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Harnessing Ambient Energy: A Review of Spiral Antenna Designs for IoT-Driven Rectenna Systems

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Abstract: The Internet of Things (IoT) represents a global network of interconnected devices capable of sensing, communicating, and acting upon their environment. Within this ecosystem, sensors serve as the fundamental components that bridge the physical and digital worlds by detecting parameters such as temperature, humidity, pressure, motion, and pollution levels, and converting them into digital signals for decision-making. Sensors and actuators embedded in physical objects form the interface through which real-world information is acquired and controlled. However, one of the major challenges in deploying large-scale IoT systems lies in providing a continuous and sustainable power supply to numerous sensors, especially flexible or wearable ones. To overcome this limitation, energy harvesting technologies have emerged as a promising solution by capturing and converting energy from ambient sources such as solar radiation, infrared (IR) light, and radio frequency (RF) signals. This enables self-powered operation in diverse applications ranging from wearable and textile-based electronics to medical implants and environmental monitoring systems. In such systems, the rectenna—a combination of a receiving antenna and a rectifying circuit—is often employed to convert ambient electromagnetic energy into direct current (DC) power. The antenna plays a crucial role as the primary energy collector, and its geometry directly affects the harvesting efficiency. Among the various geometries explored, this paper discusses how spiral antenna structures fulfill these design requirements and contribute to efficient multi-source energy harvesting systems.
Keywords: RF Energy Harvesting, Rectenna Spiral Antenna, Self-Powered Sensors, Internet of Things (IoT), Wireless Power Transfer.

I. INTRODUCTION

The Internet of Things (IoT) can broadly be described as an intelligent and interconnected ecosystem of physical objects such as sensors, actuators, machines, smartphones, wearable devices, and other smart technologies that communicate with one another through the internet [11]. These “smart” objects are capable of continuously sensing a wide range of environmental parameters — such as temperature, pressure, humidity, light intensity, motion, and acceleration — and processing this data in real time. The collected information is then transmitted to cloud-based platforms or edge computing systems for further analysis and decision-making. Through this seamless exchange of data, IoT systems enable automation, remote monitoring, and intelligent responses to dynamic environmental changes or specific events of interest. This integration of sensing, communication, and computation has made IoT one of the foundational technologies driving innovations in healthcare, smart homes, industry, and environmental monitoring. In modern times, sustaining the power requirements of autonomous, wireless, and portable electronic devices has become a major technological challenge [12]. Although significant advancements have been made in energy storage systems such as batteries and supercapacitors, their progress has not kept pace with the rapid evolution of microprocessors, memory storage, and wireless communication modules. For instance, in large-scale wireless sensor networks (WSNs), thousands of small, battery-powered sensor nodes are deployed to continuously monitor environmental or structural conditions over extended periods. Regular battery replacement or maintenance for such distributed systems is not only impractical but also economically and environmentally inefficient.

To overcome these limitations, researchers have increasingly turned to ambient energy harvesting, a concept that enables electronic devices to extract energy directly from their surrounding environment. These ambient power sources include solar radiation, infrared and visible light, thermal gradients, mechanical vibrations, and radio frequency (RF) waves, and they can provide sufficient energy to power small devices, including IoT sensors, wearable electronics, and medical implants. By integrating energy harvesting modules with IoT devices, it becomes possible to drastically reduce maintenance requirements, extend device lifetimes, and enable sustainable operation even in remote or inaccessible areas. This approach, often referred to as power scavenging, represents a significant step toward fully self-sustaining sensor networks and portable electronics.

A. RF Energy Harvesting

In today's increasingly wireless world, the environment is saturated with a vast array of ambient electromagnetic waves spanning a wide range of frequencies. These include signals from cellular networks (GSM, 3G/4G/5G), Wi-Fi routers, Bluetooth devices, digital television and radio broadcasts, satellite communications, and countless other wireless technologies. While these waves are typically used for information transfer, they also represent a ubiquitous and largely untapped source of energy that permeates urban, suburban, and even rural areas. Studies have shown that the power densities of these ambient RF signals, although low compared to conventional energy sources, are sufficient to generate usable electrical energy for low-power electronic devices such as IoT sensors, wearable electronics, and remote monitoring nodes. This concept, known as RF energy harvesting, offers a promising approach to powering distributed, battery-constrained devices in a sustainable manner, reducing maintenance costs and extending operational lifetimes.

The increasing demand for sustainable and self-powered electronics has positioned EH as a vital research area across multiple disciplines. In the biomedical field, for instance, harvested energy can be used to power implantable devices such as pacemakers, glucose monitors [13], and neural stimulators, enabling wireless charging and communication. Similarly, in smart home applications**,** EH enables battery-free temperature, humidity, and motion sensors, reducing maintenance and environmental impact. In agricultural monitoring systems**,** RF-powered soil moisture and pH sensors offer cost-effective and scalable solutions for precision farming. These applications highlight how RFEH bridges the gap between low-power electronics and sustainable operation, paving the way for the next generation of autonomous devices.

B. Working Principle of RF Energy Harvesting

The fundamental principle of RF energy harvesting involves capturing ambient electromagnetic energy present in the environment and converting it into usable electrical power to supply low-power electronic devices. In a typical RF energy harvesting system, the surrounding environment contains a myriad of radio frequency sources, including Wi-Fi routers, cellular base stations, television and radio broadcasts, and Bluetooth devices. Although the power density of these sources is relatively low compared to conventional energy sources, it is sufficient to provide energy for sensors, wearables, and other IoT devices operating in low-power modes.

The rectenna, a combination of a receiving antenna and a rectifying circuit, is the core element of this energy conversion process. The antenna captures incident RF waves over a range of frequencies and delivers the induced alternating current (AC) to the rectifier. To ensure maximum power transfer from the antenna to the rectifying circuit, an impedance-matching network is often employed between them.

The components of an RF Energy harvesting circuit are given below:

1) Antenna: The antenna is designed to intercept electromagnetic waves from the environment — for example from Wi-Fi routers, cellular base stations, broadcast transmitters, Bluetooth devices, etc. These ambient RF sources result in a non-zero power density that the antenna can capture. The antenna induces an alternating current (AC) voltage in response to the incoming RF fields.
2) Impedance Matching Network: To extract maximum power, the antenna output must be matched to the input impedance of the rectifier circuit. A mismatch causes reflection and loss of harvested energy. Many designs employ an L-network, T-network or other impedance-matching topology to ensure the antenna and rectifier are well-matched across the frequency band of interest.
3) Rectifier: The rectifier converts the induced AC voltage into DC voltage (or current). This is typically done using diodes (e.g., Schottky diodes), voltage multipliers, or voltage doubler circuits. This process also incorporates filtering (to reject harmonics) and smoothing (to stabilize the DC output).
4) Energy Storage: The DC output from the rectifier can be used directly to power a load (e.g., an IoT sensor node) or could be stored (in a capacitor, battery, or supercapacitor) for continuous or intermittent operation. The efficiency of conversion and the amount of harvested power determine how feasible the load operation will be.

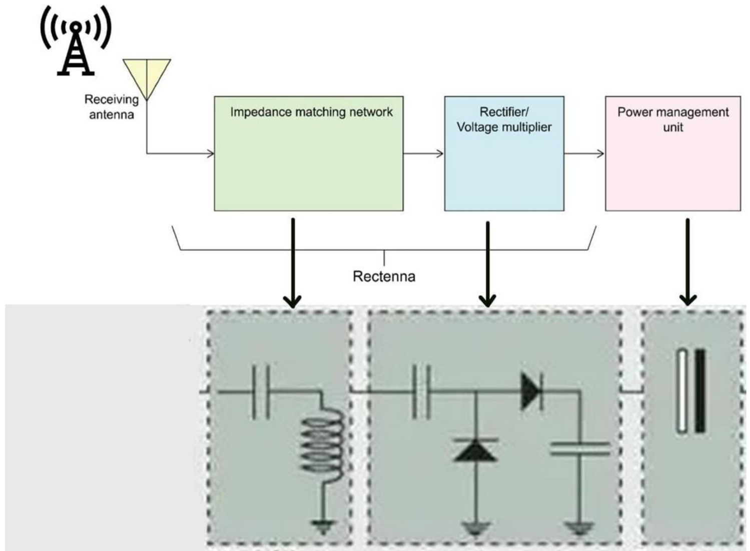

Figure 1. RF Energy Harvesting Process

The amount of radio frequency (RF) power captured by the receiving antenna in a rectenna system can be theoretically estimated using the Friis transmission equation [15], which relates the transmitted power, antenna gains, wavelength, and propagation distance as:

$$P_r = P_t G_t G_r (\lambda/4\pi R)^2$$

where P_t and G_t represent the power and gain of the ambient RF source, and G_r corresponds to the gain of the spiral receiving antenna integrated within the rectenna.
The received RF power P_r is subsequently converted into DC power P_{DC} by the rectifying circuit, with an overall RF-to-DC efficiency given by:

$$\eta = P_{DC} / P_r$$

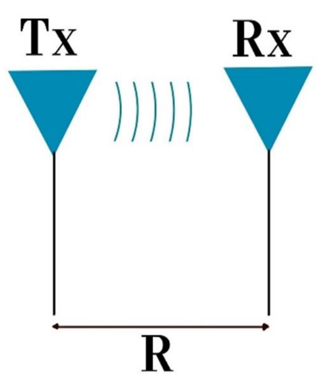

Figure 2. Power transfer between transmitting and receiving antennas modeled using the Friis transmission equation.

II. ANTENNA REQUIREMENTS

Meeting these design goals is important to enhance the amount of ambient RF energy that can be harvested and thus improves the viability of powering low-power IoT sensors and devices.

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1) Broadband / Multi-band Operation: To effectively harvest ambient RF energy, the antenna should operate across multiple frequency bands or have a wide bandwidth. This ensures that energy from diverse RF sources, such as cellular networks, Wi-Fi, and broadcast signals, can be captured efficiently.
2) High Efficiency & Gain: The antenna must have high radiation efficiency so that the captured RF energy is not lost within the antenna itself. Good gain improves the antenna's effective area, allowing it to collect more energy from the surrounding environment.
3) Compact Size & Form Factor Suitability: For IoT devices, wearables, and textile applications, the antenna should be physically small or conformal without significantly compromising performance. For example, designs using low-cost FR4 substrates have achieved compact size while maintaining sufficient gain and bandwidth.
4) Polarization, Radiation Pattern & Orientation: Circular or omnidirectional polarization is preferred to capture RF waves coming from multiple directions. The radiation pattern should allow wide coverage to maximize energy capture.
5) Integration Considerations (Wearables, Textiles, IoT Devices): For wearable and textile applications, the antenna may require flexibility, durability, and low profile, allowing integration with fabrics or curved surfaces without performance degradation.

Over the past three decades, RF energy harvesting technology has progressed significantly—from basic wireless power transfer concepts to the development of advanced broadband, polarization-independent, and flexible rectennas**.** These modern systems have enabled practical energy harvesting in real-world scenarios, powering Internet of Things (IoT) nodes, wearable devices, and biomedical implants**.** Among the various antenna geometries explored for RFEH, spiral antennas—such as the Archimedean, logarithmic, and Fibonacci-based designs—have emerged as leading candidates due to their inherent broadband response, compactness, and polarization-insensitive characteristics. Their unique structure allows efficient energy capture from multiple frequency bands simultaneously, making them particularly well-suited for ambient RF environments where signal strength and frequency vary dynamically.

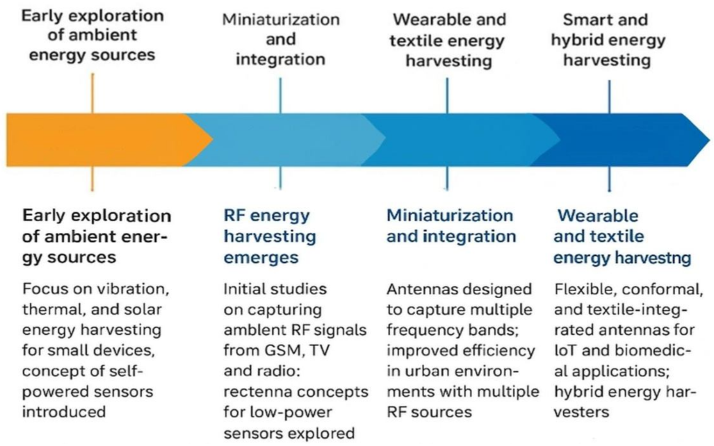

Figure 3. Evolution Of RF Energy Harvesting Research and Rectenna Design

III. SPECIAL CHARACTERISTICS OF SPIRAL ANTENNAS

A. Properties of Spiral Antenna

Spiral antennas, typically composed of two or more arms, are widely recognized as frequency-independent structures due to their ability to operate efficiently across a broad frequency spectrum while preserving consistent polarization, radiation patterns, and impedance characteristics. Among these, the Archimedean spiral stands out for its geometry, where the radius increases linearly with the angle of rotation. This planar configuration not only supports broadband performance but also integrates seamlessly onto planar substrates, as its inner radius expands proportionally with the spiral's angular progression [8].

Traveling wave antennas—such as spiral, helical, and Yagi-Uda types—operate primarily through guided wave propagation, which serves as their core radiating mechanism. While some of these antennas can function in omnidirectional modes, they are generally favoured for directional applications due to their improved efficiency. Among them, spiral antennas have gained significant attention in wearable energy harvesting research owing to their low-profile planar geometry and broad operational bandwidth. Their radiation characteristics can be finely tuned by modifying parameters such as the spiral's radius, number of turns, spacing between turns, and arm width, making them highly adaptable for wearable use.

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Figure 4. Two-arm, tightly-wrapped, logarithmic and Archimedean spiral antennas

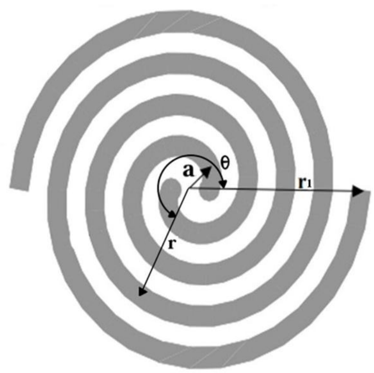

Figure 5. Geometrical Representation of Archimedean spiral

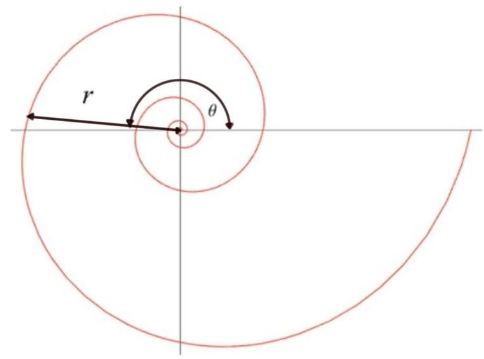

Figure 6. Geometrical Representation of Logarithmic spiral

In Archimedean spiral the radius of each arm increases linearly with the angular rotation, and is described by the following relationship:

$$r = a + b\theta$$

Where:

- a: initial radius
- b: growth rate
- θ: angular rotation

In an Archimedean spiral antenna, the operational bandwidth is primarily determined by its inner and outer radii. The outer radius governs the *lowest* frequency that the antenna can effectively operate at, while the inner radius defines the *highest* frequency limit, the low frequency operating point of the spiral is determined by outer radius and is given by $f_{low} = c / 2\pi r_1$ and high frequency operating point of the spiral is determined by inner radius and is given by $f_{high} = c / 2\pi a$ [14].

The logarithmic spiral, also known as the equiangular spiral, is described by an exponential relation [16]:

$$r = r_0 e^{\alpha\theta}$$

Where:

- r_0 → initial radius,
- α → growth constant controlling the rate of expansion,
- θ → angular coordinate.

Unlike the Archimedean spiral, the arm spacing of a log spiral increases *exponentially* with angle, allowing it to maintain self-similar radiation **characteristics** across frequencies. This property provides stable gain, circular polarization, and pattern invariance.

B. Textile Integration

Conventional wireless energy harvesters are typically constructed using printed circuit boards (PCBs), which tend to be rigid, bulky, and heavy. These physical limitations make them less suitable for body-worn applications, particularly when aesthetics and wearer comfort are critical [9]. To address these challenges, textile-based wireless energy harvesting systems have emerged over the past decade. Leveraging flexible and lightweight textile materials, this new class of harvesters can be seamlessly embedded into garments, offering both visual appeal and ergonomic comfort. Moreover, the expansive surface area of clothing enables the deployment of multiple harvesting units, thereby enhancing the overall power output.

Textile antennas, including spiral and patch designs, can be fabricated using a range of techniques involving electrically conductive and insulating fibers, yarns, and fabrics. Notably, spiral antennas are among the most extensively studied configurations for wearable energy harvesting, while patch antennas also remain a popular choice due to their compact form and ease of integration.

With the rapid rise of body-centric wireless devices and wearable sensors, the need for compact, battery-independent power sources has become increasingly important. Among various ambient energy sources, radio frequency (RF) energy harvesting offers a promising solution for powering on-body electronics. To achieve this, researchers have explored textile-integrated antennas capable of capturing ambient electromagnetic power. In this context, wideband logarithmic spiral antennas have emerged as highly suitable for wearable applications due to their broad frequency response, stable radiation patterns, and geometric scalability. When embroidered onto clothing using conductive fabrics, these antennas can efficiently harvest energy from multiple communication bands while remaining lightweight, flexible, and visually unobtrusive—making them ideal for practical wearable systems.

Figure 7. Textile Printed Spiral Antenna

C. Biomedical Applications

In implantable medical devices, continuous operation can be supported either through external power sources or internal batteries. However, tethered cables used for power and data transmission pose risks such as skin irritation and infection, while implantable batteries carry concerns related to fluid leakage and potential biohazards. As a result, wireless power transfer has gained prominence as a safer and more practical alternative, effectively mitigating the risks associated with conventional power delivery methods [9]. Spiral antennas have emerged as a promising solution for powering biomedical sensors through ambient energy harvesting, particularly in implantable and wearable medical devices. Their compact, planar geometry and inherent broadband characteristics make them ideal for capturing electromagnetic energy across a wide frequency spectrum, The circular polarization and omnidirectional radiation pattern of spiral antennas enhance their ability to harvest energy regardless of the orientation or polarization of incident waves, which is critical for dynamic or embedded biomedical applications. Moreover, their frequency-independent behaviour allows for consistent performance across multiple bands, enabling simultaneous energy harvesting and data transmission. These features collectively support the development of self-sustaining biosensors for applications such as continuous glucose monitoring, neural stimulation, and cardiac telemetry, where reliable and maintenance-free operation is essential.

IV. LITERATURE REVIEW

1) A comprehensive RF energy-harvesting system was designed, fabricated, and experimentally validated by integrating a miniaturized Archimedean spiral antenna with a half-wave Cockcroft–Walton multiplier circuit. The antenna, fabricated on FR4, operates across an ultrawideband from 0.35–16 GHz, exhibiting circular polarization, omnidirectional radiation, and high efficiency, making it ideal for capturing ambient RF signals of unknown direction and polarization. Indoor and outdoor measurements revealed that 98% of harvested power originated from mobile communication bands, primarily around 800 MHz and 900 MHz, yielding total powers of 480 μW indoors and 1535 μW outdoors—sufficient to operate ultra-low-power sensors (<30 μW). Far-field characterization at 830 MHz confirmed omnidirectional behaviour with two main lobes and stable circular polarization over wide elevation angles. Laboratory testing with a Vivaldi transmitter demonstrated practical energy conversion, successfully charging a storage capacitor beyond 1.25 V to power a sensor displaying temperature and humidity. Ultrawideband operation enabled environmental spectrum characterization, highlighting dominant peaks for rectifier design, while impedance steps at the antenna edges optimized bandwidth and matching performance, ensuring efficient ambient RF energy harvesting [1].
2) A double spiral arm antenna was designed and simulated in CST Microwave Studio to enable broadband ambient RF energy harvesting from 700 MHz to 3.5 GHz. The antenna was constructed on a cost-effective FR4 substrate (thickness 0.8 mm, ε_r = 4.3, loss tangent 0.025) and fed via a 130 Ω discrete port for proper excitation and impedance-matching. Initial simulations captured energy efficiently between 1.2–3.5 GHz; to extend the lower-frequency response without enlarging the footprint, a 2 mm metallic frame was introduced around the spiral, enabling reception as low as 700 MHz. This modification enhanced bandwidth, produced a quasi-omnidirectional radiation pattern, and facilitated circular polarization across multiple bands, reducing polarization mismatch losses. Observed gains ranged from 2.2–5.5 dB, supporting effective power capture from variable-direction RF sources such as cellular networks, Wi-Fi, and broadcasting signals. The combination of broadband operation, compact geometry, circular polarization, and omnidirectional radiation makes this design highly suitable for powering low-power electronics and sensor nodes in diverse ambient RF energy-harvesting environments [2].
3) Conventional photovoltaic technologies primarily harvest visible light (400–750 nm), leaving over 50% of solar radiation in the infrared (IR) region—peaking at 10.6 μm (~28.3 THz)—largely untapped. To address this, a metal–insulator–metal (MIM) log-spiral nano-rectenna was designed for efficient IR energy capture. The spiral geometry, traditionally used in RF applications, was miniaturized to operate at THz frequencies, with arms serving as electrodes for a quantum-tunneling MIM diode. An Al_2O_3 insulator was positioned at the antenna hotspot to maximize electric field coupling and rectification efficiency. The antenna followed the expression $r_n = r_0 e^{a(\alpha+\phi n)}$, with quartz substrate (ε_r = 3.78, tan δ = 0.0001) and 62 nm gold conductors optimized for performance and fabrication. Simulations in CST Microwave Studio included parametric optimization of insulator length and gap size, with the Drude model describing electron transport. The optimized Au–Al_2O_3–Au diode configuration demonstrated effective THz rectification, highlighting the design's strong potential for practical IR energy-harvesting systems [3].
4) Recently, optical nano-antennas (NAs) have emerged as a promising approach for solar energy harvesting. In this study, a modified rectangular Archimedean spiral NA was proposed to enhance radiation efficiency and directivity. The design consists of two opposing silver arms arranged tip-to-tip with a 10 nm gap, 1.5 turns each, planar dimensions L_1 = 100 nm, L_2 = 140 nm, and thickness 60 nm. Excitation was provided by a circularly polarized plane wave aligned along the X-axis. The spiral geometry concentrates electric fields within the gap, making it highly effective under randomly polarized sunlight. A silicon dioxide (SiO_2) substrate (L_s = 1370 nm, W_s = 1080 nm, T_s = 400 nm) was employed to optimize radiation behaviour. Using the finite integration technique, the design achieved maximum radiation efficiency of 97.9% and directivity of 19.1 at 500 nm, outperforming conventional Archimedean spiral NAs by 10% in efficiency and 208% in directivity. Total harvesting efficiency reached 98.1%, highlighting the rectangular spiral NA's superior performance for solar energy collection [4].
5) A 64-element Archimedean spiral rectenna array that worked over a very wide frequency range from 2 to 18 GHz was studied. Each spiral acted not only as the receiving antenna but also helped in matching the impedance with the Schottky diode used for converting RF energy into DC. The design was able to harvest energy even from very weak ambient signals, as low as 1 μW/cm². They also observed that the nonlinear behaviour of the diode produced some harmonic reradiation, which showed strong interaction between the spiral geometry and the rectifier circuit. By connecting the spiral elements together in series and parallel, the efficiency increased from below 1% for a single spiral unit to around 13–20% for the whole array. This work showed that spiral rectennas can be scaled into larger arrays and still maintain good efficiency across a broad range of frequencies, making them useful for modern broadband and low-power energy harvesting applications [5].

6) Nanoantennas are resonant metallic structures that confine optical energy within extremely small volumes through high-frequency currents, making them highly effective for light absorption in visible and infrared regions. In this work, thermoelectric TiNi square spiral nanoantennas are proposed to recover optical energy via the Seebeck effect, generating a voltage difference at the bimetallic junction due to localized heating. The antenna consists of two symmetrical arms with seven elements each, 200 nm wide and 200 nm thick, made of titanium and nickel for low thermal conductivity and significant thermoelectric power. The structure was placed on a semi-infinite SiO_2 substrate and illuminated by a 10.6 µm plane wave with irradiance of 117 W/cm², circularly polarized to match the spiral. Numerical modeling revealed strong localized heating at the bimetallic interface, with temperature asymmetry between arms due to differing thermal conductivities. The resulting Seebeck voltage was 2.9 µV, with a responsivity of 20 mV/W, surpassing comparable rectifier-coupled nanoantennas. Performance can be further enhanced by reducing substrate thermal conductivity, e.g., suspending the antenna in air [6].
7) Nature-inspired antenna geometries have attracted attention due to their efficiency, compactness, and structural elegance. Patterns in leaves, flowers, shells, and spiral galaxies reflect self-similarity and proportional growth, which can be applied in antenna engineering. Among these, Fibonacci-based spirals are particularly effective, offering wide impedance bandwidth, circular polarization, and reduced size, suitable for wireless communication, radar, satellite, and energy-harvesting applications. This study investigates four Fibonacci spiral designs. Design 1 **(**EWFS**)** uses uniform arm widths based on the Fibonacci sequence (2, 3, 5, 8), while Design 2 (IWFS) gradually increases arm width outward, improving impedance and return loss. Designs 3 and 4 incorporate triangular elements along the arms, with Design 3 (EWFS with Triangle) and Design 4 (IWFS with Triangle) enhancing radiation performance and gain. Simulations show resonances from 3–10 GHz, with maximum gains of ~4.16 dB for Design 3 and 3.70 dB for Design 4. Surface current, E-field, H-field, and return-loss analyses confirm that these structural variations significantly influence performance. Integration with rectifiers can form efficient rectennas, validating the potential of Fibonacci-inspired geometries for compact, broadband, and energy-harvesting antenna applications [7].
8) A circular spiral antenna was designed to achieve multiband resonance suitable for harvesting ambient RF energy. The structure consists of ten turns in the main spiral patch and three additional inner turns, with optimized spacing to enable resonance across multiple frequencies from 550 MHz to 2.3 GHz. The antenna was modeled in CST Studio Suite on a low-cost FR-4 substrate (ε_r = 4.4, loss tangent = 0.02, thickness 1.57 mm) with a 0.035 mm copper conducting layer, overall dimensions 70 × 70 mm. Symmetrical orthogonal slots were incorporated to improve impedance-matching and support multiple working bands. Simulation results show distinct resonances at approximately 554, 675, 800, 900, 1019, 1135, 1270, 1390, 1490, 1590, 1730, 1850, 1970, 2100, 2240, and 2330 MHz, with bandwidths ranging from 12.8 to 48.1 MHz. The coiled geometry induces circular polarization, enhancing energy capture from mobile, radio, and broadcast sources. Its self-similar, space-filling structure supports multiband operation in a compact form, making it highly efficient for wireless power capture and RF energy-harvesting applications [8].
9) A center-fed circular spiral antenna with a 3 mm diameter was designed and simulated to operate at 524.8 MHz on a dielectric substrate with relative permittivity ε_r = 4.6, loss tangent tan δ = 0.01, and thickness of 1 mm, using a 0.01 mm thick aluminum conducting layer. The spiral geometry was optimized with a radius of 1.5 mm, 20 turns, arm width of 0.015 mm, and inter-turn spacing of 0.05 mm. Simulations in Agilent ADS demonstrated that the antenna satisfies the −10 dB return loss requirement between 520–529 MHz, with a low return loss of −30.93 dB at resonance, indicating excellent impedance matching. Radiation characteristics show an average gain of −39 dBi and directivity of 2 dBi at 524.8 MHz. Wireless power transmission experiments revealed mutual coupling between transmitting and receiving antennas, shifting resonance to 473.8 MHz and achieving a maximum transmission coefficient of −5.659 dB. With antennas separated by 1.5 cm, the received power was ~2 mW, corresponding to 53% efficiency, which dropped to 274 µW (4% efficiency) when a 1.5 cm tissue layer and 1 cm air gap were introduced. Incorporating a single PN diode rectifier, the harvested DC power reached 489 nW, confirming the antenna's feasibility for low-power wireless energy harvesting [9].
10) A wearable energy-harvesting system was designed to wirelessly power on-body sensors. The setup includes a logarithmic spiral textile antenna integrated with a rectifier that converts received RF energy into usable DC power. Since rectifier efficiency is limited by diode nonlinearity, low input voltage, and impedance-matching challenges, the focus was placed on optimizing the antenna to capture sufficient ambient power. The antenna operates over a wideband range of approximately 500 MHz to 9 GHz, covering key wearable and communication bands. Designed and simulated in CST Microwave Studio, it maintains nearly stable radiation patterns due to its self-similar spiral geometry, which remains invariant under scaling. The fabricated textile antenna shows a slightly capacitive impedance with a real part near 188 Ω.

In measurements, the realized gain ranged from −2 dBi to +2 dBi, around 4–5 dB lower than simulations, primarily because of reduced conductivity of the embroidered yarn (three orders of magnitude lower than copper) and sewing imperfections. The study concludes that improved conductive yarn and precision manufacturing could substantially enhance harvesting performance in future wearable designs [10].

V. FUTURE DIRECTIONS

Recent research indicates several promising directions for energy-harvesting antennas:

1) Design Optimization – Spiral and fractal geometries dominate RF harvesting for their broadband and polarization-independent performance; further geometric optimizations could enhance efficiency across multiple bands.
2) Nano and Optical Antennas – THz and visible-range nano-antennas show high efficiency for solar and IR harvesting; future studies should focus on scaling these designs for practical implementation.
3) Wearable and Implantable Integration – Compact, flexible, and textile-based antennas have demonstrated potential, but improvements in fabrication, materials, and mechanical stability are required.
4) Hybrid Energy Harvesting – Combining RF, solar, and thermal harvesting could increase overall energy availability and reliability for low-power devices.
5) Circuit and Material Improvements – Optimizing rectifier circuits, impedance-matching, and exploring high-conductivity or low-loss materials can significantly enhance harvested DC output.

VI. CHALLENGES

Despite Despite notable advances in energy-harvesting technologies, several critical challenges persist that must be systematically addressed to enable widespread adoption and long-term reliability:

1) Low Conversion Efficiency – Particularly for weak ambient RF signals or miniature nano-scale antennas.
2) Material Limitations – Conductivity issues in textile antennas, substrate losses in printed antennas, and fabrication limitations in nano-antennas.
3) Integration Issues – Incorporating antennas into wearable or implantable devices introduces constraints on size, flexibility, and biocompatibility.
4) Standardization – Lack of uniform testing methodologies and environmental conditions makes cross-study comparisons difficult.
5) Bandwidth vs. Size Trade-off – Achieving wideband operation in small form factors remains a persistent design challenge.

VII. CONCLUSION

Energy-harvesting antennas hold great potential for powering low-energy electronics, sensors, and wearable or implantable devices. Among the various designs, spiral and fractal geometries have proven especially effective for broadband RF harvesting, while nano-antennas are opening new avenues for capturing energy from infrared and visible light. To translate these technologies into practical applications, it is essential to overcome material limitations, enhance conversion efficiency, and ensure seamless integration with existing systems. Ongoing research into hybrid harvesting techniques, circuit-level optimization, and novel antenna geometries is paving the way towards reliable, efficient, and scalable energy-harvesting solutions.

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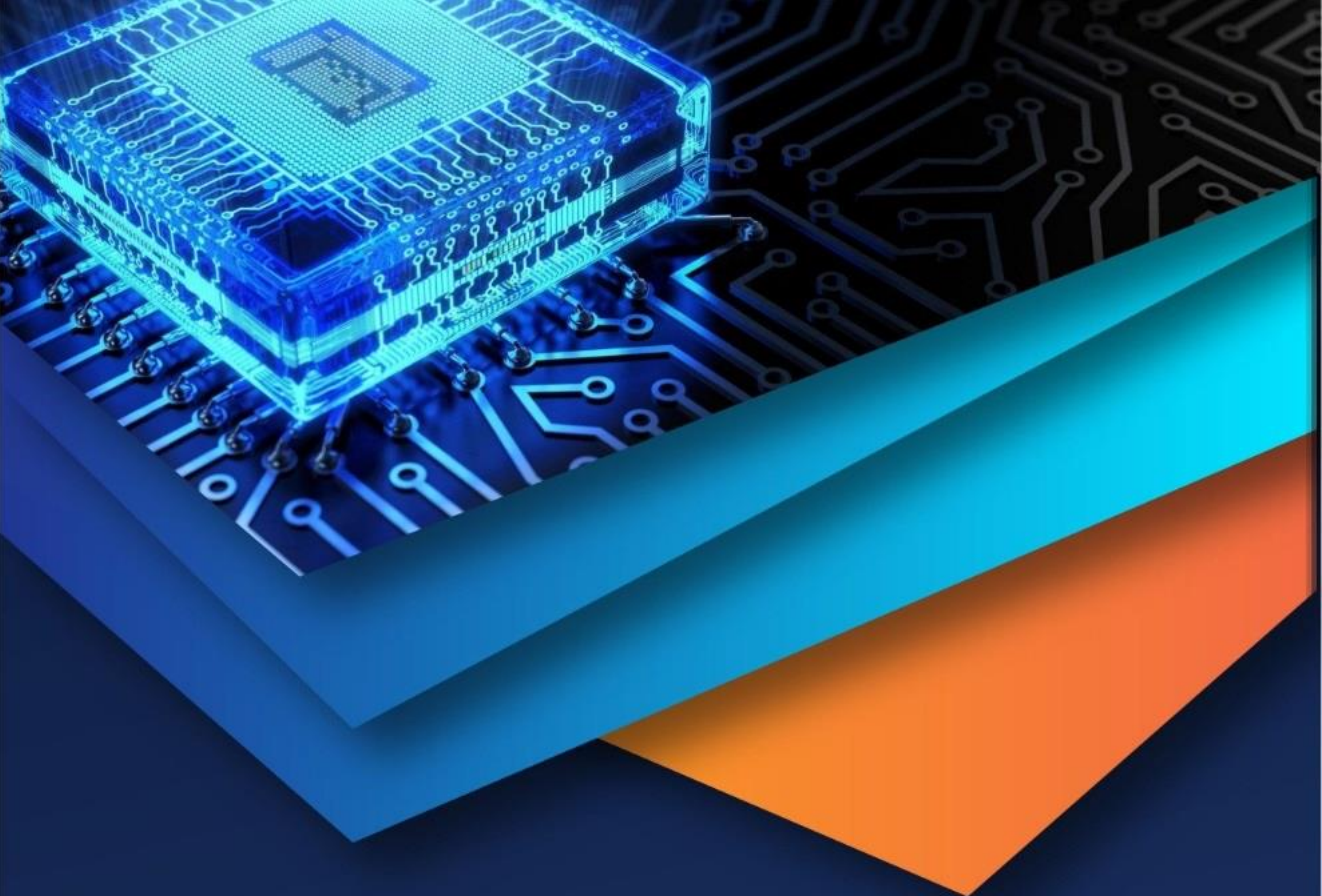

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