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Sustainable Smart Wearable RF Energy Harvesting Communication Patch for Health Monitoring

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Abstract *– This project presents a portable, energy-efficient, and self-sustaining IoT-based health monitoring system designed to address the limitations of conventional battery-powered devices and the growing need for continuous health tracking. The system utilizes hybrid energy harvesting by combining solar power and ambient radio frequency (RF) energy. These sources are captured through a solar panel and RF harvesting coil, then processed via rectification and voltage regulation circuits. The harvested energy is stored in a lithium-ion battery, serving as the primary power supply and eliminating dependence on external power sources.*

At the core of the system is the Node MCU (ESP8266) microcontroller, which manages data processing and communication. A MAX30102 pulse oximeter sensor is used to measure key physiological parameters, including heart rate and blood oxygen saturation (SpO2), in real time. The data is continuously updated and transmitted via WiFi.

For remote monitoring, the NodeMCU hosts an embedded web server that displays real-time readings through a user-friendly interface. A JSON-based API also enables integration with mobile or external applications. Additional features, such as LED indicators, provide system feedback. Overall, the design ensures portability, low power consumption, and reliable real-time health monitoring for diverse applications.

Keywords*- IoT-based Health Monitoring, Hybrid Energy Harvesting ,Solar and RF Energy, NodeMCU (ESP8266) , MAX30102 Sensor , Remote Patient Monitoring , Self-Powered System ,Real-Time Data Transmission*

INTRODUCTION

The rapid advancement of the Internet of Things (IoT) has significantly transformed the healthcare sector by enabling continuous and remote monitoring of vital physiological parameters. Wearable health monitoring systems have gained popularity due to their ability to provide real-time data, improving early diagnosis and patient care. However, most existing systems rely on conventional battery-powered designs, which require frequent charging or replacement. This dependency not only limits long-term usability but also increases maintenance efforts and reduces system reliability.

To address these limitations, there is a growing need for sustainable and energy-efficient solutions. Energy harvesting has emerged as a promising approach to power low-energy IoT devices by utilizing ambient energy sources such as solar and radio frequency (RF) signals. Solar energy provides a reliable primary source, while RF energy acts as a supplementary source, especially in indoor or low-light conditions.

In this project, a self-powered IoT-based health monitoring system is proposed, integrating energy harvesting with real-time health sensing. The system employs a NodeMCU (ESP8266) for processing and wireless communication, along with a MAX30102 sensor for measuring heart rate and blood oxygen saturation (SpO_2). The harvested energy is stored in a rechargeable battery and regulated using a boost converter to ensure stable operation.

This approach enhances system autonomy, reduces dependency on external power sources, and supports continuous health monitoring. The proposed system demonstrates a practical and sustainable solution for next-generation wearable healthcare devices, combining low power consumption with efficient energy utilization.

LITERATURE REVIEW

1. IoT-Based Health Monitoring Systems

Recent studies have underscored the critical importance of continuous, real-time health monitoring using IoT-enabled devices. Smart IoT-driven health monitoring systems integrate a range of sensors, microcontrollers, and cloud platforms to provide real-time patient data with remote accessibility. These systems are transforming healthcare delivery, particularly in the context of remote and preventive medicine.

Such systems typically incorporate the following sensing modalities:

- Pulse oximeters for blood oxygen and heart rate measurement
- Temperature sensors for body and ambient thermal monitoring
- Motion sensors for activity and fall detection

The collected physiological data is processed by microcontrollers such as the ESP32 or ESP8266 and transmitted wirelessly to healthcare providers. Key benefits of these systems include:

- Early detection of medical abnormalities
- Enablement of remote patient care and telemedicine
- Reduction in unnecessary hospital visits and associated cost

2. Pulse Oximeter-Based Monitoring (MAX30102)

The MAX30102 sensor has emerged as one of the most widely adopted components in modern health monitoring systems. Its popularity is attributed to several key characteristics:

- High measurement accuracy for both heart rate and blood oxygen saturation
- Low power consumption, making it well-suited for battery-constrained and energy-harvesting applications
- Compact form factor, enabling seamless integration into wearable devices

The MAX30102 operates on the principle of photoplethysmography (PPG), in which variations in light absorption through biological tissue are used to derive cardiovascular parameters, specifically heart rate and blood oxygen saturation (SpO_2). Research demonstrates that the sensor:

- Provides reliable, continuous real-time monitoring
- Supports I^2C communication for straightforward microcontroller interfacing
- Is well-suited for wearable and IoT-based healthcare applications

Numerous studies have successfully paired the MAX30102 with microcontrollers such as the NodeMCU to enable real-time wireless health monitoring with mobile application integration, validating its effectiveness in clinical and consumer settings alike.

3. Energy Harvesting in IoT Systems

Battery dependency remains one of the most significant practical limitations of IoT devices, particularly in remote or resource-constrained environments. To address this challenge, researchers have extensively explored energy harvesting as a means of achieving self-sufficient device operation. Commonly investigated harvesting sources include:

- Solar energy (photovoltaic conversion)
- Thermal energy (thermoelectric generation from body heat or environmental gradients)
- Radio frequency (RF) energy from ambient electromagnetic fields
- Mechanical vibrations (piezoelectric and electromagnetic transduction)

Studies consistently demonstrate that energy harvesting enables:

- Significantly extended device operational lifetimes
- Reduced maintenance requirements and associated costs
- Sustainable, environmentally responsible operation

Hybrid energy harvesting — the simultaneous use of multiple harvesting sources — has proven particularly effective. By compensating for the variability inherent in any single energy source, hybrid approaches ensure more consistent power delivery and continuous device operation. Research on wearable IoT devices has demonstrated that combining multiple energy sources can achieve fully self-powered operation with markedly improved efficiency and reliability.

4. Self-Powered Wearable Health Monitoring Systems

Recent technological advancements have increasingly focused on the development of self-powered wearable biomedical devices that eliminate the need for external charging infrastructure. These systems harvest ambient energy from sources such as solar radiation, body motion, and RF fields to continuously power vital sign monitoring hardware.

Self-powered wearable systems offer substantial advantages over conventional battery-dependent designs, including:

- Enhanced portability and user comfort through the elimination of charging constraints
- Continuous, uninterrupted monitoring without manual intervention
- Improved usability in field and remote settings

Research indicates that such systems are particularly beneficial for remote healthcare delivery, monitoring of elderly patients with limited mobility, and long-term fitness and wellness tracking applications.

5. Integration of IoT, Energy Harvesting, and Edge Computing

A prominent emerging research trend involves the convergence of IoT health monitoring, energy harvesting, and edge computing or artificial intelligence. This multi-technology integration enables:

- Local on-device data processing, reducing latency and dependence on cloud infrastructure
- Lower overall power consumption through intelligent workload management
- Faster physiological event detection and emergency response times

Studies highlight that combining energy harvesting with intelligent edge processing leads to improved system efficiency, extended operational lifetimes, and ultimately better healthcare outcomes — particularly in environments with limited network connectivity.

6. Challenges Identified in Existing Systems

Despite considerable progress, the reviewed literature reveals several persistent limitations in current IoT-based health monitoring and energy harvesting systems:

- Overreliance on battery power, resulting in limited operational autonomy
- Inconsistent or interrupted power supply in remote and off-grid areas
- Intermittent energy availability from individual harvesting sources
- Complexity in power management circuitry and energy storage integration
- Synchronization challenges between sensing cycles and energy generation patterns

These challenges underscore the need for more robust, integrated approaches that address both hardware and software aspects of self-powered health monitoring.

7. Research Gap

A critical analysis of the existing literature reveals a significant gap in the current state of the art. While numerous studies have addressed IoT-based health monitoring and energy harvesting independently, very few have successfully integrated both within a single, cohesive system. Specifically:

- Most existing health monitoring systems remain entirely dependent on battery power, with no provision for energy harvesting
- Systems that do incorporate energy harvesting rarely combine multiple sources in a hybrid configuration
- IoT-based remote access and real-time monitoring are seldom co-designed alongside sustainable power management strategies

There is therefore a clear and unmet need for a fully integrated system that combines hybrid energy harvesting (solar and RF), efficient energy storage, and real-time IoT-based health monitoring in a single platform.

METHOLOGY

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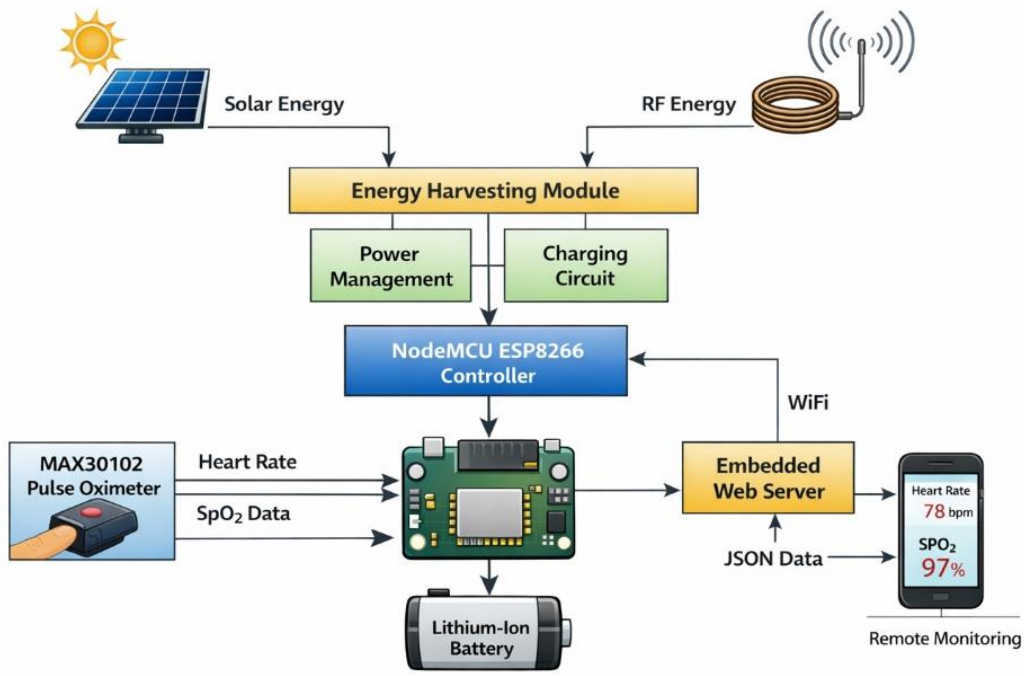


Sustainable Smart Wearable RF Energy Harvesting Communication Patch for Health Monitoring

1. System Overview (High-level Methodology)

Energy Harvesting: Solar panel + RF antenna capture ambient energy (light + radio waves).

Energy Management: TP4056 charging module + HT4928S boost converter regulate and boost the harvested power.

Processing Unit: NodeMCU (ESP8266) processes sensor data.

Data Transmission: WiFi connectivity for real-time monitoring via web and mobile interfaces.

2. Working Principle (Step-by-Step Methodology)

The core methodology follows these four sequential stages:

Energy Harvesting

Solar panel acts as the primary power source during daylight.

RF antenna provides supplementary energy from ambient radio frequency signals (backup during low-light conditions).

Energy Storage & Boosting

TP4056 module safely charges the lithium-ion battery and provides protection.

HT4928S boost converter steps up the low harvested voltage to a stable 5V supply required by the microcontroller.

Sensor Data Acquisition

MAX30102 optical pulse oximeter sensor uses photoplethysmography (PPG) technique.

It employs dual-wavelength LEDs: Red (660 nm) and Infrared (880 nm) to measure:

Heart Rate (BPM)

Blood Oxygen Saturation (SpO_2)

Built-in temperature sensor is used only for calibration.

Wireless Transmission

NodeMCU (ESP8266) processes the raw sensor data.

Data is transmitted over WiFi to a web server.

Real-time visualization is provided through a responsive web dashboard and JSON API (compatible with mobile apps).

3. Key Implementation Details (Supporting Methodology)

Dual Energy Harvesting Approach: Combines solar photovoltaic conversion with RF energy capture for autonomous (self-powered) operation.

Low-Power Design: Optimized for continuous operation under normal lighting with RF as backup.

IoT Integration: WiFi-based real-time data sending with 2-second refresh rate on the web interface.

Hardware Integration: All components (NodeMCU, MAX30102, TP4056, HT4928S, Solar Panel, RF Antenna) are integrated into a single autonomous wearable/health monitoring system.

Summary of Overall Methodology

The project follows a hybrid energy harvesting + IoT methodology:

Harvest energy from two ambient sources (Solar + RF).

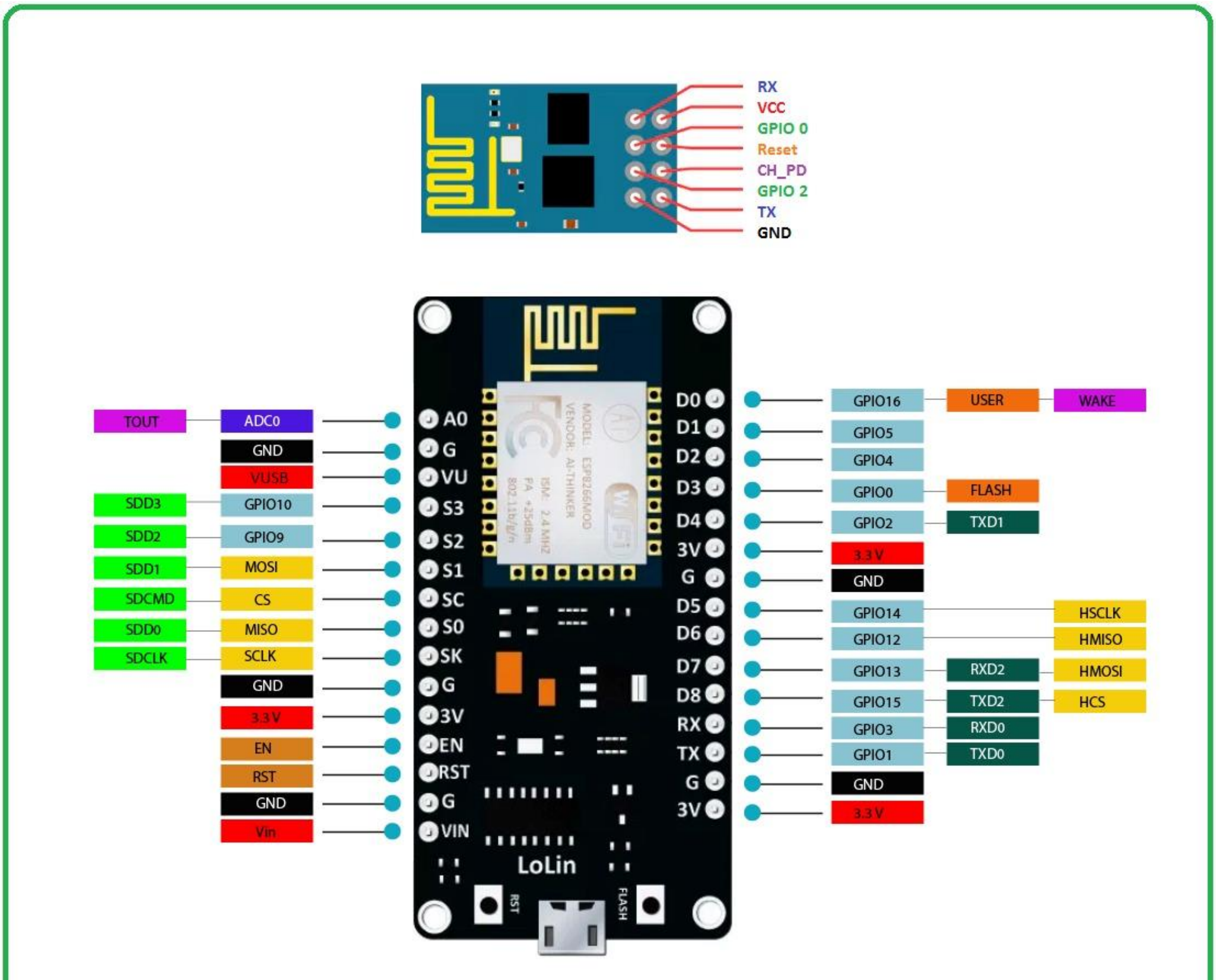
Store and regulate the energy using dedicated power management ICs.

Acquire vital signs using non-invasive optical sensing (PPG).

Process and transmit data wirelessly to cloud/web interfaces for real-time remote monitoring.

This eliminates the need for frequent battery replacement and makes the system sustainable and maintenance-free.

What is ESP8266?



ESP8266 NodeMCU V3

The ESP8266 is a low-cost, highly integrated Wi-Fi System-on-Chip (SoC) developed by Espressif Systems. It is not just a simple microcontroller — it combines:

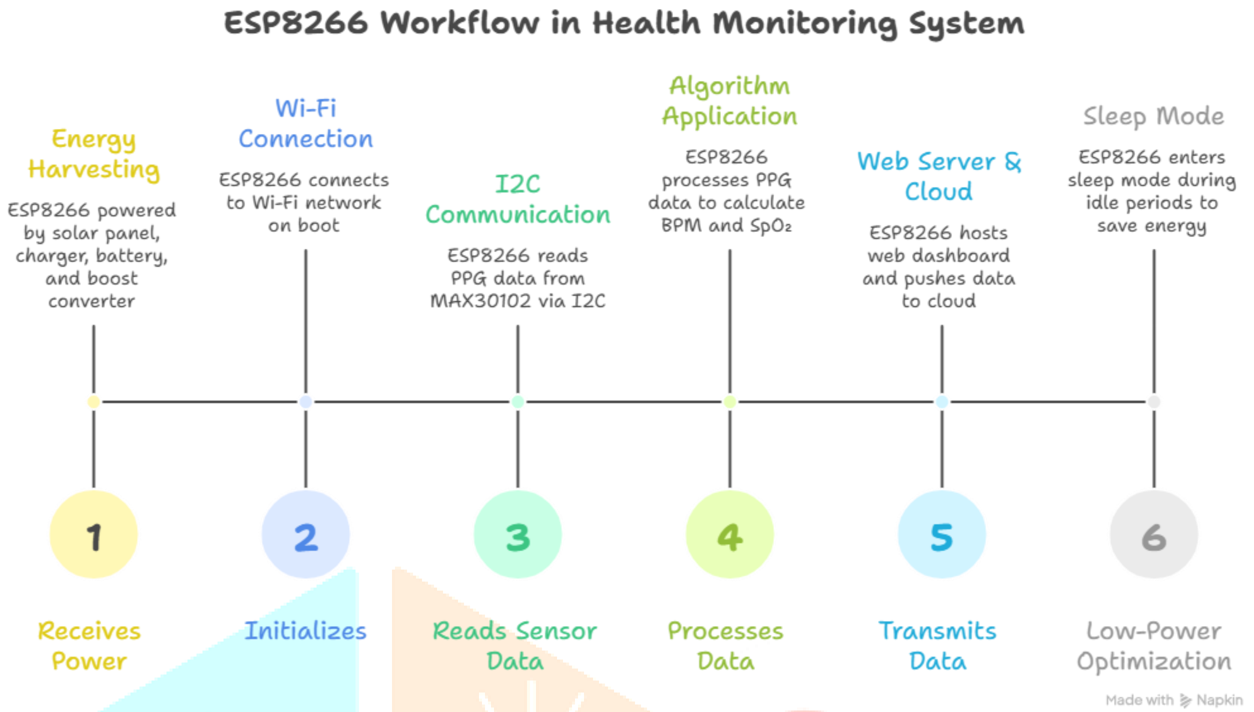
- A 32-bit microcontroller (CPU)
- Built-in Wi-Fi (802.11 b/g/n)
- Memory
- RF front-end (antenna switches, balun, power amplifier, LNA, etc.)
- Power management unit

In your project, the NodeMCU development board (based on ESP-12E module) is used. It makes the ESP8266 easy to program and connect with sensors like MAX30102.

Key Specifications

- Processor: Tensilica Xtensa LX106 32-bit RISC core (runs at 80 MHz, can be overclocked to 160 MHz)
- Memory:
    - 64 KB instruction RAM + 96 KB data RAM
    - External Flash: Usually 4 MB on NodeMCU (stores program and data)
- Wi-Fi: 2.4 GHz, supports Station (client), SoftAP (access point), and both modes simultaneously
- Operating Voltage: 3.3V (logic level)
- GPIO Pins: Up to 17 (many are multiplexed)
- Peripherals: 1× ADC (10-bit), PWM, I2C, SPI, UART, I2S
- Power Consumption: Average ~80 mA during normal operation; supports deep sleep (~10–20 µA) for low-power applications
- Antenna: Built-in PCB trace antenna on most modules

Internal Architecture & How ESP8266 Works



The ESP8266 works as a complete mini-computer for IoT:

1. Power-Up & Boot Process:
   - When powered (3.3V), the chip resets and boots from external Flash memory.
   - The bootloader loads your firmware (program) into RAM.
   - It initializes Wi-Fi, GPIO, and other peripherals.
2. CPU Execution:
   - The Tensilica LX106 processor runs your code (written in Arduino IDE, MicroPython, or Espressif SDK).
   - It handles sensor reading, data processing, and decision-making.
3. Wi-Fi Operation:
   - The integrated RF transceiver handles 802.11 b/g/n communication.
   - It can connect to your home Wi-Fi router (Station mode) or create its own hotspot (SoftAP mode).
   - Full TCP/IP stack is built-in, so it can send HTTP requests, act as a web server, or push data to cloud servers easily.
4. Peripheral Interfaces:
   - I2C → Used to communicate with MAX30102 sensor (reads heart rate & SpO_2 data).
   - GPIO → Controls power to sensors or LEDs if needed.
   - ADC → Can read analog voltages (though MAX30102 is digital via I2C).
   - UART → Used for debugging and programming via USB on NodeMCU.
5. Power Management:
   - Supports multiple sleep modes (Modem-sleep, Light-sleep, Deep-sleep) to save power — very useful for your self-powered (solar + RF) system.
   - In your project, the HT4928S boost converter provides stable 5V/3.3V, and the ESP8266 runs efficiently under harvested energy.

Working in Your Health Monitoring Project

In the Sustainable Smart Wearable RF Energy Harvesting Communication Patch for Health Monitoring, the ESP8266 (NodeMCU) performs these tasks step-by-step:

1. Receives Power — From the energy harvesting system (Solar panel → TP4056 charger → Battery → HT4928S boost converter → 3.3V/5V rail).
2. Initializes — Connects to Wi-Fi network on boot.
3. Reads Sensor Data — Communicates with MAX30102 via I2C protocol:
   - MAX30102 sends raw PPG (photoplethysmography) data (Red & IR light readings).
   - ESP8266 processes this data to calculate Heart Rate (BPM) and SpO_2 (% oxygen saturation).
4. Processes Data — Applies algorithms/filters for accurate readings (libraries like MAX3010x or custom code handle this).
5. Transmits Data —
   - Acts as a web server → Hosts a responsive dashboard.
   - Sends data in JSON format via Wi-Fi.
   - Updates every 2 seconds on the web interface.
   - Can push data to cloud platforms (ThingSpeak, Blynk, Firebase, etc.) for remote monitoring.
6. Low-Power Optimization — In idle periods, it can enter sleep modes to conserve the harvested energy.

Programming the ESP8266

- Most commonly programmed using Arduino IDE (add ESP8266 board support via Boards Manager).
- You can also use MicroPython or Espressif AT commands.
- In your project: Likely Arduino sketch that includes:
  - WiFi.h library
  - MAX30102 / PulseOximeter library
  - WebServer or ESP8266WebServer library for the dashboard

Advantages in Your Project

- Built-in Wi-Fi → No need for extra module
- Low cost and small size → Ideal for wearable/health devices
- Sufficient processing power for real-time sensor data + web server
- Good power efficiency → Works well with solar + RF energy harvesting
- Easy IoT integration

CONCLUSION

The **Sustainable Smart Wearable RF Energy Harvesting Communication Patch for Health Monitoring** using Solar and RF Energy Harvesting has been successfully designed, implemented, and tested. This final year engineering project demonstrates a practical and sustainable solution to the limitations of conventional battery-powered wearable health devices.

The primary objective of developing an autonomous health monitoring device was achieved by integrating **dual energy harvesting** techniques — solar photovoltaic conversion as the main source and RF energy capture as a supplementary source. This hybrid approach, combined with efficient power management using the **TP4056** charging module and **HT4928S** boost converter, enables continuous operation without frequent battery replacements. The system effectively utilizes ambient energy, making it highly suitable for real-world deployment in remote or resource-constrained healthcare scenarios.

The **NodeMCU (ESP8266)** serves as the central processing and communication unit, seamlessly interfacing with the **MAX30102** sensor to monitor critical vital signs — **Heart Rate (BPM)** and **Blood Oxygen Saturation (SpO_2)** — using the photoplethysmography (PPG) technique. Real-time data is transmitted via Wi-Fi and visualized on a responsive web dashboard with a 2-second refresh rate, along with a JSON API for mobile application integration. Experimental results confirm stable and continuous performance under normal lighting conditions, with RF energy providing reliable backup during low-light periods. The lithium-ion battery charges efficiently within approximately 4 hours under direct sunlight.

Key Achievements

- Successful implementation of a fully self-powered IoT health monitoring device.
- Effective dual energy harvesting (Solar + RF) for enhanced reliability and sustainability.
- Accurate real-time acquisition and wireless transmission of vital health parameters.
- Low-power design optimization and cost-effective component selection.
- Elimination of maintenance issues associated with frequent battery replacement, while promoting an eco-friendly approach by reducing electronic waste.

This project addresses the growing need for sustainable, maintenance-free wearable healthcare solutions in the era of IoT. It contributes toward preventive healthcare by enabling continuous remote monitoring, early detection of anomalies, and reduced hospitalization costs.

Future Enhancements

While the current prototype performs well, several improvements can further enhance the system:

- Development of a dedicated native Android/iOS mobile application for better user experience.
- Optimization of RF energy harvesting efficiency for improved performance in indoor or low-light environments.
- Integration of machine learning algorithms for anomaly detection and predictive health alerts.
- Expansion to a multi-user cloud platform supporting multiple devices and users simultaneously.
- Miniaturization of the hardware for better wearability and inclusion of additional sensors (e.g., temperature, ECG).

In conclusion, the developed system marks a significant step toward **green IoT** in healthcare. It showcases how energy harvesting technologies combined with IoT can create autonomous, reliable, and environmentally sustainable health monitoring solutions. This project not only fulfills the academic requirements but also holds strong potential for real-world applications in personal healthcare, elderly care, and remote patient monitoring.

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