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A Systematic Review of Wireless Energy Harvesting from Radio Frequency Signals: Technological Developments and Applications

Dr.WINSTON DUNN

Assistant Professor
Government Engineering College, Banka, Bihar, India

Abstract

Radio frequency (RF) signals can be used for wireless energy harvesting (EH), which has shown promise in enhancing environmentally friendly technologies and providing energy for battery-free devices. This technology captures ambient radiation from RF sources, including mobile phones, Wi-Fi networks, and radio signals, converting it into usable power for low-energy applications. As the market for energy-efficient equipment keeps expanding, understanding For upcoming advancements in wireless technology and Internet of Things (IoT) devices, RF-EH's potential is essential. It is the goal of this study to offer an extensive evaluation of the developments and applications of RF-EH devices. We used the PRISMA technique to review the articles from renowned academic databases, such as WoS and Scopus. The review includes studies published in the last decade, focusing on RF-EH systems' design, efficiency, and applications. Inclusion criteria focused on studies detailing technological innovations, efficiency improvements, and practical implementations of RF energy harvesting. Excluded were papers lacking experimental or quantitative data. The results highlight key improvements in RF-to-DC conversion efficiency, advancements in rectenna designs, and emerging applications such as self-powered sensors and wearable technologies. This review concludes that RF-EH holds significant potential for enhancing the efficiency and scalability of wireless power solutions; however, challenges related to power density and range remain areas for future research.

Keywords: Wireless Energy Harvesting, Radio Frequency (RF) Signals, Systematic Review, PRISMA Model.

1. Introduction

The growing demand for sustainable power for wireless communication and IoT devices has driven interest in wireless EH (WEH). Among various WEH methods, RF-EH stands out for its ability to convert ambient RF signals from cellular networks, Wi-Fi, and TV broadcasts into usable electrical power [1]. The technology offers a sustainable and continuous power supply for low-power devices, especially in densely populated areas where RF signals are abundant. RF-EH has potential uses in 5G communications, smart environments, and WSN health monitoring. However, it also faces significant challenges, including low energy density, conversion inefficiencies, and regulatory issues that limit widespread adoption [2]. WSNs have become increasingly important in ICT, with applications in various fields like IoT, medical, agriculture, and military. However, energy sources were limited, and energy efficiency is achieved through energy-efficient protocols. To maintain continuous operation, energy-harvested systems were needed. Techniques like solar, RF, mechanical, thermal, and vibrations are available. [3]. Four different signals with modulation from the signal power source, with varying broadcast levels of power ranging from 1 to 10 dBm in increments of 1 dBm, were used to test the circuit [4]. The market for wearable sensors that use vital sign monitoring, such as body temperature, heart rate, and physical activity, has increased dramatically. Wearable sensors can be used in certain situations, though, as they usually require batteries that must be changed or recharged regularly. RF-EH is a viable approach for sensor powering in situations where regular sensor battery replacement or recharge is not practical [5]. A voltage multiplier, rectifier, energy storage, and antenna, device make up an RF-EH circuit. The rectifier transforms RF signals into DC electricity after the antenna has picked them up. The voltage multiplier increases the output of DC voltage, particularly when a supercapacitor or battery is utilized as a mechanism for storing energy and the electromagnetic field's power density fields determine the effective circuit. Figure 1 illustrates the RF-EH system's structural design.

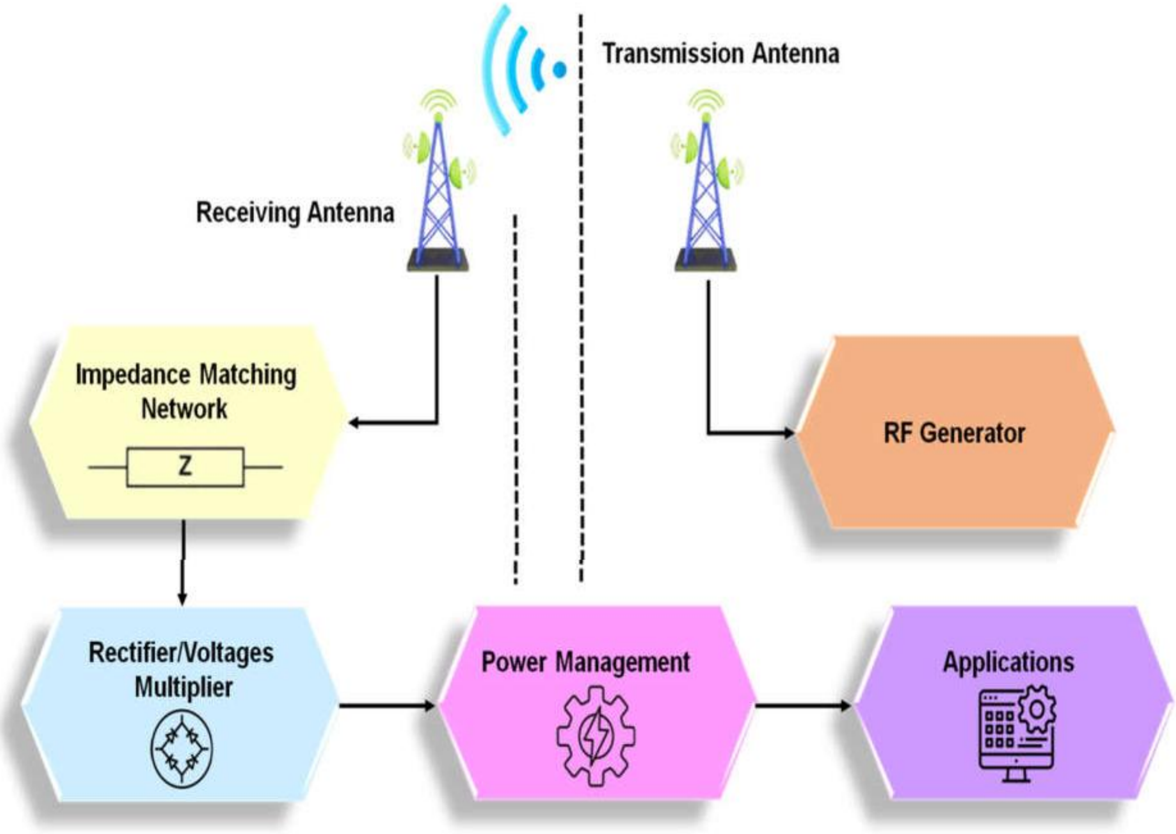

Figure 1:A hypothetical block schematic for RF energy collecting systems

Wearable devices, small, inexpensive, and low-power wireless devices, were increasingly sought after for their ability to sense small variations in magnetic fields at low frequencies and amplitudes, despite the challenges of environmental noises in this frequency range [6]. The study explores wireless power transmission and EH strategies for UWC in decision agriculture. It investigates various methods of external power transmission and discusses EH systems using wind, sun, and vibration. It also evaluates vibration-based EH models. The development of an effective wireless subterranean communication system for extended field operation is made possible by these energy collecting techniques [7, 8]. This study evaluates the advancements in wireless EH from radio frequency signals, concentrating on the effectiveness of antenna design and RF-to-DC conversion. It explores practical applications in self-powered sensors and wearable devices, highlighting the potential of RF EH for sustainable power solutions.

2. Methodology

A systematic literature, review on wireless RF-EH signals was conducted for the study. The review addresses two key research questions, what were the technological advancements in RF-EH systems? and how were these technologies applied in various applications. The PRISMA method was employed to ensure a comprehensive and unbiased review. The PRISMA method was widely used for systematic reviews. The methodology comprised inclusion and exclusion criteria to find relevant research, and it employs statistical methods for interpreting the results. Identification, screening, eligibility, and inclusion were the four phases that make up the PRISMA process. Figure 2 illustrates the PRISMA stages flow diagram used in the review.

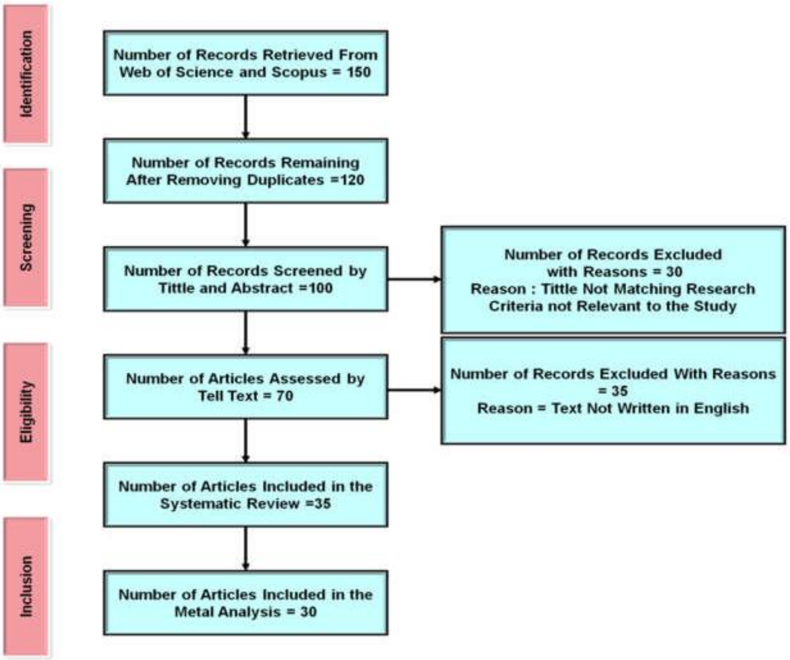

Figure 2: The flow diagram of PRISMA

Identification

The WoS and Scopus databases were accessed to locate a total of 150 articles. These data sources were chosen due to their relevance to the field of RF-EH signals and their extensive coverage of relevant research. Finding a lot of full-text and open-access papers made choosing these databases easier ensuring comprehensive and unbiased access to the literature. The online accessibility of these databases streamlines the process of obtaining and reviewing relevant research articles.

Search strategy

The following keywords were used to perform a search on the chosen database, EH wirelessly and RF signals. When appropriate, the AND operator was used to combine the terms in the queries. The search terms that were utilized were, TITLE ("wireless AND energy AND harvesting AND radio AND frequency AND signals") for the Scopus database and "wireless EH AND RF signals" (title) for the WoS. Before the screening procedure, a total of 75 papers were collected from the WoS and another 75 documents were acquired from Scopus.

Screening

The procedure entails assessing the listed publications' titles and abstracts to ascertain their applicability to the systematic review. Documents that address the research questions related to technology development and applications of wireless RF-EH signals were selected based on a binary inclusion decision. Articles were excluded for several reasons, including lack of open access and irrelevance to address the designated research objectives and queries.

Eligibility

The first step was to find suitable articles to download by utilizing the search phrases. To guarantee that relevant documents were retrieved, filtering criteria were used. To verify the reliability of the sources, only peer-reviewed journal and conference publications were taken into consideration. To focus on recent developments, articles published between 2019 and 2024 were selected. The search approach and inclusion criteria applied throughout the evaluation process are shown in Table 1.

Table 1: Methodology for searching and inclusion standards

Stage	Qualifications for inclusion	Records taken from the Web of Science	Documents that were taken from Scopus
1	Articles containing the words “wireless EH”AND “RF signals in the title	75	75
2	Select articles published between 2019 to 2024	60	62
3	Choose just journal and conference papers	50	55
4	Choose just English-language materials	48	52
5	Choose only full-text publications with open access	10	8

Inclusion

Once the inclusion and exclusion criteria have been applied, the relevant BibTex files were exported once articles were obtained from the databases. These flies were imported into R data frames, merged and duplicates were removed. Following the process, 30 unique and relevant records were selected for meta-analysis. The Bibliometrics R package, and open-source tool for comprehensive bibliometric analysis were used to conduct the mapping and study of the literature.

3. Technologies improvements of RF-EH

RF-to-DC conversion efficiency

The section explores the significant improvements in the efficiency of converting RF energy to DC. Modern development in the field has been driven by several key innovations. Enhanced rectifiers, such as those in corrupting high-efficiency Schottky diodes and advanced semiconductor materials like GaN and SiC have played a crucial role in improving conversion efficiency [9]. These materials were known for their superior electrical characteristics and high-frequency performance, leading to significant reductions in power losses. Moreover, novel circuit designs, including advanced impedance matching networks and optimized rectifier configurations, have further enhanced the effectiveness of energy conversion [10]. Techniques such as multi-stage rectification and the use of adaptive matching circuits have been employed to maximize energy capture and reduce mismatches between the RF sources and the rectifier. The integration of these technologies has not only improved the overall conversion efficiency but also enabled the creation of RF energy collecting devices that were more portable and effective. Because of the development of RF-to-DC conversion technology has made it possible to employ RF-EH in more efficient and practical ways, which will increase the technology's popularity across a range of industries, including wireless sensor networks and IoT devices [11]. An RF-DC conversion system typically comprises a voltage regulator, a matching network, a receiving antenna to detect incident RF power and a rectifier. The amount of radiofrequency power that was received from the environment was not as high as that which might be produced by a dedicated source, but these sources can provide electricity all day long (except during maintenance periods), in contrast to solar sources that only produce power in favorable weather. rms, or dBm levels, were commonly used to express an antenna's power level, as seen below in Equation (1).

$$(w \quad) = \frac{{}^{2}_{,r}}{Q_k}(w \quad); \quad (\quad) = 10 \quad {}_{10}| \frac{0 \quad (w \quad)}{1} \qquad (1)$$

Here, , was the , voltage for a received , rmspower level, and $_k$the rectifier's input resistance, visible through the antenna, was crucial for the harvesting module's effectiveness and the least amount of initial electricity needed. Due to its availability throughout the day and in overcast conditions, radiofrequency power was a desirable source for accumulating and supplying DC power for implantable and portable devices. The amplitude of 22.36 mV was obtained from the received RF signal strength of around 20dBm for a standard 50 X antenna. Put another way, the AC signal's maximum amplitude was significantly less than the diode's threshold. Incident RF signal waves are converted into DC signals by the RF-DC converter circuit using a voltage multiplier. High frequency frequencies are filtered by the output inductor and capacitor. Figure 3 presents the signal voltage multiplier utilized in the circuit of the converter [12].

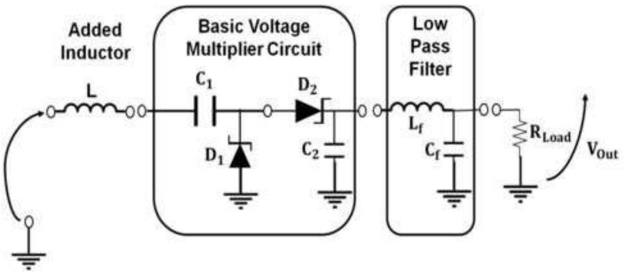

Figure 3: RF-DC converter circuit

4. Antenna

An antenna is a specialized device designed to transmit or receive electromagnetic radiation, mostly in the RF spectrum. To transmit or receive, it converts electrical signals into radio waves or vice versa. Various shapes and sizes, each suited for specific applications, such as communication, broadcasting, and navigation. Common types include dipole antennas, which consist of two conductive elements; micro strip antennas, which focus signals for long distance communication. The performance of an antenna is characterized by parameters like gain, radiation pattern, bandwidth, and impedance, which determine its efficiency and effectiveness in transmitting or receiving signals. In recent years such as wireless communication, IoT and EH systems, where they capture ambient RF energy and convert it into useable power, highlighting their versatility and importance in modern electronic systems.

5. **Rectenna design:** For EH are the most effective. Rectenna combine the functions of an antenna and a rectifier circuit, making them created especially for RF energy collecting devices, as seen in Figure 4.

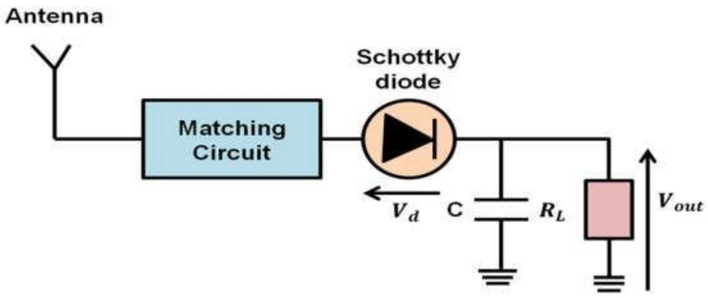

Figure 4: Block diagram Rectenna design

High efficiency in RF-to DC conversion: Rectenna are optimized to capture ambient RF signals and directly convert them into DC power, minimizing losses in the conversion process.

Frequency agility: Rectennas can be made to work at a variety of frequencies, including those that are frequently used in RF-EH applications like Bluetooth, cellphone, and Wi-Fi.

Compact design: It can be integrated into small, portable, or wearable devices, making them ideal for applications like wireless sensor networks, IoT device, and battery free gadgets.

Rectenna technology has significantly improved performance in RF-EH systems. Advanced meta materials have been created to improve efficiency, directivity, and bandwidth, resulting in high-performance antennas. Research has been concentrated on developing compact and high-gain antennas for small devices and systems. These designs frequently utilize sophisticated techniques, such as resonator dielectrics and patch antennas, which improve performance and compactness. Overall, these developments help to improve energy extraction and transformation in RF-EH systems [13]. Improvements to rectifying circuits were also important. Innovations such as harmonic rectifiers, multiplying rectifiers, and improved rectifier diodes have improved the efficiency of energy transfer from RF to DC. These improvements lower power losses and increase the overall efficiency of rectenna, which makes them more successful at turning captured RF energy into usable power. Another notable innovation is the introduction of multi- and wide-band rectennas. These designs allow for the capture of RF energy over many frequency bands, boosting the versatility and effectiveness of rectennas. By allowing for a greater range of frequencies, multiple bans, and wide bands [14]. The capability not only increases it’s EH potential, but also facilitates the integration of rectenna into a variety of applications and locations. Furthermore, nanomaterials and microfabrication techniques have enabled the development of rectenna with superior performance characteristics. The incorporation of graphene and carbon nanotubes into rectenna designs provided great conductance and flexibility, which contributed to increased efficiency and downsizing. Furthermore, developments in 3D printing and micro manufacturing techniques have allowed for the design of more sophisticated and optimal Rectenna structures [15]. Microstrip antennas are also used in EH systems because they are inexpensive and simple to integrate, but they are often paired with rectifying circuits for optimal energy conversion. Rectennas are most effective type of antenna for energy harvesting, maximize the efficiency of capturing and converting ambient RF energy into usable power.

6. Matching network

It is an electrical circuit used to ensure maximum power transfer between two components with differing impedances, such as an antenna and load. Its primary purpose is to align one device's output impedance with another's input impedance, thereby minimizing reflections and losses in the signals. It can be constructed using various configurations of passive components including capacitors, inductors and resistors and can be categorized into lumped, distributed and conventional types. By optimizing the impedance match, these networks enhance the efficiency of power transfer, making them crucial in applications like wireless communications, devices like RF-EH that are electronic. As shown in Figure 5, to optimize the power transmission from the antenna to the rectifier circuit.

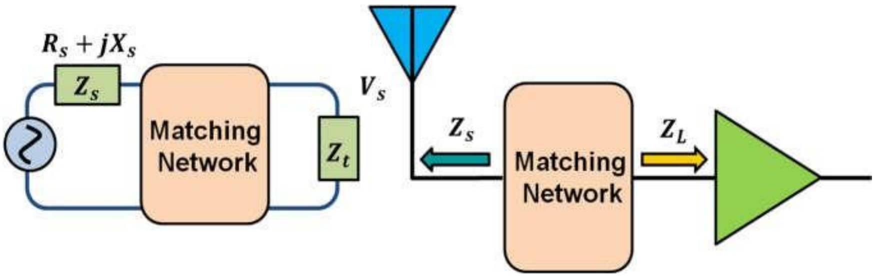

Figure 5: Block diagram of matching network

6.1 **Lumped matching network:** It is consisting of discrete passive components, such as capacitors and inductors, utilized to ensure that the impedance of the antenna and the load. It was typically and compact and easy to design for specific frequency bands. Their advantages include low cost and straightforward implementation. However, lumped networks can have limitations in bandwidth and cannot perform well over a wide frequency range. It suitable for applications where the frequency is fixed, making them ideal for low power EH systems.

6.2 **Distributes Matching network:** It is uses transmission line segments (like microstrip lines) to achieve impedance matching. These networks are more complex than lumped networks but offer better performance in terms of bandwidth and efficiency, especially for wideband applications. Distributed networks can be made to function over a variety of frequencies, which makes them appropriate for EH systems that needed to capture signals from various RF sources. It provides flexibility in design and can be integrated into circuit layouts with minimal space

6.3 **Conventional Matching networks**: It typically refers to traditional design that can use a combination of lumped and distributed elements. The often characterized by their systematic approach to matching impedance and can include configurations like L-networks, T-networks or - networks. The networks can be tuned for specific applications balancing performance and complexity while they are effective in various scenarios, the choice between lumped and distributed elements largely depends on the particular specifications of the EH system, including the frequency range, size limitations, and efficiency targets.

The best matching network for EH systems often depend on the specific applications and frequency range. For narrowband systems, lumped matching network can suffice due to their simplicity and cost-effectiveness. However, for applications requiring broader bandwidth or better efficiency, distributed matching network are generally preferred as that can optimize power transform across a range of frequencies, making them more effective in capturing ambient RF energy for conversion into usable power.

7. Rectifier

An electronic device called a rectifier is necessary for many applications, such as EH and power supply systems, since it transforms alternating current (AC) into direct current (DC). Rectifiers function by permitting current to flow despite being blocked in the opposite direction, thus creating a unidirectional flow of electrical energy. Common types of rectifiers include diode rectifiers, which utilize semi-conductor diodes, CMOS rectifiers, which utilized complementary metal-oxide semi-conductor technology for low voltage drop and high efficiency, and cross coupled rectifiers, which improve efficiency through a specific diode arrangement. The choice of rectifier affects designs like Schottky diodes, full-wave rectifiers, and active rectifiers being favored for their ability to minimize power losses and optimize energy conversion, especially in low power scenarios as shown in Figure 6.

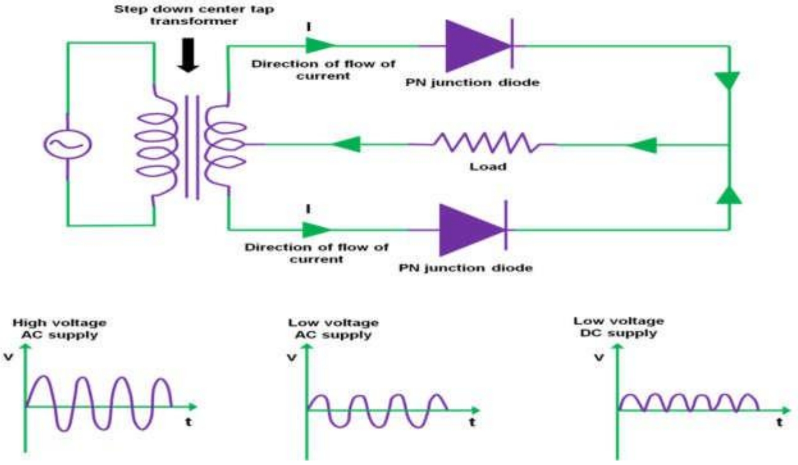

Figure 6: Block diagram of rectifier

7.1 **CMOS rectifier:** CMOS machinery is used to transform AC signals into DC. It typically consists of a combination of n-channel and p-channel MOSFET's which switch on and off in response to the input AC signal. This type rectifier benefits from low power threshold voltage of CMOS devices allows for applications where harvested energy is minimal. CMOS rectifiers are often preferred for their compact size, integration capabilities, and energy efficiency

7.2 **Cross- coupled rectifier:** It is a specific type of rectifier that uses a network of diodes arranges in a configuration that allows for effective rectification of AC signals, enabling both halves of the input waveform to contributor to the output voltage. The configuration helps to reduce the voltage drop across the diodes, enhancing overall efficiency. Cross-coupled rectifiers are particularly advantageous for EH applications where low voltage and high efficiency are crucial. It provides performance compared to traditional diode rectifiers due to their lower forward voltage drop.

7.3 **Efficiency comparison:** CMOS rectifiers tend to offer better than traditional diode-based rectifiers, including cross-couples design especially at low power levels. The low voltage drop of CMOS devices significantly minimized power loss during rectification, making them ideal for EH applications that require high efficiency and effective operation with minimal input power.

7.4 **Schottky diode rectifiers:** Schottky diodes, which are renowned for their quick switching times and minimal forward voltage drop, are used in these rectifiers. Their great efficiency makes them commonly utilized in EH, particularly in low voltage applications.

7.5 **Full-wave rectifiers:** The rectifiers can be configured to utilize both halves of the input AC waveform, providing higher output voltage and efficiency compared to half-wave rectifiers, they can use either diodes or transistors.

7.6 **Boost rectifiers:** In some EH systems, boost convert is integrated with rectification to step up the harvested voltage before conversion. In this method cam improve overall efficiency, especially when dealing with low input voltages.

7.7 **Active rectifiers:** These rectifiers replace traditional diodes with active devices (like MOSFETs) to achieve lower voltage drops and higher efficiencies. They are particularly useful in low-power EH scenarios.

The choice of rectifier in EH applications depend on specific requirements such as efficiency, voltage levels and integration with other circuit components.

8. Power management module

It is an integrated circuit or system created to control and monitor the distribution of electricity in electronic devices ensuring efficient energy utilization and battery management. PMM are crucial in applications such as battery powered devices, RE systems and EH applications, where the optimize the power flow and enhance overall system efficiency. These modules typically include several key functions, such as voltage regulation, battery charging, energy storage management and power distribution. It can manage different power sources, including batteries super capacitors and energy harvested from ambient sources like solar or RF signals. PMMs employs techniques such as buck/boost conversion to adapt to varying input and output voltage requirements, ensuring devices operate within their optimal voltage ranges.

Advanced PMMs also incorporate features like load monitoring, dynamic voltage scaling, and thermal management to protect components and extent the lifespan of the devices. By effectively managing power consumption and maximizing energy efficiency, PMMs play a vital role in enabling longer battery life, reducing energy waste, and enhancing the performance of modern electronic systems as shown in Figure 7.

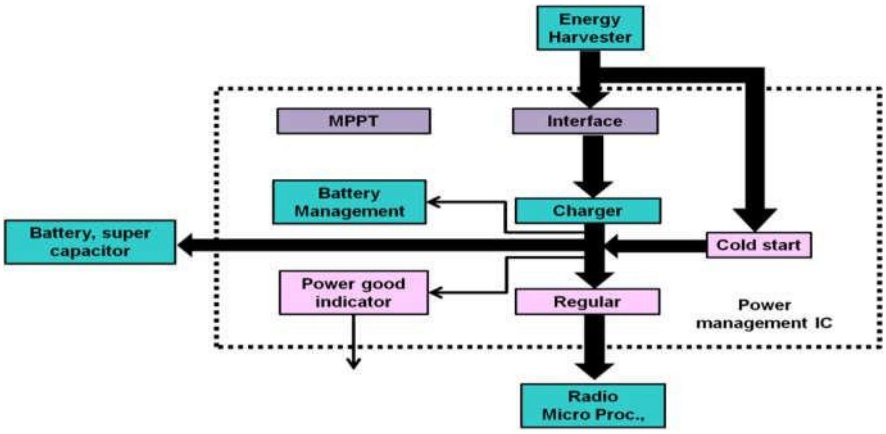

Figure 7: Block diagram of rectifier

9. Power management and storage

Power management and storage were crucial for optimizing RF-EH systems, ensuring efficient utilization and storage for various applications. High-efficiency energy storage devices like supercapacitors and advanced batteries were essential for storing intermittent and low-power energy harvested from RF signals. Advancements in battery technology, High energy density and enhanced safety were provided by batteries like solid-state and lithium-sulfur ones, which increase the amount of RF energy that can be stored [16]. Smart power management systems balance energy supply and demand, improving overall efficiency. These systems use energy-aware algorithms and adaptive power control techniques to dynamically adjust power consumption based on harvesting energy availability, minimizing energy waste. Techniques like maximum power point tracking optimize power transformation from the Rectenna to the storage unit. Figure 8 depicts a block schematic of a common wireless sensor that harvests radiofrequency energy. One system that functions effectively in well-matched and established operational environments was the passive RFID tag. Nonetheless, there were several uses for broad wireless sensors that function across a range of unidentified circumstances, with a great deal of uncertainty and wide fluctuations in features of the RF field and reception. These interval-based circumstances make it difficult to maximize the energy that was gathered and encourage the usage of online optimization power management circuits [17].

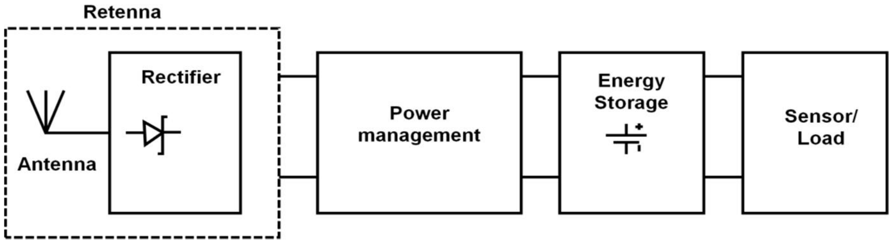

Figure 8: A flow diagram of Power management and storage

Hybrid storage solutions combine batteries and supercapacitors, offering long-term energy storage from batteries and rapid energy discharge from supercapacitors. Research into miniaturized energy storage units and integrated power management circuits enables the development of compact, efficient RF-EH harvesting modules embedded in small, portable, or wearable devices. Integrating these strategies ensures that harvested RF energy was captured, stored, and utilized sustainably, supporting the practical operation of wireless and IoT devices, particularly for applications requiring uninterrupted power supply [18].

Application of RF-EH

10. Self-powered sensor

RF-EH has become increasingly pivotal in the development of self-powered sensors, which operate independently of traditional battery sources. To fuel their operations, these sensors harvest ambient radiofrequency energy from a variety of sources, including Wi-Fi networks, cellphone signals, and radio waves. Notable examples include environmental monitoring sensors that measure air quality or temperatures and were deployed of such sensors in distant or difficult-to-reach places where conventional power sources were impractical. For instance, self-powered sensors used in infrastructure monitoring can track the health of bridges and buildings, transmitting data without the need for frequent battery replacements [19]. It could be feasible for wireless and portable electronic gadgets to run entirely on renewable energy, negating the need for regular battery replacement. Numerous environmental energy sources, including light, heat fluxes, motion, electromagnetic impacts, airflow, and sound waves, can be used to gather energy. When compared to the energy stored in energy-storage devices like batteries, capacitors, and similar components, atmospheric energy was almost infinite. Not every application calls for the use of a certain energy source. The evaluation of energy sources should be based on their respective generating capacities [20].For certain IoT devices to function constantly throughout their lifespan, they must be self-powered. It was possible to turn tiny quantities of mechanical energy into electric current by creating nano generators. The initial nanogenerators relied on the piezoelectric action and tribal electrification process. Beginning with the Maxwell equations, the fundamental theory of nanogenerators was introduced. The similarities and differences between traditional electromagnetic generators, piezoelectric nanogenerators, and tribe TENG were also covered [21].

11. Wearable energy

The integration of RF-EH in wearable technologies has marked significant advancements in devices for monitoring health and personal gadgets. Wearable such as fitness trackers, smart watches, and health monitoring devices were being designed to harness RF energy to extend battery life or even eliminate the need for batteries entirely. Recent development includes smart clothing embedded with RF-EH components that power sensors for monitoring physiological metrics independently of external power sources, such as body temperature and heart rate. The technology not only improves convenience for users but also enables continuous monitoring of health metrics in a non-intrusive manner [22]. Harvesting RF energy was one of the greatest methods available. The effectiveness of RF RF-EH will determine wearable gadget technology in the future.

These characteristics greatly increase the likelihood of capturing RF waves. It captured energy and be utilized to excite portable low-power gadgets [23]. For wearable technology to be both useful and eco-friendly, clean, renewable, and sustainable energy was needed. There were a variety of energies present in the environment, such as energy that comes from the environment and energy that comes from the human body [24].

12. IoT devices

In the realm of the IoT, the RF-EH layer play as crucial role in powering an ideal range of connected devices. IoT devices, including the wireless sensors, and remote controls, benefit from RF-EH by utilizing ambient RF signals to maintain operations without frequent battery changes. The integration of RF-EH allows for the development of self-sustaining IoT networks, reducing maintenance costs and supporting the scalability of IoT applications. Examples include smart environmental sensors in agricultural fields that monitor soil moisture and weather conditions, or smart home devices like automated lighting systems that operate independently of traditional power sources [25].The energy efficiency and novel energy sources of IoT devices have been extensively studied. However, it was unlikely that the energy consumption issue caused by the growing number of IoT devices can be adequately resolved if only one of the aforementioned factors was taken into account. As a result, the study offers a fresh viewpoint on integrating wireless energy transmission with energy conservation, addressing the issue of energy efficiency through an integrated approach [26].Since PV technology was first developed for outdoor applications, it has expanded to encompass inside solar systems as a result of improvements in circuitry, manufacturing techniques, and IoT device designs [27].

Evaluation Metrics for RF-EH

Depending on what the application requires, the main performance measures for assessing RF power in EH systems were outlined in the section. The harvesting system efficiency, resonance factor, output power, harvester sensitivity, and range distance separating the sender and the recipient were some of these characteristics. For comparison, comparing these parameters was essential. Receiver sensitivity, power conversion efficiency, and maximizing output power, were the primary goals selecting the incident signal's ideal operating frequency was crucial.

13. Range and frequency

Because it impacts the system's frequency, the working distance of the energy transmission and reception was a crucial aspect of radiofrequency power efficiency. Low-frequency impulses may pass through matter farther than higher-frequency systems because of their longer wavelengths, which makes them more vulnerable to attenuation. Transmission frequencies for implanted devices that use radiofrequency power harvesting shouldn't go over a few megahertz [28].

14. Conversion efficiency

When assessing the efficacy of RF harvesting systems, one important consideration was power conversion efficiency. It was computed by splitting the power that was sent by the electricity that the antenna transmits, to the demand. The performance of a voltage multiplier, rectifiers, and memory device were all included in the phrase. Estimates of conversion efficiency usually do not account for RF transmission loss in Equation (2).

$$= \frac{0}{0_r \quad _r} \qquad (2)$$

Where was the power that the antenna harvests and was the power that was supplied to the load.

15. Resonance factor

A system that can transport and store energy in different storage modes, including prospective or fluid energy, was referred to as resonance. The best configuration for energy harvesters to maximize power production was with resonant frequency functioning. The dimensionless factor, which characterizes the resonance's breadth and intensity, indicates that the highest voltage increases as the whole thing echoes at the frequency that was resonant in Equation (3).

$$= 2 \frac{\mathrm{r}}{\quad} \qquad (3)$$

Where the total energy was dissipated every cycle and was the total energy stored. Therefore, it follows that an elevated factor suggests a strong voltage gain and a small resonant bandwidth. Additionally, Equation (3) suggests that the factor isnegatively correlated with the quantity of energy lost during each discharge cycle.

16. Sensitivity

The least amount of incident power necessary to start a system was known as its sensitivity. It was the capacity to function at a low power density while harvesting energy. Because of the intensity of the incident signal, a harvesting system's sensitivity determines its conversion efficiency and, consequently, its performance. The equation (4) can be used to calculate sensitivity.

$$\mathrm{B}\ (\quad) = 10 \quad {}_{10}\frac{0}{1} \qquad (4)$$

Where was the lowest power needed by a system to complete a job. It was important to remember that the threshold voltage affects sensitivity. A lower threshold provides more sensitivity but at the expense of larger current leakages, which eventually reduces system efficiency [29].

17. Output Power

Another important statistic for assessing the efficacy of power harvesting systems was output power, which was typically expressed as determining the DC power, adding the ( ) to the voltage ( ) applied by the load. The performance of a system that was dependent. The measurement shows the effect on the load resistance of load . As an illustration,when a sensor serves as the load, ( )was more significant than ( ). In contrast, was more prevalent than V in applications that use electrolysis or LEDs [30].

Conclusion

The systematic review's main goal was to offer comprehensive assessment of the technological advancements and applications in wireless RF-EH signals. The objective was to assess recent developments, improvements in efficiency, and the use of RF-RH devices in real life. The review was conducted using the PRISMA methodology. Articles from prominent academic databases such as Elsevier, IEEE, and Wiley, published over the past decade, were systematically reviewed. The focus was on studies that detailed technological innovations, efficiency improvements, and practical applications of RF-EH systems. Studies lacking experimental or quantitative data were excluded. The review highlights several key advancements in RF-EH technologies. The review also identifies emerging applications, such asself-powered sensors and wearable technologies that benefit from these technological developments. The findings underscore the potential of RF-EH to greatly increase wireless energy systems' flexibility and effectiveness.

18. **Limitation and future scope:** Despite the advancement several limitations remain, challenges related to power density and the effective range of RF-EH systems are significant obstacles that need to be addressed. Additionally, there was a need for further research into optimizing the systems for a border range of applications and environments. Future research should focus on improving power density, expanding the range of RF-EH, and exploring novel materials and designs to enhance overall system performance. For RF-EH to reach its full potential in a variety of useful applications, resolving these issues will be essential.

Reference:

1. Clerckx, B., Popović, Z. and Murch, R., 2022. Future networks with wireless power transfer and EH [scanning the issue]. Proceedings of the IEEE, 110(1), pp.3-7.
2. Liu, L., Guo, X. and Lee, C., 2021. Promoting smart cities into the 5G era with multi-field IoT applications powered with advanced mechanical energy harvesters. Nano Energy, 88, p.106304.
3. Sansoy, M., Buttar, A.S. and Goyal, R., 2020, February. Empowering wireless sensor networks with RF energy harvesting. In 2020 7th International Conference on Signal Processing and Integrated Networks (SPIN) (pp. 273-277). IEEE.
4. Cansiz, M., Altinel, D. and Kurt, G.K., 2020. Effects of different modulation techniques on charging time in RF energy-harvesting system. IEEE Transactions on Instrumentation and Measurement, 69(9), pp.6904-6911.
5. Kwan, J.C., Chaulk, J.M. and Fapojuwo, A.O., 2020. A coordinated ambient/dedicated EH scheme using machine learning. IEEE Sensors Journal, 20(22), pp.13808-13823.
6. Das, D., Nasrollahpour, M., Xu, Z., Zaeimbashi, M., Martos-Repath, I., Mittal, A., Khalifa, A., Cash, S.S., Shrivastava, A., Sun, N.X. and Onabajo, M., 2020. A RFmagnetoelectric antenna prototyping platform for neural activity monitoring devices with sensing and EH capabilities. Electronics, 9(12), p.2123.
7. Raza, U. and Salam, A., 2020. On-site and external EH in underground wireless. Electronics, 9(4), p.681.
8. Mouapi, A., 2022. Radiofrequency EH systems for IoTapplications: A comprehensive overview of design issues. Sensors, 22(21), p.8088.
9. Reed, R., Pour, F.L. and Ha, D.S., 2021, May. An energy efficient RF backscatter modulator for IoT applications. In 2021 IEEE International Symposium on Circuits and Systems (ISCAS) (pp. 1-5). IEEE.
10. Li, K., Zhang, B., Li, X., Yan, F. and Wang, L., 2021. Electric field mitigation in high-voltage high-power IGBT modules using nonlinear conductivity composites. IEEE Transactions on Components, Packaging and Manufacturing Technology, 11(11), pp.1844-1855.
11. Niotaki, K., Carvalho, N.B., Georgiadis, A., Gu, X., Hemour, S., Wu, K., Matos, D., Belo, D., Pereira, R., Figueiredo, R. and Chaves, H., 2023. RF EH and wireless power transfer for energy autonomous wireless devices and RFIDs. *IEEE Journal of Microwaves*, *3*(2), pp.763-782.
12. Chaour, I., Fakhfakh, A. and Kanoun, O., 2017. Enhanced passive RF-DC converter circuit efficiency for low RF energy harvesting. Sensors, 17(3), p.546.
13. Abbasizadeh, H., Hejazi, A., Samadpoor Rikan, B., Kim, S.Y., Bae, J., Lee, J.M., Moon, J.H., Park, J.J., Pu, Y.G., Hwang, K.C. and Yang, Y., 2020. A high-efficiency and wide-input range RF energy harvester using multiple rectenna and adaptive matching. Energies, 13(5), p.1023.
14. Gu, X., Guo, L., Hemour, S. and Wu, K., 2020. Optimum temperatures for enhanced power conversion efficiency (PCE) of zero-bias diode-based rectifiers. IEEE Transactions on Microwave Theory and Techniques, 68(9), pp.4040-4053.
15. Song, C., Huang, Y., Zhou, J., Zhang, J., Yuan, S. and Carter, P., 2015. A high-efficiency broadband rectenna for ambient wireless energy harvesting. IEEE Transactions on Antennas and Propagation, 63(8), pp.3486-3495.

16. Wang, Y., Yang, K., Wan, W., Zhang, Y. and Liu, Q., 2021. Energy-efficient data and energy integrated management strategy for IoT devices based on RF energy harvesting. IEEE IoTJournal, 8(17), pp.13640-13651.
17. Dolgov, A., Zane, R. and Popovic, Z., 2010. Power management system for online low power RF EH optimization. IEEE Transactions on Circuits and Systems I: Regular Papers, 57(7), pp.1802-1811.
18. Iqbal, M.Z., Faisal, M.M. and Ali, S.R., 2021. Integration of supercapacitors and batteries towards high-performance hybrid energy storage devices. International Journal of Energy Research, 45(2), pp.1449-1479.
19. Liu, L., Guo, X., Liu, W. and Lee, C., 2021. Recent progress in the EH technology—from self-powered sensors to self-sustained IoT, and new applications. Nanomaterials, 11(11), p.2975.
20. Nundrakwang, S., Yingyong, P. and Isarakorn, D., 2020, July. EH for self-powered systems. In 2020 6th International Conference on Engineering, Applied Sciences and Technology (ICEAST) (pp. 1-4). IEEE.
21. Elahi, H., Munir, K., Eugeni, M., Atek, S. and Gaudenzi, P., 2020. EH towards self-powered IoT devices. Energies, 13(21), p.5528.
22. De Alwis, C., Kalla, A., Pham, Q.V., Kumar, P., Dev, K., Hwang, W.J. and Liyanage, M., 2021. Survey on 6G frontiers: Trends, applications, requirements, technologies and future research. IEEE Open Journal of the Communications Society, 2, pp.836-886.
23. Joseph, S.D., SH, H.S. and Huang, Y., 2021, August. Rectennas for wireless EH and power transfer. In 2021 IEEE International Symposium on Radio-Frequency Integration Technology (RFIT) (pp. 1-3). IEEE.
24. Gu, X., Hemour, S. and Wu, K., 2021. Far-field wireless power harvesting: Nonlinear modeling, rectenna design, and emerging applications. Proceedings of the IEEE, 110(1), pp.56-73.
25. Finnegan, J., Niotaki, K. and Brown, S., 2020. Exploring the boundaries of ambient RF EH with LoRaWAN. IEEE IoTJournal, 8(7), pp.5736-5743.
26. Mohd Aman, A.H., Shaari, N. and Ibrahim, R., 2021. IoT energy system: Smart applications, technology advancement, and open issues. International Journal of Energy Research, 45(6), pp.8389-8419.
27. Sanislav, T., Mois, G.D., Zeadally, S. and Folea, S.C., 2021. EH techniques for IoT. IEEE access, 9, pp.39530-39549.
28. Chen, D., Li, R., Xu, J., Li, D., Fei, C. and Yang, Y., 2023. Recent progress and development of radio frequency EH devices and circuits. Nano Energy, p.108845.
29. Mahenge, E., Sinde, R., Dida, M.A. and Sam, A.E., 2024. Radio Frequency EH for Underground Sensor Nodes: Possibilities and Challenges. IEEE Access, 12, pp.43772-43788.
30. Calautit, K., Nasir, D.S. and Hughes, B.R., 2021. Low power EH systems: State of the art and future challenges. Renewable and Sustainable Energy Reviews, 147, p.111230.

Acronyms	Description
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RF	Radiofrequency
EH	energy harvesting
IoT	Internet of Things
WEH	Wireless energy harvesting
Wi-Fi	Wireless fidelity
WSN	wireless sensor network
ICT	Information and communication technology

dBm	Decibel-milliwatts
DC	direct current
UWC	underground wireless Communications
WoS	Web of Science
GaN	Gallium nitrides
SiC	silicon carbide
rms	Root mean square
mV	Millivolt
AC	Alternating current
3D	Three dimensional
TENG	tribo-electrification nanogenerators
PV	photovoltaic
CMOS	Complementary metal-oxide-semiconductor