ENT9098EE01 - Design and Experimental Evaluation of RF Energy Harvesting Circuits for Battery-Assisted Low-Power IoT Sensors

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Background of the problem

The rapid growth of IoT sensor networks in smart buildings, industrial monitoring, environmental sensing, and smart city applications has increased the need for reliable low-power sensing systems. However, many IoT nodes still depend on batteries, creating challenges related to maintenance cost, replacement frequency, and accessibility, especially in harsh or hard-to-reach locations.

RF energy harvesting has emerged as a potential solution for supporting battery-assisted or intermittent low-power sensor operation. It captures ambient or dedicated electromagnetic energy from sources such as Wi-Fi, GSM/LTE, 5G, or ISM-band transmitters and converts it into DC power using a rectenna system. A typical RF energy harvesting system consists of a receiving antenna, impedance matching network, rectifier, energy storage element, and low-power load. Previous studies show that the available RF power in real environments is often very low, making continuous sensor operation difficult. Therefore, practical RF harvesting systems usually focus on improving antenna efficiency, impedance matching, RF-to-DC conversion efficiency, energy storage, and duty-cycled sensor operation. The technology is more realistic for extending battery life or enabling intermittent sensing rather than fully replacing batteries in all conditions.

This project builds on these concepts by designing and experimentally evaluating a compact RF energy harvesting circuit for battery-assisted low-power IoT sensors. The study is relevant to Bahrain's digital transformation, IoT, smart city, and Industry 4.0 priorities, where low-maintenance wireless sensor systems can support applications such as environmental monitoring, safety sensing, predictive maintenance, and smart infrastructure.

List of publications related to the field

Publications have attached.

Research Objectives and Expected Outcomes:

Aim

The aim of this study is to design, prototype, and experimentally evaluate an RF energy harvesting circuit capable of supporting battery-assisted low-power IoT sensor operation. The project will investigate the feasibility of capturing RF energy from ambient or controlled radio-frequency sources, converting it into DC power, and storing the harvested energy for intermittent sensor operation. The study supports Bahrain's interest in IoT, M2M communication, smart cities, environmental monitoring, and digital transformation.

Objectives

- To review existing RF energy harvesting techniques, rectenna designs, RF-to-DC conversion circuits, and low-power IoT sensor applications.
- To identify suitable RF frequency bands for energy harvesting, such as Wi-Fi, GSM/LTE, 5G, or ISM-band signals.
- To design a compact receiving antenna or rectenna suitable for low-power RF energy harvesting.
- To design and simulate an impedance matching network and RF rectifier circuit for efficient RF-to-DC conversion.
- To fabricate and experimentally test the RF energy harvesting prototype under different RF input power levels, frequencies, and load conditions.
- To evaluate key performance parameters, including output DC voltage, harvested power, RF-to-DC conversion efficiency, capacitor charging time, and load response.
- To investigate whether the harvested energy can support or extend the operation of a battery-assisted, low-duty-cycle IoT sensor node.
- To provide practical recommendations on the feasibility and limitations of RF energy harvesting for low-power IoT applications in smart industrial and urban environments in Bahrain.

Expected Outcomes

The project is expected to deliver a working RF energy harvesting prototype for battery-assisted low-power IoT sensor applications. The prototype will include a compact receiving antenna, impedance matching network, RF rectifier, and energy storage stage.

The study will produce experimental results showing the output DC voltage, harvested power, RF-to-DC conversion efficiency, capacitor charging time, and load performance under different RF input levels and operating conditions. It will also assess whether the harvested energy can support intermittent operation of a simple low-power IoT sensor node.

The project will provide a realistic evaluation of the feasibility and limitations of RF energy harvesting for extending battery life in low-power IoT systems. The final outcome will include design recommendations, measurement results, and guidance for possible use in Bahrain's smart building, industrial monitoring, environmental sensing, and Industry 4.0 applications

Research Design/Methodology

This study will adopt an experimental and applied research design focused on the design, simulation, fabrication, and testing of an RF energy harvesting prototype for battery-assisted low-power IoT sensor applications. The research will combine RF circuit design, antenna development, laboratory measurements, and performance analysis to evaluate the feasibility of harvesting RF energy for intermittent sensor operation.

The first stage will involve a review of relevant literature on RF energy harvesting, rectenna design, impedance matching, RF-to-DC conversion, energystorage, and low-power IoT sensor systems. This will help identify suitable frequency bands, circuit topologies, components, and performance benchmarks for the proposed prototype.

The second stage will focus on system design and simulation. A compact receiving antenna will be designed for a selected RF band such as 900 MHz, 2.4 GHz, or another suitable ISM/communication band. An impedance matching network and RF rectifier circuit will then be designed to maximise RF-to-DC conversion efficiency at low input power levels. Simulation tools will be used to analyse antenna performance, impedance matching, output voltage, rectifier behaviour, and load response before fabrication.

The third stage will involve prototype development. The RF energy harvesting circuit will be fabricated using suitable RF components, such as Schottky diodes, capacitors, inductors, SMA connectors, and PCB materials. The prototype will include the receiving antenna, matching network, rectifier, and energy storage element, such as a low-leakage capacitor or small supercapacitor where appropriate.

Data collection will be conducted through laboratory measurements using available RF and electronics test equipment, including a signal generator, spectrum analyser, vector network analyser, oscilloscope, multimeter, and DC load. The prototype will be tested under different RF input power levels, frequencies, distances, and load conditions. The main data collected will include output DC voltage, harvested power, RF-to-DC conversion efficiency, capacitor charging time, load voltage stability, and the ability to support a low-duty-cycle IoT sensor node.

The analysis will compare measured results with simulated results to assess design accuracy and practical limitations. Performance will be evaluated using quantitative indicators such as conversion efficiency, minimum usable input power, charging time, and available energy for intermittent sensor operation. The study will also assess whether the harvested energy can extend battery life or support short sensing tasks such as measuring temperature, humidity, or light. Where possible, the project may include an applied case study related to smart buildings, industrial monitoring, or environmental sensing in Bahrain. Potential contextual applications include low-maintenance IoT sensors for industrial facilities, smart infrastructure, or telecom-supported environments. If an industry partner is available, feedback may be obtained regarding possible deployment requirements, environmental constraints, and practical use cases.

Ethical considerations are expected to be minimal because the project does not involve human participants or personal data collection. However, the research will follow safe laboratory practice when using RF equipment and electronic circuits. RF power levels used in testing will remain within safe and permitted limits. Any field measurements, if conducted, will avoid collecting private communication content and will focus only on signal strength or energy availability.

The final outcome will be a tested RF energy harvesting prototype, experimental performance results, and practical recommendations on the feasibility, limitations, and potential use of RF energy harvesting for battery-assisted low-power IoT sensor applications in Bahrain.

Significance and potential impact of research in Bahrain

This research addresses a key challenge in IoT deployment: the dependence of wireless sensor nodes on batteries. In smart buildings, industrial plants, environmental monitoring, and smart city systems, battery replacement can be costly and difficult, especially in remote or hazardous locations.

The study investigates RF energy harvesting as a method to support battery-assisted low-power IoT sensors. The proposed system will use a compact antenna, matching network, RF rectifier, and energy storage circuit to convert ambient or dedicated RF signals into usable DC power. Although harvested RF power is typically low, it may help extend battery life or enable intermittent sensor operation.

The project supports Bahrain’s digital transformation, IoT, smart city, and Industry 4.0 priorities. It is relevant to applications such as real-time monitoring, predictive maintenance, safety sensing, and automation in industrial, smart building, environmental, and telecom sectors.

The expected outcome is a tested RF energy harvesting prototype and a realistic evaluation of its feasibility and limitations for battery-assisted low-power IoT sensor applications in Bahrain.

Alignment with Bahrain's national research strategy

Contribution to Bahrain Society

This project supports Bahrain's move toward smart cities, IoT, environmental monitoring, and digital transformation by developing low-maintenance sensor power solutions. By reducing dependence on frequent battery replacement, the research can support more sustainable and reliable sensing systems for smart buildings, environmental monitoring, and public infrastructure.

Alignment with Industry

The project aligns with Bahrain's Industry 4.0 direction by supporting battery-assisted low-power IoT sensors for real-time monitoring, safety sensing, predictive maintenance, and automation. It is relevant to sectors such as aluminium, oil and gas, telecommunications, smart buildings, and industrial facilities, where large numbers of wireless sensors may be deployed in difficult-to-access locations.

Alignment with National Research Priorities / Strategy

The study supports Bahrain's priorities in IoT, NB-IoT, M2M communication, smart cities, environmental monitoring, and digital infrastructure. It also contributes to sustainable technology development by investigating energy-aware sensor systems that can improve the reliability and lifetime of IoT deployments.

Alignment with EDB Policies

The project is aligned with Bahrain's economic diversification and digital economy goals by contributing to applied research in electronics, IoT, and smart infrastructure. It supports innovation in technology-enabled industries and can strengthen Bahrain's position as a regional hub for digital transformation and industrial innovation.

Benefits for Industry Partner

An industry partner may benefit from a tested RF energy harvesting prototype, experimental data, and practical recommendations on whether RF harvesting can extend battery life in low-power IoT sensor nodes. The findings can support future low-maintenance monitoring systems, reduce sensor maintenance costs, and improve the feasibility of large-scale industrial or smart-city sensor deployment.