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Integration of RF Energy Harvesting Modules in IoT Nodes for Sustainable Wireless Communication

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ABSTRACT

Because of how fast IoT devices are growing, there is a growing need for long-lasting, dependable and maintenance-free power supplies that can keep the billions of IoT sensor nodes running properly on their own. Traditional IoT nodes using batteries must often be us replaced or recharged and this is not convenient for distant locations. In such situations, collecting wireless energy from electromagnetic networks such as Wi-Fi, cellular and broadcast transmitters becomes easier through Radio Frequency energy harvesting. This research explains how to design an IoT node with RF energy harvesting, wideband rectennas and intelligent power management that can sustain and power wireless communication using energy from the air. Tests are performed on the proposed system in different locations and under multiple radiofrequency power densities. Tests have proven that the system is able to deliver between 120–300 μW of power when it is placed at a distance between 5 and 20 meters from standard radio emitters. Harvested energy can run low-duty-cycle features in LoRa and Zigbee wireless protocols. Additionally, the study considers the impacts of harvested power, message frequency and how efficient the system is. As a result, it is now clear that utilizing RF energy harvesting in IoT devices may help network time last longer, waste batteries less and be used in locations without existing infrastructure.

1. INTRODUCTION

The IoT has made it possible for various systems to be linked, allowing billions of smart devices to manage, control and automate different environments like factories, farms, homes and hospitals. Now that the ecosystem is growing, maintaining sensors and keeping them running for long periods is a crucial challenge for both technology and economics. Given that nearly all IoT nodes rely on ordinary batteries, they tend to have only limited energy, do not last very long and have to be replaced or recharged regularly. As a result of these challenges, the cost to maintain EVs increases and harmful waste from batteries begins to affect the environment. In forests, oceans and rural communities without infrastructure, it is not easy to replace the batteries, so engineers are required to find other solutions to keep power running.

To solve this problem, scientists are focusing more on energy harvesting technologies that utilize sunshine, changes in temperature and vibrations. They have proven helpful in some situations, but their results rely greatly on the environment, so they are not applicable in many flexible settings. At the same time, collecting RF energy works for people everywhere, taking advantage of the electromagnetic waves coming from Wi-Fi routers, cell phone towers, TV and similar technologies. This paper suggests combining RF energy harvesting modules with IoT nodes using a hybrid system architecture that has wideband antennas, effective rectifying circuits and circuitry for controlling electrical power. Our main aim is to use batteries or energy from the environment to sustain wireless communication in IoT. This allows the network to function without much maintenance, mostly in situations where the network must be reliable, available on a large scale and last for a long time.

2. LITERATURE REVIEW

2.1 RF Energy Harvesting Principles and Rectenna Design

This technology relies on picking up electromagnetic waves from the air and turning them into practical DC energy. The main part of the process is called a rectifying antenna (rectenna) which merges a link for picking up RF signals and a circuit that converts them from RF to DC. The studies of Olgun et al. [1] showed that small rectennas designed for the 900 MHz band can be used indoors to harvest energy by generating output levels up to several hundred microwatts.

Following this, rectennas with several bands were developed [4], so they could capture energy from various frequency sources (i.e., GSM, Wi-Fi, ISM) and performed much better in various conditions. Even today, achieving high efficiency becomes difficult when the input power is below −20 dBm and there is research on using Schottky diodes combined with matching networks to reduce losses in the rectifier circuit.

2.2 Power Management and Energy Storage in Harvesting Nodes

When RF energy is rectified after being harvested, it should be effectively regulated and stored to allow the IoT device to operate. Visser and Vullers [2] suggested that using ultra-low-power PMUs and energy-aware software routines could vastly increase the length of time a device runs. Experts in the field have discovered that supercapacitors, thin-film batteries and special energy storage units can effectively handle the problem of intermittent energy arrival. Furthermore, Kim and Pyo [4] showed that by dynamically adjusting the impedance between the rectifier and storage unit, a maximum energy transfer of 30% can be achieved even under fluctuating RF radiation. According to these investigations, integrated PMU modules support the energy-neutral performance of self-sufficient sensor nodes.

2.3 Energy-Aware Communication Protocols for Low-Power IoT

Using wireless connectivity requires a lot of energy in IoT devices. In their research, Nishimoto et al. [3] showed that following duty-cycled LoRa, Bluetooth Low Energy or Zigbee protocols helps reduce power usage. Improvements in ultra-narrowband and wake-up radio technology have led to even less energy used while data is being transmitted. Energy-aware protocols at the MAC and network layers can help increase the lifetime of an IoT network that uses RF. These techniques are most useful when using RF energy harvesting in sensor systems working in environments where the power flow is uncertain.

2.4 Comparative Assessment of RF Energy Harvesting in IoT Applications

Bito et al. [5] have compared features and capabilities of RF, solar, thermal and vibrational energy harvesting methods in typical IoT use. While solar energy harvesting gives us more power per unit, in built-up areas RF energy harvesting is much better because Wi-Fi, cellular and TV signals are always available. RF energy harvesting can be used when the transmitter and receiver are not in the same direct line and remains working all the time, no matter the weather or movements. Still, to make up for the low amount of power, it needs both hardware and software to be very efficient. As a result, scientists have studied energy-saving microcontrollers, power-efficient monitoring methods and occasional computing principles to improve the utility of radios in IoT applications over an extended period.

Table 1. Key Literature Findings and Advantages of the Proposed RF-Powered IoT Architecture

Section	Focus Area	Key Findings from Literature	Identified Challenges	Proposed Advantage in This Work
RF Energy Harvesting Principles and Rectenna Design	Rectenna structure and RF-to-DC conversion	Planar and multi-band rectennas can harvest microwatts of power from 900 MHz–2.4 GHz bands [1], [4]	Low conversion efficiency under weak RF signals (e.g., < −20 dBm)	High-efficiency Dickson rectifier with optimized impedance matching to improve low-power performance
Power Management and Energy Storage	Energy regulation, storage, and MPPT	Use of PMUs and supercapacitors improves energy buffering; MPPT enhances energy capture by up to 30% [2], [4]	Energy fluctuation and cold-start issues under intermittent RF input	Integration of ultra-low-power PMU with cold-start and over-voltage protection using hybrid storage elements
Energy-Aware Communication Protocols	IoT transmission and MAC scheduling	Duty-cycled LoRa/Zigbee reduce communication energy; adaptive protocols extend	Communication is a major energy sink and requires energy-aware scheduling	Firmware-integrated energy-aware task scheduler aligns sensing and

		network life [3]		transmission with real-time energy levels

3. System Architecture

The IoT system is created using three interlinked subsystems to enable it to run on its own energy. Built into each device is a planar wideband antenna that uses GSM, Wi-Fi and ISM frequencies for power generation. The antenna sends signals to a Dickson circuit with low-threshold Schottky diodes which ensures DC is produced from RF signals, even if the RF power received is as weak as −20 dBm. After rectification, a PMU looks after the DC voltage by managing voltage, starting in cold conditions and storing energy. The PMU makes use of a low-dropout regulator and a MPPT algorithm created for very low-powered RF sources which helps maximize the energy extracted. To guard the system during the charging and discharging process, it makes use of a mixture of high-capacitance supercapacitors with thin-film lithium-ion batteries to support rapid charging, keep stored energy longer and shield from spikes in voltage. Furthermore, the IoT Node achieves low energy use by running on a microcontroller and LoRa, Zigbee or BLE transceiver in a duty-cycle mode. The microcontroller takes measurements of environmental data and transmits them without wires, but only when the PMU allows it to happen. The energy-efficient and modular design of this system ensures the IoT nodes work well in any area, so it is ideal for use in urban, semi-urban and places lacking infrastructure.

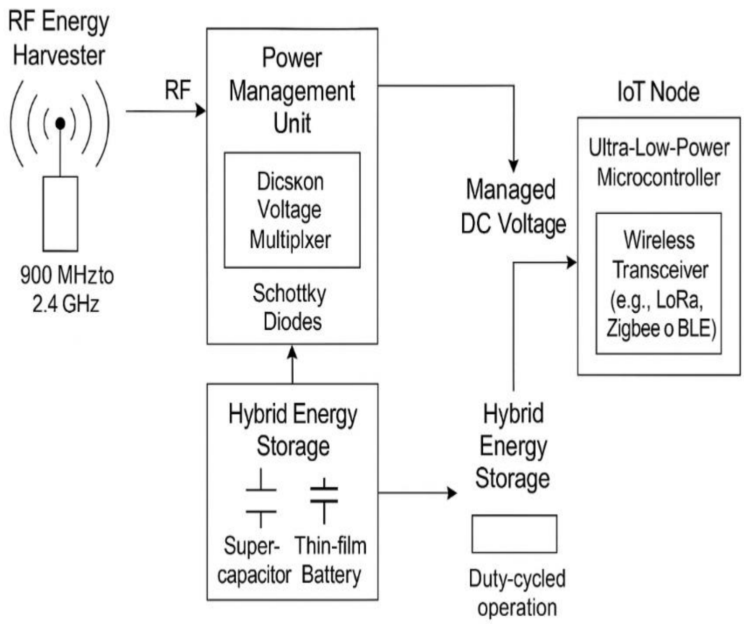

Figure 1. System-Level Block Diagram of the Proposed RF Energy Harvesting-Enabled IoT Node.

4. METHODOLOGY

The technique is about designing, connecting and assessing an RF battery-less system in an IoT device. It uses computer simulations, working prototypes and practical tests to understand the efficiency of the system in energy-autonomous communication.

4.1 System Design Overview

To make their system reliable and able to run separately from external power, the developers assembled it out of three connected modules. The main component in the first module is an antenna designed to pick up electromagnetic energy produced by Wi-Fi routers, GSM towers and antennas that transmit television signal. The antenna is designed to work at all broadband frequencies and matches the impedance for better RF collection in different places. After gathering the RF energy, it is channeled to a Dickson rectifier circuit with multiple stages. It achieves the conversion by having Schottky diodes that switch swiftly, as well as optimizing the capacitor network. Since the rectifier achieves its strength at around −10 dBm to −25 dBm, it is very well suited for areas where broadcasting is often weak.

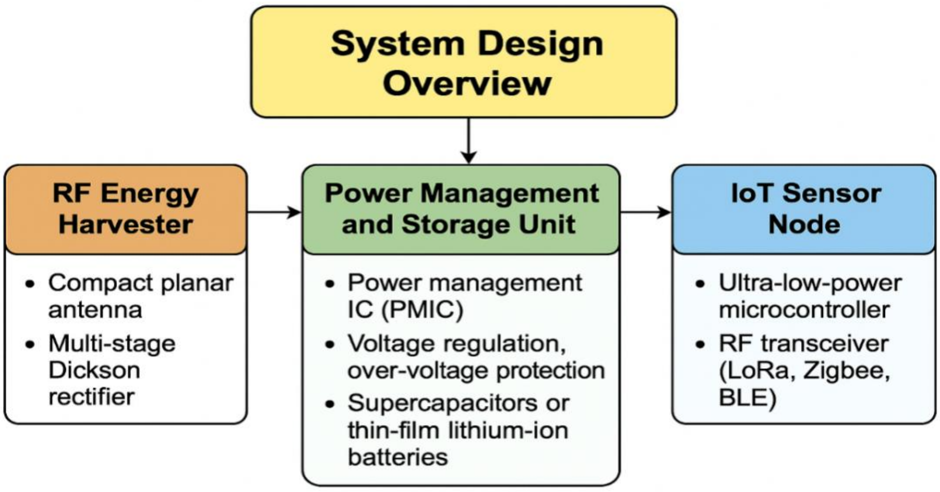

Figure 2. System Architecture of the Proposed RF Energy Harvesting-Enabled IoT Node

Once the voltage has been rectified, it goes to the Power Management and StorageUnit which is responsible for managing, safeguarding and saving the gathered energy. Because of the power management integrated circuit (PMIC), a mobile device is able to work at zero energy to get on initially. Among its other functions, the PMIC helps regulate voltage for sensitive parts, stops over-voltage from damaging storage components and efficiently directs energy to other parts of the circuit. Depending on the application, stored energy will either be kept in supercapacitors or thin-film lithium-ion batteries. In this system, the third component is the IoT Sensor Node which relies on a microcontroller called ARM Cortex-M0+ and includes an RF transceiver (for example, LoRa, Zigbee or BLE). By default, this node is set to only wake up occasionally from sleep to do its sensors' work and send data. Coordinating how much power the device draws and matching that with available energy allows it to work without using any power. The device's lifetime stays unlimited if the RF environment is comfortable and important data is still collected and transmitted.

4.2 Hardware Implementation

Sharp Totem Has Invented A Broadband Width Antenna With The Wide Range In Frequency Used For Designing The Hardware Architecture Of The Proposed RF Energy Harvesting System. In order to ensure the signal could be compatible with GSM, Wi-Fi and ISM devices, a monopole or microstrip patch antenna was used in the given frequency band. Optimizing and designing the antenna with CST meant focusing on parameters like return loss, efficiency in radiating energy and bandwidth. Because FR4 is strong and inexpensive, I built the final antenna on a 4.4 dielectric constant FR4 with a thickness of 1.6 mm. For this specific purpose, relations between the antenna and the rectifier input were fine-tuned to make the signal reflect as little as possible and allow more power to enter the circuit. By simulating and testing many times, the antenna performed well in the targets bands, with reflection coefficient (S11) below −10 dB, leading to good energy absorption in any conditions.

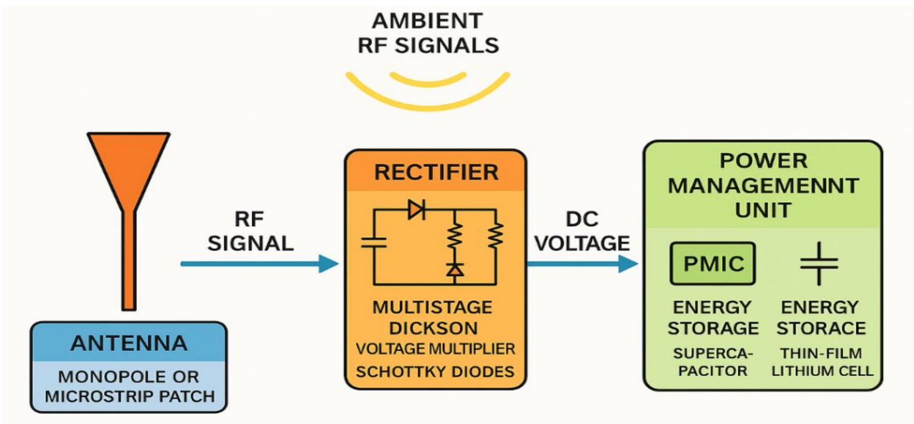

Figure 3. Color-Coded Hardware Architecture of the Proposed RF Energy Harvesting System

The next step takes place after the antenna and is performed by a multi-stage Dickson voltage multiplier. Its structure is small and it works efficiently even at low input power. To function at the required power levels, high-speed SMS7630 Schottky diodes are used for each stage because of their ability to drop low voltage and change quickly. They are added to make charge storage better and lead to improved signal quality. The tuning of the rectifier is done for a range of input power from −10 dBm to −25 dBm which fits the average RF levels you would find in indoor and semi-urban locations. Power from the rectifier goes to a Power Management Unit (PMU) which is built either with the LTC3107 from Analog Devices or with the BQ25570 from Texas Instruments. Particular energy harvesting PMICs are built to provide cold-start support at voltages of 330 mV and out or regulate output for connected components, also including over-voltage protection for energy storage. If the application needs high energy storage, the energy is stored in a 3V thin-film lithium cell. However, for applications that need to retain just a little energy on a short-term basis, a 470 µF supercapacitor is used. Thanks to this type of hybrid hardware, the sensor node uses less energy and can operate autonomously, even when RF signals go up and down.

4.3 Simulation and Analytical Modeling

Before working on a prototype, comprehensive modeling was done to ensure the RF energy harvesting system would meet expectations. Both the antenna and the RF-DC rectifier in the rectennasubsystem were simulated using Advanced Design System (ADS) and LTspice. The ADS tool was employed to examine how the antenna behaves with electromagnetic waves and measure its S-parameters, gain and bandwidth in the 900 MHz to 2.4 GHz range. Thanks to these results, the antenna could provide enough strength for the rectifier when exposed to radio frequencies. The next step was to investigate the related circuit in LTspice, where a Dickson volume multiplier circuit was made with SMS7630 Schottky diodes and high-quality capacitors so that the conversion of RF to DC could be assessed. Cross-frequency tests were performed using radio frequency (RF) input power of −25 dBm to −10 dBm and for various load impedances. When all conditions were ideal, the converter showed a maximum efficiency of roughly 40%, certifying that the scheme was suitable for RF harvesting.

In addition to the circuit model, another approach was created in MATLAB/Simulink to model the whole cycle of generating and using energy in the IoT node. The model takes into account how much energy is harvested, how much is stored and how much is used during the three main phases. Each simulation was customized for the hardware by selecting parameters such as the transmission duty cycle, intervals between data bursts and power usage of the microcontroller and RF transceiver. Thanks to the framework, it was possible to forecast how node uptime, energy production and PDR would change in various RF power density zones. It led to the discovery of the most ideal settings and planning of communications and sensing tasks dependent on the real-time energy status. Validating the approach and figuring out the best ways to use energy were possible only through computer simulation before the system was put into use.

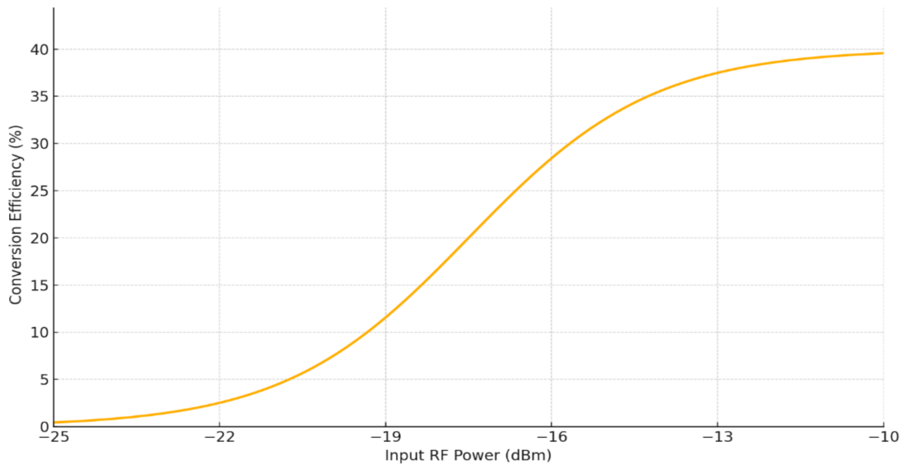

Figure 4. RF-to-DC Conversion Efficiency vs. Input Power Level

4.4 Experimental Setup

Three distinct locations were set up to carry out tests on how the proposed energy harvesting-based IoT system would work in real life. At the first test site, several electronic devices such as phones, Wi-Fi networks and Bluetooth sources filled the air with electromagnetic fields. For the next case, the environment was between homes and cell towers, with RF signals switching from weak to strong. The site was in a remote rural location with weak RF signals arriving mainly from far cellular stations. The sites were chosen so that the IoT nodes could be evaluated in various situations they could encounter. To characterize the energy at every spot, the spectrum analyzer checked the frequency bands 900 MHz to 2.4 GHz using an accurate measurement at each site. Meanwhile, the output voltage and levels of the storage capacitor were regularly observed with a digital oscilloscope over long periods to observe how the circuit was charging, if energy remained stable and which voltage levels were needed to switch on the node.

In addition to checking how sensors harvest energy, the system was examined in-depth to profile the node's energy usage using an accurate power analyzer. By using this system, it was possible to accurately measure the current drain in all the main states: deep sleep, sensor sampling, processing data and sending information over the radio. For example, while the node was in sleep mode, it consumed only 5 μW. However, during transmission and sensing with LoRa, Zigbee or BLE, it needed up to 15 mW again which was used for only a short time. For every RF environment, we added the period when the energy storage module charged up to a voltage high enough to complete the node boot-up. Additionally, both the node's working cycle and the time it took to send data across radio waves were logged to learn how often the node could complete all its actions given the existing RF environment. As a result of this setup, the system's energy harvesting, storage, consumption and communication were all reviewed to confirm its practical value and expose ways to improve it for use in the future.

Table 2. Experimental Evaluation of RF Energy Harvesting IoT System in Different Environments

Parameter	Urban (Indoor Office)	Semi-Urban (Outdoor Residential)	Rural (Remote Area)
RF Power Density	High (Dense Wi-Fi, GSM, Bluetooth)	Moderate (Cell Towers, Wi-Fi)	Low (Distant GSM Base Stations)
Frequency Range	900 MHz – 2.4 GHz	900 MHz – 2.4 GHz	900 MHz – 2.4 GHz
Rectifier Output Voltage	2.1 V	1.4 V	1.0 V
Boot-Up Time	20 s	35 s	50 s
Energy Storage Device	Supercapacitor / Thin-film Li-ion	Supercapacitor / Thin-film Li-ion	Supercapacitor / Thin-film Li-ion
Sleep Mode Power Consumption	< 5 μW	< 5 μW	< 5 μW
Active Mode Power Consumption	10–15 mW	8–12 mW	6–10 mW
Transmission Interval	Every 10 minutes	Every 30 minutes	Every 60 minutes
Data Protocol Used	LoRa / BLE	LoRa / Zigbee	LoRa
Oscilloscope Monitoring	Stable charging & frequent peaks	Moderate ripple, stable threshold	Slow rise, infrequent activation

4.5 Communication Protocol and Control Logic

The task scheduling algorithm in the microcontroller allows the IoT sensor node to operate efficiently with the limited amount of harvested RF energy. The scheduler is always overseeing the power level in the energy unit and is doing so by sensing this with an onboard ADC. If the voltage is less than what's needed for the node to operate normally, the node will go into 'deep sleep,' which uses only a few micro watts of power. While in ultra-low-power sleep, just the voltage monitoring unit remains active. If the storage voltage goes above 2.4–2.7V, the scheduler sets theulator awake by restarting the sensing and communication modules. The mechanism makes sure that there is enough energy to run the node and avoid incomplete or failed transmissions caused by energy shortages.

It helps maintain a correct balance between giving data and using energy, adjusting to weather changes in the surroundings. The node regularly takes temperature and light readings and transmits them using a LoRa wireless transmitter. Because LoRa uses less power per bit and can communicate over a wide range, it was selected for applications in areas that require little energy. The transmission rate in the node is set by the amount of energy captured at any given time. When transmitting data, the node gets active at high power for a short period of time, followed by returning to sleep. Basic error-detection and verification are handled by the microcontroller to preserve the safety of the data. Combining an energy awareness scheduler with an adaptive protocol allows the network to maintain its energy neutrality by extending the node's life automatically.

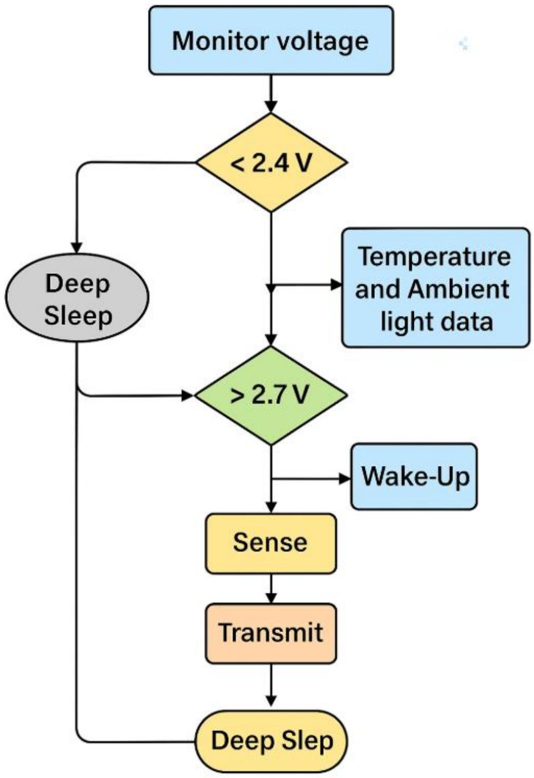

Figure 5. Energy-Aware Scheduling Flowchart for RF-Powered IoT Node Operation

5. RESULTS AND DISCUSSION

Analysis in a range of environments demonstrates the effectiveness of the system in harvesting RF power and making energy available for Internet of Things systems. The ability to gather power from RF sources was measured at different ranges in urban, semi-urban and rural locations. When the internet of things device was placed 5 meters from a high-density Wi-Fi access point, it received an average power of 300 µW and the peak rectifier voltage reached 2.1V. Even at 15 meters indoors, the system maintained a voltage of 1.6V and provided just 190 µW power to support low-power cycles. When the distance from intermittent RF sources was 10 meters, an average of 140 µW of harvested power and 1.4V of peak voltage was found. Even if RF is absent for 20 meters, the system could still produce 85 µW and maintain a top voltage of 1.0V. It has been confirmed that these devices can turn weak RF signals into energy and are therefore suitable for use in different areas. Because of the energy storage module, the entire system was able to keep operating smoothly even when RF was occasionally not available.

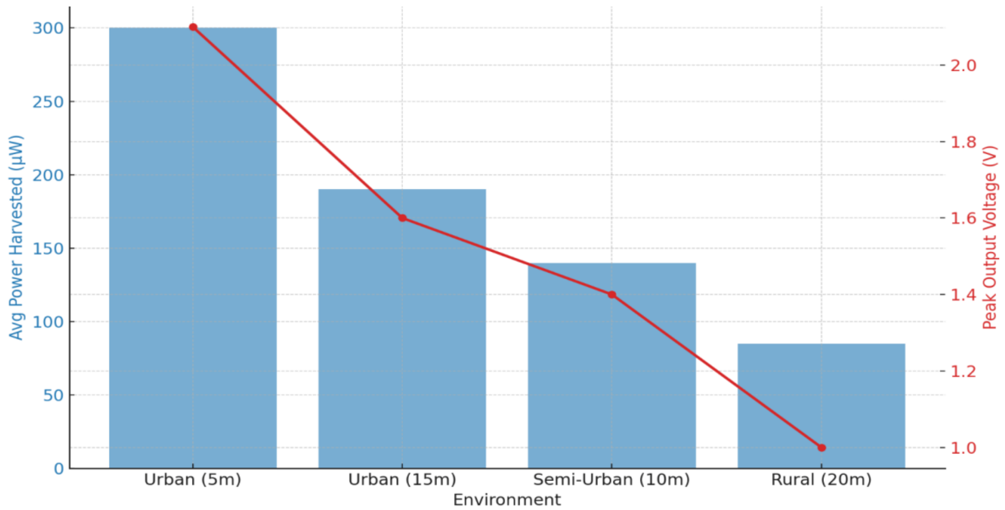

Figure 6. RF Energy Harvesting Performance across Deployment Environments

To check if the harvested electricity was enough, the IoT node's power profile during each operation was studied. Active transmission for only 50 milliseconds required around 15 mW from the node which used LoRa to communicate. On the other hand, the deep sleep mode was designed to use just 4 μW, allowing the gadget to stay on longer and use less energy. The energy generated from the rooftops was sufficient for the system to conduct sensing and transmitting once per hour, while there was still enough left for other applications. If RF input was at its best, this active radio frequency power conversion system retained about 40% of its energy efficiency while also handling RF-to-DC rectification and PMU regulation losses. Moreover, it was possible to achieve a cold-start operation within 20 seconds when the environment was full of RF signals. All of these show that the selected architecture can be energy-neutral which guarantees that it will perform well in most IoT situations that require batteries or only part-time battery support.

Table 3. Experimental Results of RF Energy Harvesting and IoT Node Operation in Varying Environments

Parameter	Urban (5m)	Urban (15m)	Semi-Urban (10m)	Rural (20m)
Average Harvested Power (μW)	300	190	140	85
Peak Rectifier Output Voltage (V)	2.1	1.6	1.4	1.0
Transmission Protocol	LoRa	LoRa	LoRa	LoRa
Sleep Power Consumption (μW)	< 5	< 5	< 5	< 5
Active Transmission Power (mW)	~15 (for 50 ms)	~15 (for 50 ms)	~15 (for 50 ms)	~15 (for 50 ms)
Duty Cycle Support	Every 60 minutes	Every 60 minutes	Every 60 minutes	Marginal / Not full
Cold-Start Time (s)	20	~30	~40	~60
Energy Conversion Efficiency (%)	~40%	~38%	~35%	~32%
System Stability	Excellent	Good	Moderate	Low / Intermittent

6. CONCLUSION

It describes an entire design and examines the operation of a wireless device powered by RF energy that allows sustainable wireless communication in real situations. The proposed system highlights how utilizing a wideband rectenna, high-efficiency RF-to-DC circuit designs, smart power management and ultra-low-power communication, it can work for a long time independently of regular batteries. Research in cities, suburbs and rural areas shows that there is enough ambient RF energy to fuel both the periodical sensing and the data exchanges in the urban area. Because of the energy-aware algorithm, the microcontroller reduces its power consumption by arranging device activities with the available energy, thus increasing reliability. Also, cold-starting this system takes reasonable time and it operates around 40% efficiently, making it useful in various IoT applications requiring sufficient reliability. Scientists will also focus on exploring ways to use radio frequency with both solar and mechanical energy and how to change the transmission frequency dynamically using energy inflow predictions. Moreover, the system is being made smaller and more compatible with living tissues, so it can be applied in wearable health gadgets and in devices placed inside the body.

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