Harvesting Antennas for Self-Powered Biosensors in Biomedical Applications: A Systematic Review

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Abstract: Energy harvesting antennas have emerged as a promising solution for enabling self-powered biosensors in biomedical applications, addressing the critical limitations of battery-dependent systems such as limited lifetime, bulky form factors, and maintenance requirements. This systematic review presents a comprehensive analysis of recent advancements in energy harvesting antenna technologies tailored for biomedical biosensors. It examines various harvesting mechanisms, including radio-frequency (RF), microwave, and hybrid energy sources, with emphasis on antenna design, miniaturization, impedance matching, and biocompatible materials. Performance metrics such as harvested power density, conversion efficiency, operating frequency bands, and safety constraints (SAR limits) are critically reviewed. The integration of antennas with rectifiers, power management circuits, and biosensing modules is also discussed. Furthermore, challenges related to human body effects, tissue losses, and variability in ambient energy availability are highlighted. Finally, the review identifies key research gaps and future directions toward fully autonomous, reliable, and implantable or wearable biomedical biosensing systems. This work aims to serve as a reference for researchers and designers developing next-generation self-powered biosensors for healthcare monitoring and medical diagnostics.

Keywords: Energy harvesting antennas; Self-powered biosensors; Biomedical applications; RF energy harvesting; Wearable and implantable sensors

Introduction

The proliferation of wearable and implantable biomedical devices has transformed modern healthcare by enabling continuous, real-time physiological monitoring and personalized medical intervention. Biosensors capable of measuring parameters such as glucose levels, electrocardiogram (ECG) signals, body temperature, and neural activity play a crucial role in early diagnosis and long-term disease management. However, the widespread adoption of these systems is fundamentally constrained by their dependence on conventional electrochemical batteries.

Batteries introduce several limitations, including finite lifespan, increased device volume, periodic replacement, and environmental concerns. In implantable medical devices (IMDs), battery replacement often requires invasive surgical procedures, posing risks to patients and increasing healthcare costs. In wearable systems, frequent charging reduces user compliance and device reliability. These challenges have motivated extensive research into self-powered biomedical devices, particularly those powered through RF energy harvesting [2], [6].

Among various energy harvesting approaches—such as thermal, mechanical, and biochemical—radio frequency (RF) energy harvesting has emerged as a promising solution due to its compatibility with low-power electronics and wireless communication systems [2], [6]. RF energy harvesting antennas enable wireless power delivery using ambient or dedicated RF sources, making them well suited for both wearable and implantable biomedical applications [7].

Classification of Energy Harvesting Antennas

Energy harvesting antennas for biomedical applications can be broadly classified based on the energy transfer mechanism, operational range, and integration strategy**.** Each category presents distinct advantages and limitations in terms of efficiency, safety, and applicability to wearable or implantable biosensors.

RF Energy Harvesting Antennas (Far-Field)

Far-field RF energy harvesting systems exploit propagating electromagnetic waves radiated from ambient or dedicated RF sources. These systems typically consist of an antenna, impedance matching network, rectifier, and power management unit, collectively referred to as a rectenna system [2], [6]. The far-field regime enables wireless energy transfer over relatively long distances, making it suitable for both wearable and implantable biosensors.

Most far-field biomedical rectennas operate within industrial, scientific, and medical (ISM) bands, MedRadio, or cellular frequency ranges, due to regulatory availability and infrastructure support [2], [7]. The widespread presence of Wi-Fi routers, cellular base stations, and medical telemetry systems makes RF energy harvesting a practical option for continuous low-power operation [6].

Recent studies highlight that multiband and broadband antenna architectures significantly improve harvesting capability by capturing energy from multiple RF sources simultaneously [1], [2]. In particular, dual-band implantable antennas designed for medically allocated frequency bands have demonstrated improved harvested power while maintaining acceptable specific absorption rate (SAR) levels [1]. However, far-field RF harvesting is inherently limited by low power density, which is further reduced by path loss, polarization mismatch, and absorption in biological tissues [7]. These factors necessitate careful antenna optimization and system-level co-design.

Near-Field and Inductive Coupling Antennas

Near-field energy harvesting relies on magnetic or electric field coupling between closely spaced transmitter and receiver structures. Inductive coupling is widely used in implantable biomedical devices due to its high power transfer efficiency at short distances and reduced sensitivity to tissue absorption compared to far-field RF methods [7].

In recent years, magnetoelectric antennas have emerged as a promising solution for extreme miniaturization. These antennas exploit the coupling between magnetic and electric domains, enabling operation at dimensions far below the conventional electromagnetic wavelength [7]. Such characteristics make them highly suitable for microscale biomedical implants, including neural interfaces and intracortical sensors.

Despite their efficiency advantages, near-field systems suffer from limited operational range, sensitivity to alignment, and reliance on dedicated external transmitters [7]. Consequently, their application is generally restricted to scenarios where close proximity between the power source and implant can be guaranteed.

Hybrid Energy Harvesting Systems

Hybrid energy harvesting systems integrate RF energy harvesting with additional sources such as thermal gradients, vibration, or body motion. These architectures aim to overcome the intermittency and low power density associated with standalone RF harvesting systems [2], [5].

Systematic reviews and meta-analyses indicate that hybrid harvesting approaches provide greater operational continuity and robustness, particularly in dynamic biomedical environments where RF exposure varies with time and location [5]. By combining multiple energy modalities, hybrid systems enhance reliability and reduce dependence on any single energy source, making them attractive for long-term biomedical sensing applications [2].

Design Considerations for Biomedical Energy Harvesting Antennas

Designing energy harvesting antennas for biomedical applications requires careful consideration of electromagnetic performance, physical constraints, and biological safety.

Antenna Miniaturization and Efficiency Trade-Offs

Miniaturization is essential for ensuring user comfort and implant feasibility. However, reducing antenna dimensions often leads to degraded radiation efficiency, reduced bandwidth, and impedance mismatch [1], [7]. Implantable antennas face additional challenges due to the high dielectric constant and conductivity of biological tissues, which cause detuning and increased ohmic losses [7].

To address these issues, advanced miniaturization techniques such as meandered geometries, high-permittivity substrates, and compact dual-band structures have been widely employed [1]. Dual-band designs are particularly effective in implantable systems, as they allow simultaneous energy harvesting and communication without significantly increasing antenna size [1].

Impedance Matching and Rectifier Integration

Efficient RF-to-DC conversion is critical for energy harvesting systems operating under ultra-low input power levels. Accurate impedance matching between the antenna and rectifier is essential, yet challenging due to the nonlinear behavior of rectifying elements [3], [8].

Recent studies emphasize the co-design of antenna and rectifier systems, leading to fully integrated rectenna architectures with enhanced conversion efficiency [3]. Furthermore, miniaturized rectenna integrated circuits (ICs) have demonstrated improved sensitivity, reduced losses, and compact form factors suitable for implantable biomedical applications [8].

SAR, Biocompatibility, and Safety Constraints

Biological safety is a primary concern in RF-powered biomedical systems. Antenna designs must comply with international SAR limits to prevent tissue heating and damage [1], [7]. Implantable antennas require careful electromagnetic modeling to ensure compliance under worst-case operating conditions.

Encapsulation using biocompatible materials such as PDMS and Parylene-C is commonly adopted to ensure long-term stability and prevent adverse tissue reactions [7]. In wearable devices, flexible and stretchable substrates improve comfort, mechanical reliability, and user compliance [3], [4].

Frequency Bands and Regulatory Considerations

Biomedical RF energy harvesting systems operate within strictly regulated frequency bands, including ISM (2.4 GHz), MICS (402–405 MHz), and MedRadio (401–406 MHz) [1], [2], [7]. Lower frequency bands offer improved tissue penetration but require larger antenna dimensions, while higher frequencies enable compact designs at the cost of increased absorption losses.

Regulatory constraints significantly influence antenna geometry, transmitted power levels, and system architecture, particularly for implantable medical devices [7].

Applications in Biomedical Sensing

Wearable Biosensors

Wearable biosensors for ECG, temperature monitoring, and physiological tracking benefit significantly from RF energy harvesting by reducing or eliminating the need for batteries. Ultra-thin and flexible rectennas integrated with power management units enable lightweight, conformal wearable systems suitable for long-term use [3].

Graphene-based rectennas exhibit excellent mechanical flexibility, electrical conductivity, and durability, making them promising candidates for next-generation wearable biomedical devices [4].

Implantable Medical Devices (IMDs)

In implantable applications, RF energy harvesting enables long-term operation of devices such as glucose monitors, pacemakers, and neural implants without battery replacement. Dual-band implantable antennas facilitate simultaneous wireless power transfer and data telemetry, reducing system complexity and improving reliability [1], [7].

Neural Interfaces and Microscale Sensors

Emerging neural interfaces demand ultra-miniaturized, wirelessly powered sensors capable of operating in constrained biological environments. Integrated rectenna ICs and advanced implantable antenna designs demonstrate strong potential for powering such microscale biomedical systems while maintaining safety and efficiency [7], [8].

Comparative Analysis and Future Directions

Comparative studies indicate that near-field techniques offer higher power transfer efficiency, while far-field RF harvesting provides greater flexibility and scalability [5], [6]. Hybrid harvesting systems combine the advantages of both approaches and demonstrate improved reliability for biomedical applications [5].

Future research directions include:

Flexible and stretchable materials such as graphene and nanomembranes [4]. Integrated rectenna–PMU architectures for ultra-low-power operation [3], [8]

Meta surface-inspired antenna designs

AI-assisted optimization for adaptive performance in complex biological environments [5]. These advancements are expected to accelerate the realization of fully autonomous, self-powered biomedical biosensing systems.

Table 1. Comparative tabular analysis

Reference	Classification	Design Considerations	Biomedical Applications	Future Directions
[1]	Dual-band implantable rectenna	Compact microstrip, dual-band, biocompatible	Implanted biosensors (glucose, ECG)	Adaptive matching, deep-tissue use
[2]	RF rectenna	Rectifier-integrated patch,SARmanagement	Wearables & IMDs	Hybrid RF-thermal harvesting
[4]	Flexible rectenna	Polymer substrate, PMU integration	ECG, temperature monitoring	Graphene miniaturization

[5]	Graphene-based rectenna	Graphene nanomesh film, multi-band	Skin-mounted patches	RF-DC efficiency improvement
[5]	Hybrid rectifier systems	Impedance optimization, multi-source	Systematic RFEH review	AI-based adaptive networks
[6]	Low-power RF harvester	Multiband topology, low-power optimization	Wearable IoT sensors	Hybrid mechanical harvesting
[7]	Implantable antennas	Slotting, dielectric layering	Neural stimulators, telemetry	Biocompatibility packaging
[8]	Miniaturized rectenna IC	CMOS integration, on-chip RF-to-DC	Implantable rectenna	SoC integration for telemetry

Conclusions

This systematic review has presented a comprehensive analysis of energy harvesting antennas for self-powered biosensors in biomedical applications. The limitations of battery-dependent wearable and implantable devices have been identified as a major challenge, motivating the exploration of RF energy harvesting as a sustainable and maintenance-free power solution. Various energy harvesting mechanisms, including far-field RF harvesting, near-field and inductive coupling, and hybrid systems, were critically examined with respect to antenna design, efficiency, safety, and application suitability.

The review highlights that while far-field RF energy harvesting offers flexibility and scalability, its performance is constrained by low power density and human tissue losses. Near-field approaches provide higher efficiency for implantable devices but are limited by range and alignment requirements. Advances in antenna miniaturization, dual-band designs, flexible materials, and integrated rectenna–power management architectures have significantly improved the feasibility of autonomous biomedical biosensors. Emerging materials such as graphene and the integration of rectifier ICs further enhance system efficiency and reliability.

Despite notable progress, challenges related to SAR compliance, regulatory constraints, and real-world biomedical validation remain. Future research should focus on intelligent antenna optimization, metasurface-enabled harvesting, hybrid multi-source systems, and full system-level integration to enable robust, clinically viable self-powered biomedical sensing platforms.

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