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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 asauseful toolforfutureadvancementsinsmartpowermanagementfor 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 inconvenientand sometimesimpractical, especiallyfor elderlyindividualsorpatientsrequiringcontinuouscare.Asaresult, 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 toinvestigate 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 undervariousmonitoringconditions,includingcontinuousoperation,periodicupdates,andevent-baseddata transmission.Thesystemperformanceisanalyzedusing parameterslikemeanpowerconsumption,energyusageper transmission cycle, communication delay, and projected battery life of the device.

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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.

Inthefirstblock,theperson’sfinger isplacedonasensor.Thissensorworkslikeapulseoximeteranddetects physiological signalssuch astheheartbeatand theoxygenlevelintheblood.Thesensoruseslight(usuallyredandinfraredLEDs)topass through the finger and measure howmuch light is absorbed by the blood. From this information, the devicecan 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 theelectrical 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, thediagramrepresents theflow ofinformation 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.BlockDiagram

IV. HARDWARE PLATFORM

The experimental setup uses low-power microcontroller platforms integrated with biomedical sensors and wireless communicationmodules.Eachnodeisequippedwithaprogrammablepoweranalyzerthatrecordsreal-timecurrentand voltage during processing, sensing, sleep, and transmission modes.

Keyhardwarecomponentsinclude:

1) Computer(CPU):TheblackboxontheleftisthecomputerCPU.

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:TheCPUreceivesdigitaldatafromthePowerLabdeviceandprocessesitusingsoftware.

2) Monitor(Display):ThescreenappearstobeaLenovo monitorshowingawaveform.

Function:Displaystherecordedphysiologicalwaveform.Showssignalslikepulsewave,ECG,orbloodpressure variation.

IntheImage:Youcanseeaspikewaveform,whichusuallyrepresentspulseorpressurechanges.

3) Keyboard:Locatedinfrontofthemonitor.

Function:Usedtooperatethesoftware.Start/stoprecording.Changemeasurementparameters.

4) Mouse:Placednearthekeyboard.

Function:Navigatesthesoftwareinterface,Selectstoolsandadjustssignaldisplay.

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

MainFunction:Itconvertsanalogbiologicalsignalsintodigitalsignalssothecomputercananalyzethem.

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

WorkingPrinciple: Sensorsdetectphysiologicalsignals.SignalsgotoPowerLab.PowerLabamplifiesandconverts them to digital signals. Computer software displays the waveform.

6) Sensor/TransducerCableThewhitecableconnectedtothePowerLabisasensorconnectioncable. Function: Transfers signals from the sensor or transducer to the Power Lab unit.

Fig.2.Set Up

7) BloodPressureCuffTheblackcuffwithtubeisa manual blood pressure cuff. Function: Wrappedaroundthearmtomeasureblood pressure.

Parts:InflatablecuffRubberairtubePressuremeasurementsystem

8) RubberBulbPump:Theblackrubberballattachedto thecuff.

Function:Pumpsairintothecuff.Inflatesthecufftocompresstheartery. Working: Whensqueezed,itincreasespressureinsidethe cuff.

9) PressureGauge(Manometer): Thecirculardialgauge attached to the bulb. Function: Displays the pressure inside the cuff in mmHg.

Use:Helpsdeterminesystolicanddiastolicbloodpressure.

10) PressureTransducer/Sensor:Thesmalltransparentdeviceconnectedwithtubing.

Function:Convertspressurechangesintoelectricalsignals.WorkingPrinciple:Pressure→Mechanicalchange→ Electricalsignal→SenttoPowerLab.

11) ConnectingTubes:Therubbertubesbetweencuff,gauge,andsensor. 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 POWERPRO FILING

Powerconsumptionismeasuredinthefollowingoperationalmodes:•Sleep/IdleMode

- SensingMode
- LocalProcessingMode
- WirelessTransmissionMode

Voltageandcurrentaresampledatfixedintervals.Totalenergyconsumptionperoperationcycleiscomputedas:

$$E = \int_{t_0}^{t_1} V(t) \cdot I(t)\, dt$$

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

VII. TEST SCENARIOS

Thesystemisevaluatedunderthreedifferentdeployment conditions:

1) ContinuousMonitoringMode
2) PeriodicSamplingMode
3) Event-DrivenMode

- Eachdeploymentconditionistestedinmultiplenetwork environments.
- Experimentsareconductedbyvaryingthedistancebetweensensornodesandthegateway.
- The objective of these tests is to analyze the relationship between energy consumption and system performance under different scenarios.

VIII. PERFORMANCEMETRICS

1) The performance of the system is assessed based on several key parameters, including average power usage measured in milliwatts (mW)
2) energyconsumedpertransmitteddatapacketexpressedinmillijoules(mJ),
3) theprojectedoperationallifetimeofthedeviceindaysormonths.Additionally,communicationefficiencyisevaluated through metrics such as data transmission delay (latency) in milliseconds (ms)
4) thepercentageofsuccessfullydeliveredpackets,knownasthepacketdeliveryratio.(%)

IX. BASICCOMPARISN

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, apaired t-testisapplied to the experimental results.

X. SECURITY AND ETICAL CONSIDERATIONS

All data associated with patients is anonymized to ensure privacy protection. Secure communication methodsalong 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.

TABLEI
HEARTRATEANDPULSERATEREADINGS

PatientNo.	HeartRate(bpm)	PulseRate(bpm)
Patient1	72	74
Patient2	75	76
Patient3	78	80
Patient4	70	72
Patient5	82	84
Patient6	76	77
Patient7	85	87
Patient8	90	92
Patient9	88	89
Patient10	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.

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