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# EMPOWERING TOMORROW: UNLEASHING THE POTENTIAL OF RADIO FREQUENCY (RF) ENERGY HARVESTING SYSTEMS: A STUDY FOR HIGH SCHOOL STUDENTS

**[1]Agamjot Kaur, [2]Hardeep Singh Manhas***
[1]High School Student, [2]Researcher
[1]12th Grade
[1] Queen's Valley School, Dwarka, New Delhi

## Abstract

The surging dependence on electronics fuels an insatiable demand for electricity, pushing traditional energy generation methods to their limits. This growing pressure not only exhausts precious resources but also burdens the environment with pollution. Finding clean, sustainable alternatives is no longer a choice, but a necessity. Along with renewable energy solutions like wind and solar energy, one promising solution lies in harvesting the vast, untapped potential of radio waves that permeate our surroundings. This ubiquitous energy source holds the potential to be converted into usable electricity, powering small devices or even contributing to the larger grid, if developed as a larger energy project. This research explores the viability of utilizing rectenna technology to capture this energy from the airwaves, offering a potentially transformative approach to address our ever-increasing energy needs. By harnessing this readily available resource, we can not only alleviate the pressure on conventional methods but also pave the way for a cleaner, more sustainable future. This endeavour delves into the technical aspects of rectenna design, analysing its efficiency and power conversion capabilities. Further, it assesses the feasibility of integrating such systems into various environments, considering real-world factors like distance from radio wave sources and environmental conditions. Ultimately, this research aims to unlock the potential of radio wave energy harvesting, offering a promising path towards a more secure and sustainable energy future.

**Keywords: Energy harvesting; Radio Waves; Radiofrequency Energy; RF-harvesting techniques; Radiofrequency Antenna; Wireless Energy; Wireless sensor networks**

## I. Introduction

Our reliance on electronic devices contributes to an escalating demand for electricity, straining conventional energy production methods. This demand not only depletes crucial resources but also results in environmental pollution. The pursuit of clean and sustainable alternatives is no longer a mere choice; it is now imperative. A promising avenue involves tapping into the vast, untapped energy potential of radio waves permeating our environment. These waves, facilitating communication between cell phones, Wi-Fi routers, and radio broadcasts, hold the potential to power low-energy devices or contribute to the broader power grid. Radio waves, a type of EM waves (electromagnetic) having wavelengths higher than infrared light, operate within a frequency range of 3 kHz to 300 GHz and exhibit wavelengths ranging from 1 millimetre to 100 kilometres.[1] Invisibly transmitting music, conversations, images, and data over vast distances daily, these waves play a crucial role in various devices, including cell phones, wireless networks, radio-controlled toys, television broadcasts, satellite communications, and cordless phones. The ambient electromagnetic radiation emitted by these sources can be harnessed and converted into electrical energy, which is then stored for diverse applications.[2] The core concept is to extract energy from the radio waves present in the air to generate electricity, offering a sustainable and clean energy solution.

This research seeks to explore the technical feasibility and practical applications of utilizing rectenna technology for this purpose. Comprising antennas and rectifiers, the system can convert the oscillating energy of radio waves into direct current electricity, rendering them usable for various applications.[2] Ultimately, this endeavour aims to unlock the untapped potential of radio wave energy harvesting, paving the way for a more sustainable future where clean energy is readily accessible.

Although the power density of these waves diminishes over distance, it proves adequate for devices with modest energy requirements, offering the potential to power LED lights, sensors, and microprocessors using energy derived from the ambient air.[3]

The primary purpose of this study is to delve into the technical feasibility and practical applications of such a system. Despite the relatively low power output from this energy conversion concept, it presents an avenue for the development of converters with low power demands. Furthermore, it sparks the potential creation of innovative devices designed to efficiently utilize small amounts of power. This research thus not only explores the system but also sets the stage for future advancements in clean and sustainable energy utilization.

## II. Requirement for Energy Harvesting from Radio Waves

Initially, the concept of a wireless power transmission system was introduced as a mechanism that emits electrical power from one location and captures it elsewhere in the Earth's atmosphere without the need for wires or any supporting medium. [4] This originated the Radio Wave power harvesting in free space dating back to the late 1950s. [5]

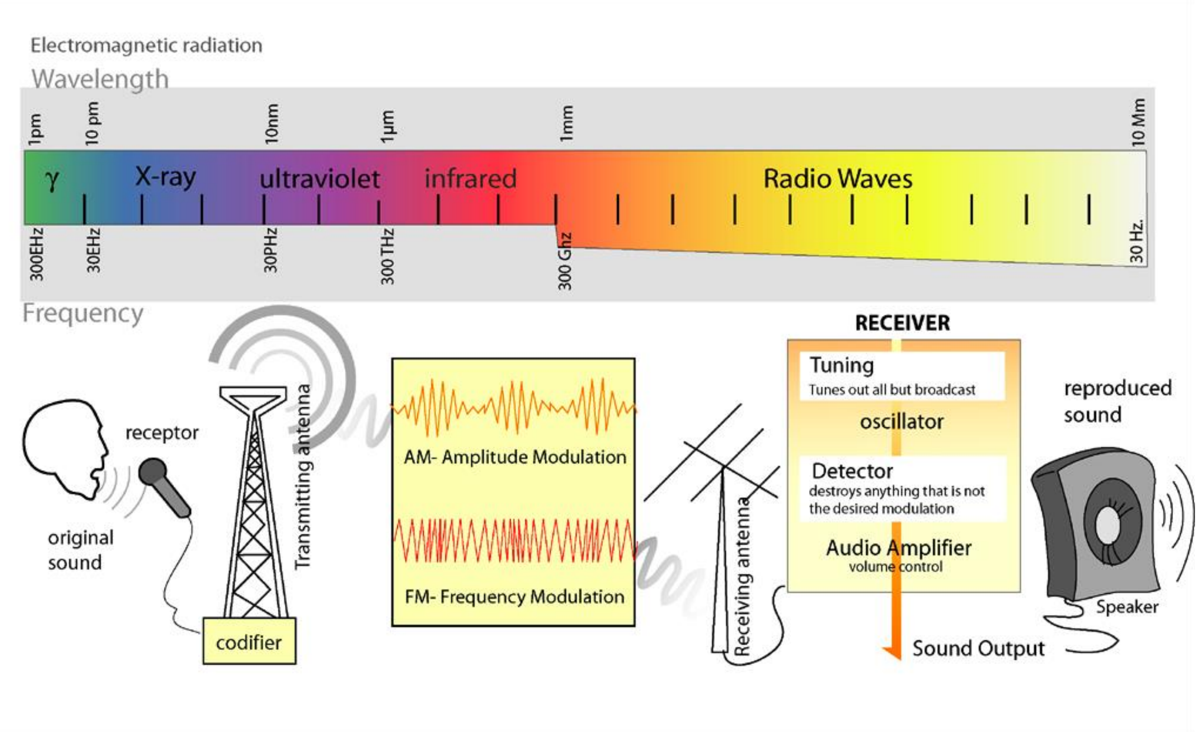

Fig.1. Image showing Electromagnetic Spectrum showing Radio waves ranging from 300Ghz (1mm) to 30 (10Mm), and radio wave transmission for broadcasting applications. [Wikimedia Image]

Subsequently, the concept of power harvesting emerged as a method to extract energy from the surrounding environment through various means, including thermoelectric power, vibrational energy, solar energy to electricity, and pressure changes. This method holds significant potential for replacing miniature batteries in low-power electronic devices and sensors. Presently, the majority of low-power remote sensor devices and embedded equipment rely on batteries for power, but these batteries have limited lifespans and need regular replacements. By employing energy harvesting methods, devices and systems can achieve self-sustainability in terms of the power needed to operate, resulting in an unrestricted operating span. Consequently, the need for energy and power preservation becomes negligible.[6]

Addressing the critical issue of processing battery waste, a significant number of batteries end up in landfills, contributing to pollution.[7] The highly beneficial solution to reduce battery waste is to minimize their use. The application of this technology can decrease dependency on batteries, positively impacting the environment. Furthermore, the method of utilising radio wave energy does not generate waste, making it a sustainable power source. In comparison to thermal or kinetic energy, radio wave energy is not constrained by space or time. Radio waves are present both outside and inside houses, in countryside and city areas, the whole day. Despite its lower energy density in the surroundings, specialised sources can be added for more effective energy generation and power transfer, and a boosting circuit can be tailored to meet the load application requirements. This characteristic encourages efforts to prioritise this technique in applications such as wireless sensor networks (WSNs)[8] and the Internet of Things (IoT).[9]

Table 1. Comparison of different options for Energy Harvesting Systems.

| Energy Source | Power Density | Advantages | Disadvantages |
|---|---|---|---|
| Solar [10] | Moderate to High | • Abundant and renewable energy source.<br>• Low environmental impact during operation.<br>• Scalable and suitable for various scales of applications. | • Intermittent energy production due to weather conditions.<br>• High initial installation costs.<br>• Dependency on sunlight, reduced efficiency during night. |
| Wind [11] | High | • Clean and renewable energy.<br>• Scalable, suitable for both small and large-scale applications.<br>• Low greenhouse gas emissions. | • Impact on wildlife, particularly birds and bats.<br>• Intermittent energy production based on wind availability. |

| | | | |
|---|---|---|---|
| | | | • Noise pollution and visual impact on landscapes. |
| Thermal [12] | Moderate to High | • Continuous energy production.<br>• Can provide both electricity and heat.<br>• Low environmental impact during operation | • High initial costs for construction and maintenance.<br>• Limited to specific geographic locations with high temperature differentials.<br>• Efficiency depends on temperature differentials. |
| Radio Wave [13] | Low to Moderate | • Abundant and omnipresent energy source.<br>• Constant availability throughout the day.<br>• Potentially unlimited operating lifespan.<br>• Minimal environmental impact during operation. | • Low power density, requiring efficient harvesting technology.<br>• Challenges in efficient conversion due to lower energy density.<br>• Limited power for high-energy-demand applications.<br>• Limited intentional sources for boosting power transmission. |

## III. Methodology for Designing a system to harvest Electrical Power from Radio Waves

A Radio wave energy harvesting system comprises two essential elements: an antenna designed to capture Radio waves and transform them into alternating current (AC) voltage, and a rectifier circuit responsible for converting AC voltage into direct current (DC) voltage, facilitating the power supply to the intended device. In most energy harvesting systems, the antenna and rectifier are integrated into a singular component known as the rectenna. [14]

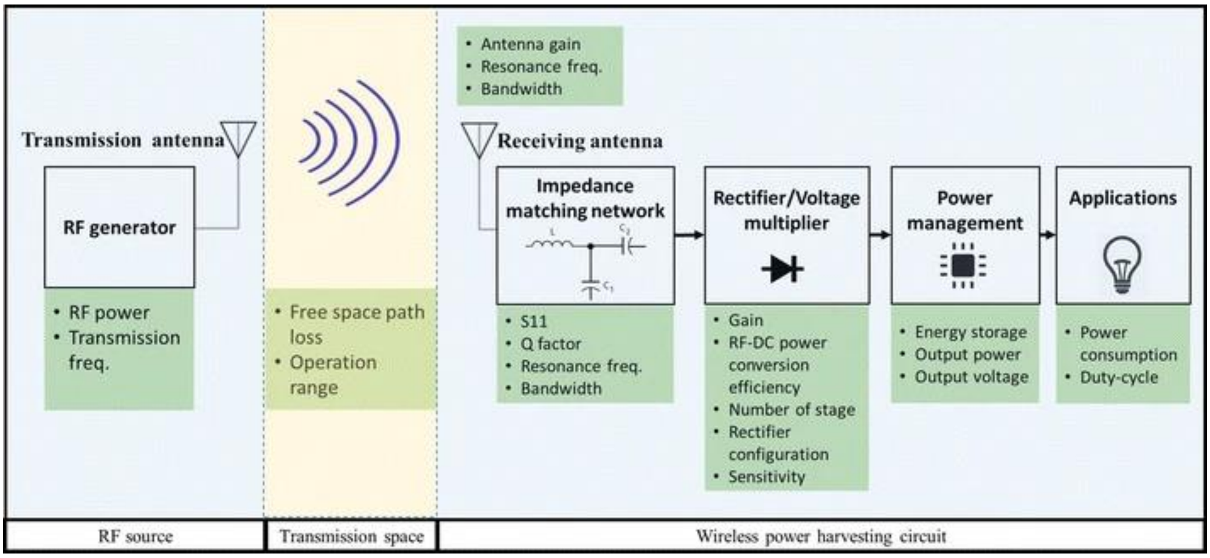

Fig. 2. Block diagram for Radio wave energy harvesting system. [15]

### Antenna for Energy Harvesting System

An antenna is a specialized device designed to intercept and capture radio waves from the surrounding environment. The antenna consists of conductive elements configured in a specific geometry to maximize its efficiency in capturing radio waves.[16] When radio waves, carrying information and energy, pass through the antenna's structure, they induce oscillating electric currents within the antenna elements. This process is based on the principle of electromagnetic induction, where the changing magnetic field associated with the radio waves induces a flow of electric current in the conductive material of the antenna.[17] In essence, the antenna acts as a transducer, converting the energy carried by radio waves into electrical energy. The geometry and size of the antenna are carefully designed to resonate with specific frequencies, enhancing its ability to capture and absorb radio waves effectively. Once the antenna captures these waves, the induced electric currents are then directed to the subsequent components of the RF energy harvesting system, such as the rectifier circuit, to further process and convert the AC voltage into usable DC voltage for powering electronic devices or systems.

For an antenna used in an RF harvesting system, several key parameters are crucial for its design and performance, including antenna gain, resonance frequency, and bandwidth. Antenna gain is a measure of the ability of an antenna to direct or focus the transmitted or received RF energy in a specific direction.[18] Other than an isotropic antenna that transmits or receives waves uniformly in all directions, a specially designed antenna can transmit or receive waves in a specific direction. Antenna gain (G) is defined as the proportion of the highest density of power exhibited by an antenna at a specific distance to the density of an ideal antenna (isotropic) operating at the same distance and radiating an equivalent power. Essentially, antenna gain serves as a measure of the antenna's directivity. The power density for the receiving antenna is defined by Equation 1.

$$S = \frac{P_R G_R}{4\Pi R^2} \qquad \text{Equation 1}$$

Where S is the power density (in watts per square meter, W/m²), $P_R$ is the power received by the antenna (in watts, W), $G_R$ is the antenna gain, and R is the distance from the transmitting antenna to the receiving antenna (in meters, m).

Every antenna has its own operating natural frequency. Resonance occurs when the natural frequency of the antenna matches the frequency of the incoming RF signals. The resonance frequency is the frequency at which an antenna exhibits maximum efficiency in capturing and converting RF waves into electrical energy.[2] It is determined by the physical dimensions and characteristics of the antenna and can be calculated using the formula in Equation 2 for the resonant frequency of a half-wave dipole antenna.

$$fo = \frac{c}{2L} \qquad \text{Equation 2}$$

Where fo is the resonance frequency (in Hertz, Hz) c is the speed of light in a vacuum (approximately $3\times10^8$ m/s), and L is the length of the antenna (in metres, m).

The resonance frequency decreases as the dimensions of the antenna increase. Consequently, utilizing large apertures is necessary for transmitting and receiving low-frequency waves, making it complicated for applications involving small devices.[19]

The antenna's bandwidth refers to the span of frequencies over which the antenna can function effectively.[20] A broad bandwidth antenna can capture signals across a broader frequency range compared to a narrow bandwidth antenna. While a wide bandwidth antenna is beneficial for capturing a diverse range of incident energy, it also poses a higher susceptibility to interference from unwanted frequencies, introducing the risk of noise interference.

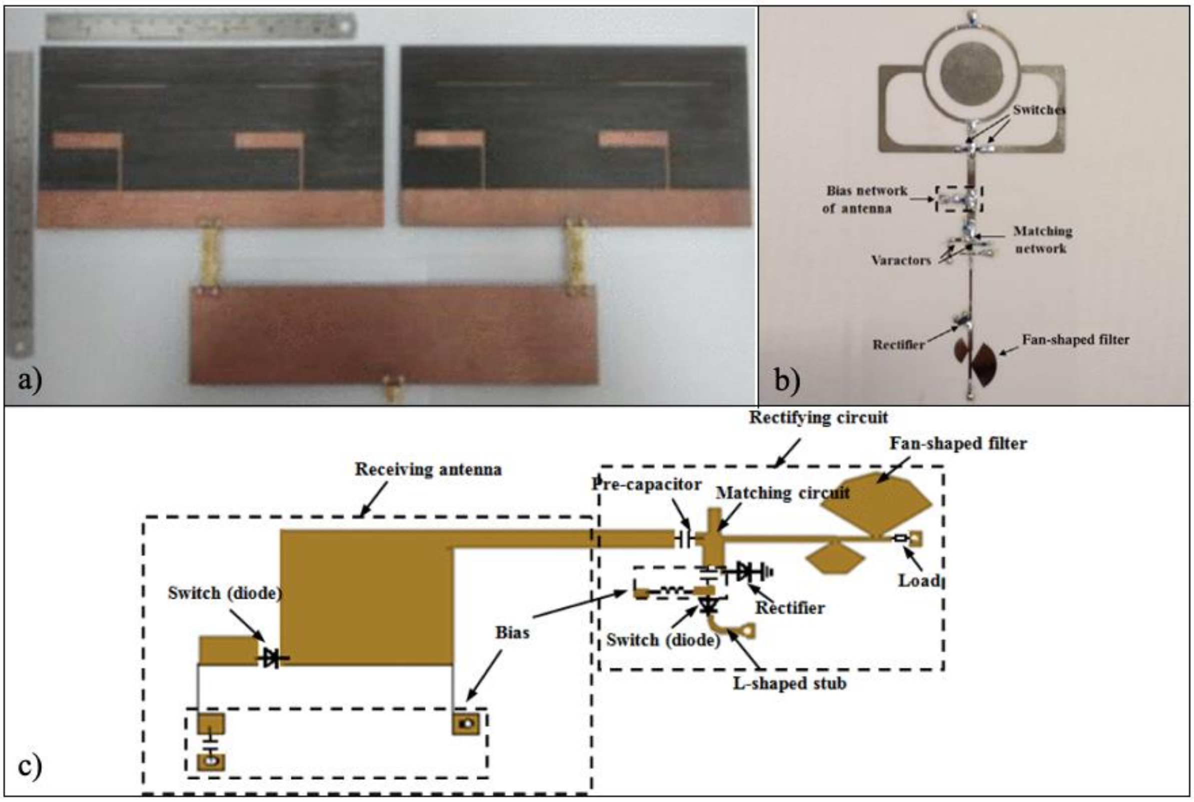

Fig. 3. Radiowave Energy Harvesting Antenna system demonstrated by some groups, a) Photo of 1×4 quasi-Yagi array antenna[26], b) Photo of the fabricated plate rectenna, 100mmX160mm[21], and c) Photo of compact reconfigurable rectenna 68mmX34mm[23].

Power-harvesting antennas are currently undergoing extensive research and development. Technological advancements have facilitated the emergence of diverse methods for designing and fabricating antennas, contributing to their compactness and maturity. Plate antennas find wide popularity and numerous applications[21][22], with on-chip antennas being favoured for compact and small-scale uses. In a study, antennas resonating at 4.9 and 5.9 GHz demonstrated power conversion efficiencies (PCEs) of 65.2% and 64.8%, respectively.[23] Another antenna presented in a study stands out for its capability to operate simultaneously at 2.45 and 5.8 GHz, yielding a 2.6 V output, an efficiency of 65%, and a power density of 10 mW/cm2.[24] Array antennas, favoured over large aperture antennas, eliminate the need for high breakdown voltage diodes for operation. Array antennas can be connected pre- or post-rectification, with the former enhancing power retrieval at the main beam and the latter expanding the capability to harvest power from various angles away from the main beam[25]. Array antennas can be connected in series or parallel to achieve high voltage or large current. To illustrate antenna arrays, a group introduced a T-junction connecting four quasi-Yagi antennas. A notable feature of this work is the flexibility of the T-junction, enabling a transition from a 1 × 4 array to 2 × 2 array topology. As a result, the system operated at an ambient power level as low as 455 µW/cm2 while achieving a 40% efficiency.[26]

### Impedance Matching Network

In low-power electrical systems, addressing power leakage during transmission is crucial to prevent energy insufficiency. Incorporating an impedance matching network ensures optimal power transfer between the Radio wave source and load, where the receiving antenna acts as the source and the rectifier/voltage multiplier functions as the load.[27] Maintaining identical impedances between the source and load is essential for efficient power transfer in RF circuits, as any mismatch results in reflected power flow, reducing system efficiency. The system, consisting of reactive components, aligns the impedances of the source and load.

Three fundamental matching configurations—L, T, and π networks—are commonly used.[28] L matching, popular for its simplicity with two components and no impact on the circuit's quality factor (Q), is widely employed. T and π configurations are more intricate, and organizing them into multiple stages alters the Q factor, beneficial for enhancing voltage boost.

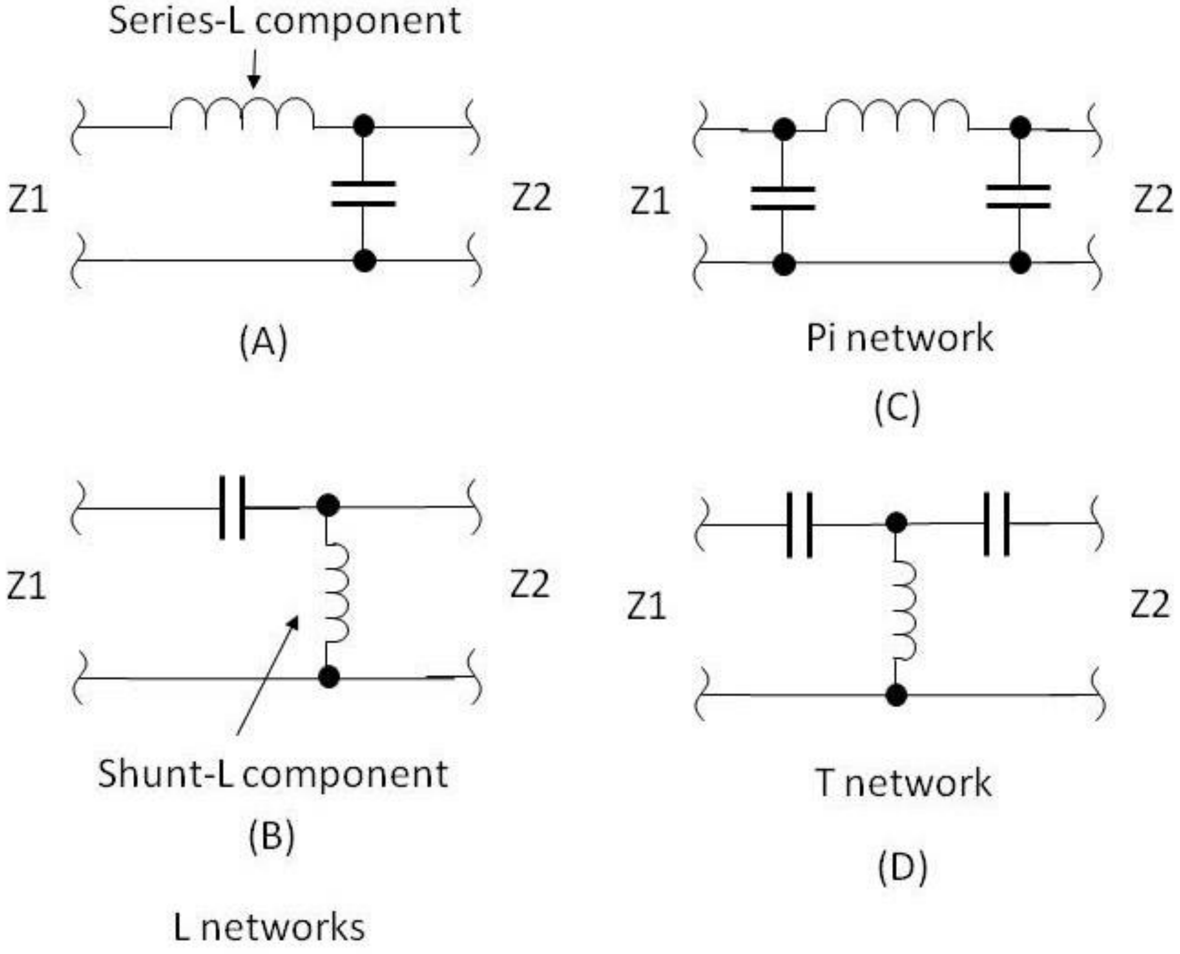

Fig. 4. Various configurations for Impedance Matching networks utilised in Radio wave energy harvesting system. [29]

For instance, suboptimal impedance matching and multiport ladder matching methods introduced by a group aimed to enhance matching performance and harvested power but increased circuit complexity due to additional components.[30] Another group utilized transmission lines and self-designed metal–insulator-metal diodes for THz frequency IMN applications, deviating from traditional lumped components.[31] Additionally, fixed and tunable IMN approaches were introduced to achieve better matching with wide-band and multi-band antennas.[32]

### Rectifier for Energy Harvesting System

The power density of Radio wave energy obtained from free space diminishes at a rate of $1/d^2$, where d is the distance from the radio wave source.[33] Consequently, a power amplifier circuit becomes necessary to generate sufficient DC energy from electromagnetic waves to drive loads. Two scenarios arise, if the load's power consumption is lower than the average power harvesting, electronic devices may operate continuously; otherwise, if the load consumes more energy than the harvesting circuit generates, continuous device operation becomes unfeasible.[34]

Diodes are commonly employed for rectifying Radiowave signals in power harvesting applications.[35] Rectification typically employs diode-based circuits, with the half-wave rectifier being fundamental but inefficient due to power loss. A more effective solution is the full-wave rectifier, offering stability and efficiency by utilizing both positive and negative cycles of the AC input. A bridge rectifier rectifies both cycles.[36]

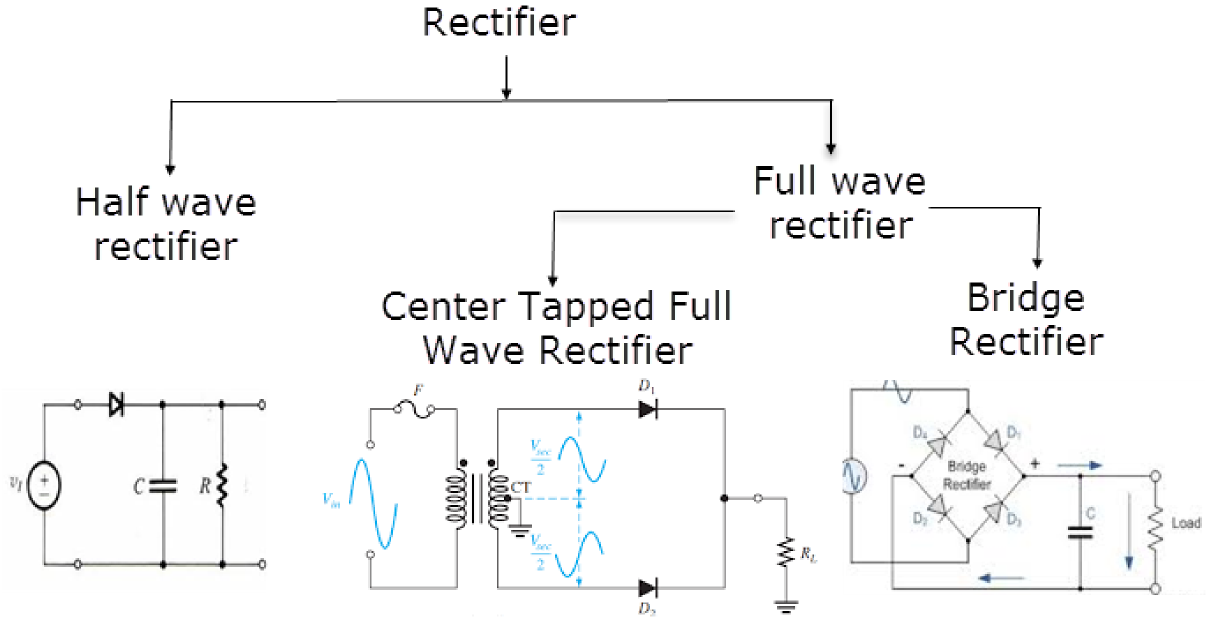

Fig. 5. Half Wave and Full Wave rectifier configurations for energy harvesting applications.[36]

MOSFET technology is emerging as an alternative for rectification and boosting, allowing integration into ICs with low threshold voltages and high efficiency.[37] The differential drive voltage multiplier is widely used for its low leakage current and adaptability for specific applications.[38] The number of stages in a voltage multiplier impacts sensitivity and efficiency. Increasing stages results in higher voltage multiplication but also increased loss. Conversely, a few stages exhibit less voltage drop but demand higher threshold voltages. Optimal stage selection depends on application targets, considering the trade-off between sensitivity and efficiency.[39]

## IV. Applications of Radio Wave Energy Harvesting System

RF energy harvesting technology demonstrates versatile applications, spanning wireless sensor networks (WSNs)[8], wireless charging[40], active RFID tags[41], IoT networks[9], and medical devices[42].

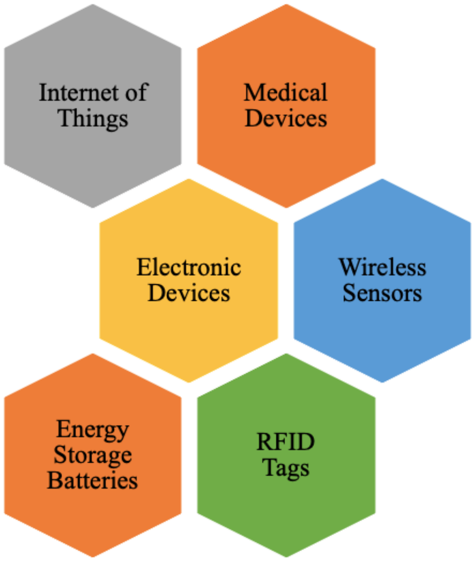

Fig. 6. Various Applications for Radio Wave Energy Harvesting Technology

In the realm of WSNs, these harvesters empower sensors with wireless functionality, mitigating costs associated with battery replacements and extending their deployment possibilities to challenging locations. The wireless charging of portable devices harnesses ambient RF energy, providing a cost-effective and connector-free charging solution. The efficiency of active RFID tags improves significantly as RF energy harvesters eliminate the reliance on batteries, enhancing their overall performance. In IoT networks, RF energy harvesting emerges as a pivotal technology to optimize energy efficiency and extend the battery life of relay nodes. By using RF energy harvesters, these nodes can self-power from ambient RF signals, ensuring prolonged and sustainable operation. Additionally, the application of RF energy harvesting extends to the medical field, particularly in battery-free bio-signal processing systems. These systems enable continuous monitoring of vital signals, such as electrocardiogram (ECG), electromyogram (EMG), and electroencephalogram (EEG), with a reduced device size. This advancement holds promise for enhancing healthcare technologies, offering continuous monitoring without the constraints of frequent battery replacements.

## V. Challenges for Radio Wave Energy Harvesting Systems

The limitations of RF power harvesting systems include a reduction in energy density over propagation distance, governed by the inverse square law.[43] Compliance with regulations, such as maximum transmitter power output in different nations, imposes constraints. Miniaturizing sensor designs is crucial for RF harvesting, requiring a balance between size reduction and harvesting efficiency improvement. The sensitivity of RF harvesting circuits influences performance, especially at varying distances. Impedance mismatch and energy loss in non-line of sight environments are challenges, while scheduling policies and energy fairness among nodes need attention for optimal system performance. Practical experimentation is lacking in many proposed Medium Access Control (MAC) protocols for energy harvesting networks.[44]

## VI. Conclusion

This article provides an overview of the methodology and current status of Radio wave energy harvesting technology, emphasizing its potential to replace conventional techniques shortly. Several practical applications have already been realized, with a fundamental Radio wave energy harvesting unit comprising three main components: the antenna, impedance matching network (IMN), and rectifier. The integration and synergy of these modules determine the overall system efficiency. Radio waves, the electromagnetic waves, being benign and abundant, offer an alternative energy source, particularly beneficial for low-power electronics devices, healthcare applications, and the advancement of Wireless Sensor Networks (WSNs) and the Internet of Things (IoT). Despite recent advancements, there are ongoing efforts to enhance Radio wave energy harvesting, focusing on areas like extended operation range, reduced transmission loss, improved Power Conversion Efficiency (PCE), and compact system dimensions. Addressing these challenges could propel Radio wave energy harvesting into a prominent role, ushering in a new era of sustainable energy.

## Author’s Bio

Passionate about environmental science, I'm driven by a desire to make a meaningful impact on the world. My curiosity fuels my love for scientific inquiry, providing a platform to delve into the depths of knowledge. With a steadfast commitment to understanding our planet's intricacies, I seek to contribute to solutions that address environmental challenges. Eager to explore and innovate, I aspire to leverage science as a tool for positive change, embracing the endless possibilities it offers for exploration and discovery.

## References

[1]. Brown WC. The history of power transmission by radio waves. IEEE Transactions on microwave theory and techniques. 1984 Sep;32(9):1230-42.

[2]. Shinohara N. The wireless power transmission: inductive coupling, radio wave, and resonance coupling. Wiley Interdisciplinary Reviews: Energy and Environment. 2012 Nov;1(3):337-46.

[3]. Shinohara N. Wireless power transfer via radiowaves. John Wiley & Sons; 2014 Jan 17.

[4]. Brown WC. The history of wireless power transmission. Solar energy. 1996 Jan 1;56(1):3-21.

[5]. Brown WC. Experiments involving a microwave beam to power and position a helicopter. IEEE Transactions on Aerospace and Electronic Systems. 1969 Sep(5):692-702.

[6]. Shih E, Bahl P, Sinclair MJ. Wake on wireless: An event driven energy saving strategy for battery operated devices. InProceedings of the 8th annual international conference on Mobile computing and networking 2002 Sep 23 (pp. 160-171).

[7]. Harrist DW. Wireless battery charging system using radio frequency energy harvesting (Doctoral dissertation, University of Pittsburgh).

[8]. Raghavendra CS, Sivalingam KM, Znati T, editors. Wireless sensor networks. Springer; 2006 Dec 15.

[9]. Kamalinejad P, Mahapatra C, Sheng Z, Mirabbasi S, Leung VC, Guan YL. Wireless energy harvesting for the Internet of Things. IEEE Communications Magazine. 2015 Jun 10;53(6):102-8.

[10]. Sharma H, Haque A, Jaffery ZA. Solar energy harvesting wireless sensor network nodes: A survey. Journal of Renewable and Sustainable Energy. 2018 Mar 1;10(2).

[11]. Jushi A, Pegatoquet A, Le TN. Wind energy harvesting for autonomous wireless sensor networks. In2016 Euromicro Conference on Digital System Design (DSD) 2016 Aug 31 (pp. 301-308). IEEE.

[12]. Lu X, Yang SH. Thermal energy harvesting for WSNs. In2010 IEEE International Conference on Systems, Man and Cybernetics 2010 Oct 10 (pp. 3045-3052). IEEE.

[13]. Zungeru AM, Ang LM, Prabaharan S, Seng KP. Radio frequency energy harvesting and management for wireless sensor networks. Boca Raton, FL, USA: CRC Press; 2012 Mar 5.

[14]. Song C, Huang Y, Zhou J, Zhang J, Yuan S, Carter P. A high-efficiency broadband rectenna for ambient wireless energy harvesting. IEEE Transactions on Antennas and Propagation. 2015 May 11;63(8):3486-95.

[15]. Tran LG, Cha HK, Park WT. RF power harvesting: a review on designing methodologies and applications. Micro and Nano Systems Letters. 2017 Dec;5:1-6.

[16]. Shrestha S, Noh SK, Choi DY. Comparative study of antenna designs for RF energy harvesting. International Journal of Antennas and Propagation. 2013 Jan 1;2013.

[17]. Daniels JJ, Vendl M, Ehsani MR, Allred BJ. Electromagnetic induction methods. Handbook of agricultural geophysics. 2008 Jun 10:109-28.

[18]. Benner E, Sesay AB. Effects of antenna height, antenna gain, and pattern downtilting for cellular mobile radio. IEEE Transactions on Vehicular Technology. 1996 May;45(2):217-24.

[19]. Shinohara N. Beam efficiency of wireless power transmission via radio waves from short range to long range. Journal of electromagnetic engineering and science. 2010;10(4):224-30.

[20]. Harrington RF. Effect of antenna size on gain, bandwidth, and efficiency. J. Res. Nat. Bur. Stand. 1960 Jan 1;64(1):1-2.

[21]. Lu P, Yang XS, Li JL, Wang BZ (2016) Polarization reconfigurable broadband rectenna with tunable matching network for microwave power transmission. IEEE Trans Antennas Propag 64:1136–1141

[22]. Chou JH, Lin DB, Weng KL, Li HJ (2014) All polarization receiving rectenna with harmonic rejection property for wireless power transmission. IEEE Trans Antennas Propag 62:5242–5249

[23]. Lu P, Yang XS, Li JL, Wang BZ (2015) A compact frequency reconfigurable rectenna for 5.2- and 5.8-GHz wireless power transmission. IEEE Trans Power Electron 30:6006–6010

[24]. Ren YJ, Farooqui MF, Chang K (2007) A compact dual-frequency rectifying antenna with high-orders harmonic-rejection. IEEE Trans Antennas Propag 55:2110–2113

[25]. Olgun U, Chen CC, Volakis JL (2011) Investigation of rectenna array configurations for enhanced RF power harvesting. IEEE Antennas Wirel Propag Lett 10:262–265

[26]. Sun H, Guo Y, He M, Zhong Z (2013) A dual-band rectenna using broadband yagi antenna array for ambient RF power harvesting. IEEE Antennas Wirel Propag Lett 12:918–921

[27]. Hoarau C, Corrao N, Arnould JD, Ferrari P, Xavier P. Complete design and measurement methodology for a tunable RF impedance-matching network. IEEE transactions on microwave theory and techniques. 2008 Oct 24;56(11):2620-7.

[28]. Sun Y, Fidler JK. Design method for impedance matching networks. IEE Proceedings-Circuits, Devices and Systems. 1996 Aug 1;143(4):186-94.

[29]. Schweber, B. (2021, July 14). VSWR and impedance, Part 5: Making a match. Analog IC Tips. https://www.analogictips.com/vswr-and-impedance-part-5-making-a-match-faq/

[30]. Shen S, Murch RD (2016) Impedance matching for compact multiple antenna systems in random RF fields. IEEE Trans Antennas Propag 64:820–825

[31]. Etor D, Dodd LE, Wood D, Balocco C (2015) Impedance matching at THz frequencies: optimizing power transfer in rectennas. In: 2015 40th international conference on infrared, millimeter, and terahertz waves (IRMMW-THz), pp 1–2

[32]. Marrocco G (2008) The art of UHF RFID antenna design: impedance-matching and size-reduction techniques. IEEE Antennas Propag Mag 50:66–79

[33]. Hatay M (1980) Empirical formula for propagation loss in land mobile radio services. IEEE Trans Veh Technol 29:317–325

[34]. Radiom S, Vandenbosch G, Gielen G (2008) Impact of antenna type and scaling on scavenged voltage in passive RFID tags. In: International workshop on antenna technology: small antennas and novel metamaterials, 2008. iWAT 2008, pp 442–445

[35]. Dai H, Lu Y, Law MK, Sin SW, Seng-Pan U, Martins RP. A review and design of the on-chip rectifiers for RF energy harvesting. In2015 IEEE International Wireless Symposium (IWS 2015) 2015 Mar 30 (pp. 1-4). IEEE.

[36]. Agarwal, T. (2020, May 22). Differences between Full Wave Bridge & Center Tapped Full Wave Rectifier. ElProCus - Electronic Projects for Engineering Students. https://www.elprocus.com/full-wave-bridge-rectifier-versus-center-tapped-full-wave-rectifier

[37]. Lin GC, Lee MW, Hsu YC. An AC-DC rectifier for RF energy harvesting system. In2012 Asia Pacific Microwave Conference Proceedings 2012 Dec 4 (pp. 1052-1054). IEEE.

[38]. Kotani K, Sasaki A, Ito T (2009) High-efficiency differential-drive CMOS rectifier for UHF RFIDs. IEEE J Solid-State Circuits 44:3011–3018

[39]. Rodriguez AN, Cruz FRG, Ramos RZ (2015) Design of 900 Mhz AC to DC converter using native Cmos device of TSMC 0.18 micron technology for RF energy harvest application. Univers J Electr Electron Eng 3:7

[40]. Ansari TR, Khan A, Ansari I. Wireless charging of mobile battery via optimization of RF energy harvesting system. International Journal of Scientific & Engineering Research. 2015 Jul;6(7):942-9.

[41]. Ferdous RM, Reza AW, Siddiqui MF. Renewable energy harvesting for wireless sensors using passive RFID tag technology: A review. Renewable and Sustainable Energy Reviews. 2016 May 1;58:1114-28.

[42]. DeLong B, Chen CC, Volakis JL. Wireless energy harvesting for medical applications. In2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting 2015 Jul 19 (pp. 1213-1213). IEEE.

[43]. Le T, Mayaram K, Fiez T. Efficient far-field radio frequency energy harvesting for passively powered sensor networks. IEEE Journal of solid-state circuits. 2008 Apr 22;43(5):1287-302.

[44]. Sherazi HH, Zorbas D, O’Flynn B. A comprehensive survey on RF energy harvesting: Applications and performance determinants. Sensors. 2022 Apr 13;22(8):2990.