A Comprehensive Review On Recent Developments, Techniques and Applications of Radio Frequency Energy Harvesting in Wireless Energy Harvesting

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ABSTRACT

The ambient energy sources often considered as waste, can be captured from the surroundings and morphed into usable electricity power for all small electronic devices using Wireless Energy Harvesting (WEH). Energy harnessing is mostly recognized as an effective method for powering low energy appliances through ambient energy sources. These sources include Radio Frequency (RF), Solar Energy, Kinetic Energy, and Thermal Energy. Advancement of wireless communication technologies leading to increase in transferred power density has enabled the harvesting of RF energy. Thus, it poses a practical and sustainable solution for high energy demands. Applications like health well-being wearables, remote sensors, and industrial automation require uninterrupted power, which can be supplied through this process. This paper investigates energy harvesting from wireless networks and their advanced spectrum as hybrid energy sources where RF energy is incorporated with other ambient sources. In particular, multiple energy harvesting techniques, such as rectenna based RF energy harvesting, have been analysed for the level of efficiency achieved and ease of implementation of energy harvesting devices. Further, the key issues of low power conversion efficiency, interference, and optimization techniques to enhance energy transfer efficiency are examined. Additionally, the paper outlines its possible uses in the IoT, smart cities, and automated sensor networks. The merging of energy harvesting with 5G and Wi-Fi systems acts as a bridge towards self-sustaining wireless communication systems which will further aid in promoting green and sustainable communication technologies.

Keywords: Radio Frequency, rectenna, 5G Wi-Fi networks

1. Introduction

As wireless communication technologies rapidly expand, 5G and Wi-Fi networks radiate large quantities of radio frequency (RF) energy to facilitate data transmission. Yet, much of this energy is wasted and radiated as electromagnetic radiation into the surrounding environment [1]. Such wasted RF energy presents an underutilized source of sustainable energy harvesting, particularly in urban areas where 5G and Wi-Fi signals are prevalent. At the same time, traditional battery operated devices, including IoT sensors and mobile electronics, are hampered by limited battery life, expensive maintenance, and environmental issues related to disposing of batteries [2]. These constraints necessitate an immediate need for new power solutions that will maximize the operating life of wireless devices without constant battery replacements. Wireless energy harvesting (WEH) steps in as a viable solution by harvesting and converting surrounding RF energy to obtain electrical energy. RF energy harvesting was first introduced as a method to make passive and battery free communication systems possible, and initial uses were observed in passive RFID tags and distant sensing hardware [3]. Since then, technological advancements in rectifying circuits, antenna, and power management have greatly enhanced the efficiency of RF-EH systems, and thus they are applicable to a vast majority of applications like intelligent cities, wearable electronics including autonomous sensor networks. This review paper thoroughly analyses the salient features of RF energy harvesting from 5G and Wi-Fi networks. It investigates the main sources of ambient RF energy, new methods of efficient energy harvesting, and the chief challenges in actual implementation. It also presents solutions to counter these drawbacks and analyses the potential applications that WEH technology will likely advance. Based on integrating latest research directions, this paper strives to offer a vision of RF-EH's feasibility and direction for the future towards making wireless systems sustainable and self-powered.

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2. Literature Review

2.1 Essentials of Wireless Energy Harvesting:

The naturally abundant energy sources observed in the surroundings can be harvested to convert them into electrical power. These energy sources are referred to as ambient energies. These energy sources are often considered waste, however they can be captured from the given surroundings and be changed in usable electricity for all low powered electric appliances. This methodology altogether is called as Wireless Energy Harvesting (WEH) [4]. There are mainly four sources of WEH which are radio frequency energy, solar energy, kinetic energy and thermal energy as shown in Fig1. These are explained below.

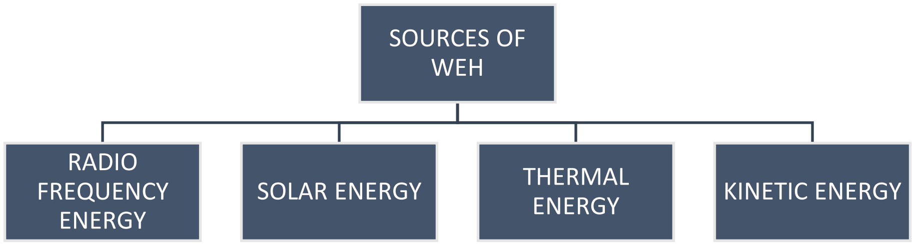

Fig.1. Main sources of Wireless Energy Harvesting.

Radio Frequency Energy Harvesting converts energy carried by EM waves from the communication network, the likes of Wi-Fi routers, 5G base stations, and other RF signal sources, into electrical power that can then be used. It is in this process that rectennas, or rectifying antennas, come in, and they convert the alternate radio waves in a constant voltage power source Magnitude, frequency, and design of the rectenna play their roles among other factors that determine how well RF energy harvesting will work. Whereas low power conversion efficiency (PCE) used to be a long-time bottleneck to RF harvesting, very high rates of energy conversion are now achieved through the recently introduced mixed-material rectennas and beamforming techniques. These advancements have made RF energy harvesting a cost effective and sustainable way of operating energy efficient devices. The innovation could be leveraged more efficiently in wireless sensor networks, IoT devices located at remote ends, and wearable electronics that are power-on revved [5]. With the reduction or complete elimination of traditional battery changes, RF energy harvesting enables the realization of self-sustaining electronic systems whose dependability can be improved and lifetime extended. This is particularly beneficial for telemonitoring, smart home technologies, industrial automation and medicine, where power supply needs to be constant to ensure proper functioning of operations**.**

On the other hand, Solar energy harvesting is one of the most popular decentralized means of converting sunlight into electricity using photovoltaic (PV) cells and provides the basic element for stable renewable power within a day period. This is absolutely indispensable for hybrid energy systems. Thin-film and organic PV cells can be combined with RF energy harvesters to expand the possibilities for delivering constant and reliable power both indoors and outdoors. An alternative energy system, RF energy, operates with full dependence on network traffic, environmental conditions, and signal strength but solar energy provides an alternative source of power during specific hours of the day. That is why innovative technologies that trap both natural and artificial light, like transparent solar panels and perovskite-based solar cells, have been researched for better energy capture and use, especially for urban areas where sunlight intensity is low.

Mechanical energy from motion, vibrations, pressure is captured by the Kinetic Energy Harvesting mechanism and is converted into electricity using electromagnetic transducers. Wearable electronics, smart textiles and self powered sensors make use of this technique the most. Proper and continuous power supply is ensured by integrating kinetic systems into hybrid harvesters alongside RF techniques in dynamic environment. For example, the performance of wireless sensor networks is enhanced by combining triboelectric nanogenerators with RF energy harvesting in particular scenarios where environment vibration is present [6]. Healthcare monitoring and industrial automation makes most use of these hybrid systems, as continuously a fixed amount of energy supply is crucial despite any frequent movement. Furthermore, Thermal energy harvesting leverages temperature gradients to create electricity using thermoelectric generators (TEGs). These devices make wrong usage of the Seebeck effect, where a voltage is produced across a material due to a temperature difference. In hybrid systems, thermal energy harnessing is particularly advantageous in the industrial or urban area were waste heat from electronic devices, HVAC systems, or 5G base stations can be converted into usable power [7]. Researchers are trying to find more adaptable and nanostructured thermoelectric materials to increase energy changing efficiency and merge them effortlessly with other harnessing technologies. Hence, these multiple sources of energy are combined together in Hybrid Energy harvesting process to provide reliable supply of energy with enhanced power generation. This reduces the dependence on any single energy source and hence gives a more stable and higher power output. The integration of different energy inputs including RF waves, solar, kinetic , as well as heat based sources let devices to autonomously work with minimal external power input which mitigates the limitations of individual harvesting techniques as demonstrated in Fig2. This enables widespread use across domains like smart urban systems, healthcare, and IoT networks. Guo et al. have designed an all-fibre hybrid nanogenerator for wearable applications that combines piezoelectric and triboelectric mechanisms, demonstrating for the first time the possibility of harvesting diverse energy sources to drive smart textiles [8]. Such developments play a part in the development of independent electronic devices by helping eliminate batteries and allowing the formation of eco-friendly, wireless energy systems.

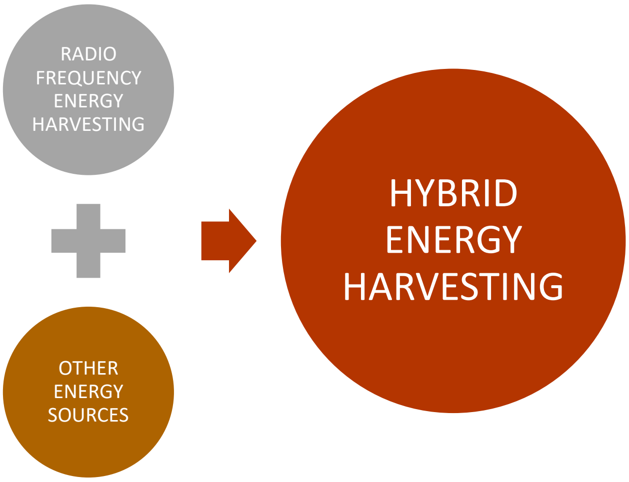

Fig.2. Representation of integration of energy sources for Hybrid Energy Harvesting.

2.2 RF Energy Harvesting Mechanism:

Nowadays, in communication devices like mobile phones, RF signals are persistently radiated by devices like Wi-Fi Routers and 5G transmitters. These signals can be transformed through a method known as RF energy harvesting (RFEH), which alters them in such a way and transforms them into useful electrical energy. This method 'RFEH' follows a systematic energy conversion process comprised of four essential steps intended to achieve energy efficiency for multiple low powered technologies including portable devices, Internet of Things (IoT) devices, and remote-control surveillance devices. The primary four processes of harvesting RF energy are as shown in Fig.3.

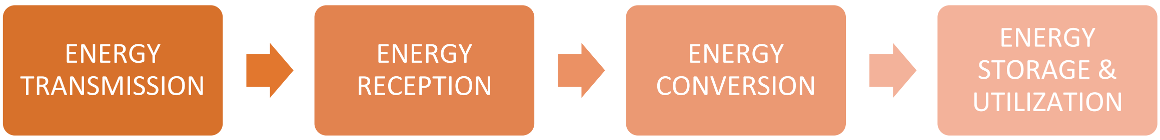

Fig.3. Representation of RF Energy Harvesting Mechanism

The energy transmission involves sources of RF signals. The ambient RF energy is consistently present due to the expansion of wireless communication networks. While solar or thermal energies relies on environment, RF energy can be captured both indoors and outdoors making RF energy an excellent alternative for uninterrupted power supply. There are major RF energy sources such as 5G base stations. 5G towers with ultra-high frequencies and dense network coverage, provide a continuous and powerful RF energy source. Along with towers, public spaces, homes and offices are occupied with Wi-Fi access points operating at 2.4 GHz and 5 GHz which can be leveraged for energy harvesting. Cellular networks, broadcasting towers, and IoT devices and wearables also are the sources of RF energy. The accessibility and strength of RF energy relies on various factors such as distance from the source, interference, and signal propagation characteristics [9]. Although they provide more energy, higher frequencies (e.g., millimetre-wave 5G) generally have shorter propagation ranges.

Then, energy reception involves capture of RF waves using antennas. The maximum power transfer can be achieved if the captured RF waves are efficiently absorbed. This process of absorption is carried out through specially designed antennas, that is crucial for determination of efficiency of energy harvesting system. The size and design of the antenna relies on the frequency of RF signals being captured. Although compact, highly efficient antennas can capture higher frequencies, larger antennas are used for lower frequencies. For instance, electronics and IoT applications widely use Microstrip Patch due to their compact and lightweight design. Dipole and monopole antennas are considered ideal for smart city and industrial applications due to

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omnidirectional reception. Metamaterial-Based Antennas enhance RF absorption efficiency by improving energy collection from weak signals, characteristic to their advanced designs. Wideband antennas increase overall energy harvesting capacity by capturing RF signals across a broad range of frequencies [10].

Afterwards, energy conversion requires rectification and power conditioning. The captured RF signals must be converted into usable electrical energy. While the most electric devices need direct current (DC) power, RF waves are actually alternating current (AC) signals. A rectifying circuit, often referred to as rectenna (rectifying antenna), is used to perform this conversion. The key components of the rectification process include matching circuit which optimizes impedance between the antenna and rectifier to maximum power transfer efficiency. Rectifier (Schottky Diodes/ Transistors) is used to convert high frequency AC signals into DC power. Low-Pass filter eliminates high frequency noise and produces effortless DC output. Voltage Booster and Power management circuit elevates the voltage level to match device requirements and efficiently distribute power. Recent research has aimed on innovating high-performance Schottky diodes and advanced rectifier circuits to enhance the power conversion efficiency of RF harvesting systems.

The harvested energy subsequent to conversion should be stored for later use or transmitted directly to electronic devices which comes under Energy storage and utilization process. Energy storage plays a significant role in achieving stable and reliable operation as RF signals generally harvest low power levels. Supercapacitors are one of the common storage components which provide quick energy storage and discharge, that is ideal for intermittent RF energy sources. Thin-Film batteries are used in wearables and medical sensors where small form factors are essential. Few ultra-low power IoT devices can function without storage by utilizing energy as it is harvested. RF energy harvesting is often combined with other energy sources to improve efficiency known as hybrid energy systems. While solar energy along with RF is harvested for outdoor applications, thermal energy converts heat produced by 5G base stations and industrial equipment into additional power. Wearable devices can combine the motion based energy with RF for energy harvesting to enhance performance.

2.3 Techniques used in RF Energy Harvesting

The RF energy harvesting (RFEH) technique encompasses a range of methods for capturing, transforming, and using passive radio frequency signals for the operation of low power electrical devices. The processes of capture, transmission, reception, rectification, power management, and storage of energy are all interlinked and determine the overall performance of RF energy harvesting. It is these techniques that guarantee the power signals capture RF are transformed to electrical power. Implementation of metamaterials, multi-band energy harvesters, and modernized structures like rectenna has greatly increased the efficiency of RFEH and its potential practical use. The key techniques in RF energy harvesting are as shown in Fig4.

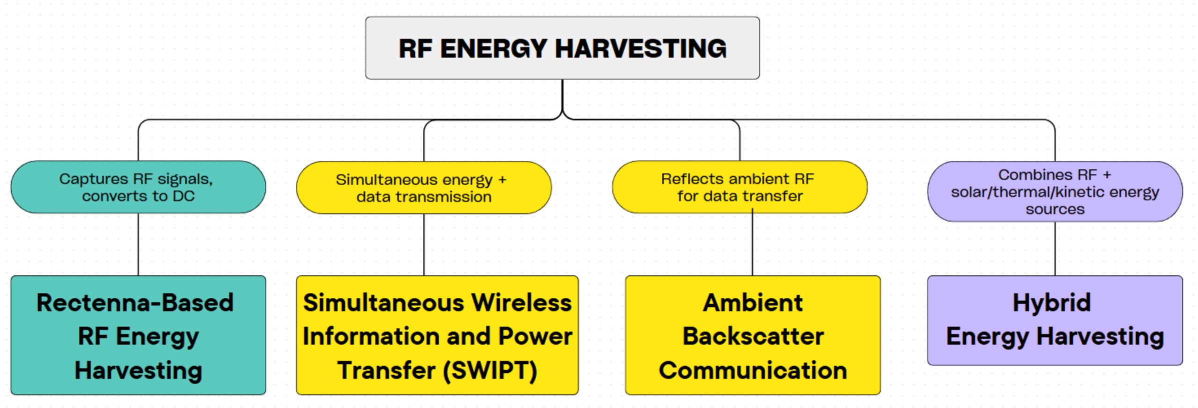

Fig.4. Different Techniques used in RF Energy Harvesting

The fundamental component to RF energy harvesting systems is rectenna (rectifying antenna). Thus, Rectenna-Based RF Energy Harvesting includes conversion of electromagnetic waves into direct current (DC) electricity through a rectenna. It is composed of an antenna that captures RF signals and a rectifier circuit which converting these alternating current signals into usable DC power. Recent advancements in rectenna design have focused on improving impedance matching, enhancing rectification efficiency, and integrating metamaterial structures to optimize power transfer, making them ideal for IoT applications and wireless sensor networks [11]. Another technique is Simultaneous Wireless Information and Power Transfer (SWIPT). It is a novel technology enabling the simultaneous data and power transmission over the same RF signal. This dual functionality specifically benefits the autonomous IoT devices and smart grids, improving the efficiency of wireless networks. It has been recognised as a potential solution for the energy constraints in IoT based scenarios, combining wireless power transfer and wireless information transfer to enhance efficacy. Further advancement into Pulse Position Modulation schemes for SWIPT has also shown potential in eliminating receiver complexity and energy usage, making it apt for low power IoT devices [12].

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The Ambient backscatter communication reduces the need for dedicated power sources, enabling devices to transmit data by reflecting current ambient RF signals. It is significant for developing battery free IoT devices. A practical ambient backscatter communication system was demonstrated in a study in which battery free devices communicate through modulation and reflection of ambient signals from various sources such as TV towers, enabling ultra-low power communication[13]. It can also utilize mobile RF sources like Wi-Fi access points to improvise communication dependency and spread for IoT applications. Additionally, Hybrid Energy harvesting integrates RF energy harvesting with other energy sources, like solar, thermal, kinetic energy, maximizing the efficiency and ensure consistent functioning of devices, especially in wearables, smart cities, and industrial IoT sensors. A wearable hybrid energy harvester was recently developed which captured energy from human motion as well as ambient light, showcasing improved performance over single sourced harvesters [14]. Hybrid harvesters have the potential of harnessing multiple energy forms at the same time due to the development in its material and structural framework, leading to enhanced sustainability and efficacy of energy harvesting systems.

3. Applications of Wireless Energy Harvesting

The Wireless Energy Harvesting being sustainable and green solution for the constantly increasing demand of energy, is applied at various sectors for different uses. Some of them are explained in this section. WEH (Wireless Energy Transmission) enables battery free and low power IoT devices to work effectively minimizing the manual intervention needed for changing batteries. Some of the WEH applications includes Smart Homes Sensors used in the automation of homes, security, and energy systems that are wirelessly powered. In Industrial IoT (IIoT), RF powered sensors are used for the perpetual surveillance of machinery in the factories to diagnose faults and decrease downtime. Wireless sensors used in Smart Agriculture for real-time monitoring of soil moisture, temperature, and health of crops on the farms becomes independent of battery usefulness as observed by RFID-based sensing platforms powered by ambient RF signals [15]. Other applications include its usage in the field of Biomedical and Wearable Electronics where WEH enhances the convenience and accepts a reduction in the health care intervention needed to treat the patient so that medical implants, wearable sensors, and health monitoring devices can accept a powered solution. Now the Wearable Health Sensors which include Smart watch and fitness bands, are powered using the surrounding RF energy, to optimize the use of their battery. It is also used in pace makers for heart patients. Moreover, Remote Patient Monitoring involves wireless powered biosensors to monitor and track the patient's vitals with low-frequency charging. It can be observed in wireless-powered medical implants using ambient RF harvesting as discussed in [16]. Its applications also further stretch to the infrastructural development which include Smart Cities and Infrastructure. Here, wireless energy harvesting is central in large-scale applications for urban infrastructure. RF-powered roadside cameras and sensors reduce maintenance in Traffic Monitoring Systems. It also aids in Environmental monitoring through Wireless-powered air quality and pollution sensors dispersed throughout cities. Smart Streetlights also utilizes RF-powered sensors that dynamically adjust lighting based on pedestrian traffic and ambient light. Additionally, WEH reduces dependence on traditional power sources in critical Military and Defence Applications. Unmanned aerial vehicles (UAVs) harvest ambient RF energy to extend flight times.

4. Challenges in RF Energy Harvesting

Harvesting of RF energy sources often faces due to low power conversion efficiency (PCE), primarily due to the weak ambient RF power density and losses in the rectification processes. The effectiveness of RF to DC conversion is straightaway influenced by the rectifier circuit design, impedance matching networks, and the operating frequency of the harvester. Another barrier which hinders RF energy harvesting is advanced rectifier designs. To enhance PCE(Power commission efficiency), researchers are finding high-efficiency rectifiers using Schottky diodes and CMOS-based rectifiers. For example, an extremely low powered rectenna designed by Li et al. demonstrated >50% conversion efficiency at -20 dBm input power, making use of a dual band impedance matching circuit [17]. AI powered optimization techniques have also been inculcated to improve dynamic impedance matching and power adaptation. A study highlights the use of reinforcement learning to flexibly adjust circuit parameters [18].

One of the main limitations of RF energy harnessing is the low energy density of ambient signals. The power levels of Wi-Fi and 5G signals mostly ranges between -30 dBm to -10 dBm, which results in limited power availability for practical applications. RF energy harvesting faces a fundamental challenge due to low ambient power densities. Unlike solar or kinetic energy sources, RF power levels are weak and dispersed. RF energy harvesting observes a very basic challenge because of low ambient power densities. Unlike solar or kinetic energy sources, RF power levels are weak and dispersed. There are various key challenges such as weak power level, distance based power delegation, and regulatory power limits in energy density observed. In most cases RF power in urban areas is around -30 dBm to -10 dBm (1μW - 100μW), which is insufficient for high-power applications like smartphones or industrial IoT. For instance, Kim et al. showed that harvested RF power from a 5G base station at a 50m distance was only 12μW [19]. RF signals follow the inverse square law, which tells us that power significantly decreases as distance increases. It was stated that RF power at 10m distance was 50% lower than at 5m [20]. Also, FCC imposed limitations and restrictions makes the RF transmission power to 4Watt EIRP for 5G band signals, making high-power RF harvesting tedious as impositions have set a particular harvesting limit which falls low. Huang et al. suggested that metamaterial antennas to focus RF power, overcoming these regulatory constraints [21].

The potential solutions to enhance RF energy density are required to overcome these challenges. Gathering energy from multiple RF frequencies which include Wi-Fi, 4G, 5G, Bluetooth by introducing way for multiple antennas slot. This enables multiple frequencies to combine in an efficient powerful manner and make multi band antennas and rectennas having multiple frequencies as told by Zhu et al. developed a triple-band rectifier(2.4 GHz, 5 GHz, and 28 GHz) that increased energy density by 50% [22]. Many rows of rectennas can enable us to harness or capture more energy and improve energy conversion efficiency. Rectifiers work by making use of electromagnetic waves. Arranging rectennas in rows enhances the total effective orifice and domain, meaning a larger surface area is available to intercept incoming RF signals. Beamforming antennas enables us to concentrate energy in a specific direction, increasing power collection. Beamforming is a technique where a list of antennas steers and focuses RF waves in a particular direction instead of receiving energy uniformly from all directions. This concentration enhances the power density at the rear rectenna making. In constructive interference, signals received at different parts of the antenna array are adjusted so that they add up constructively and evenly in the desired direction. However, in destructive Interference, signals from not specified directions are cancelled out, reducing noise and improving signal-to-noise ratio (SNR). Beamforming antennas in Adaptive Directional Reception can track the strongest RF sources, such as Wi-Fi routers, 5G base stations, or other RF transmitters. Wang et al. proposed an adaptive beamforming system that improved power density by 50% [23].

Interference from other RF sources affects harvesting efficiency. Common issues include sources of interference, spectrum crowding and more. In multipath interference, RF waves reflect off buildings, water, and metal surfaces, causing signal fading. Chen et al. developed a frequency selecting corrector that avoids multipath interference [24]. The spectrum crowding refers to urban areas having high RF congestion from Wi-Fi, 5G, Bluetooth, and industrial signals. As illustrated by Wang et al. created an AI-based spectrum analyser to dynamically select less crowded frequencies [25].The interference mitigation challenge can be overcome through Adaptive Impedance Matching. Tuning circuits that adjust impedance based on RF signal variations can enhance efficiency. A real time adaptation was developed which matches circuit that reduced interference by 40% as demonstrated in [26]. Flexible antennas can switch between different frequency bands to avoid interference. Traditional antennas operate at fixed frequencies, making them weak and to interference from nearby signals in the same band. In contrast, frequency-switchable antennas dynamically adjust their resonance to avoid congested or noisy frequency band. Tunable Resonance where antenna's electrical properties are adjusted to resonate at a different paradigm of frequency can also be a potential solution. Zhang et al. designed a tunable rectenna system that improved energy efficiency in dense urban networks [27].

5. Conclusion

Wireless Energy Harvesting (WEH) is a promising technology to power low-energy electronic devices sustainably by harvesting ambient energy from Wi-Fi and 5G signals. With the rising need for wireless communication, the higher signal density and installation of 5G infrastructure create new possibilities for effective RF energy harvesting. Despite its promise, some of the major challenges like low power conversion efficiency (PCE), low ambient power density, and regulatory issues still hinder its mass adoption. Improvements in rectenna technology, multi-band energy harvesting, large-array antenna systems, and machine learning-based impedance optimization have provided substantial improvements in the efficiency of energy conversion. Beamforming antennas, metamaterial surfaces, and adaptive impedance matching circuits are the best examples of development that increase the harvesting of RF signals while providing reduced interference. A great potential for hybrid energy harvesting approaches has also been observed where the integration of multiple sources of energy, like kinetic and thermal energy, provides improved overall power reliability. The future of energy harvesting from wireless networks rests in the innovation of autonomous smart devices, IoT devices, and sensor networks free from traditional batteries. Integration of RF energy with 5G and Wi-Fi networks may lead to sustainable and enhanced efficiency of power solutions for the upcoming communication systems. However, additional research is needed to optimize energy transfer mechanisms, mitigate regulatory power constraints, and enhance real-world implementation efficiency. The ongoing research into high-performance energy harvesting materials, AI-based power management, and scalable rectenna architectures will be the key to wireless energy harvesting becoming a mainstream technology. The achievement of highly efficient WEH systems will enable the development of smart cities and industrial automation, as well as lead to a more sustainable and energy-efficient technology.

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