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Energy Harvesting Antennas for Sustainable IoT Solutions

Pratibha Sharma[1]*, Shivangi Gupta[2], Kunal Meher[3], Rajasekar. B[4], Manoranjan Das[5], Hannah Jessie Rani R[6], Kothakonda Sairam[7]

[1]Centre of Research Impact and Outcome, Chitkara University, Rajpura- 140417, Punjab, India,
[2]Quantum University Research Center, Quantum University, Roorkee, Uttarakhand, 247667, India.
[3]Assistant Professor, uGDX, ATLAS SkillTech University, Mumbai, India,
[4]Professor, Department of Electronics and Communication Engineering, Sathyabama Institute of Science and Technology, Chennai, India,
[5]Associate Professor, Centre for Internet of Things, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha, India,
[6]Assistant Professor, Department of Electrical and Electronics Engineering, Faculty of Engineering and Technology, JAIN (Deemed-to-be University), Ramanagara District, Karnataka - 562112, India,
[7]Centre for Multidisciplinary Research, Anurag University, Hyderabad, Telangana, India.

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Abstract

Energy harvesting antennas represent a pivotal technology for enabling sustainable solutions in the Internet of Things (IoT). By harnessing ambient energy sources such as radio frequency (RF) waves, these antennas provide a pathway toward self-sustaining IoT devices with reduced reliance on traditional batteries. Existing IoT systems heavily depend on battery-powered devices, which face challenges such as limited energy capacity, frequent maintenance, and environmental concerns from battery disposal. These issues hinder the scalability and longevity of IoT networks, especially in remote or hard-to-access locations. The proposed framework leverages IoT-based energy harvesting [IoT-EH] using highly efficient antennas that collect RF energy from ambient sources like cellular networks, Wi-Fi signals, and broadcast systems. This harvested energy powers low-energy IoT devices, ensuring uninterrupted operation. The framework integrates energy harvesting antennas with energy management systems to optimize power allocation and usage dynamically. The proposed method facilitates sustainable IoT deployments by eliminating the need for frequent battery replacements and minimizing environmental impact. It is particularly beneficial in applications such as smart agriculture, environmental monitoring, and industrial automation, where continuous device operation and minimal maintenance are critical. The findings demonstrate that the proposed approach significantly extends the device lifecycle, reduces maintenance costs, and enhances system reliability. Moreover, experimental results reveal an efficient conversion of ambient RF energy, ensuring that IoT devices achieve energy autonomy. This method presents a scalable and eco-friendly solution to the growing energy demands of IoT ecosystems.

Author's e-mail: pratibha.sharma.orp@chitkara.edu.in, shivangi.gupta@quantumeducation.in, kunal.meher@atlasuniversity.edu.in, rajasekar.ece@sathyabama.ac.in, manoranjandas@soa.ac.in, jr.hannah@jainuniversity.ac.in, kothakondasairam.ks@proton.me

Author's Orcid id: 0009-0000-4708-182X, 0009-0005-4285-8974, 0000-0003-2940-4247, 0000-0003-1182-848X, 0000-0002-7875-6276, 0000-0002-5449-104X, 0009-0007-0074-4172

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Introduction

Healthcare, food production, and smart cities are just a few among hundreds of examples with the rapid spreading of the Internet of Things revolutionizing how various fields function by enhancing smooth connectedness and data-related decisions.[1] However, several batterydependent Internet of Things gadgets exhibit various shortcomings. In other words, they include some defects that include inferior power resources, periodic renewal or refreshing requirements, and environmental effects to be faced concerning its degradation processes.[3] These limits greatly handicap scalability and longevity in IoT networks, especially in distant or hard-to-access locations. Another highly appealing option is energy harvesting antennas, using which the IoT device will be in a position to convert sun rays, vibrations, as well as radio frequency waves, and RF into useful electrical current.[3] Getting rid of conventional batteries enables this novel technique to develop autonomous IoT devices.[2] This paper looks into the design and implementation of energy harvesting devices as an environmentally friendly framework to solve the present energy limits and to improve the durability of the devices on the applications of the IoT (Internet of Things).[8, 15] With an increased rise in IoT device usage, it is the need of time to deploy renewable energy-based options, for standard battery-powered systems would face the restraints that will arise under such increasing usage.[12] Providing a sustainable and cost-effective option by offering the capability for IoT devices to self-sustain through energy harvesting antennas, they ensure a decrease in maintenance requirements as well as environmentally friendly deployments.[5] The issues associated with traditional battery-powered Internet of Things devices are mainly related to low energy capacity, infrequent maintenance, and environmental damage during battery disposal.[4] These are significant challenges that make the growth and sustainability of IoT networks challenging, especially in rural regions.[16] Thus, a need exists to come up with ways to control the devices without compromising the power.[14] The introduction addresses the issues of energy problems that conventional battery-powered gadgets bring along such as short lifetimes and the need for periodic upkeep, and environmental problems, and explains how the Internet of Things revolutionizes several businesses.[7] The more promising prospects for solving those problems and bringing forth such self-maintaining Internet of Things devices are, in fact, through energy collection antennas.[10]

In Section 2, it analyses existing energy options and their inadequacies. Section 3 proposes a new paradigm for energy harvesting antennas, using which Internet of Things applications are made green.[6] We analyze the results and discuss how the proposed approach is green, efficient, and scalable in Section 4. Section 5 Conclusion: This study concludes and outlines possible ways forward for future studies that will enhance the harvesting of energy for Internet of Things ecosystems.

Related Works

EH (Energy Harvesting)

The development of low-power electronic sensors has garnered significant attention due to the fast expansion of the Internet of Things (IoT). A wide variety of industries, including transportation, energy, smart buildings, the natural world monitoring, medicine, defense, manufacturing, and production, rely on the data collected by wireless sensors that are now an integral part of IoT systems.[13] Despite enabling cheap overall system costs, the using of batteries to power wireless sensors has traditionally been problematic due to their detrimental effects on the network's performance and durability.[17] A potential eco-friendly alternative that may prolong the life of these sensors and, in some instances, eliminate the need for battery power is energy harvesting (EH) technology.

Channel State Information (CSI)

With the impending 6G era, wireless transfer of energy (WET) has emerged as a potential method for powering potential Internet of Things (IoT) devices. For effective and scalable wireless powering, this article provides a high-level overview of the key topologies, problems, and solutions. Energy beamforming (EB), distributed antenna structures (DASs), distributed ledger technology, new spectrum prospects, developments in devices' hardware and programmable media, resource scheduling, and other candidates' enablers are detailed. The focus is on the topic of whether or not techniques that are restricted or free of channel state information (CSI) are suitable for powering a large number of devices at once.

Radio Frequency (RF)

Energy harvesting plays a crucial role in envisioning a low-carbon net zero future and holds significant political importance. This survey aims to provide a comprehensive review of various energy harvesting techniques including radio frequency (RF), multisource hybrid, and energy harvesting using additive manufacturing technologies. However, special emphasis is given to RF-based energy harvesting methodologies tailored for battery-free wireless sensing, and powering autonomous low-power electronic circuits and IoT devices.

Proposed Methods

Energy harvesting antennas are one of the proposed components included in the collection of RF ambient energy to power devices utilized in the Internet of Things. The integration of an innovative energy management system integrates energy conversion, storage, and usage to ensure devices with sustainable, environmentally friendly, and continuous operation.

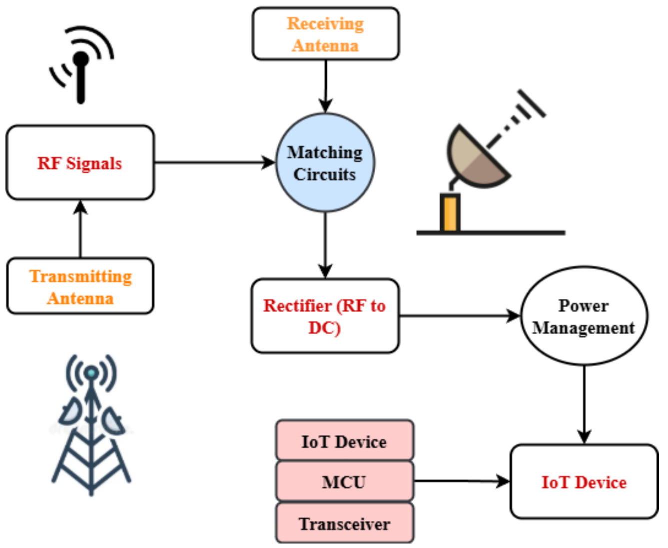

Fig. 1: Image of Harvesting RF Energy System

Fig. 1 demonstrates that electromagnetic signals, such as those from the wireless internet, broadcast and satellite communication stations, and digital multimedia broadcasts, may be transformed into electrical energy through an antenna and a circuit composed of rectifiers. These signals fall within the frequency spectrum, which ranges from 3 kHz to 300 GHz. You may find this kind of energy at all times, day or night, and it's there everywhere. Although this energy may be recovered indefinitely, it has many drawbacks, including a low density and an efficiency that decreases as one moves farther away from the source.

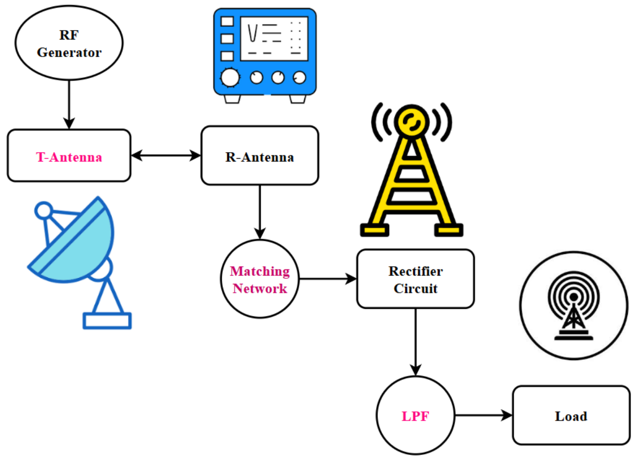

Fig. 2: Image of Energy System Harvesting

An energy-collecting circuit is shown in Fig. 2 as a block diagram. A transmitter (Tx), antennae, matching network, rectifier circuit, lowpass filter (LPF), and load are the components shown in Fig. 2 of an energy harvesting circuit. To transmit the maximum power that is received from the directional antenna to the conversion circuit, a matching system is used. An Rx antenna is used to collect radio frequency (RF) signals from the ambient. Energy-harvesting circuits that convert RF energy into direct power rely on rectifying-antenna (rectenna) circuits, the most crucial component of such circuits.

The proposed approach resolves the energy challenges of the Internet of Things by employing energy-harvesting antennas and continuous energy management, offering a scalable platform for applications in the environmentally friendly Internet of Things, which decreases dependence on the battery and increases the autonomy of devices in operating contexts.

Results and Discussion

In this section, analyze the conversion productivity of energy, the autonomy of the device, and the scalability of the proposed architecture. Comparing our results with prevailing methods helps us prove that the technique proposed is a success and environmentally friendly for the purposes of the scenario.

Analysis of Conversion Productivity of Energy

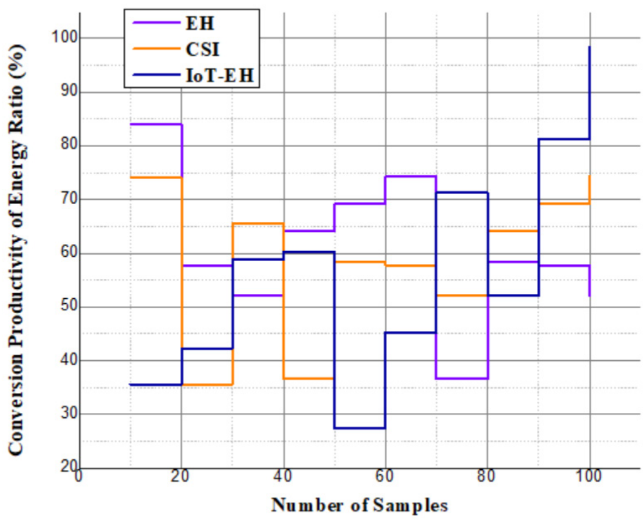

Fig. 3: Analysis of Conversion Productivity of Energy

Figure 3 demonstrates that 98.3 % more energy conversion efficiency is concerned, IoT-EH achieves better performance than the existing EH and RF techniques. To ensure that the function is more efficient and sustainable, the results reveal that the ambient energy is successfully converted by the IoT-EH. Due to this, the IoT device functions become more independent and reliable as well.

∂_g *T[lf-Wqf']:¤Nj[7v-ptr]-Vfd[4wq-gm"]* (1)

In the context of Internet of Things (IoT) systems, the equation 1, depicts a complicated interaction including power management , device functioning , and energy transformation . The goal is to improve device freedom in IoT applications by optimizing energy delivery and management, which in turn ensures analysis of conversion productivity of energy.

Analysis of scalability

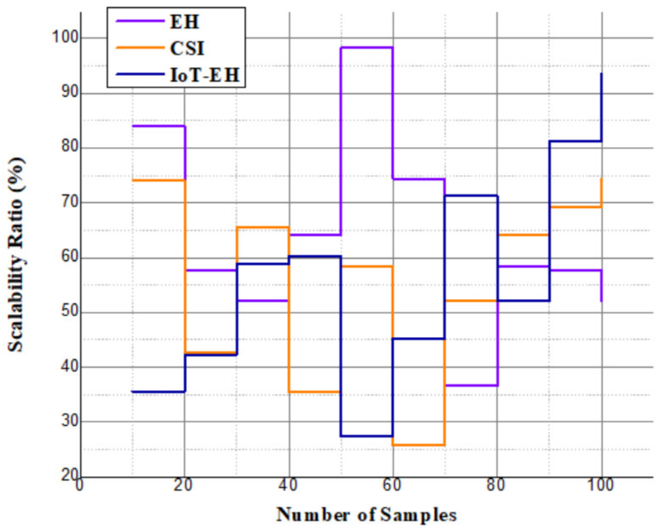

Fig. 4: Analysis of Scalability

Figure 4 denotes comparing scalability between traditional EH/RF approaches and IoT-EH with a better scalability of 93.5%. Results for the case of IoT, the simulation results have presented that it can scale effectively with its ability in terms of fitting more numbers of IoTs without decreasing the performance at the end. This way, scalability allows it to be adopted in a diversity of IoT ecosystems.

$\propto_w$ *Gp[k-jy"]:→Bd[v-5vsw"]+Ha[l-ld"]* (2)

As a symbol of energy generation *Bd[v-5vsw"]* and distribution inside IoT devices $\propto_w$ Gp, equation 2 may be understood *k-jy"* within the framework of the suggested energy *Ha[l-ld"]* harvesting technique. Its goal is to keep the system autonomous and efficient in the Internet of Things applications by facilitating the smooth transfer of power from analysis of scalability.

Findings have proven that the proposed approach has the potential to extract energy from the environment, significantly extending the lifespan of IoT devices. By comparison analysis, comparative study depicts its promising prospect in deploying extensible, environment-friendly Internet of Things across numerous applications, with a higher performance rate than the traditional methods.

Conclusion and Future Works

Energy-collecting antennas offer an innovative way to overcome the energy limitations of traditional Internet of Things systems. With sophisticated algorithms for energy management and energy harvesting from ambient radio frequency waves, this proposed architecture ensures green and self-sustaining Internet of Things device operation. This is a viable method for large-scale Internet of Things deployment, reducing dependence on batteries, increasing the lifespan of devices, and minimizing the environmental impact. Thereby, experimental results have testified to the reliability and high energy conversion efficiency of that method, which can be successfully utilized in many different fields like smart neighborhoods, agriculture, or medicine. This solution has increased operational cost-effectiveness and ecological sustainability for even more widely used sustainable Internet of Things (IoT) systems by eliminating the need to periodically maintain and replace the batteries.

Future work is expected to optimize antenna designs towards higher energy conversion efficiency while integrating multi-source energy harvesting and adaptive energy allocation algorithms for further enhancement of the performance and applicability towards diverse IoT environments.

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