manage charging and discharging efficiently, balancing storage size against leakage losses and startup latency. Recent studies highlight that improper buffer sizing can negate harvesting gains due to leakage currents dominating harvested energy, especially at nanowatt power levels [77]. Power-aware load management is increasingly integrated into modern PMUs to maximize system functionality under constrained energy budgets. Rather than providing continuous power, PMUs often support event-driven or duty-cycled operation, enabling loads only when sufficient energy is available. This includes voltage supervisors, energy-threshold detectors and power-gating switches that isolate subsystems until predefined energy conditions are met. Such mechanisms are essential for preventing brownout conditions and ensuring reliable intermittent operation. Emerging research trends emphasize codesign of PMUs with rectifiers and communication modules, recognizing that power management cannot be optimized in isolation. For instance, adaptive PMUs that adjust output voltage levels based on communication mode (e.g., sensing vs. backscatter transmission) have been shown to reduce overall energy consumption. Additionally, ML-assisted PMUs have been explored to predict harvested energy patterns and dynamically adjust regulation and scheduling policies, further improving long-term energy efficiency in battery-free deployments [78, 79].

4.4 | Energy Storage Alternatives (Supercapacitors and Hybrid Storage)

Energy storage plays a supporting but critical role in battery-free RF and microwave systems by buffering harvested energy and enabling intermittent operation. Unlike battery-assisted systems that rely on long-term chemical storage, battery-free platforms typically employ short-term storage elements such as capacitors or supercapacitors to accumulate energy and deliver it in bursts for sensing or communication. The choice of storage technology directly impacts system latency, efficiency, leakage losses, and achievable duty cycles. Supercapacitors have emerged as a preferred storage option for battery-free systems due to their high cycle life, fast charge–discharge capability, and compatibility with ultralow-power operation. Compared with conventional batteries, supercapacitors exhibit significantly longer lifetimes and tolerate frequent charge–discharge cycles without degradation, making them well suited for EH scenarios. However, their relatively high leakage currents and lower energy density impose limitations, particularly in environments with very weak or infrequent RF energy availability [80]. To address these trade-offs, hybrid storage architecture combining small supercapacitors with thin-film microbatteries or high-density capacitors has been proposed. In such designs, the supercapacitor handles rapid energy fluctuations and cold-start operation, whereas the auxiliary storage element provides longer-term buffering. This hybrid approach improves reliability and reduces leakage losses without sacrificing the maintenance-free advantages of battery-free systems [81]. Storage sizing is another critical design consideration. Oversized storage elements increase leakage losses and startup latency, whereas undersized buffers limit achievable duty cycles and communication reliability. Recent studies emphasize co-optimization of storage capacity, PMU efficiency, and system workload to ensure energy-neutral operation under realistic ambient RF conditions. Adaptive storage management strategies that dynamically adjust operating thresholds based on harvested energy statistics have also been proposed to improve long-term performance [82, 83]. Overall, energy storage in battery-free RF and microwave systems is best viewed not as a primary energy source, but as a transient energy buffer tightly integrated with power management and system scheduling. Advances in low-leakage supercapacitors, hybrid storage architectures, and adaptive energy buffering techniques continue to enhance the practicality and robustness of autonomous battery-free wireless platforms.

5 | Battery-Free Communication and Signal Processing Techniques

Battery-free RF and microwave systems require communication and signal-processing approaches that operate reliably under extremely tight energy budgets. Traditional active radios (which generate carriers) are often infeasible for battery-free nodes because carrier generation dominates the energy budget. Consequently, battery-free systems rely on ultralow-power modalities especially backscatter communication with specially tailored modulation, coding, and network protocols that explicitly account for intermittent power and highly variable link quality. This section surveys the main approaches used today: ambient and dedicated backscatter, ultralow-power modulation schemes designed for low energy per bit, and energy-aware MAC and networking protocols that coordinate device activity to match available harvested energy.

5.1 | Backscatter and Ambient Backscatter (AmBC) Communication

Backscatter communication enables a tag to convey information by changing its antenna load to modulate the reflection coefficient of an incident RF wave. Because the tag does not generate its own carrier, power consumption is orders of magnitude lower than that of active transmitters. AmBC extends this concept by using existing ambient signals such as TV broadcasts, Wi-Fi, and cellular transmissions as carriers instead of a dedicated continuous-wave source, enabling truly battery-free operation in many settings. Backscatter is therefore well suited for battery-free systems, as tags modulate and reflect received energy and their transmit energy cost is essentially limited to the switching energy of the load network and minimal control logic. This extremely low energy-per-bit enables sensing and communication from nodes that harvest only microwatts or less [84]. Practical systems combine RF EH (rectennas) with backscatter front-ends and ultralow-power control circuits to realize maintenance-free sensing nodes. Zhan et al. demonstrated a flexible, wearable, battery-free backscatter system that integrates RF harvesting with low-power modulation to enable continuous color-imaging sensors in wearable form factors. The system employs a hybrid RF–solar EH array that efficiently harvests both ambient RF and visible light, ensuring continuous operation in diverse environments. This work represents a concrete example of a battery-free backscatter platform supporting sensing-rich applications [85]. The LoRa backscatter family of work has shown that backscatter communication can be extended to long ranges—on the order of hundreds of meters by leveraging low-power wide-area network (LPWAN) modulations and careful PHY and receiver design. Because backscatter tags are typically duty-cycled and event-driven, MAC and network layers must support asynchronous activations, collision avoidance under limited tag capabilities, and energy-aware scheduling. High-throughput LoRa backscatter systems employing nonlinear chirps and ultralow-power demodulators have proposed MAC strategies and receiver designs that balance energy consumption against throughput and latency, demonstrating practical wide-area battery-free IoT operation through prototype evaluations [86, 87].

Recent prototypes have also used ambient Wi-Fi signals as carriers to achieve reliable backscatter communication for higher-throughput tasks, including video transmission in laboratory and demonstration settings. These results highlight the rapid progress of backscatter techniques toward richer battery-free applications [88]. Nevertheless, AmBC systems face several detection and synchronization challenges because the ambient carrier is uncontrolled, time-varying in amplitude and phase, and often correlated with the backscattered signal. Receiver designs therefore focus on robust symbol detection under residual synchronization errors and correlated interference, exploiting known signal structures (e.g., Wi-Fi preambles) for synchronization and channel estimation, as well as interference cancellation and multitag separation for dense deployments. Recent studies propose new detectors, coding strategies, and synchronization methods tailored specifically to AmBC channels [6, 89]. Overall, backscatter systems excel in ultralow power consumption and low-cost tag design but trade these advantages for reduced communication range, lower signal-to-noise ratio (SNR) margins, and increased dependence on receiver sensitivity and ambient carrier availability. AmBC further inherits the spatial and temporal variability of ambient RF sources, necessitating energy-aware link adaptation and buffering strategies. Emerging mmWave and metamaterial-enhanced backscatter variants are aimed at supporting higher data rates, although they face stricter alignment requirements and propagation challenges [89, 90].

5.2 | Ultralow-Power Modulation Schemes

Ultralow-power modulation schemes are essential in battery-free RF and microwave systems because communication energy often dominates the total power budget even when harvesting is moderately successful. Unlike conventional radios that can expend milliwatts or more to actively transmit and receive, battery-free nodes require modulation and waveform techniques that minimize energy per bit, often operating in the microwatt to nanowatt range. Ultralow-power modulation thus focuses on simple signal representations that (i) require minimal processing for transmission, (ii) support low-complexity, energy-efficient receivers, and (iii) allow robust demodulation under low SNR conditions typical of ambient RF environments. At a high level, modulation schemes can be classified into noncoherent and coherent formats. Noncoherent schemes such as on-off keying (OOK) and simple frequency shift keying (FSK) avoid the strict phase-synchronization requirements of coherent methods, thereby reducing receiver complexity and power. In contrast, coherent schemes (e.g., phase-shift keying variants) require precise phase alignment and tracking, increasing circuitry and energy cost, often prohibitive for battery-free operation. In practice, battery-free systems generally employ noncoherent or simplified modulation formats for downlink and backscatter links to balance energy use with acceptable bit error rates (BER) under low harvested power budgets.

5.2.1 | Simple Binary Modulation for Low Power

The simplest and most widespread ultralow-power modulation used in battery-free and EH networks is OOK, a form of amplitude shift keying where:

$$s(t) = \begin{cases} A\cos\left(2\pi f_c t\right), binary^{\varepsilon}1^{\varepsilon} \\ 0, binary^{\varepsilon}0^{\varepsilon} \end{cases} \tag{14}$$

whereA is the carrier amplitude and f_c iscarrier frequency. OOK requires only toggling between a transmitted carrier and silence, enabling extremely low hardware complexity and power consumption at the transmitter (or tag backscatter modulator) and a simple envelope detector at the receiver [91]. In AmBC systems, OOK is often adopted because it can be implemented by toggling the antenna load between high-reflection and high-absorption states, consuming only control logic energy rather than power for a local carrier generator. Another common simple noncoherent modulation is binary FSK, where bit values are encoded as different discrete frequencies:

$$s(t) = A\cos\left(2\pi\left(f_c \pm \Delta f\right)t\right) \tag{15}$$

FSK increases robustness to amplitude noise compared with OOK at a modest increase in receiver complexity. It has been incorporated in many wireless sensor systems where energy cost must be balanced against reliability, even when harvesting energy from ambient RF. [92]. Studies on wake-up receivers (WuRs) and ultralow-power PHY layer designs show that simple noncoherent modulation like OOK and FSK paired with duty cycling is widely used to achieve submicrowatt power budgets, at the expense of lower data rates and basic synchronization requirements [93]. Ambient Wi-Fi-based backscatter systems that modulate incoming OFDM subcarriers using simple digital modulation approaches have demonstrated throughput improvements while maintaining low tag power consumption by exploiting ambient infrastructure signals [94].

In backscatter systems specifically, the modulation is often not actively generated but imposed on a carrier already present in the environment. Tags achieve this by switching the antenna load impedance Z_L in time according to a modulation waveform. The reflection coefficient Γ at the tag's antenna is as follows:

$$\Gamma = \frac{Z_L(t) - Z^{*}{}_{ant}}{Z_L(t) + Z_{ant}} \tag{16}$$

where Z_{ant} is the antenna impedance. By toggling between states, the tag imposes different backscattered waveforms corresponding to data symbols with very low energy cost.

5.2.2 | Spread and Chirp Modulations

For ultralow power systems requiring wide area coverage and interference resilience, chirp spread spectrum (CSS) and LoRa-like chirp modulations offer attractive energy trade-offs. CSS encodes information in frequency-modulated chirps that sweep linearly across a predefined band. The CSS symbol for bit k can be described as follows:

$$s_k(t) = A\cos\left(2\pi\left(f_c \pm \frac{B}{T}t\right)t\right) \, for \, t \in [0, T] \tag{17}$$

where B is the spread bandwidth and Tis chirp period [95, 96]. This continuous frequency variation provides processing gain that improves sensitivity at low SNR at the cost of longer symbol time. LoRa PHY, a practical industry implementation of CSS, can tradeoff data rate for sensitivity using the spreading factor (SF); higher SF increases receiver sensitivity and range while lowering throughput. Such modulation formats are widely adopted in LPWAN solutions including LoRaWAN and other ambient IoT targets, because they balance energy per bit with range and robustness advantages desirable even in battery-free communication contexts where energy budgets are constrained [86]. LoRa backscatter prototypes use chirp-like spread modulation at the tag while preserving low tag complexity, enabling hundreds of meters range with ultraefficient modulation and energy use [96].

5.2.3 | Pulse and Position-Based Schemes

When receiver simplicity is paramount, pulse-position modulation (PPM) offers a low-complexity alternative where information is represented by the time position of a pulse within a time frame. Each symbol encodes m bits as one of 2^m

$$T_s = \frac{1}{2^m} T \tag{18}$$

where T is the symbol duration and T_s is the spacing of possible pulse slots. Because PPM can be detected with simple thresholding on pulse timing and does not require phase or frequency synchronization, it is attractive for hardware with very limited energy and processing. Although used extensively in ultralow-power optical wireless and RFID systems, research has explored PPM's viability in RF contexts when combined with simple envelopes and energy detectors. The energy efficiency advantage arises because the receiver integrates only short bursts of energy instead of continuous energy over time, reducing average power consumption [97, 98].

In designing ultralow-power modulation schemes, several key trade-offs emerge. Low-power schemes like OOK minimize circuitry and energy usage but are typically more susceptible to noise than FSK or CSS. FSK improves spectral separation and SNR resilience but can require slightly more complex switching or frequency translation circuits, which must still operate within the tight energy budget of battery-free system. Passive tags place most of the signal generation burden on the receiver. Receivers must detect weak backscattered signals, often requiring advanced demodulation strategies (e.g., correlation for CSS, envelope detectors for OOK/FSK) to maximize performance in low SNR conditions. Due to the intermittent nature of harvested energy, tags are typically duty-cycled. Modulation schemes must therefore be compatible with occasional bursts of data, synchronized with energy availability. Dynamically adjusting symbol rates and modulation choice based on instantaneous energy can further enhance effective throughput for a given energy budget.

5.3 | Energy-Aware MAC and Networking Protocols

In battery-free RF and microwave systems, communication is controlled not by data traffic demands but by energy availability. A battery-free node cannot transmit simply because it has data to send; it can only communicate when it has harvested enough energy to power its circuits. This fundamental constraint changes the purpose of MAC (medium access control) and networking protocols. Instead of mainly resolving channel contention or maximizing throughput, MAC protocols in battery-free systems are designed to ensure that communication happens only when sufficient energy is present, preventing system failure due to energy depletion. Because harvested RF energy is weak and unpredictable, battery-free nodes typically operate in an intermittent manner. They spend most of their time harvesting energy while inactive and only become active briefly when their stored energy reaches a level that can support sensing and transmission [99]. This behavior is often described using the energy queue model introduced earlier in Equation (13) where the node can communicate only when the stored energy E(t)) is greater than the energy cost of communication C(t). MAC decisions are therefore triggered when E(t)) exceeds a predefined operational threshold. This approach avoids brownout failures and ensures energy-neutral operation over time. In practice, this means the node “wakes up” automatically when its capacitor voltage crosses a threshold, performs sensing and transmission, then returns to a harvesting state. Communication is therefore energy-triggered, not schedule-triggered. Practical implementations of such energy-threshold MAC have been demonstrated in AmBC and RF-harvesting sensor networks, where nodes transmit only after capacitors charge to a safe voltage level, resulting in asynchronous but sustainable network behavior [100]. Another important characteristic of battery-free networks is that nodes cannot afford to keep their radios on to listen for channel activity. Continuous listening consumes more power than the node can harvest. To solve this, many battery-free systems use a receiver-initiated approach. A powered reader, gateway, or access point controls communication by sending a carrier or interrogation signal. Battery-free tags respond only when illuminated by this signal. This shifts most of the networking complexity to the powered infrastructure while keeping the tags extremely simple and energy efficient. This approach is common in RFID-inspired and AmBC systems. Because battery-free tags cannot perform complex channel sensing or contention algorithms such as CSMA/CA, lightweight alternatives are used. Instead of competing for the channel, tags are often polled sequentially by the reader or they respond in assigned time slots. In some systems, tags use simple randomized waiting times based on how much energy they have harvested before attempting to respond. These methods reduce collisions without requiring computation or continuous listening at the tag [101].

Energy variability also means that communication parameters must adapt to the amount of energy available. When a node has accumulated more energy, it can afford to transmit longer packets or use more robust modulation. When energy is scarce, it may send only short status messages or reduce its data rate. This dynamic adjustment of packet length, symbol rate, or modulation scheme improves overall network reliability while ensuring that nodes do not exhaust their harvested energy. Further complication arises because battery-free nodes frequently lose power completely. When this happens, they lose clock timing and network state information. MAC protocols must therefore allow nodes to rejoin the network without relying on stored state. Some systems use the structure of incoming signals, such as Wi-Fi beacons or reader preambles, to help nodes quickly regain synchronization after waking up. Packet formats are also designed so that each transmission is independent and does not rely on previous communication history. At larger scales, networking becomes more complex because nodes in different locations harvest different amounts of RF energy. Nodes closer to strong RF sources can communicate more frequently than distant ones. Recent approaches address this by allowing powered gateways to coordinate communication schedules based on expected energy availability, or by organizing nodes into clusters where better-powered nodes help relay information for weaker ones [102–104].

6 | Energy-Efficient RF and Microwave Circuit Design

Battery-free RF and microwave systems depend not only on effective EH and communication protocols, but also on extremely energy-efficient circuit design. Even if sufficient RF energy is harvested and efficient backscatter techniques are used, poor circuit design can consume more power than the system can sustain. As a result, the design of RF front-ends, antennas, and microwave integrated circuits (MICs) for battery-free nodes must follow a strict ultralow-power philosophy. Unlike conventional wireless devices that operate comfortably in the milliwatt range, battery-free RF/microwave circuits must function reliably in the microwatt or even nanowatt regime. This requires careful optimization of transistor operation regions, leakage reduction, simplified architecture, and codesign between RF, analog and digital blocks. Designers must ensure that every stage, from signal reception to baseband processing, consumes as little energy as possible while still supporting reliable communication. A major principle in battery-free circuit design is eliminating unnecessary active RF generation. This is why backscatter communication is favored over traditional transmitters. Instead of generating RF carriers, circuits modulate reflections of existing signals, removing the most energy-intensive part of a radio system. Where active RF blocks are required, designers employ subthreshold CMOS operation, passive mixing, envelope detection, and minimalist amplification strategies. Another important design consideration is leakage current. At ultralow power levels, leakage can exceed harvested power if not carefully controlled. This has driven the use of power gating, subthreshold biasing, and minimalist bias networks in modern RF EH nodes. This section examines how RF and microwave circuits are designed specifically for battery-free operation, focusing on low-power transceivers, antenna considerations, and MICs tailored for extreme energy constraints.

6.1 | Low-Power Transmitters and Receivers

In battery-free RF and microwave systems, one of the most important design decisions is to avoid building a conventional radio transmitter, because generating and amplifying an RF carrier is the most power-consuming operation in wireless devices. Traditional transmitters operate in the milliwatt range, far beyond what a battery-free node powered by harvested RF energy can sustain. Instead, battery-free communication relies on backscatter modulation, where the node does not create its own RF signal but reflects and modulates an existing

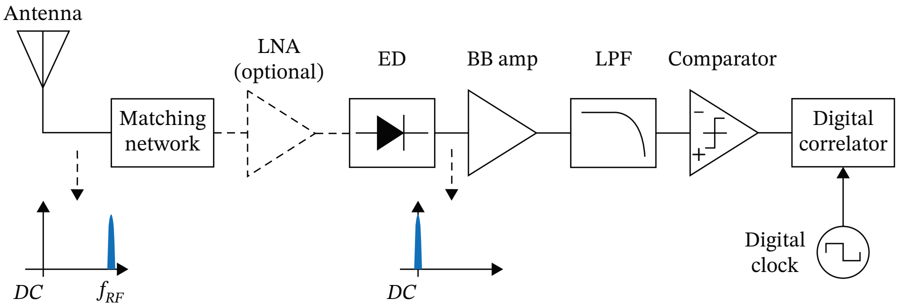


FIGURE 8 | Typical block-level architecture of an ultralow-power wake-up receiver using envelope detection and a threshold comparator [105].

one by switching the antenna load impedance. This replaces energy-hungry RF oscillators and power amplifiers with simple MOSFET or varactor switching circuits that consume only the small amount of energy required for impedance toggling, often less than $1\,\mu$W, compared with tens of milliwatts in conventional radios. On the receiver side, battery-free systems must also avoid complex radio architectures that require continuous bias currents for mixers, oscillators, and amplifiers. Rather than performing frequency conversion or coherent demodulation, these systems use envelope detectors and simple comparators shown in Figure 8 to extract information from incoming RF signals. An envelope detector captures the amplitude variations of the received signal without phase synchronization, and the output is compared with a threshold to determine the transmitted bit. This minimalist approach dramatically reduces power consumption and is widely used in WuRs and backscatter readers, where continuous listening is impossible but occasional signal detection is necessary [105, 106].

To further reduce power usage, designers employ passive or near-passive techniques such as passive mixers and operate transistors in the subthreshold CMOS region, where current is exponentially related to gate voltage. In this mode, devices conduct extremely small currents, allowing low-noise amplifiers (LNAs), comparators, and baseband blocks to function using only microwatts or less. Although subthreshold operation reduces circuit speed, this limitation is acceptable because battery-free communication typically occurs at low data rates [107]. Practical RF front-ends based on this philosophy have demonstrated receiver power consumption below 5–$10\,\mu$W, making them suitable for EH and battery-free platforms. Together, subthreshold circuit design, impedance switching for transmission, and envelope-based reception reduce overall circuit consumption from milliwatts to microwatts, enabling true energy-autonomous wireless operation [108].

In Figure 8, at the front end, the antenna captures ambient RF energy and feeds it to an envelope detector, which extracts amplitude variations in the received waveform without requiring mixers or local oscillators. Because envelope detection is essentially an amplitude demodulation process, it avoids the components that dominate power consumption in conventional radios. A low-gain amplifier may be included to slightly boost the detected envelope while still operating at ultralow power. An ultralow-power comparator then compares this signal to a predefined threshold to determine whether a wake-up event or specific bit pattern is present. Finally, simple control logic activates the primary communication subsystem only when a valid wake-up sequence is detected. Designs such as those by Liao et al. demonstrate WuRs operating down to 6.4 nW with −75 dBm sensitivity using similar envelope detection and comparator architectures [109], clearly illustrating how simplified RF front-ends enable practical battery-free operation.

6.2 | Antenna Design for Battery-Free Systems

Antenna design in battery-free RF and microwave systems is driven less by communication range and more by the need to maximize captured electromagnetic energy under weak, spectrally diverse and time-varying ambient conditions. Because the antenna is the first element in the harvesting chain, its gain, bandwidth, polarization behavior and impedance characteristics directly determine how much RF power reaches the rectifier and ultimately how much usable DC power the node can obtain. At nanowatt–microwatt levels, even small improvements in antenna gain, polarization tolerance or impedance stability can produce noticeable increases in harvested energy. Designing such antennas therefore follows a practical workflow that differs from conventional communication antenna design. Rather than starting from a standard frequency band or radiation requirement, designers begin by identifying which ambient RF bands actually contain the highest power density in the intended deployment environment. Measurement campaigns and published surveys consistently show that GSM-900/1800, LTE, Wi-Fi (2.4/5 GHz), and increasingly 5G bands dominate the ambient RF landscape in populated areas. This ensures that the antenna resonates where harvestable energy truly exists rather than where communication standards are defined [24]. Based on this spectral understanding, the designer chooses whether to implement a multiband or wideband topology. Multiband resonant structures such as slot-loaded patches, fractal geometries, stacked patches, and hybrid radiators allow the antenna to resonate at several discrete frequency bands without proportional size increase. Alternatively, wideband structures such as log-periodic, monopole, or tapered slot (Vivaldi) antennas enable continuous capture across a broad spectrum, trading peak efficiency at a single band for aggregate harvested power across many services [110, 111]. These approaches increase the probability that the antenna encounters a strong ambient source at any given time, thereby improving overall energy availability in real environments.

Polarization becomes a much more critical factor than in conventional antennas. Ambient signals arrive after reflections, scattering, and multipath propagation that often randomize their polarization. For this reason, CP or polarization-diverse antennas are frequently adopted to reduce polarization mismatch losses and improve energy capture reliability in indoor and urban environments [112, 113]. Material and substrate selection further influence performance. Low-loss microwave substrates such as Rogers RO4003, Kapton, or textile dielectrics are commonly used to maintain radiation efficiency and impedance stability while enabling compact, flexible, or wearable implementations suited for IoT and body-centric applications [114]. A key point where battery-free antenna design diverges sharply from traditional practice is impedance matching. The antenna is not designed for a standard $50\,\Omega$ load. Instead, its impedance must be compatible with the nonlinear, power-dependent input impedance of the rectifier obtained from harmonic balance simulations. Designers iteratively adjust antenna geometry so that its impedance locus overlaps the rectifier's optimal operating region across the target bands. This codesign requirement ensures that variations in antenna impedance do not severely degrade RF-to-DC conversion efficiency [115, 116]. Additional performance enhancement can be achieved by integrating metasurfaces or FSS as superstrates or reflectors. These structures act as spatial filters that reshape the incident electromagnetic field, increase effective aperture, and selectively reinforce desired frequency bands without enlarging the antenna footprint, an especially useful strategy in spectrally dense indoor environments [117]. Finally, validation of the antenna–rectifier pair is performed not only with laboratory signal generators but under real ambient RF conditions across locations and times. This closes the loop between theoretical design and practical harvesting performance. Unlike conventional communication antennas optimized for S11, gain, and bandwidth alone, battery-free rectenna antennas are engineered to maximize captured power, maintain impedance synergy with a nonlinear rectifier, tolerate polarization diversity, exploit spectral opportunism, and integrate into compact node architectures. This methodology shown in Figure 9 reflects how modern antennas for battery-free RF and microwave systems are practically designed in recent research rather than how traditional antennas are conceived for communication purposes.

CP antennas have emerged as particularly effective structures for RF EH in realistic environments where signal polarization is random due to multipath propagation, scattering, and reflections. Unlike linearly polarized antennas, CP antennas eliminate polarization mismatch losses by maintaining consistent power reception regardless of the incident wave orientation. This makes them highly suitable for ambient RF harvesting scenarios in indoor and urban environments. Recent studies have demonstrated that CP rectennas can significantly improve harvested power stability compared with single-polarized designs, especially under dynamic channel conditions. Dual-CP and CP patch antennas have been widely adopted in multiband and wideband rectenna systems to enhance robustness and overall energy capture efficiency [118, 119]. In addition to circular polarization, dual-polarized rectenna architectures have been proposed to further enhance EH performance. These systems employ orthogonal polarization modes to simultaneously capture energy from multiple polarization components of incident RF signals. Dual-polarized rectennas are particularly effective in multipath-rich environments, where signal polarization varies rapidly. By combining outputs from multiple polarization channels, these designs improve harvested power density and provide more stable energy delivery to the rectifier stage [120–122].

6.3 | MICs for Energy-Constrained Platforms

MICs used in battery-free RF and microwave systems are designed with a fundamentally different objective from conventional RFICs. Rather than maximizing linearity, bandwidth or transmit power, the dominant goal is to minimize static and dynamic power consumption while retaining just enough RF functionality to support sensing, wake-up detection, backscatter communication and ultralow-rate data transfer. This shift in objective leads to architectures that deliberately avoid energy-hungry RF blocks and instead rely on subthreshold operation, passive signal processing, and tight codesign with the rectifier and PMU. A defining feature of these MICs is that most traditional RF functions are either eliminated or implemented in passive or near-passive form. In battery-free nodes, RF carrier generation is avoided completely. Instead of oscillators and power amplifiers, data transmission is achieved through backscatter modulation, where the antenna load impedance is switched using MOSFET or varactor devices [123]. The energy cost of this operation is only the switching energy of the device, typically below one microwatt. The reflection coefficient that governs this process is shown in Equation (16). By toggling Z_L between two states, the node encodes data onto an existing RF carrier without generating its own signal. On the receiver side, the same philosophy of simplification is applied. Mixers, local oscillators, and coherent demodulators are avoided because they require continuous bias currents. Instead, envelope detectors and simple comparators are used to extract information from incoming RF signals. Envelope detection performs amplitude demodulation without phase synchronization or frequency translation, drastically reducing circuit complexity and power consumption. This architecture is widely used in WuRs and backscatter readers, where continuous listening is necessary but energy budgets are extremely limited. A key enabler of these ultralow-power circuits is operating transistors in the subthreshold region [105, 124]. In this regime, the drain current is approximately

$$I_D \approx I_O e^{(V_{GS}-V_T/nV_T)} \tag{19}$$

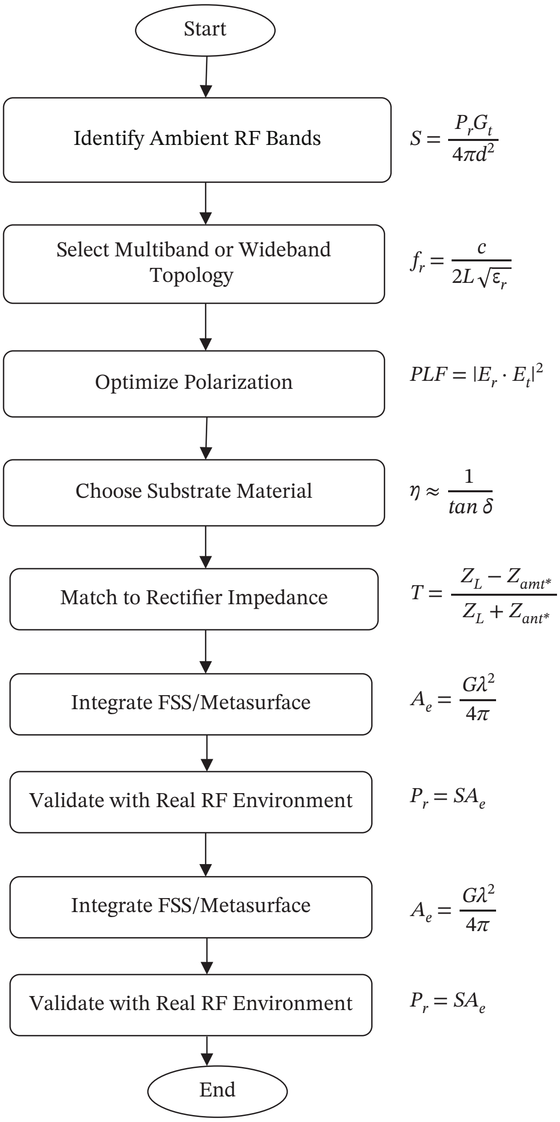


FIGURE 9 | Antenna design workflow for battery-free rectennas.

Where I_D is the drain current of the MOSFET, I_O is process-dependent current constant (depends on device size and technology), V_{GS} is gate-to-source voltage, V_T is threshold voltage of the MOSFET, nis subthreshold slope factor (typically 1.2–1.6). This exponential relationship shows that useful amplification and switching can occur with nanoampere-level currents when $V_{GS} < V_T$ which is the fundamental reason subthreshold CMOS operation enables ultralow-power RF front-ends and WuRs in battery-free systems. It means that useful gain and switching behavior can be achieved with nanoampere bias currents [125]. Although subthreshold operation reduces circuit speed, this is acceptable because battery-free communication typically occurs at very low data rates. Subthreshold CMOS LNAs, comparators, and baseband blocks have demonstrated total receiver power consumption below 5–10 μW, making continuous or semicontinuous listening feasible in EH nodes [126]. A major practical embodiment of these ideas is the ultralow-power wake-up receiver, which remains active, whereas the rest of the node sleeps and only triggers the main circuitry when a valid RF signature is detected. Such receivers typically integrate an antenna interface, an envelope detector, a low-gain subthreshold amplifier, and a nano-power comparator. State-of-the-art designs report sensitivities below −70 dBm while consuming only nanowatts to a few microwatts, making them ideal for battery-free RF platforms [127].

Another important characteristic of microwave ICs in these systems is that they are not designed independently of the rectifier and PMU. The input impedance of the RF front-end, the nonlinear loading behavior of the rectifier, and the operating point of the PMU are tightly coupled. Figure 10 illustrates a practical embodiment of this codesign philosophy in a fully integrated RF EH front-end. The antenna inputs feed an on-chip impedance matching network directly connected to multistage rectifiers, whose outputs are processed through a charge pump, control unit, and energy storage interface. This architecture clearly shows how impedance matching, rectification, energy conditioning, and control logic are implemented within a single MIC rather than as separate blocks [128]. Such tight integration minimizes interconnect losses, reduces leakage, and ensures that the rectifier, PMU, and RF front-end operate at compatible bias and impedance conditions, which is essential for battery-free operation under weak ambient RF energy. Designers increasingly rely on harmonic balance and circuit cosimulation so that the rectifier sees its optimal load, the RF detector operates at minimum bias, and the overall system remains energy neutral. This codesign approach ensures that energy harvested at the antenna is not lost through impedance or bias mismatches within the IC [129]. Technology choices further support this low-power philosophy. Standard CMOS is widely used for integrating ultralow-power analog and digital control, whereas silicon-on-insulator (SOI) CMOS reduces leakage and parasitic effects. Flexible and thin substrates allow integration with textile or Kapton antennas for wearable and IoT form factors. These technologies enable RF detection, control logic, and PMU supervision to coexist on a single chip consuming only microwatts [114, 130]. Recent experimental demonstrations from 2022 onward show sub-10 μW RF front-ends for EH sensor nodes, nanowatt WuRs based on envelope detection and backscatter interface circuits implemented purely with impedance switching [131–133]. These results illustrate that microwave IC design for battery-free systems is largely about removing conventional RF blocks, simplifying what remains and biasing every active device at the edge of conduction. Through subthreshold design, passive RF processing and impedance-based transmission, microwave circuit consumption is reduced from milliwatts to microwatts or less, making true energy-autonomous wireless operation achievable with harvested RF and microwave energy alone.

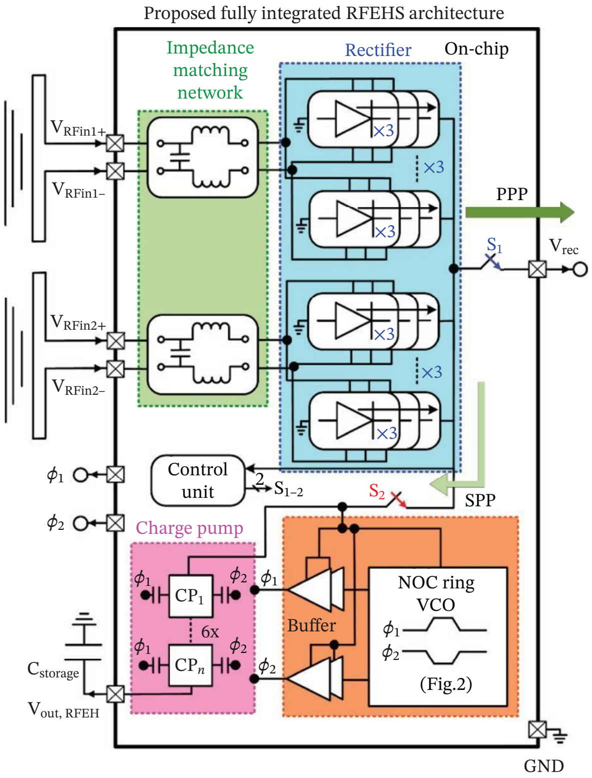


FIGURE 10 | Fully integrated RF energy harvesting front-end showing impedance matching network, multistage rectifier, charge pump, control unit and storage interface implemented on-chip for energy-constrained platforms [128].

7 | Recent Developments and State-of-the-art Systems

The past few years have seen battery-free RF and microwave systems move from theoretical feasibility and laboratory prototypes to practical, application-driven platforms deployed in real environments. Advances in rectenna sensitivity, ultralow-power MICs, adaptive power management, and backscatter-based communication have collectively enabled battery-free nodes to perform meaningful sensing, data acquisition, and wireless reporting tasks under ambient RF energy conditions. As a result, recent research no longer focuses only on individual components such as antennas or rectifiers, but on complete system demonstrations that integrate harvesting, storage, control, sensing, and communication into compact, energy-autonomous platforms. These state-of-the-art systems illustrate how the concepts discussed in earlier sections: energy autonomy, ambient RF characterization, rectenna optimization, ultralow-power circuit design, and energy-aware communication come together in practical deployments. They also reveal important trade-offs between harvested power, sensing capability,

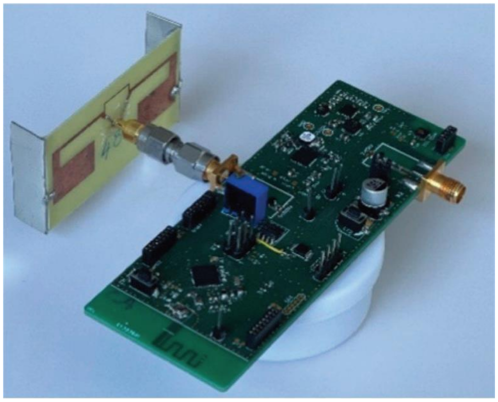


FIGURE 11 | Prototype of a multifunctional battery-free Bluetooth Low Energy (BLE) wireless sensor node powered solely by multiband RF energy harvesting [134].

communication range, duty cycling, and reliability across different application domains. Recent implementations can be broadly observed in three major areas. First, battery-free IoT and wireless sensor networks demonstrate how distributed sensing nodes operate in indoor, urban, and industrial environments using only harvested RF energy. Second, wearable and implantable RF systems show how flexible rectennas, textile antennas, and ultralow-power circuits enable body-centric sensing without batteries. Third, smart environment and industrial monitoring applications leverage ambient RF harvesting for infrastructure sensing, asset tracking, and condition monitoring in locations where battery maintenance is impractical. The following subsections review representative systems that exemplify these advances, highlighting how full battery-free RF/microwave platforms are engineered, validated, and deployed in realistic scenarios.

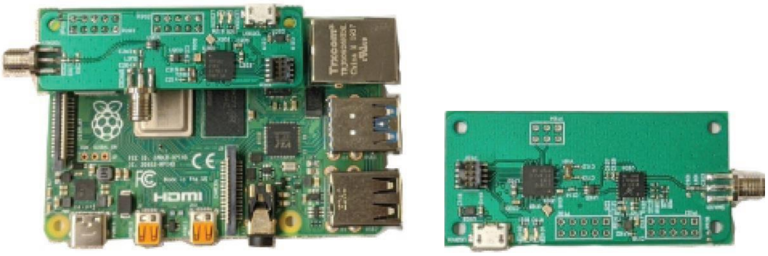
7.1 | Battery-Free IoT and Wireless Sensor Networks

In recent years, battery-free IoT and wireless sensor network platforms have transitioned from proof-of-concept experiments to field-validated systems capable of sustained operation under ambient RF and microwave energy. These systems typically integrate highly optimized rectennas, ultralow-power microcontrollers or application-specific chips, energy-aware communication protocols and lightweight sensors, all operating without conventional chemical batteries. By combining opportunistic EH with energy-adaptive control, such systems can execute sensing, data logging and periodic wireless reporting in indoor, urban and industrial environments. A number of representative works have demonstrated practical battery-free IoT nodes that harvest ambient signals such as cellular, Wi-Fi and TV broadcasts to sustain sensing and communication. A practical demonstration of how the harvesting, rectification, power management, and communication concepts discussed in Sections 3–6 can be integrated into a real system is shown in a battery-free wireless sensing node developed for structural monitoring of reinforced concrete and shown in Figure 11. Rather than relying on a single harvesting path, the node employs rectifiers operating at two ISM bands (868 MHz and 2.45 GHz), allowing it to opportunistically harvest whichever ambient band provides higher power density at a given time. The harvested energy is buffered in a capacitor through an efficient PMU and used to power low-power sensing circuitry and a Bluetooth Low Energy (BLE) transmitter operating in broadcast mode. Experimental evaluation demonstrated that the system can repeatedly perform sensing and wireless transmission cycles using only harvested RF energy, with recharge times on the order of tens of seconds under realistic far-field conditions. This work is significant because it validates that multiband rectification, efficient power management, energy buffering, and low-power communication can be combined into a fully autonomous battery-free sensing platform suitable for embedded infrastructure monitoring. It provides concrete evidence that the architectural principles presented earlier in this review are practical for real-world deployments [134]. One of the long-standing limitations of battery-free backscatter systems is their short communication range and difficulty scaling beyond single-reader deployments. Recent work has demonstrated that this limitation is not fundamental to backscatter itself, but rather to how the surrounding network infrastructure is designed. A notable implementation in Figure 12 showed that by deploying multiple coordinated transmitters and receivers across a building, battery-free sensor nodes can reliably communicate over large indoor areas without increasing tag complexity or energy consumption. In this system, low-cost TX units illuminate the environment, whereas multiple RX units collaboratively decode backscattered signals from distributed battery-free nodes. Experimental evaluation across a two-floor building (23,400 ft^2) demonstrated reliable communication and showed that network throughput increases linearly with the number of receivers and coverage area [135]. This work is important because it demonstrates that the range and scalability challenges of battery-free backscatter systems can be addressed at the network architecture level, rather than by increasing tag power or complexity.

These implementations highlight that energy buffering is critical, of which most nodes include small supercapacitors to accumulate energy between measurement and transmission events. Also, duty-cycled operation enables sensing and communication only once enough energy is harvested, balancing node activity with ambient energy availability. Backscatter communication remains the dominant low-power method for wireless reporting, as it avoids active RF transmission and leverages existing ambient carriers for signal propagation. Collectively, these systems show that battery-free IoT networks are feasible not only in laboratory settings but also in real environments with realistic RF energy landscapes. They underscore the importance of codesign across EH, power management, energy-aware communication, and system scheduling themes that recur across the broader field of energy-autonomous wireless platforms.

7.2 | Wearable and Implantable RF EH Systems

Wearable and implantable electronics represent one of the most compelling application domains for battery-free RF and microwave systems because frequent battery replacement is impractical, uncomfortable, or medically unsafe. In these contexts, RF EH offers a pathway toward long-term, maintenance-free sensing platforms that can operate from ambient electromagnetic



(a) RX Unit (b) TX unit

(c) Sensor node (d) Camera (e) Microphone

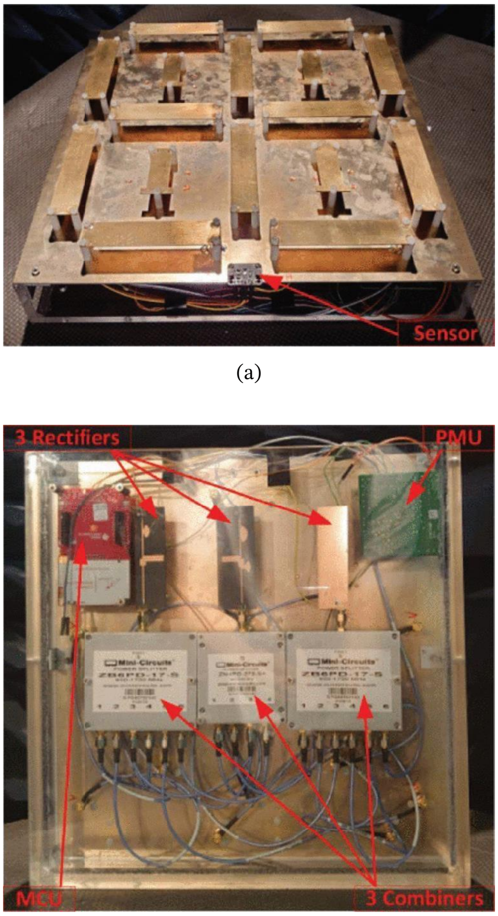
FIGURE 12 | Prototype of a scalable battery-free backscatter network using coordinated TX and RX base units to extend communication coverage [135]. (a) RX unit, (b) TX unit, (c) sensor node, (d) camera, and (e) microphone.

energy present in everyday environments. Unlike fixed IoT nodes, wearable and implantable devices must also satisfy constraints related to flexibility, biocompatibility, mechanical deformation, and detuning effects caused by proximity to the human body. As a result, rectenna and circuit designs for these applications differ significantly from rigid, free-space RF harvesting systems. Recent research demonstrates that flexible and textile-based rectennas can successfully harvest ambient RF energy while conforming to body movement. Fabric-integrated rectennas have been experimentally validated on clothing and wearable substrates, showing stable RF-to-DC conversion even when bent or folded during human motion. For example, flexible all-fabric rectennas operating in the 2.4 GHz ISM band have been demonstrated using conductive textiles and embroidered radiators, confirming that wearable materials can serve as effective RF harvesting antennas without rigid metallic structures. These works show that wearable RF harvesters can maintain sufficient gain, impedance stability and conversion efficiency while integrated into garments [136]. A complementary line of work uses printed textile rectennas fabricated with conductive inks on flexible substrates. A recent study in [137] demonstrated a 2.45 GHz textile-printed rectenna using scalable screen-printing techniques, achieving reliable harvesting performance under repeated bending and mechanical stress. This work is important because it shows that wearable RF harvesting can be manufactured using low-cost printing methods compatible with mass production of smart clothing and body-worn sensors.

Multiband wearable rectennas have also been explored to improve energy availability in dynamic environments. A 2025 study in [138] presented a dual-band magnetoelectric dipole rectenna designed on a flexible substrate, capable of harvesting energy from two ambient bands while maintaining stable operation when placed on the human body. Such designs are particularly attractive because body movement and multipath propagation constantly change the polarization and incident angle of RF waves, making multiband and polarization-robust antennas essential for reliable energy capture. Although wearable RF harvesting has seen several practical demonstrations, implantable RF EH remains more challenging. Human tissue introduces significant attenuation, detunes antennas, and imposes strict size and biocompatibility constraints. Most current implantable EH systems rely on near-field WPT rather than far-field ambient RF harvesting. However, reviews in [139] discuss the feasibility of integrating ultralow-power RF rectifiers, miniaturized antennas, and subthreshold electronics into implantable medical devices. These studies highlight key challenges such as tissue absorption, antenna miniaturization, impedance detuning, and safety regulations, but also indicate that as rectifier sensitivity improves and circuit power drops into the nanowatt regime, far-field RF harvesting for implantables may become feasible for very low–duty-cycle sensing applications. Across both wearable and implantable contexts, several design principles emerge that mirror those discussed earlier in this review. Flexible low-loss substrates such as Kapton, textile dielectrics, and polymer films are preferred to maintain radiation efficiency while allowing mechanical conformity. CP or polarization-diverse antennas reduce mismatch losses due to body motion and multipath. Impedance codesign with rectifiers remains critical because antenna detuning caused by the body can severely degrade RF-to-DC conversion if not properly accounted for. Finally, ultralow-power WuRs and backscatter communication are commonly adopted so that harvested energy is not consumed by active RF transmission. These developments demonstrate that battery-free RF and microwave systems are no longer limited to fixed sensor nodes but are increasingly being adapted to body-centric and biomedical platforms. Wearable rectennas fabricated on fabrics and flexible substrates, along with ongoing research into implant-compatible RF harvesters, illustrate how the principles of energy autonomy, multiband harvesting, impedance codesign, and ultralow-power circuitry can be translated into practical health monitoring and biomedical sensing applications.

7.3 | Smart Environments and Industrial Monitoring

Battery-free RF and microwave systems are increasingly being validated in real smart-environment and industrial monitoring



(a)

(b)

FIGURE 13 | Prototype of multiband dual-polarized ambient RF powered wireless sensor system: (a) 3D view; (b) backside view identifying the key modules [140].

scenarios where large numbers of sensor nodes must operate for years without maintenance. In such deployments, smart buildings, warehouses, factories, and logistics facilities: the cost and impracticality of battery replacement make RF EH combined with ultralow-power communication an attractive alternative. Unlike laboratory demonstrations, these works show that the principles discussed in earlier sections of this review (rectennas, PMUs, backscatter, sub-μW receivers, and energy-aware scheduling) can be integrated into practical sensing platforms operating under realistic RF conditions. A clear real-world validation of ambient RF-powered sensing in smart indoor environments is demonstrated by a fully integrated RF-powered IoT wireless sensor system [140]. The system shown in Figure 13 integrates multiband dual-polarized antennas, rectifiers, a PMU, a supercapacitor for energy buffering, a microcontroller, sensing unit, and RF transceiver into a single battery-free platform. The novelty of this work lies in the antenna design, which employs triple-band operation and dual polarization with hybrid combining to compensate for the extremely low ambient RF power density typically found indoors. Experimental measurements conducted in an indoor campus environment showed background RF levels as low as −28.6 dBm at 950 MHz, yet the system was able to harvest sufficient energy to measure temperature, humidity, and pressure and wirelessly transmit data to a central server every 15 min. Even under cold-start conditions with a fully discharged supercapacitor, the first data transmission occurred after approximately 6 h, after which periodic sensing and reporting were sustained purely by ambient RF energy. This work provides concrete experimental proof that ambient RF energy available in modern buildings is sufficient to power practical IoT sensing tasks when combined with multiband antenna design, efficient rectification, power management, and duty-cycled operation.

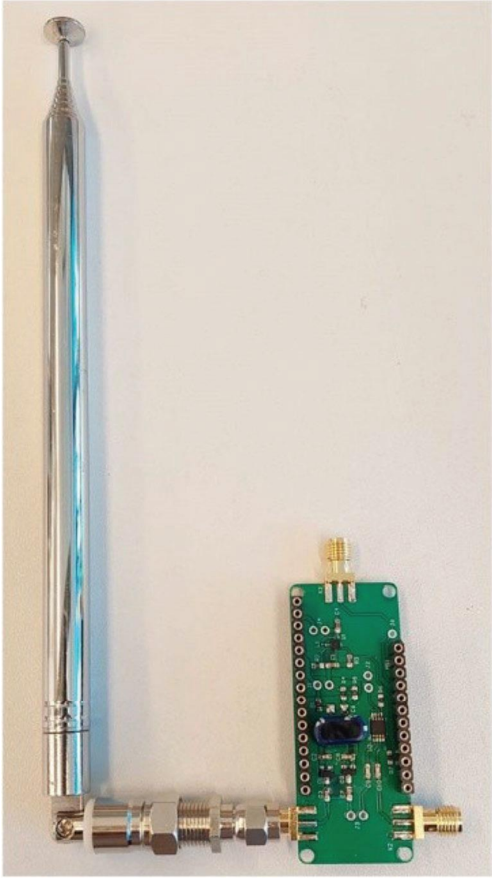


FIGURE 14 | Static RF harvesting platform with telescopic antenna used for industrial RF evaluation [141].

A strong industrial validation of RF EH for IoT monitoring is demonstrated in the static RF harvesting platform shown in Figure 14 [141], where researchers showed that ambient RF signals commonly present in factories and industrial spaces can sustain the operation of wireless sensing motes without batteries. The platform integrates multiband rectification, autonomous energy management, and adaptive WPT to ensure reliable operation under varying RF conditions. Experimental evaluation showed that ambient RF sources alone could support useful sensing data rates, whereas adaptive WPT extended operational reliability at distances up to 3 m. This work is particularly important because it demonstrates that the dense RF infrastructure in industrial environments creates a predictable and sustainable energy source for battery-free condition monitoring and asset tracking. Warehouses and logistics centers provide another practical environment where battery-free sensing is enabled by existing RFID and wireless infrastructure. Recent studies demonstrated battery-free RFID sensor tags capable of monitoring temperature and humidity across supply-chain environments [142–145]. These tags harvest energy directly from RFID reader emissions and use it to power sensing circuitry, effectively extending traditional RFID technology into battery-free environmental monitoring platforms. This work illustrates how battery-free sensing can scale by leveraging infrastructure that is already present, eliminating the need for dedicated energy transmitters.

Across these smart and industrial deployments, common system characteristics emerge. Energy buffering using small capacitors or supercapacitors allows nodes to accumulate energy between sensing and reporting events. Duty-cycled operation ensures that sensing and communication occur only when sufficient energy has been harvested. Backscatter or ultralow-power communication techniques are preferred because they avoid active RF transmission. Most importantly, these works demonstrate that battery-free RF and microwave systems are no longer limited to proof-of-concept prototypes but are capable of functioning in real buildings, factories, and logistics networks where maintenance-free sensing is essential. These validated implementations confirm that the architectural concepts discussed throughout this review are practical tools enabling sustainable battery-free IoT deployments in smart environments and industrial monitoring applications.

8 | Performance Metrics and Evaluation Criteria

Evaluating battery-free RF and microwave systems requires metrics that reflect both EH performance and end-to-end system usefulness. The metrics should connect physical-layer harvesting (how much DC the rectenna produces) to system-level outcomes (how often the node can sense/transmit, how reliable links are, and how the network scales). Commonly used evaluation criteria are as follows: (i) energy efficiency and RF-to-DC PCE, (ii) communication range and reliability (including sensitivity and BER under harvested-power constraints), and (iii) scalability and expected system lifetime under real ambient conditions. A practical evaluation couples measured PCE curves and rectified DC power versus input power (or power density) with experimental duty-cycle and recharge-time results from fully integrated nodes. Below we define the key metrics, show which published figures are best to analyze, and explain what to extract from them to quantify performance.

8.1 | Energy Efficiency and PCE

Energy efficiency in battery-free RF and microwave systems is fundamentally determined by how effectively incident electromagnetic power is converted into usable DC power at the rectifier output. This metric is commonly expressed as the RF-to-DC PCE, as defined in Equation (8). In practice, PCE in battery-free systems is strongly influenced by three tightly coupled factors: the input RF power level, the load impedance presented to the rectifier, and the nonlinear behavior of the diode at low drive amplitudes. Consequently, PCE is not a fixed property of a rectifier or rectenna but a dynamic quantity that varies with environmental RF conditions and the circuit operating point. Two recent experimental studies clearly illustrate the practical limits and design implications of PCE in ambient RF harvesting scenarios. Huang et al. [146] presented measured rectifier efficiency as a function of load resistance for different input power levels, shown in Figure 15. A key observation from this figure is that each input power level corresponds to a different load resistance that maximizes conversion efficiency. At low input powers such as −5 dBm and 0 dBm—levels much closer to realistic ambient RF conditions—the conversion efficiency increases almost linearly with load resistance up to an optimal point, after which it decreases. This behavior is extremely significant for battery-free design because it demonstrates that there is no single fixed load that guarantees optimal performance. Even small impedance mismatches at low input power can cause large efficiency degradation, and the optimal operating point shifts continuously as ambient RF power changes. This experimental evidence directly justifies the need for adaptive impedance matching, MPPT, and rectifier–antenna codesign discussed in earlier sections. Without such techniques, a rectifier optimized for one input power level will perform poorly when environmental RF conditions vary.

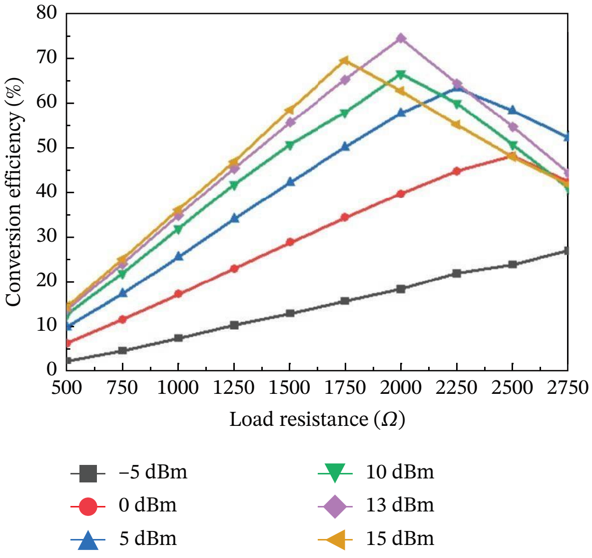


FIGURE 15 | Conversion efficiency versus load resistance [146].

A complementary perspective is provided by Jing et al. [147], where the authors measured the efficiency of a complete rectenna as a function of incident power density expressed in μW/cm^2, a unit commonly used in ambient RF measurement studies. As shown in Figure 16, at an input power of 0 dBm, the maximum conversion efficiencies reach 55% at 1.90 GHz, 60% at 2.35 GHz, 55% at 2.45 GHz, and 65% at 2.60 GHz, respectively. At very low input power levels, RF-to-DC efficiency drops sharply when the incident power density falls below approximately 1 μW/cm^2, a range typical of indoor Wi-Fi and cellular environments. Importantly, this drop is not caused by antenna inefficiency but by the diode threshold voltage and insufficient RF amplitude to properly drive the rectifier. In this region, the diode operates below its optimal conduction point, and much of the incident RF energy is lost due to threshold and reactive effects. To mitigate this limitation, the authors employed low-forward-voltage Schottky diodes, wideband impedance matching using impedance compression techniques,

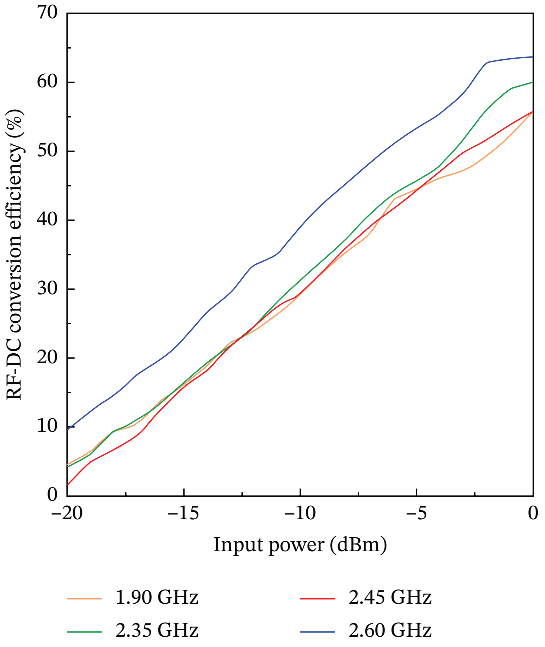


FIGURE 16 | Measured rectenna efficiency versus input power [147].

and careful rectifier optimization specifically targeted at low-power operation. The results provide experimental proof that diode physics, rather than antenna gain, is often the primary limitation in battery-free RF harvesting under weak ambient conditions. Taken together, these results reveal an important insight: Battery-free RF harvesting efficiency is dominated by nonlinear impedance behavior and low-power diode limitations rather than classical antenna efficiency metrics. They show that PCE is highly sensitive to both input power level and load impedance, that optimal performance requires continuous adaptation to environmental RF variations, and that improving antenna gain alone does not guarantee improved DC output at very low power densities. These observations explain why modern rectenna and PMU designs increasingly incorporate adaptive matching, MPPT, low-threshold diodes, and cosimulation of antenna–rectifier behavior instead of treating components as independent subsystems. For a battery-free node operating in indoor environments where ambient RF power densities fluctuate in the sub-μW/cm^2 range, these figures effectively define the minimum usable RF input required for meaningful DC harvesting. They also clarify why energy buffering, duty cycling, and energy-aware scheduling are essential system strategies. The system cannot rely on continuous high PCE but must instead accumulate energy during favorable RF conditions and operate intermittently. Therefore, energy efficiency in battery-free RF and microwave systems should be evaluated not by peak PCE at high input power levels, but by how effectively the rectenna maintains usable efficiency under weak, variable, and realistic ambient RF conditions.

8.2 | Communication Range and Reliability

Communication range and reliability in battery-free RF and microwave systems are not governed primarily by transmit power, as in conventional radios, but by how frequently the node can accumulate sufficient harvested energy to activate its communication circuitry. In these systems, the limiting factor is not the classical link budget, but energy availability over time. Consequently, two system-level metrics become more meaningful than traditional RF metrics: the delay before the first transmission (cold-start delay) and the recharge time between successive transmissions (duty cycle). These parameters directly determine how reliably a battery-free node can sense and report data under realistic RF conditions. A clear experimental demonstration of this behavior is provided by Sidibé et al. [134], where a fully integrated battery-free sensing node was evaluated under controlled RF illumination. The authors measured the time required for the node to perform its first transmission from an empty storage capacitor and how frequently it could subsequently transmit as a function of the effective isotropic radiated power (EIRP) incident on the antenna. Figure 17 shows the measured first-start duration and recharge periodicity of the sensing node versus EIRP. At low RF power levels, the node requires a long period to accumulate sufficient energy for the first transmission. As the incident RF power increases, both the cold-start delay and the recharge time decrease sharply. This figure provides direct experimental evidence that communication reliability in battery-free systems is fundamentally governed by how fast energy can be harvested, that the duty cycle of sensing and reporting is controlled by ambient RF conditions, and that battery-free nodes cannot transmit continuously but instead operate in energy-scheduled bursts. Even with efficient rectifiers and PMUs, the communication frequency of the node is dictated more by the surrounding RF environment than by radio design alone. This observation justifies the need for energy buffering, duty-cycled operation, and energy-aware scheduling as discussed in earlier sections.

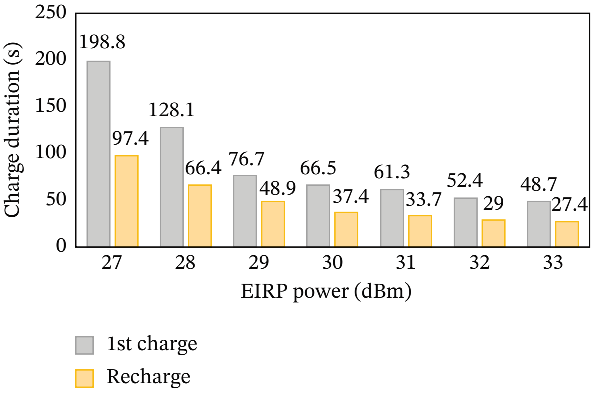


FIGURE 17 | Measured charge duration of the sensing node with a connected antenna in an anechoic chamber under different EIRP power levels [134].

Although Figure 17 explains how often a battery-free node can communicate, it does not explain how far communication can be sustained. This complementary aspect is demonstrated in the static RF harvesting platform by Thangarajan et al. [141], where the authors evaluated how achievable data rate degrades with increasing distance between a wireless power transmitter and a battery-free node. Figure 18 plots the sustainable data rate of battery-free nodes versus distance from the RF power source for BLE, LoRa, and Sigfox

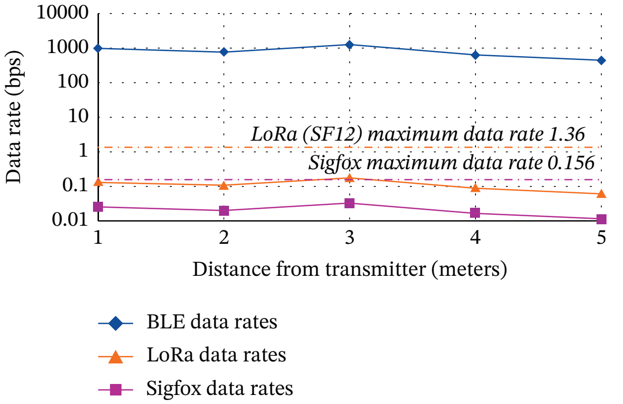


FIGURE 18 | Sustainable data rates for BLE, LoRa, and Sigfox using ambient RF energy harvesting at different distances from the RF source [141].

communication. The figure shows a rapid drop in sustainable data rate as distance increases, approximately following an inverse relationship with harvested power. At short range (≈1 m), the node can support multiple messages per hour, whereas at larger distances the data rate drops to only a few messages per hour or less.

This result reveals that communication range in battery-free systems is tightly coupled to available RF energy, that data rate degrades predictably with distance because harvested power decreases, and that extending range requires infrastructure solutions such as multiple transmitters and receivers rather than increasing tag power or complexity. Scalability of battery-free networks therefore depends more on deployment architecture than on node design. Together, Figures 17 and 18 provide a complete system-level view of communication reliability in battery-free RF systems. Figure 17 shows that the time between transmissions is energy-limited, whereas Figure 18 shows that the distance from RF sources directly limits achievable data rates. These results demonstrate that classical communication metrics such as link budget, SNR, or transmit power are insufficient for evaluating battery-free systems. Instead, energy-time metrics (recharge duration and duty cycle) and energy-space metrics (distance-dependent data rate) define practical performance. These experimental studies confirm that reliable communication in battery-free IoT deployments is achieved not by stronger radios, but by efficient EH and buffering, duty-cycled sensing and reporting, strategic placement of RF sources or readers, and network-level coordination to compensate for limited per-node energy. Communication range and reliability in battery-free RF and microwave systems must therefore be evaluated in terms of how environmental RF energy determines when and how far a node can communicate, rather than how strongly it can transmit.

8.3 | Scalability and System Lifetime

Scalability and system lifetime are defining performance metrics for battery-free RF and microwave systems, particularly in large-scale IoT and sensing deployments where thousands of nodes may be required to operate maintenance-free for years. Unlike battery-powered networks, where lifetime is primarily limited by stored energy capacity, battery-free systems derive their longevity from the balance between harvested energy, energy consumption per operation, and network coordination efficiency. As a result, scalability and lifetime must be evaluated at the network level, not merely at the individual node level. A key challenge in scaling battery-free systems is that individual nodes operate with extremely limited instantaneous power, often relying on intermittent EH and duty-cycled operation. If scalability were approached by increasing per-node transmission power or complexity, the battery-free paradigm would immediately break down. Instead, recent research demonstrates that scalability is achieved by architectural and protocol-level strategies, such as deploying multiple receivers, coordinating carrier sources, and enabling spatial reuse of spectrum without increasing tag energy consumption. A clear experimental validation of scalable battery-free networking is provided by the MultiScatter backscatter network reported by Katanbaf et al. [135]. In this work, the authors evaluate how network throughput scales as the number of receiver (RX) units and battery-free sensor nodes increases. Rather than relying on a single reader, the system distributes multiple low-cost RX units across the environment, each serving a subset of battery-free nodes. The nodes themselves remain unchanged and battery-free, communicating via backscatter modulation.

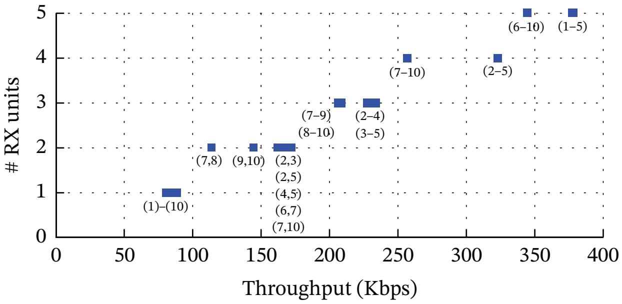


FIGURE 19 | Aggregated throughput with multiple RX units [135].

Figure 19 shows the measured aggregate network throughput as the number of RX units increases from one to five. Each RX unit is assigned two sensor nodes, and the total throughput is computed by summing the individual throughputs of all active RX units. The results show a near-linear increase in aggregate throughput as additional RX units are deployed. With five RX units and ten battery-free sensor nodes, the network achieves an aggregate throughput of approximately 375 kbps, which is more than four times higher than the throughput achievable with a single sensor–receiver pair. This figure provides several important insights into scalability. First, it demonstrates that battery-free backscatter nodes can operate simultaneously without mutual exclusion, provided that the infrastructure is designed to support parallel reception. Second, it shows that throughput limitations in battery-free systems are not inherent to the nodes themselves but are instead dictated by how readers and carriers are deployed. Third, it confirms that spectrum reuse across spatially separated RX units enables scalable growth in network capacity without increasing per-node energy consumption. The same study also highlights practical limits to scalability. When battery-free nodes are placed very close to each other and communicate with different RX units, interference between wake-up radios and overlapping carrier signals can reduce throughput. This effect is visible in measurements where closely spaced nodes exhibit lower aggregate throughput than nodes placed farther apart. Importantly, this limitation arises from receiver interference and carrier collision rather than from energy depletion at the nodes, indicating that scalability challenges are primarily network-architectural, not energy-architectural.

From a system lifetime perspective, the implications are significant. Because battery-free nodes do not consume stored chemical energy, their operational lifetime is theoretically unbounded, limited only by component aging rather than energy exhaustion. As long as sufficient ambient RF energy exists and the node's duty cycle is adapted to harvesting conditions, the node can continue operating indefinitely. The MultiScatter results demonstrate that lifetime does not degrade as network size increases, if communication responsibilities are offloaded to infrastructure rather than to the nodes themselves. In contrast to battery-powered IoT systems, where adding more nodes increases maintenance burden and reduces overall system lifetime, battery-free systems exhibit a fundamentally different scaling behavior. Network lifetime is decoupled from node count, and scalability is achieved by increasing reader density or coordination rather than energy storage. This paradigm shift is critical for applications such as smart buildings, industrial monitoring, and logistics environments, where sensor density is high and long-term maintenance is impractical. Overall, the experimental results in Figure 18 demonstrate that battery-free RF and microwave systems can scale to large deployments while maintaining indefinite system lifetime. Scalability is enabled not by increasing node capability, but by careful network design, spatial reuse and multireceiver coordination. These findings confirm that battery-free IoT systems are viable not only as isolated nodes, but as long-lived, large-scale sensing networks suitable for real-world deployment.

9 | Challenges and Open Research Issues

Despite the rapid progress in battery-free RF and microwave technologies, several fundamental technical and system-level challenges continue to limit their widespread deployment. Unlike conventional wireless systems, battery-free platforms must simultaneously solve problems related to extremely low and intermittent power availability, tight hardware integration constraints, and secure operation under highly resource-limited conditions. Addressing these challenges requires coordinated advances across device physics, circuit design, antenna engineering, communication protocols, and system-level energy management. This section discusses the most critical open issues that must be resolved to enable reliable, large-scale adoption of battery-free RF and microwave systems.

9.1 | Energy Intermittency and Reliability

The most significant challenge in battery-free RF systems is the temporal and spatial variability of harvested RF energy. Ambient RF power densities in indoor and urban environments typically range from tens of nW/cm^2 to a few μW/cm^2 and fluctuate continuously depending on user activity, wireless traffic patterns, environmental obstructions, and node location. As a result, harvested energy cannot be assumed to be continuously available, causing battery-free nodes to operate intermittently with unpredictable sensing and communication intervals. Energy intermittency affects multiple system functions simultaneously. First, it increases cold-start delays, especially when storage capacitors are fully discharged. Second, it introduces variable duty cycles, making reliable periodic sensing difficult without adaptive scheduling. Third, it can cause brownout conditions where nodes lose computational state or communication synchronization when stored energy temporarily drops below operational thresholds. These reliability issues become particularly critical in monitoring applications such as structural health sensing, industrial automation, and medical telemetry where missed measurements may compromise system performance [148–150]. Several research directions are emerging to mitigate these limitations. Multisource EH that combines RF with solar, vibration, or thermal energy can reduce dependence on a single energy source. Energy prediction algorithms based on historical harvesting statistics are being explored to enable predictive scheduling of sensing and communication tasks. Cooperative energy sharing and infrastructure-assisted WPT are also being investigated to stabilize the energy supply in dense battery-free networks [151–153]. However, achieving predictable long-term reliability without significantly increasing system complexity remains an open challenge requiring further interdisciplinary research.

9.2 | Hardware Constraints and Miniaturization

Battery-free nodes must integrate antennas, rectifiers, matching networks, PMUs, sensors, and communication circuitry into extremely compact form factors while maintaining ultrahigh energy efficiency. This requirement introduces a fundamental size–efficiency trade-off, since smaller antennas typically exhibit lower gain and reduced harvesting capability. Similarly, rectifiers optimized for ultralow input power require precise impedance matching that becomes difficult to maintain across wide frequency ranges, temperature variations and fabrication tolerances. Another critical challenge is the tight coupling between system components. In battery-free rectenna systems, the antenna impedance, rectifier nonlinear behavior and PMU load characteristics interact dynamically, meaning that independent optimization of each block often results in suboptimal overall performance. Achieving optimal operation therefore requires codesign methodologies that simultaneously consider electromagnetic behavior, circuit nonlinearities, and energy management constraints. Although cosimulation techniques and integrated system-in-package technologies are advancing rapidly, they introduce fabrication complexity and increase design cost. Emerging technologies such as flexible substrates, printable electronics, metasurface-enhanced antennas, and heterogeneous CMOS-RF integration offer promising solutions for miniaturized battery-free platforms. However, maintaining low leakage currents, stable impedance behavior and high conversion efficiency at extremely small device scales remains a major engineering challenge that continues to drive research in ultralow-power semiconductor technologies and advanced packaging methods [154–156].

9.3 | Security and Privacy in Battery-Free Systems

Security and privacy represent a relatively new but rapidly growing research challenge in battery-free wireless networks. Traditional wireless devices rely on continuous power availability to support encryption, authentication, and secure key-management algorithms. In contrast, battery-free nodes often operate with intermittent power and extremely limited computational resources, making the implementation of conventional cryptographic protocols difficult or impractical. Backscatter-based communication introduces additional vulnerabilities because transmitted signals are extremely weak and may be intercepted by nearby receivers without the need for sophisticated equipment. Furthermore, malicious transmitters could intentionally alter RF illumination levels to disrupt node operation, create denial-of-service conditions, or manipulate sensing schedules. Multireader backscatter networks also introduce new attack surfaces where adversaries could impersonate legitimate readers or inject unauthorized commands. Addressing these concerns requires the development of ultralightweight cryptographic algorithms, energy-aware authentication schemes, and physical-layer security techniques that exploit channel randomness and spatial diversity. Research is also exploring cooperative security approaches where infrastructure nodes assist battery-free tags in performing authentication and key distribution while minimizing tag-side energy consumption [157–160]. Ensuring secure and privacy-preserving operation without sacrificing the ultralow-power advantages of battery-free systems remains one of the most important open research directions for future large-scale deployments.

10 | Future Opportunities and Research Directions

Battery-free RF and microwave systems are transitioning from early laboratory demonstrations toward scalable infrastructure-level deployments. Continued advances in wireless communications, AI, semiconductor technologies, and advanced materials are expected to significantly expand the capabilities of energy-autonomous devices. Future research is therefore increasingly focused not only on improving harvesting efficiency but also on integrating battery-free technologies into next-generation communication ecosystems and intelligent network architectures. The following subsections highlight the most promising directions expected to shape the evolution of battery-free wireless platforms over the coming decade.

10.1 | Integration With 5G, 6G, and Massive IoT

The rapid expansion of 5G networks and the anticipated deployment of 6G systems create an unprecedented opportunity for battery-free RF devices. Modern cellular infrastructures employ dense base-station deployments, millimeter-wave beamforming, and continuous downlink signaling, all of which increase the ambient electromagnetic energy available in urban environments. These signals can serve not only as communication carriers but also as dedicated or opportunistic energy sources for battery-free nodes. Future research is expected to focus on SWIPT architectures tailored to battery-free IoT devices, enabling network nodes to deliver both connectivity and usable energy through coordinated scheduling and beam steering. Massive machine-type communications (mMTC), a key component of 5G/6G visions, also aligns naturally with battery-free sensing because it requires the deployment of billions of low-cost, maintenance-free devices. Infrastructure-assisted wireless power beacons, cooperative reader networks, and energy-aware network slicing are emerging approaches aimed at supporting large-scale battery-free device ecosystems [161–163]. The convergence of battery-free technology with cellular infrastructure is therefore expected to transform IoT networks from battery-dependent deployments into long-lifetime, maintenance-free sensing fabrics.

10.2 | AI-Assisted Energy Management

AI and ML are increasingly being explored as tools for improving energy-autonomous wireless systems. Because harvested RF energy is highly dynamic and environment-dependent, predictive intelligence can significantly improve system performance by forecasting energy availability and adapting node behavior accordingly. AI-assisted energy management can enable nodes to schedule sensing, communication, and computation tasks based on predicted harvesting opportunities, thereby maximizing long-term data throughput while maintaining energy neutrality. At the network level, distributed learning techniques can optimize reader placement, RF illumination scheduling, and cooperative backscatter coordination to improve both coverage and system reliability. Lightweight embedded learning algorithms, designed specifically for ultralow-power microcontrollers, are being investigated to enable on-node adaptation without large computational overhead. In addition, reinforcement-learning approaches are being applied to adaptive impedance matching, power-management tuning, and dynamic modulation selection, allowing battery-free devices to autonomously adjust to changing spectral conditions [164–166]. These developments suggest that intelligent energy-adaptive systems will play a central role in enabling scalable and resilient battery-free IoT networks.

10.3 | Emerging Materials and Technologies

Advances in materials science and device fabrication are opening new pathways for enhancing the performance and applicability of battery-free RF systems. Flexible and stretchable conductive materials, printable antennas, and textile-integrated rectennas are enabling conformal EH devices suitable for wearable electronics, biomedical sensing, and smart-surface deployments. Metasurfaces and reconfigurable intelligent surfaces (RIS) are also being investigated to manipulate electromagnetic propagation in indoor environments, potentially increasing available RF energy density and improving harvesting reliability. On the semiconductor side, ultralow-leakage CMOS technologies, SOI processes, and emerging nano-electronic devices are reducing standby power consumption to nanowatt levels, enabling longer energy retention and improved cold-start behavior. Novel diode technologies such as tunnel diodes, backward diodes, and advanced Schottky structures with ultralow turn-on voltages are being developed to improve rectification efficiency under extremely weak RF signals [167–171]. In parallel, heterogeneous integration technologies that combine antennas, rectifiers, sensors, and digital control circuits into compact system-in-package platforms are expected to significantly reduce node size while improving system-level efficiency.

11 | Conclusions

Battery-free energy-efficient RF and microwave systems represent a transformative approach to wireless sensing and communication, eliminating the dependence on conventional batteries through the direct harvesting of ambient or dedicated electromagnetic energy. This review has presented a comprehensive examination of the theoretical foundations, system architectures, enabling circuit techniques, and practical deployments that collectively define modern battery-free wireless platforms. The discussion began with the fundamental principles of RF and microwave EH, highlighting how antenna design, rectifier nonlinearity, impedance matching, and propagation characteristics jointly determine the amount of usable harvested energy. Advances in multiband rectennas, adaptive impedance matching, ultralow-power power-management units, and hybrid energy-buffering strategies have significantly improved the feasibility of sustained operation under weak and time-varying RF environments. Equally important are communication technologies tailored for energy-constrained devices, including backscatter communication, ultralow-power modulation schemes, and energy-aware networking protocols that enable reliable data exchange while maintaining extremely low energy consumption. Recent experimental demonstrations reviewed in this work confirm that battery-free nodes are no longer limited to laboratory prototypes but are now being deployed in real applications such as IoT sensing networks, wearable and implantable devices, smart buildings, and industrial monitoring systems. Performance evaluations show that system efficiency is strongly governed by nonlinear rectifier behavior, environmental RF availability, and adaptive power-management strategies, emphasizing the importance of holistic codesign across antennas, circuits, communication protocols, and network infrastructure. Despite these advances, several open challenges remain, including the intermittency of ambient energy sources, hardware miniaturization constraints, scalable network coordination, and security concerns in battery-free communication environments. Addressing these challenges will require interdisciplinary innovations spanning wireless communications, circuit design, materials science, and intelligent energy-management algorithms. Looking forward, the integration of battery-free technologies with emerging 5G/6G infrastructure, artificial-intelligence-assisted resource management, and advanced materials such as flexible electronics and metasurfaces is expected to accelerate the transition toward large-scale, maintenance-free sensing ecosystems. Battery-free RF and microwave systems provide a compelling pathway toward sustainable and long-lifetime wireless networks. Continued progress in EH efficiency, ultralow-power circuit techniques, adaptive communication protocols, and infrastructure-assisted wireless power delivery will further enable the realization of truly autonomous IoT platforms capable of operating for years or decades without battery replacement.

Author Contributions

Stella N. Arinze: conceptualization, methodology, data curation, formal analysis, investigation, validation, visualization, writing—original draft. Augustine O. Nwajana: funding acquisition, resources, project administration, software, supervision, writing—review and editing.

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Disclosure

Both authors have read and agreed to the contents of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Not applicable as no datasets were generated or analyzed during this study.

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