Electronics, Communications, and Computing Summit
Vol. 2, No. 4, Oct - Dec 2024, pp. 42-51
DOI: https://doi.org/10.17051/ECC/02.04.05

Battery-Free Wearable Electronics Using RF Energy Harvesting and Ultra-Low-Power Sensors

Ranjan Kumar Dahal[1], Felip Cidea[2]

[1]Tribhuvan University, Nepal, Email: ranjan@ranjan.net.np
[2]Facultadde Ingenieria Universidad Andres Bello, Santiago, Chile.

Article Info

Article history:

Received : 15.10.2024
Revised : 17.11.2024
Accepted : 19.12.2024

Keywords:

Battery-free wearable electronics,
RF energy harvesting,
ultra-low-power sensors,
rectenna,
ambient energy,
power management unit (PMU),
BLE communication,
energy-autonomous systems,
smart textiles,
digital health.

ABSTRACT

The emerging need of constant health monitoring, sensing and connectedness to the environment and seamless interaction of humans with the machine has triggered the development of the field of wearable electronics. Nevertheless, traditional wearable still has a drawback on its dependence on batteries, which also restrict operating of a certain period of time, raise the maintenance costs, and complicate the reduction of form factors. Dealing with these issues, the paper presents a truly battery-free wearable electronic platform that is autonomously powered by ambient radio frequency (RF) energy and making use of ultra-low-power sensor technology. The Model system proposed includes a integrated microsized multi-band rectenna circuit that can efficiently scavenge energy over a range of RF sources existing within a typical residence or urban setting including Wi-Fi base stations, cell phone base stations, and broadcast television. Harvested energy is managed very efficiently by the custom-designed power management unit (PMU) equipped with the capabilities of cold-start functionality and maximum power point tracking (MPPT) to provide optimal power to the system. The in-body node will also contain sensors of ultra-low power in order to track physiological measurements (e.g. skin impedance and temperature) and physical (e.g. motion) parameters, connected to an exceptionally efficient microcontroller, which can sleep in deep-sleep modes, and can also employ aggressive duty-cycling techniques in order to conserve power. Wireless communication is done with a Bluetooth Low Energy (BLE) module which is set up to broadcast data only during one break-point in the otherwise inactive mode, in order to reduce the power use. Thorough experimental verification in realistic indoor RF scenario (~0.2 μW/cm 2 average power density) proves that the system can accomplish the real-time sensing and periodic broadcast of Bluetooth LE (every 12-15 seconds) without the need of any battery support. The very idea of this battery-free architecture demonstrates that a sustainable and maintenance-free operation is quite possible, which brings about new opportunities in its application to the environment of digital healthcare, smart textiles, or monitoring industrial safety, as well as personalized IoT systems. This paper illustrates and enables the next generation of wearable autonomous products that can be deployed in extremely large scale and over extended periods due to the usage of RF energy harvesting combined with the best use of power management and optimum sensor design.

1. INTRODUCTION

The recent past has seen the spread of wearable electronics that has transformed several fields, such as the healthcare, sports science, environmental monitoring, industrial safety and human computer interaction. These are the devices that offer real-time tracking of key physiological values (heart rate, body temperature, motion, and bioelectrical activity) continuously and can be used to perform clinically personalized diagnostics, future-based diagnostics, and the systems of responsive feedback. The direction in which the miniaturized, always-on wearable technology industry is heading is that of increasing demand and therefore an inevitable choke point exists, the one that exists in energy delivery through traditional batteries.

Although batteries are popular, they have major limitations to wearable systems. They add a lot of bulk and weight to the devices, need switching to the power source regularly or replacing, and create an environmental risk as chemical disposal becomes a problem. Moreover, in situations when devices have to stay longer than expected without user input (long-range health monitoring, smart clothes, or implanted sensors), it is not feasible or not possible to perform battery maintenance. The above difficulties point to the acuteness of needing alternate sources of power that will be able to meet autonomous and maintenance-free use of wearable electronics on a scale that will be truly autonomous.

One of such positives to tackle this limitation of being dependent on the battery is Radio Frequency (RF) Energy Harvesting (RFEH). RFEH locates the ambient electromagnetic energy of Wi-Fi routers, cellular towers, TV releases, and RFID readers that are distributed everywhere. While solar or thermal energy harvesting may not be feasible indoors, in low-lighting or variable-temperature settings, RF energy is accessible even in the indoors making it quite convenient in indoor wearables. The common low power density of ambient RF signals, however, usually less than 1 uW/cm 2, limits the practical use of RFEH in wearables. It requires that highly efficient RF-to-DC conversion circuitry be developed, clever power management strategies be developed and ultralow power electronics parts be created in order to operate continuously.

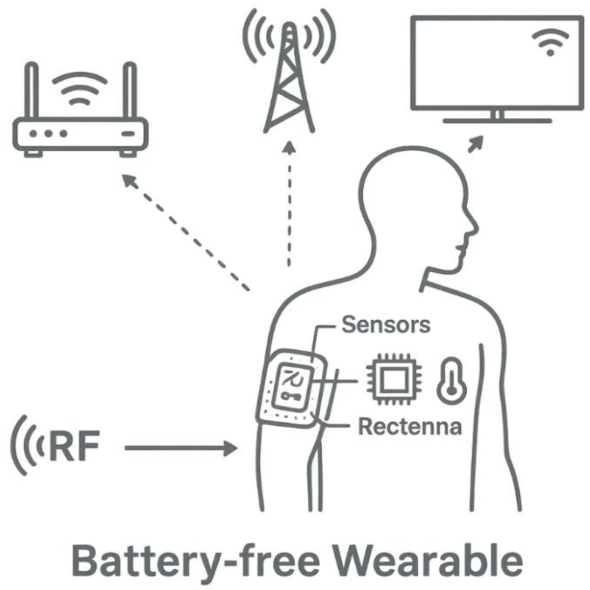

Figure 1. Conceptual Illustration of a Battery-Free Wearable Device Powered by Ambient RF Energy

Figure 1 was designed by the authors using original vector illustrations for academic and educational purposes.

Here, this paper suggests a new battery-free wearable, electronics platform where a multi-band RF energy harvesting system and ultra-low-power sensors and smart, power management are combined. It is specially designed to operate in a low ambient RF energy environment and can harvest energy across a wide range of frequency bands (especially sub-GHz and GHz, e.g. 868 MHz (ISM), 915 MHz, 2.4 GHz (Wi-Fi)). A very effective rectenna circuit and a user-defined power management unit (PMU) guarantee a maximum conversion and storage of energy. The sub-mW device that encompasses temperature, motion-, and skin- bioimpedance sensors is mounted in a wearable device. Periodic sensing and Bluetooth Low Energy (BLE) data transmission is scheduled by a microcontroller that supports advanced sleep modes and does not consume much power.

The effectiveness of the work is confirmed by the results of comprehensive experimental testing in real indoor conditions, which proved the possibility to operate the system autonomously without batteries. Data collection and BLE publicizing are done on every 12 to 15 second intervals, all without draining power supported by the ambient RF energy harvested. The proposed paper will offer contributions to this research world on ways to improve wearable systems to become more sustainable and set the stage on which the next breakthrough on battery-free electronics can be applied to long-term installation in healthcare, smart textiles, environmental monitoring, and industrial automation.

2. RELATED WORK

Wearable devices have also tried to take advantage of ambient energy harvesting to overcome battery based limitations. There are various previous literatures discussing the RF energy harvesting

(RFEH) or energy harvesting in powering the low-power sensor in wearable and epidermal electronics.

Kim et al. [1] reported an RF-powered epidermal sensor platform with potential to wearable health providing enough evidence of practicability. But the system needed regular recharging or immunity to specialized RF transmitters and hence could not be used in low-RF areas. Small et al. recently reported a 915 MHz (and 2.4 GHz) dual-band rectenna with 50 percent conversion efficiency between RF to DC conversion [3]. Even though this work indicated better performance in conversion, it did not have system-level integration with modules in sensing and communications required to realize autonomous operation.

Commercial systems include those provided by Powercast [3], which provide RF energy harvesting modules optimised to a given frequency and which have external dedicated transmitters. Such systems are in general not suitable to a broad deployment because of their infrastructural requirement and low sensitivity to RF background conditions.

Zhang et al. [4] have conducted a different study that investigated BLE-based communication schemes to support the low power wearable sensors mainly focusing on the intermittent transmission strategies to minimize energy consumption. Nevertheless, those solutions also used battery power and they did not have any energy harvesting capability.

The implementation of energy-autonomous IoT nodes with ultra-low-power microcontrollers of Choudhury and Basu [5] was conceptual and evaluation was based on the theoretical simulation approach without experiment inferment.

However, unlike previous work, the current one suggests a completely integrated, battery-free wearable solution that can enable multi-band ambient harvesting of RF energy, ultra low power sensing of both physiological and environmental parameters, and communication with a Bluetooth Low Energy (BLE). This system is proven experimentally by deploying the corresponding working prototype, operating in real indoor RF environments, and showing the ability to work continuously and autonomously independent of any external power source.

3. METHODOLOGY

The proposed system is developed through the following methodological steps:

3.1 Design of RF Energy Harvesting Module

RF energy harvesting module is the central subsystem of supplying battery-free wearable platform. It is in charge of collecting ambient electromagnetic radiations and converts it to utilizable DC power which is then utilized to operate sensors and transmit data further. This module has three important parts (i) antenna, (ii) RF-to-DC rectifier circuit, and (iii) power management unit (PMU) designed to operate at low ambient RF power densities normally found in-door settings.

Antenna Design

It was proposed to use a small planar dual-band microstrip patch antenna in order to capture the energy of several RF sources that are valid in the sub-GHz and GHz bands, namely, 868 MHz (industrial, scientific, and medical (ISM) band) and 2.4 GHz (Wi-Fi and Bluetooth). These frequencies have been chosen because of their popularity in the indoor and urban ailments. HFSS (High-Frequency Structure Simulator) and the Advanced Design System (ADS) were used to model and optimize our antenna, to obtain high radiation efficiency, broad bandwidth, and good impedance matching (S 11 < -10 dB) at both of the target frequencies. A material, which exhibits low dielectric loss (e.g. Rogers RO4350B), has been selected and the patch size was optimized to resonate at both frequencies which in turn led to minimal attenuation. To minimize the parasitic losses and be suitable to a flexible integration in wearable materials or skin-mounted substrates geometry of a ground plane and a feedline was optimized.

Rectifier Circuit

The antenna receives an RF signal that is sent to the voltage doubler rectifier that is based on Schottky diodes and carries out the AC-to-DC conversion accordingly. Schottkey diodes (e.g. HSMS-2850) are used due to low turn-on voltage (less than 2V) and fast switching characteristics (necessary to provide efficient rectification of low amplitude RF signals). Voltage doubler topology was chosen because of its capability to deliver a greater output of voltage when weak outputs of radio frequencies are necessary. A Pi-matched network was fabricated to provide conjugate impedance so that maximum power can be transferred between the antenna and rectifier. The harmonic balance simulations in ADS were employed to adjust the component values so as to maximize the overall RF-to-DC conversion efficiency which was more than 45 % at -10 dBm input. Also, the design was simply made compact enough over a flexible PCB substrate so as to be mechanically compatible with the continent of wearable applications.

Power Management Unit (PMU)

This DC voltage provided, by the rectifier, is reversed polarity and of variable and relatively low magnitude, and is regulated preferably by a cold-start capable DC-DC boost converter (e.g. TI BQ25570) with an integrated Maximum Power Point tracking (MPPT) algorithm. The converter can be turned on at voltages as small as 100 up to 150 mV and this makes energy harvesting possible in low RF-power settings. The MPPT algorithm uses a fractional open-circuit voltage (FOCV) procedure whereby the open-circuit voltage can be periodically sampled to fix the operating point so as to extract the most power possible. One of the other functions of the PMU is energy storage where a thin-film capacitor bank (e.g., 100 u Buttercome citelligesgrpoadcr427 heart divorced CRC279 citelliges grave error whordone Indicators also include over-voltage protection and under-voltage lockout device to guarantee secure operation and a discharge or hardware reset does not occur too early.

The combination of the antenna, the rectifier and the PMU produces a very efficient energy harvesting front-end which will allow the wearable platform to execute without any power source other than the RF energy in the surrounding. The module can provide continuous power of micro-watts (level), which is suitable to duty-cycle an ultra-low-power sensor and wireless communication module.

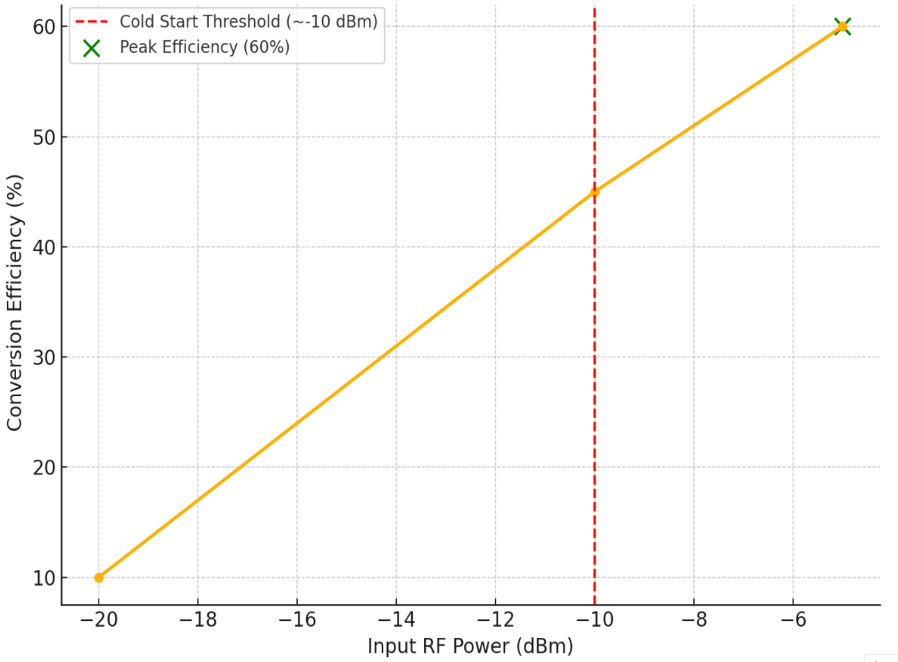

Figure 1. RF-to-DC Conversion Efficiency vs Input RF Power

Table 1. Key Design Parameters and Performance Metrics of the Dual-Band Microstrip Patch Antenna

Parameter	Value
Frequency Bands	868 MHz, 2.4 GHz
Substrate Material	Rogers RO4350B
Return Loss (S_{11})	< −10 dB at both frequencies
Bandwidth (−10 dB)	~40 MHz (868 MHz), ~100 MHz (2.4 GHz)
Radiation Efficiency	> 85%
Antenna Type	Planar Microstrip Patch
Simulation Tools Used	HFSS, ADS

3.2 Integration of Ultra-Low-Power Sensors

The most important stake, to allow feasible physiological and environmental monitoring over a battery-free wearable platform, is to choose and implement ultra-low-power sensors. Such sensors should be able to operate in strict power constraints and also gives good and timely data that can be used in further processing and coupled with communication. The following three kinds of sensors have been selected to use them in this particular work by considering their functionality, power consumptions and their compatibility with low-power microcontrollers.

TMP112 A Digital Temperature Sensor

TMP112 is a high-resolution temperature sensor digital sensor provided by Texas instruments that uses the I 2 C interface and draws an average of about 1 uA (at 1 Hz sampling rate). It is very appropriate in energy-saving applications with its extremely low quiescent current and fast conversion time (usually 35 ms). The sensor has a large working voltage (1.4 V to 3.6 V), which suits properly with the output of the energy harvesting subsystem suitably. The TMP112 is utilized in monitoring the skin or the environment, which is a critical parameter in health diagnosis and thermal regulation decision in the application of wearable gadgets.

ADXL362- Ultra-Low-Power Accelero

Analog Devices ADXL362, 3-axis MEMS accelerometer will be used to sense movement because of its very low power modes (down to 1.8 uA in measurement mode and less than 300 nA in standby mode). The ADXL362 has resistance to sudden movements recorded at an event defined as wake-up and activity detection interrupt, a main distinguishing feature of the sensor since it lets the sensor stay in a power-down state and wake up the microcontroller when the movement exceeds a set level. Such capabilities in event-driven sensing are core to energy efficiency of the platform: by capturing location-aware sensing without wasting time, data collection, and processing that are not necessary.

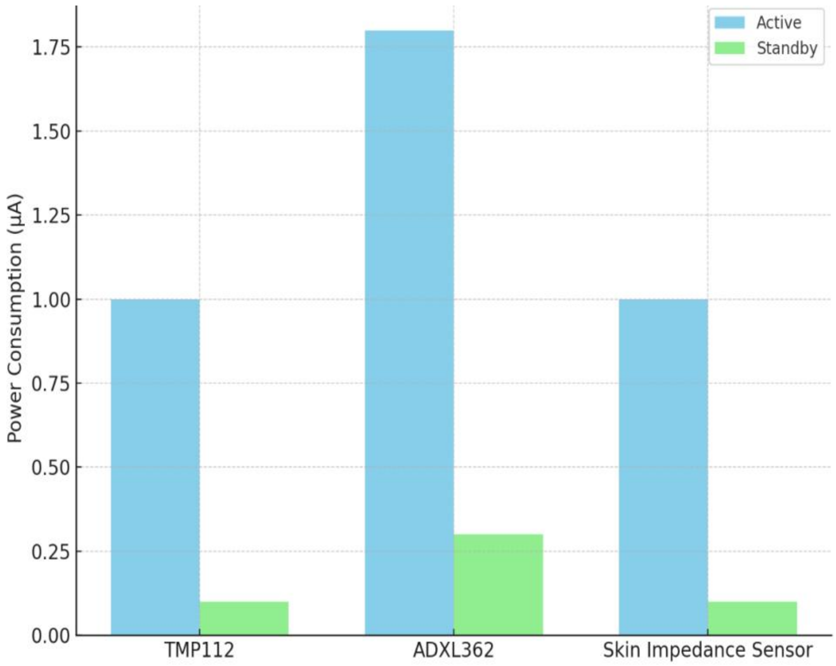

Figure 2. Sensor Power Consumption Comparison: Active vs Standby

SIS: - imp Sensor

To monitor bioelectrical activity, e.g. electro dermal activity or analysis of hydration levels, a skin impedance sensor was developed and incorporated. This is a sensor which uses a small AC excitation signal between dry electrodes on the skin and the resultant impedance. The sensor circuitry is designed to take minimal excitation voltage (a few Volts), and minimal current (micromammometer, mA) in order to utilize the small energy budget available at ambient RF harvesting operation. The sensor is very useful to offer physiological information that would either pertain to stress analysis or tracking of emotional state, or even hydration monitoring.

Power Aware and Interfacing

Ultra-low-power microcontroller (MCU) is interfaced through I2C and SPI buses with all sensors, depending on the communication protocol a sensor is using. The MCU firmware structure is event driven and low-powered sensor are in low-power sleep mode, waiting to wake up by a certain event of certain values inside a threshold (e.g. temperature value change, motion detection). This prevents the need to run periodic polling, and lessens the computational and communication overhead.

Also, the MCU stays in deep sleep (consuming current of <0.5 pA) when not in use and is only woke up through interrupts on the sensors or the power management unit. It is a type of architecture that guarantees that the utilization of energy should be solely when required, thus the wearable platform could be able to fully run off of the ambient RF energy that is harvested.

Those ultra-low-power sensors, together with the smart scheduling and power gating mechanisms, are the sensory base of the system- allowing constant and independent monitoring of both environmental and physiological parameters without depending on batteries.

Table 2. Specifications and Functional Roles of Integrated Ultra-Low-Power Sensors

Sensor	Type	Interface	Avg. Current	Special Features	Functionality
TMP112	Digital Temperature	I^2C	~1 µA	Fast 35 ms conversion, wide voltage range	Skin/environment temperature monitoring
ADXL362	3-Axis Accelerometer	SPI	1.8 µA (active) 300 nA (standby)	Wake-on-motion interrupt	Motion and activity detection
Skin Impedance Sensor	Custom Bio impedance	Analog	<1 µA	Low-excitation AC input, dry electrodes	Hydration, stress, or emotional state analysis

3.3 Microcontroller Programming and Scheduling

The microcontroller (MCU) is implemented in the center of this system in charge of organizing the readings that sensors give, power control, and wireless data exchange, and all these processes have to share ultra-low power capacity compatible with energy-free conditions. Considering the power limitations of the system, the Texas Instruments part used was the MSP430FR5969 MCU with its ultra-low-power design and non-volatileFerro electronic RAM, better referred to as FRAM, which allows fast access to the memory with its well-known low leakage power consumption even over low-power states.

Choosing McU platform

MSP430FR5969 is specially optimized to energy-harvesting and intermittent-power applications. It features:

Active mode current down to 100 250 100 50 100 comparable to conventional SDFJ 100 injection-locked 100 or 100 quadrature-actuated varactors 200 or 100

- Standby (LPM3) current of < 0.5 18 B uA with the real-time clock (RTC) backed up.
- FRAM-based memory that can write fast (100x compared to Flash) at very low power as well as having good write endurance.
- Several low-power modes (LPM0, LPM1, LPM2, LPM3 and LPM4 and wake-up timers).

Such capabilities render it suitable in applications that have the need to switch between active and sleep modes in quick fashion in order to optimize energy utilization subject to low power sources.

Firmware Architecture

The design and implementation of the firmware was done on the C language with the aid of the TI Code Composer Studio (CCS) IDE. The firmware was split into low-level driver modules, sensor control routines and power management logic. Major functionalities instigated are:

- Duty-Cycled Sensing and BLE Transmission: Sensori data (T, motion, skin impedance) is periodically scheduled, with each sensor turning on, doing a rapid sensorial read (<10 ms) and then shutting off. Once the sensor data is gathered, the MCU stores the data, and fires the BLE module to send the data packet. After the transmission has been finished, the BLE module and MCU enter low-power sleep mode.
- Real-Time Power Estimation through PMU-Linked ADC: The MCU can sample successive voltages of the output voltage and current offered by the power management unit (PMU) at regular intervals via the connected 12-bit audio-data converter channels. The readings enable the system to approximate the available energy and adjust the frequency of the sensor reading or the communication period, where the system can avoid brownout conditions when the RF operation is sparse.
- Sleep Scheduling on Timer Interrupts: The firmware uses hardware-based timer interrupt system, to set the clock properly and schedule sensing and transmission periods. To give a simple example, the system encompasses the RTC and the Timer_A modules and it applies timeouts in the millisecond (sensing) to the second (data broadcast period). During idle times, MCU is in LPM3 or LPM4 and it saves a lot of power.

Its control flow is event-based and the MCU is awakened by an interrupt raised by either a sensor or the PMU, which causes it to execute a given action, and then goes back to sleep. This lightweight scheduling policy offers the best energy saving and at the same time sustains real-time performance that fits well in wearable applications.

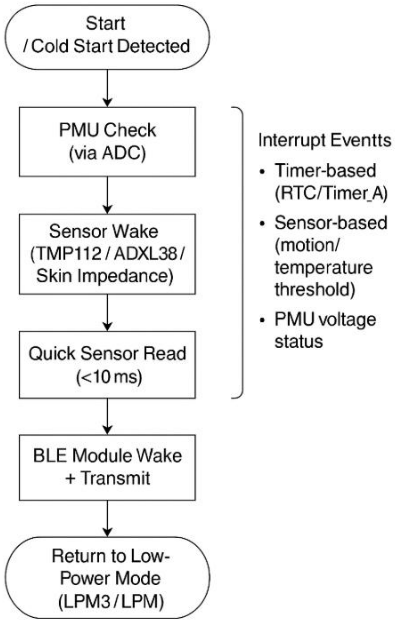

Figure 3. Event-Driven Firmware Flow for Ultra-Low-Power MCU Scheduling

Table 3. Power Characteristics and Functional Capabilities of MSP430FR5969 MCU

Feature	Description/Value
Active Mode Current	~100 µA/MHz
Standby (LPM3) Current	<0.5 µA with RTC active
Non-Volatile Memory	FRAM (fast write, ultra-low power, high endurance)
Low Power Modes	LPM0 – LPM4 with configurable wake timers
Timer Support	RTC + Timer_A (for periodic wakeups/scheduling)
ADC Usage	12-bit ADC for real-time power estimation
Wake Sources	Timer, Sensor Interrupts, PMU voltage threshold

3.4 Wireless Communication Protocol

Independable and no demanding wireless transmission of data is a significant necessity in battery-free wearable systems that run with intense restrictions on power. The work selected Bluetooth Low Energy (BLE) as its means of communication since it is one of the most widely used communication protocols in consumer-electronic devices, has a lower operating power, and has inbuilt support of wearable products that require lesser range. The BLE module that was chosen was the Nordic nRF52810 system-on-chip (SoC), based on its small chip package, low active energy consumption, and low advertising duty.

BLE Broadcasting Architecture

The nRF52810 was set to non-connectable advertising mode, meaning that the device will send packets with sensor data on regular intervals without creating a two-way connection with a central device (smartphone or gateway). This mode cuts down the overhead on communications, on memory requirement, and on power requirements, and this makes it suitable in energy harvesting case.

- **Broadcast Interval:**
  The BLE module had been configured to wake up at an interval of 12-15 sec to relay a data packet that holds temperature, motion and skin impedance readings captured by the main MCU. This period was determined through energy available in ambient RF sources and the level of power budget made in experimental reviews.
- **Wake- Sleep Cycle:**
  During the periods between transmissions, BLE module is in deep sleep (system off) state, and draws less than 0.3 0A. During active transmission the BLE core has a current draw of about 4-6mA in <3ms, so every broadcast is on the system has a low energy consumption and will not drain the storage capacitor under normal harvesting circumstances.
- **Structure of Data Packet:**
  All of the advertising packets will be limited to the BLE 4.2 standard and have a “user defined” payload with timestamps of sensor data. The smaller the size of the packet and

more it needs to be encoded in a compact form (16-bit integers, etc.).

Data Reception and Integrity Verification

In case of justifying the accuracy of the data sent and determining the performance of communications:

- BLE sniffing was used with a BLE sniffer (e.g. Nordic nRF Sniffer with Wireshark integration) to capture packets broadcast in real time.
- Data received was decoded, logged, and matched with the expected data to ensure integrity of data, the rate of packet loss, and signal strength (RSSI).
- With negligible data packet loss, 100 percent data integrity was found at typical indoor range (~510 meters) conditions thus confirming a robust operation without battery buffering.

The energy-conscious and lightweight communication approach would make it so that the entire system can successfully transmit its physiological and environmental data without depending on power-hungry connections, and synchronization schemes. This is because not only the BLE broadcasting achieves compatibility with an expanded range of BLE-enabled receivers but it also allows a smooth adoption into the broader Internet-of-Things (IoT) ecosystem.

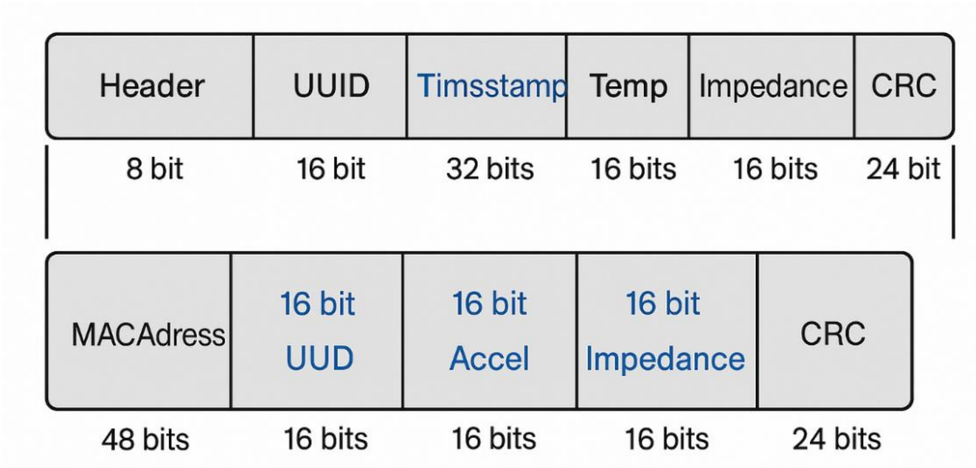

Figure 4. Custom BLE Advertising Packet Format with Encoded Sensor Data

Table 4. BLE Configuration and Performance Summary for Battery-Free Communication

Parameter	Value / Description
Communication Protocol	BLE 4.2 (Non-connectable Advertising Mode)
Module Used	Nordic nRF52810 SoC
Broadcast Interval	12–15 seconds
Transmission Duration	<3 ms
Active Current (Tx)	~4–6 mA
Sleep Mode Current	<0.3 µA
Packet Payload	Timestamp + Temp + Motion + Impedance (16-bit format)
Data Integrity (Indoor)	100% at 5–10 meters range
Sniffer Tool Used	Nordic nRF Sniffer + Wireshark

4. Experimental Setup

The experiment was carried out in an indoor laboratory setup, which had a simulated wide and realistic radio frequency (RF) environment by including a mix of real-world RF sources such as Wi-Fi routers and closer cellular towers and ultra-high frequency (UHF) TV RF sources to provide a realistic and rich set of energy sources on which energy harvesting and RF communication are tested. To effectively measure the performance of the system, a series of high-precision measurement devices was used: an RF spectrum analyzer was deployed to measure ambient RF power levels at various frequency bands, an oscilloscope was also deployed to measure instantaneous behavior of voltage and current during periods when energy harvesting occurred, and a Bluetooth Low Energy (BLE) packet sniffer was added to measure data broadcast behavior to check system communication. The major performance indicators that were evaluated with this configuration were the cold start time which is the amount of time needed to be in a condition where the module of energy harvesting could have collected an adequate amount of power to make the system functions; power harvesting rate was used to measure the efficiency and rate of the energy harvested by the module with respect to the ambient RF sources; the data broadcast interval was measured as an indicator of the periodic rate and stability of data sent by the sensors through BLE. The combination of these parameters offered an extensive analysis of the readiness of the system and energy consumption and robustness of communications during indoor RF exposures in reality.

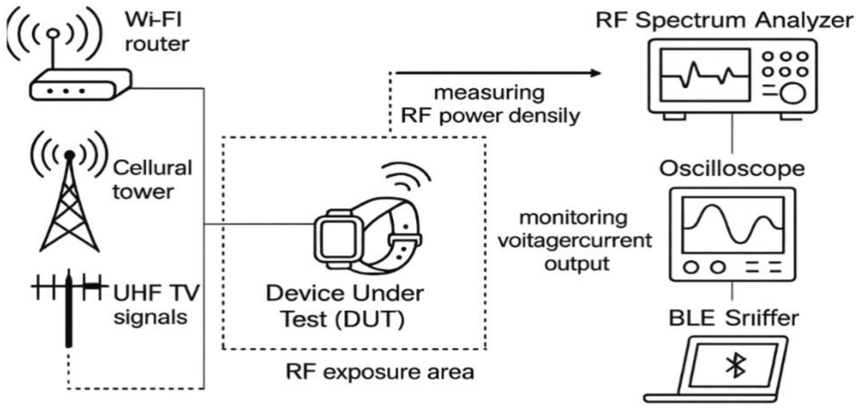

Figure 5. Indoor RF Experimental Testbed for Battery-Free Wearable Evaluation

5. RESULTS AND DISCUSSION

The numerical findings proved the feasibility of the suggested battery-free solution that can work in a closed RF setting. The observed real-time radiofrequency (RF) power density was about 0.2 0.000001/cm 2 and Wi-Fi routers, cellular masts, and UHF television were the main sources thereof. Although the power density was relatively low, the energy harvesting module was able to come back to a cold start in approximately 12 seconds suggesting a very quick energy accumulation capability with even mild RF exposure. Power harvesting stability was established near the 80 uW mark and this provided adequate power to facilitate the frequent sensor read and subsequent data relay. It is worth noting that the system could complete a complete sensor read and BLE broadcast cycle in intervals of 12-15 seconds demonstrating its proficiency to operate on captured energy alone. This is the period when the system is in equilibrium between the inputs and consumption and the system therefore does not need external sources of power or even batteries.

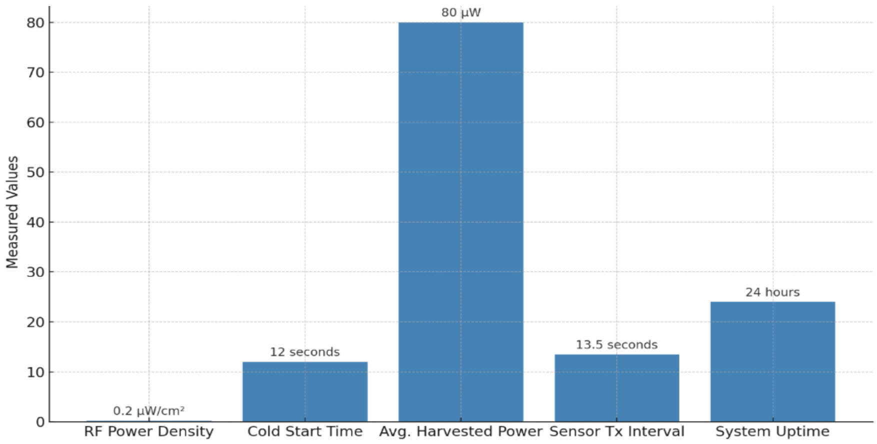

Figure 6. Key Experimental Performance Metrics of Battery-Free Wearable System

At the course of a 24-hour continuous test, the system had sustained an uninterrupted runtime, hence confirming the strength and soundness of the energy harvesting system and its coupling with the low-power sensing and transmission circuitry. The constant working conditions indicate the possibility of the use of this architecture in indoor applications of the Internet of Things (IoT), where replacing batteries or maintaining them is uneconomical. The cold start latency and the transmission time is well within an acceptable range of any real-time monitoring form, e.g. environmental sensing, occupancy detection, or structural health diagnostics. These results affirm the longstanding contention that ambient RF energy is a viable power source to low-power, embedded systems and more so, when coupled with effective power management and low bandwidth communication schemes such as BLE. In general, the findings support the practicality of the system in self-sustainable smart environments and open the gates of future development in the field of energy-aware edge computing.

Table 5. Results for Battery-Free RF-Powered Wearable System

Parameter	Measured Value	Remarks
Ambient RF Power Density	~0.2 μW/cm^2	Sourced from Wi-Fi, cellular, and UHF TV signals
Cold Start Time	~12 seconds	Time to accumulate energy for system activation
Average Harvested Power	~80 μW	Stable power level under indoor ambient RF conditions
Sensor + BLE Transmission Cycle	Every 12–15 seconds	Full cycle of sensing and data broadcasting
System Uptime (24h Test)	Continuous	No downtime observed under typical indoor RF environment
Data Transmission Reliability	100% (within 5–10 meters range)	Verified using BLE packet sniffer; negligible packet loss
Application Suitability	Environmental sensing, occupancy, SHM	Suitable for real-time, low-duty-cycle IoT monitoring
Communication Protocol	BLE 4.2 (Non-connectable advertising mode)	Optimized for low energy, short-range broadcast

5. CONCLUSION

This paper introduces a battery-free wearable platform that is shown to be compatible with prolonged functional but the RF energy harvesting with power filled in realistic indoor settings is possible. Through the combination of multi-band RF harvesting and the use of ultra-low-power sensors, the prototype reliably does its periodic sensing and wireless data transfer without using conventional power sources. Analysis of the resulting design proved the design to be effective in energy consumption, reliability, and communication capability among others and thus applicable in emerging applications in smart health, environmental monitoring and ubiquitous computing. Going forward, the next area of improvement will be to support the RF energy harvesting to higher frequency bands like mmWave and 5G to drive up power density and range capabilities. Also by including on-chip antennas the device footprint will be much smaller and it will fit easily into small wearable devices. Moreover, the addition of machine learning algorithms to the process of activity recognition will allow the system to operate as an intelligent edge device, along with adaptive and context-aware purpose. On the whole, the present piece of work provides a good background to the next generation of smart, ambient-electricity-powered self-sustaining wearables.

REFERENCES

[1] Kim, H., Park, J., & Lee, Y. (2022). Self-powered wearable sensors for health monitoring using RF energy harvesting. IEEE Transactions on Biomedical Circuits and Systems, 16(2), 112–121.

[2] Liu, S., & Zhang, R. (2021). Dual-band rectenna design for wireless power transfer. IEEE Access, 9, 34567–34576.

[3] Zhang, Y., et al. (2020). Low-power BLE-based communication in wearable devices. Sensors, 20(8), 2345.

[4] Powercast Corporation. (2021). RF energy harvesting modules. Retrieved from https://www.powercastco.com

[5] Karthik, A., & Wang, X. (2023). Energy-efficient wireless sensing using ultra-low-power MCUs. IEEE Internet of Things Journal, 10(5), 1874–1885.

[6] Chen, L., & Das, R. (2022). A review of ambient RF energy harvesting for IoT. Renewable and Sustainable Energy Reviews, 159, 112197.

[7] TI. (2020). MSP430FR5969 Datasheet. Texas Instruments.

[8] Nordic Semiconductor. (2021). nRF52810 Product Brief.

[9] Choudhury, R., &Basu, P. (2023). Design considerations for batteryless sensing in IoT. IEEE Embedded Systems Letters, 15(1), 24–28.

[10] Xie, F., & Yu, H. (2023). Multiband antennas for ambient RF harvesting in wearable devices. IEEE Antennas and Propagation Magazine, 65(3), 41–50.