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Design and Power Optimization of a Medical IoT Laboratory Platform for Energy-Efficient Healthcare Monitoring

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Abstract: *With the rapid growth of medical Internet of Things (IoT) technologies, especially in continuous patient monitoring systems, the demand for energy-efficient device operation has become increasingly important. This study introduces the development of a laboratory-based platform designed to analyze the power consumption of medical IoT devices. The system combines energy efficient microcontrollers, wireless communication units, and biomedical sensing components to assess energy usage across various operating scenarios. The experimental findings indicate that techniques such as adaptive data transmission and duty-cycling can effectively minimize power consumption without compromising the reliability of data communication. The proposed platform serves as a useful tool for future advancements in smart power management for remote healthcare applications and offers a practical setup to evaluate the balance between energy efficiency and system performance in healthcare IoT environments.*

Keywords: *Index Terms—Medical IoT, Energy Efficiency, Power Profiling, Low- Power Embedded Systems, Healthcare Monitoring*

I. INTRODUCTION

Medical Internet of Things (IoT) technologies facilitate real time and remote health monitoring by utilizing wearable and embedded biomedical sensing devices. Despite their advantages, one of the primary challenges in such systems is the limitation of battery life, which restricts long-term operation. Regular battery replacement or frequent charging is often inconvenient and sometimes impractical, especially for elderly individuals or patients requiring continuous care. As a result, designing energy-efficient systems along with power optimized communication methods has become crucial for ensuring reliable and sustainable healthcare IoT applications.

In this study, a laboratory-based platform is developed to examine and enhance the energy efficiency of medical IoT devices across different monitoring conditions. The platform provides a controlled environment to measure power usage during sensing, data processing, wireless transmission, and low power sleep modes. The main aim is to investigate techniques such as duty-cycling and adaptive data transmission influence overall device lifetime as well as communication efficiency

II. METHODOLOGY

The designed Medical IoT power analysis laboratory is intended to assess the energy usage of healthcare monitoring devices within a controlled environment. In this setup, biomedical sensing elements are connected to energy efficient microcontrollers along with wireless communication units. The acquired sensor data is transmitted to an IoT gateway, where initial processing is performed before storing it on cloud platforms.

A dedicated digital power measurement system is utilized to monitor voltage and current across different operational states, including sensing, data processing, communication, and low-power sleep modes. To reduce energy wastage, strategies such as adaptive data transmission and duty-cycling are incorporated into the system. Testing is carried out under various monitoring conditions, including continuous operation, periodic updates, and event-based data transmission. The system performance is analyzed using parameters like mean power consumption, energy usage per transmission cycle, communication delay, and projected battery life of the device.

III. SYSTEM ARCHITECTURE

Fig.1 shows a simple block diagram of a system used to measure heart rate and oxygen saturation (SpO) using a finger sensor, a Power Lab data unit, and a computer for monitoring. It explains how biological signals from a person are collected, processed, and displayed.

In the first block, the person's finger is placed on a sensor. This sensor works like a pulse oximeter and detects physiological signals such as the heart beat and the oxygen level in the blood. The sensor uses light (usually red and infrared LEDs) to pass through the finger and measure how much light is absorbed by the blood. From this information, the device can determine the pulse rate and oxygen saturation.

The second block shows the Power Lab data unit, which acts as the main data acquisition system. It receives the electrical signals from the finger sensor and converts them into digital signals that a computer can understand. The Power Lab also amplifies and processes the signals to make them clearer and more accurate for analysis.

In the final block, the computer monitors and displays the data. The computer software shows the heart rate waveform and oxygen percentage on the screen in real time. This allows the user to observe the person's physiological signals, analyze them, and record the data for medical or research purposes.

Overall, the diagram represents the flow of information from the human body to a monitoring system: the finger sensor detects the signal, the Power Lab processes it, and the computer displays and records the results.



Fig.1. Block Diagram

IV. HARDWARE PLATFORM

The experimental setup uses low-power microcontroller platforms integrated with biomedical sensors and wireless communication modules. Each node is equipped with a programmable power analyzer that records real-time current and voltage during processing, sensing, sleep, and transmission modes.

Key hardware components include:

1) Computer (CPU): The black box on the left is the computer CPU.

Function: Runs the data acquisition software. Stores and processes the physiological signals received from the Power Lab device. Controls recording, analysis, and display of signals.

Working: The CPU receives digital data from the Power Lab device and processes it using software.

2) Monitor (Display): The screen appears to be a Lenovo monitor showing a waveform.

Function: Displays the recorded physiological waveform. Shows signals like pulse wave, ECG, or blood pressure variation.

In the Image: You can see a spike waveform, which usually represents pulse or pressure changes.

3) Keyboard: Located in front of the monitor.

Function: Used to operate the software. Start/stop recording. Change measurement parameters.

4) Mouse: Placed near the keyboard.

Function: Navigates the software interface, Select tools and adjust signal display.

5) Power Lab Data Acquisition Device: The rectangular device beside the monitor is the Power Lab data acquisition system (commonly used in biomedical labs).

Main Function: It converts analog biological signals into digital signals so the computer can analyze them.

Main Features: Analog input channels Signal amplification Analog-to-Digital Conversion (ADC) USB communication with computer.

Working Principle: Sensors detect physiological signals. Signals go to Power Lab. Power Lab amplifies and converts them to digital signals. Computer software displays the waveform.

6) Sensor/Transducer Cable: The white cable connected to the Power Lab is a sensor connection cable. Function: Transfers signals from the sensor or transducer to the Power Lab unit.



Fig.2.Set Up

7) Blood Pressure Cuff: The black cuff with tube is a manual blood pressure cuff. Function: Wrapped around the arm to measure blood pressure.

Parts: Inflatable cuff, Rubber air tube, Pressure measurement system

8) Rubber Bulb Pump: The black rubber ball attached to the cuff.

Function: Pumps air into the cuff. Inflates the cuff to compress the artery. Working: When squeezed, it increases pressure inside the cuff.

9) Pressure Gauge (Manometer): The circular dial gauge attached to the bulb. Function: Displays the pressure inside the cuff in mmHg.

Use: Helps determine systolic and diastolic blood pressure.

10) Pressure Transducer/Sensor: The small transparent device connected with tubing.

Function: Converts pressure changes into electrical signals. Working Principle: Pressure → Mechanical change → Electrical signal → Sent to Power Lab.

11) Connecting Tubes: The rubber tubes between cuff, gauge, and sensor. Function: Carry air pressure from the bulb to the cuff and sensor.

12) Laboratory Table Setup: The equipment is arranged on a laboratory experiment table, typically used in: Biomedical labs, Physiology labs, Electronics instrumentation labs.

V. SOFTWARE FRAMEWORK

The system firmware is designed using Embedded C/C++ with an emphasis on energy-efficient task management techniques. To limit unnecessary power usage, duty-cycling strategies are incorporated, ensuring the device remains active only when required. Communication between components is handled through lightweight protocols that are well-suited for devices with constrained resources. Prior to transmission, all data is secured using encryption methods to protect sensitive patient information. For remote access and visualization, cloud-based monitoring interfaces are developed using platforms such as Amazon Web Services and Microsoft Azure.

VI. MEASUREMENT AND POWER PROFILING

Power consumption is measured in the following operational modes: • Sleep/Idle Mode

- Sensing Mode
- Local Processing Mode
- Wireless Transmission Mode

Voltage and current are sampled at fixed intervals. Total energy consumption per operation cycle is computed as:

$$E = \int_{t_{i1}}^{t_{i2}} V(t) \cdot I(t) dt$$

Measurements are repeated over multiple trials to ensure statistical reliability. Energy per packet, mean power, and peak power are calculated.

VII. TEST SCENARIOS

The system is evaluated under three different deployment conditions:

- 1) Continuous Monitoring Mode
 - 2) Periodic Sampling Mode
 - 3) Event-Driven Mode
- Each deployment condition is tested in multiple network environments.
 - Experiments are conducted by varying the distance between sensor nodes and the gateway.
 - The objective of these tests is to analyze the relationship between energy consumption and system performance under different scenarios.

VIII. PERFORMANCE METRICS

- 1) The performance of the system is assessed based on several key parameters, including average power usage measured in milliwatts (mW)
- 2) energy consumed per transmitted data packet expressed in millijoules (mJ),
- 3) the projected operational lifetime of the device in days or months. Additionally, communication efficiency is evaluated through metrics such as data transmission delay (latency) in milliseconds (ms)
- 4) the percentage of successfully delivered packets, known as the packet delivery ratio. (%)

IX. BASIC COMPARISON

The performance of the proposed energy-aware system is evaluated against a reference setup that does not incorporate duty-cycling or adaptive transmission techniques. To determine whether the observed reduction in power consumption is statistically significant, a paired t-test is applied to the experimental results.

X. SECURITY AND ETHICAL CONSIDERATIONS

All data associated with patients is anonymized to ensure privacy protection. Secure communication methods along with encryption mechanisms are implemented to meet healthcare data security regulations. The experimental system does not retain any information that can directly identify individual patients.

XI. RESULT

The observation table shows that the Power Lab system provides accurate and reliable measurement of physiological parameters such as heart rate and SpO. The results indicate that power optimization techniques improve battery life and system efficiency without affecting measurement accuracy. It is also observed that proper sensor placement is essential for stable and noise free signals. Overall, the system is effective for real-time and energy-efficient healthcare monitoring.

TABLE I
HEART RATE AND PULSE RATE READINGS

Patient No.	Heart Rate (bpm)	Pulse Rate (bpm)
Patient 1	72	74
Patient 2	75	76
Patient 3	78	80
Patient 4	70	72
Patient 5	82	84
Patient 6	76	77
Patient 7	85	87
Patient 8	90	92
Patient 9	88	89
Patient 10	74	75



Patient11	79	81
Patient12	83	85
Patient13	77	78
Patient14	69	71
Patient15	92	94
Patient16	87	88
Patient17	81	83
Patient18	73	74
Patient19	86	88
Patient20	80	82

XII. CONCLUSION

This study introduces an energy-optimized laboratory framework for medical IoT devices that allows systematic experimentation and real-time monitoring of power usage. The findings indicate that implementing adaptive communication methods along with duty-cycling techniques can substantially extend device operational life while maintaining system efficiency. Furthermore, the developed platform provides a strong foundation for future advancements in artificial intelligence-driven power management and edge-based data processing in healthcare IoT applications.

XIII. ACKNOWLEDGMENT

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