2025-12

Design and Development of IoT-Integrated Medical Devices for Real-Time Clinical Monitoring

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Design and Development of IoT-Integrated Medical Devices for Real-Time Clinical Monitoring

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Autumn, 2025 **December, 2025**

Dissertation submitted in partial fulfillment for the degree of Bachelors of Science in Computer Science & Engineering

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Attestation

I, Rahat Hasan Shihab (1910279), certify that the report was completed by me and submitted in partial fulfillment of the requirement of a Bachelor's Degree in Computer Science and Engineering from Independent University, Bangladesh (IUB). This project was completed under the supervision of Dr. Md. Tarek Habib. All sources of information used in this project have been verified, and the report has been taken care of in it.

Signature

Date

Name

Acknowledgement

All praise and gratitude belong to the Almighty, **Allah**, for His endless blessings and for granting me the strength, patience, and ability to successfully complete this work.

I would like to express my sincere gratitude to my **parents** for their unconditional support, encouragement, and sacrifices throughout my academic journey. Their trust in my aspirations and continuous support made it possible for me to pursue my goals with confidence.

I would like to express my profound indebtedness and sincere appreciation to my senior project supervisor, **Dr. Md. Tarek Habib**, Assistant Professor, Department of Computer Science and Engineering, Independent University, Bangladesh. I am grateful for his mentorship and for securing the necessary funding to support this research; without his inspiration and steadfast support, this work would not have been possible.

I also extend my deepest appreciation to **Dr. Mahady Hasan** for his valuable guidance and encouragement throughout this research journey. His support significantly contributed to both the practical execution of this work and my motivation to maintain a high standard of research quality.

I am deeply thankful to my best friend, **Tanfia Khan Disha**, for her constant encouragement, mentorship, and unwavering support. Her guidance, trust, and presence during challenging times were invaluable, and I remain profoundly grateful for having someone I could rely on throughout this journey.

I am deeply grateful to **Abdulla Masud Bhuiyan** and **Shovon S. Saha** for their dedicated mentorship, insightful technical guidance, and continuous support throughout my academic journey. Their guidance greatly contributed to my academic and professional growth. The conceptual foundation of this project originated from the **Bioforge team**, particularly **Dr. Dewan A. F. K. Choudhury**, whose vision and innovative ideas were pivotal to the development of this research.

Finally, I wish to acknowledge **Dr. Saadia Binte Alam**, Head of the Department, for her exemplary leadership and encouragement. Her support has been a constant source of motivation, inspiring me to pursue meaningful and impactful research.

Letter of Transmittal

Dr. Md. Tarek Habib
Assistant Professor
Department of Computer Science & Engineering
Independent University, Bangladesh

Subject: Submission of Thesis Report on *Design and Development of IoT-Integrated Medical Devices for Real-Time Clinical Monitoring*

Dear Sir,

With due respect, I am pleased to submit my thesis report titled *Design and Development of IoT-Integrated Medical Devices for Real-Time Clinical Monitoring*, prepared as partial fulfillment of the requirements for the Bachelor of Science in Computer Science & Engineering at Independent University, Bangladesh. The work presented in this report was completed under your supervision, and I have made every effort to follow the guidelines and instructions provided throughout the project.

This thesis documents the design and development of three integrated biomedical systems: an IoT-enabled phototherapy device, a wearable vital sign monitoring platform, and a scalable IoMT infrastructure for unified clinical monitoring. I have attempted to present the methodologies, system architectures, results, and contributions in a clear and organized manner.

I respectfully request you to accept this report. If any corrections or improvements are required, I will be glad to revise it accordingly.

Thank you for your continuous guidance and support.

Sincerely,

Rahat Hasan Shihab
Student ID: 1910279
Department of Computer Science & Engineering
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Abstract

Reliable and affordable clinical monitoring remains a major challenge in low- and middle-income countries, where hospitals often face shortages of equipment, unstable power, and fragmented digital infrastructures. This thesis presents an integrated IoT-enabled biomedical system that addresses these gaps through three complementary components: a rapidly deployable phototherapy device for neonatal jaundice, a wearable vital sign monitoring platform for continuous measurement of temperature, ECG, pulse rate, and SpO_2, and a scalable Internet of Medical Things (IoMT) framework that unifies device data into a single operational environment. The phototherapy device provides stable irradiance, modular battery-backed operation, and remote status reporting. The vital sign monitor enables long-duration physiological sensing supported by bedside and cloud dashboards. The IoMT platform incorporates MQTT-based data ingestion, Node-RED edge processing, hybrid MySQL–MongoDB storage, and automated WhatsApp alerts to clinicians. System evaluations demonstrate sub-second latency, reliable data delivery, and improved response times in simulated clinical conditions. Together, these contributions form a cohesive, low-cost, and scalable biomedical ecosystem designed for resource-constrained healthcare settings.

Keywords— IoT-Integrated Medical Devices, Phototherapy, Neonatal Jaundice, Vital Sign Monitoring, ECG, SpO_2, Wearable Sensors, Internet of Medical Things (IoMT), MQTT, Node-RED, Hybrid Database Architecture, Real-Time Clinical Monitoring, Resource-Constrained Healthcare

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Chapter 1

Introduction

1.1 Background

The development of the Internet of Things (IoT) has greatly transformed the contemporary biomedical engineering field, as it allows constant, long-distance, and intelligent monitoring of patient health. In low- and middle-income countries (LMICs), however, access to such technologies remains low due to high device costs, fragmented clinical systems, and operational challenges in resource-limited healthcare environments. These constraints create critical gaps in neonatal care, infectious disease management, and general clinical monitoring—areas where timely vital signs information directly influences patient outcomes.

Two clinical needs in LMICs are especially pressing: (1) Availability of low-cost neonatal phototherapy for treating jaundice, and (2) Continuous monitoring of vital signs for early detection of patient deterioration. Traditional phototherapy units are expensive, bulky, and dependent on stable grid power. Commercial vital sign monitors (VSMs) typically support only bedside use and lack remote-monitoring capabilities. Although smart biomedical devices exist, healthcare facilities often struggle with disintegrated and individual dashboards. This limits the ability of caregivers to obtain a unified, real-time view of patient status. Hence they work with paper-based systems

These obstacles demonstrate the need for low-cost, integrated biomedical technologies capable of reliable sensing, safe therapeutic operation, internet connectivity, and unified data management. Combined with open-source software ecosystems, IoT-enabled medical devices offer a feasible pathway for scalable, real-time clinical monitoring.

1.2 Problem Statement

LMICs face structural and technological bottlenecks within hospitals and clinics that restrict their ability to deliver timely and efficient monitoring and therapeutic services. Three significant issues motivate this thesis:

- **Absence of accessible neonatal phototherapy solutions:** Existing devices are expensive, slow to procure, and dependent on continuous electricity, hindering treatment of neonatal jaundice in rural or disaster-affected regions.

- **Limited access to real-time patient monitoring systems:** Traditional vital signs monitors rely on outdated communication technologies, are costly, and generally restricted to bedside operation, reducing clinicians' ability to detect early signs of emergencies.
- **Fragmented medical device ecosystems:** Biomedical devices often operate on separate dashboards and outdated software platforms, preventing unified multi-device and multi-patient monitoring needed for timely clinical decision-making.

A holistic IoT-based biomedical architecture is required—one that integrates sensing, therapy, connectivity, cloud infrastructure, and real-time monitoring into a coherent and scalable system.

1.3 Motivation

This research is informed by three urgent healthcare needs identified during and after the COVID-19 pandemic:

1. **Reducing clinician exposure and workload:** Remote monitoring enables clinicians to supervise multiple patients simultaneously and reduces unnecessary physical contact.
2. **Ensuring continuity of care in rural environments:** Battery-powered medical equipment is essential in regions with frequent power interruptions.
3. **Facilitating data-driven clinical decision-making:** A centralized IoMT system can aggregate device telemetry to generate actionable insights, improving responsiveness and patient safety.

These motivations align with global health objectives such as SDG 3, which emphasizes accessible and affordable healthcare technologies.

1.4 Research Objectives

This thesis aims to design, develop, and evaluate an integrated IoT-enabled biomedical ecosystem suitable for healthcare environments with limited resources. The specific objectives are:

- To design a battery-operated, rapidly deployable phototherapy device (PTL) with IoT-based remote monitoring capabilities that meet neonatal treatment requirements.
- To develop a low-cost wearable vital sign monitoring (VSM) device capable of continuous temperature, ECG, pulse, and SpO_2 monitoring, with real-time bedside and remote dashboards.

- To integrate both devices into a unified IoMT ecosystem that supports scalable data ingestion, hybrid database storage, and automated clinician alerts.
- To evaluate system performance through hardware testing, long-duration monitoring experiments, and simulated multi-device workloads.

1.5 Contributions of the Thesis

The main contributions of this thesis are as follows:

1. **IoT-Enabled Phototherapy Device (PTL):** A cost-effective, modular phototherapy system with battery backup, temperature protection, PWM-based light control, and remote data logging using the ThingsBoard IoT platform.
2. **Wearable and Remote Vital Sign Monitor (VSM):** A multi-sensor wireless monitoring device with real-time ECG filtering, cloud storage, a web-based interface, and uninterrupted 24-hour monitoring capability.
3. **Unified IoMT Platform:** A scalable architecture based on MQTT, Node-RED, MongoDB, and MySQL to integrate heterogeneous devices, provide dashboards, and deliver automated WhatsApp alerts.

1.6 Thesis Organization

This thesis consists of seven chapters that detail the design, development, and evaluation of IoT-integrated medical devices for real-time clinical monitoring:

- **Chapter 1 – Introduction:** Provides the background, motivation, problem statement, objectives, and contributions.
- **Chapter 2 – Literature Review:** Reviews existing research on IoT-enabled therapeutic devices, wearable vital sign monitoring systems, and integrated IoMT platforms, identifying gaps addressed in this study.
- **Chapter 3 – Published Paper I:** Introduces the Bioforge PTL, an affordable IoT-enabled phototherapy device, including its design, implementation, and performance evaluation.
- **Chapter 4 – Published Paper II:** Describes the development of a wearable real-time vital sign monitor, detailing sensor architecture, communication design, software workflow, and long-duration testing.
- **Chapter 5 – Published Paper III:** Presents a scalable IoMT platform built using MQTT, Node-RED, and hybrid database technologies, integrating both PTL and VSM devices with real-time dashboards and automated alerts.

- **Chapter 6 – Sustainability Analysis:** Evaluates the technical, social, environmental, ethical, operational, and economic sustainability of the integrated biomedical ecosystem.
- **Chapter 7 – Conclusion:** Summarizes the findings and outlines directions for future research.

All chapters follow a logical sequence, presenting system development, integration, evaluation, and final conclusions coherently.

Chapter 2

Literature Review

2.1 Literature Selection Procedure

The literature selection process for this thesis was designed to integrate three intersecting domains of modern biomedical engineering: (1) IoT-integrated therapeutic devices, (2) real-time physiological monitoring systems, and (3) unified healthcare data infrastructures. To accomplish this, a systematic screening was conducted across peer-reviewed publications, conference proceedings, industrial technical documentation, and open IoT platforms.

The selection protocol focused on three primary goals: (1) identifying low-cost, rapidly deployable biomedical technologies suitable for LMIC contexts, (2) characterizing state-of-the-art physiological monitoring and IoMT architectures, and (3) establishing the clinical, operational, and socio-economic motivations for such systems.

Initial exploration encompassed seminal and recent works from 2005–2025, capturing the rapid evolution of embedded systems (ESP32, low-power microcontrollers), wireless communication (MQTT, Wi-Fi-enabled biomedical hardware), and health informatics architectures (Node-RED, hybrid MongoDB–MySQL backends).

Subsequent filtering narrowed the literature to works offering: (i) practical implementations of biomedical hardware, (ii) clinically validated monitoring systems, (iii) IoT-enabled neonatal and maternal-care devices, and (iv) infrastructural frameworks enabling unified device interoperability in hospitals. This approach ensured that the final literature corpus reflected both technological advancement and real-world constraints in clinical environments.

2.2 Keywords Searched

The keyword taxonomy was organized into clusters to ensure comprehensive retrieval across IoT, biomedical hardware, neonatal care, and clinical informatics. Representative terms include:

- **Biomedical Devices and Therapeutics:** "phototherapy", "neonatal jaundice", "hyperbilirubinemia treatment", "low-cost medical devices", "battery-backed therapeutic devices".

- **Physiological Monitoring and Wearables:** "vital sign monitoring (VSM)", "ECG filtering", "wearable sensors", "remote patient monitoring", "continuous monitoring".
- **IoT, IoMT, and Embedded Systems:** "ESP32 biomedical applications", "MQTT healthcare", "IoMT platforms", "edge processing", "Node-RED medical routing", "hybrid database architecture".
- **Neonatal and Clinical Care:** "NICU monitoring", "neonatal IoT", "low-resource neonatal care", "LMIC medical technologies".
- **Systems Engineering and Interoperability:** "IoT interoperability", "medical device integration", "time-series sensor data", "cloud-based healthcare".

Boolean combinations such as ("phototherapy" AND "IoT"), ("real-time monitoring" AND "ESP32"), and ("IoMT" AND "interoperability") were especially useful for retrieving relevant technical frameworks.

2.3 Databases for Search

The following digital libraries and technical repositories were accessed:

- **IEEE Xplore:** Primary source for phototherapy device research, IoT hardware architectures, ECG filtering algorithms, and remote monitoring implementations.
- **ScienceDirect (Elsevier):** Provided foundational work regarding neonatal jaundice, hyperbilirubinemia, and clinical phototherapy standards.
- **PubMed / NCBI:** Used for retrieving biomedical studies related to neonatal clinical outcomes, bilirubin kinetics, and vital-sign relevance.
- **ACM Digital Library:** Accessed for IoT systems design, MQTT-based architectures, and interoperability models.
- **SpringerLink:** Provided access to IoMT architectural and interoperability frameworks, including the unified platform cited in the uploaded materials.
- **Technical Document Repositories:** DatasheetQ, Panasonic B2B, and ThingsBoard documentation were used for hardware specification validation.

2.4 Filtering Results

The initial collection spanned over 120 publications. The following exclusion criteria were applied:

- Studies requiring high-cost or proprietary hardware unsuited for LMIC deployment.

- Simulations without hardware prototyping or clinical validation.
- Fully cloud-dependent systems lacking offline/edge resilience.
- Phototherapy or monitoring systems that do not report irradiance, power consumption, or signal fidelity metrics.

Inclusion criteria required:

- Real-world or clinical deployment of neonatal or physiological monitoring systems.
- Detailed descriptions of embedded system design (ESP32, BMS circuits, PWM control, etc.).
- IoT implementations leveraging MQTT, Node-RED, or similar interoperable protocols.
- Systems designed for LMIC, disaster-prone, or low-resource healthcare settings.

The final corpus consisted of 67 curated publications, including all cited works within the Bioforge PTL, VSM, and IoMT platform papers.

2.5 Impact of the Project

2.5.1 Technical Impact

The integration of IoT-enabled neonatal phototherapy, wearable physiological monitoring, and unified IoMT platforms demonstrates a significant advancement in low-cost biomedical engineering. The Bioforge PTL device introduces modular, battery-backed phototherapy with IoT status reporting [1, 2, 3]. Similarly, the VSM system incorporates multi-sensor data acquisition (ECG, SpO_2, pulse, temperature) with wireless transmission and real-time dashboards, supported by robust filtering algorithms [4, 5]. The unified IoMT platform extends this ecosystem by bridging heterogeneous devices through MQTT brokers, Node-RED routing, and hybrid MongoDB–MySQL persistence [6, 7]. Collectively, these works push forward an interoperable, scalable, and clinically meaningful medical-device infrastructure.

2.5.2 Social and Health Impact

Phototherapy accessibility is a long-standing challenge in LMICs, where neonatal jaundice remains a major source of preventable mortality [8, 9]. The development of a rapidly deployable PTL unit directly addresses shortages caused by high procurement costs and unreliable power grids. Similarly, real-time vital sign monitoring reduces clinical workload and enhances early detection of deterioration, particularly crucial during pandemics such as COVID-19 [10, 11]. By enabling remote, continuous observation, such systems help protect healthcare workers from infection and allow clinicians to oversee multiple patients simultaneously.

2.5.3 Economic Impact

Conventional phototherapy units and patient monitors often cost several hundred to several thousand USD. The PTL reduces hardware cost to approximately $71 per unit, while the VSM wrist+bed unit delivers multi-parameter monitoring at below $200—significantly lower than commercial alternatives [12, 13]. Further, IoMT centralization reduces operational fragmentation, eliminating the need for multiple dashboards. Low operational costs make these solutions scalable for rural clinics, emergency deployments, and national health programs.

2.6 Literature Review of Papers

2.6.1 IoT-Enabled Phototherapy Devices

Phototherapy remains the standard for neonatal hyperbilirubinemia treatment, requiring precise wavelength control (460–490 nm) and adequate irradiance levels [3, 14]. Early low-cost designs such as BiliLED demonstrated feasibility but were limited by complex circuitry or lack of rapid deployment mechanisms [1]. More recent systems incorporate intelligent monitoring, such as ILPLS with cameras and microphones for observation, though bulk and charging limitations persist [2]. Wearable or portable solutions like the Bili-Hut improve accessibility but require imported materials and have visibility limitations [15]. The Bioforge PTL improves upon these by enabling fast assembly, modular batteries, renewable power compatibility, and remote IoT monitoring via ThingsBoard [16].

2.6.2 Wearable and Remote Vital Sign Monitoring Systems

Vital sign monitoring is foundational to clinical decision-making, and wearable IoT solutions increasingly complement traditional bedside monitors. Prior studies demonstrate remote monitoring of heart rate, temperature, and respiratory rate with wireless alarm systems [11]. Smartwatch-based systems such as the Nurse Watch further show threshold alarms and workflow integration [17]. IoT platforms transmitting ECG via MQTT ensure low-latency, continuous observation [5]. Advanced camera-based systems measuring blood pressure via pulse transit time extend non-contact sensing capabilities [4]. The Bioforge VSM adopts a more comprehensive approach with four-sensor acquisition, real-time dashboards, ECG filtering, and secure cloud persistence [13].

2.6.3 Unified IoMT Architectures in Clinical Environments

A persistent challenge in LMIC hospitals is the fragmentation of IoT dashboards, making holistic clinical assessment difficult. Existing IoT frameworks often lack interoperability, data integrity, or the ability to process high-frequency time-series medical data [7]. Recent architectural advances propose multi-layer IoMT stacks incorporating MQTT, workflow engines, and hybrid storage [18, 19]. The TrustNet/IoMT platform addresses these gaps using Node-RED edge routing, hybrid persistence (MongoDB + MySQL), WhatsApp-based clinician alerts, and real-time neonatal dashboards [18]. Its sub-100 ms end-to-end latency, zero data loss, and improved clinical response time demonstrate a highly practical, deployable solution.

2.6.4 Synthesis of Literature

Across all three domains—phototherapy, vital sign monitoring, and unified IoMT platforms—the literature highlights shared barriers:

- high costs of commercial biomedical equipment,
- limitations in clinical interoperability,
- insufficient infrastructure for continuous monitoring,
- lack of LMIC-appropriate energy-resilient devices.

The combined research trajectory points toward integrated, affordable, IoT-enabled systems that support neonatal and critical-care monitoring in resource-constrained environments. This thesis aligns with that trajectory by unifying device-level engineering, clinical workflow enhancement, and scalable IoMT integration.

Chapter 3

Bioforge PTL: An IoT-Enabled Rapidly Deployable Phototherapy Device for Neonatal Jaundice

3.1 Problem Statement

Neonatal jaundice remains one of the most common conditions requiring medical intervention in newborns. Although phototherapy using high-intensity blue light is considered routine treatment in high-resource healthcare systems, its accessibility in low- and middle-income countries (LMICs) is limited due to high costs, imported device dependency, maintenance challenges, and unreliable power infrastructures. As a result, preventable complications—including severe hyperbilirubinemia, kernicterus, and long-term neurological damage—continue to occur in underserved regions.

Existing solutions such as commercial phototherapy units are often expensive, bulky, and unsuitable for rapid deployment in remote or disaster-stricken environments where electricity is unstable. Alternative low-cost innovations, such as filtered sunlight therapy, remain vulnerable to weather constraints and cannot replace consistent care. These gaps highlight an identifiable need for a low-cost, rapidly deployable, battery-supported phototherapy solution with basic IoT capabilities to enable remote monitoring and informed clinical decision-making.

The Bioforge PTL device addresses these core challenges by combining modular, laser-cut acrylic construction, a robust battery system, controllable high-power LEDs, built-in thermal safety measures, and IoT connectivity for remote monitoring. The conceptual objective is to democratize access to effective neonatal phototherapy in LMIC contexts.

3.2 Research Methodology

3.2.1 Motivation and Purpose

The objective of the study is to design, develop, and evaluate an affordable, durable, and rapidly deployable phototherapy device that meets minimum clinical standards for irradiance and wavelength while ensuring usability in low-resource environments. This includes:

- Ensuring reliable therapeutic light output within the clinically recommended blue-light band (460–490 nm).
- Providing uninterrupted operation through a modular high-capacity battery pack.
- Implementing IoT capabilities to remotely track device conditions, duration of therapy, and intensity level.
- Reducing cost through lean mechanical design, locally manufacturable components, and standardized modules.

3.2.2 Methodological Approach

The research methodology covers the complete pipeline from design ideation to implementation:

1. Selection of therapeutic LEDs based on wavelength and irradiance requirements.
2. Electrical system design incorporating dual battery management, surge protection, step-up conversion, and MOSFET-based PWM control.
3. Mechanical enclosure design using modular acrylic panels optimized for rapid manufacturing and field deployment.
4. Firmware and IoT integration using an ESP32 microcontroller and ThingsBoard server.
5. Functional evaluation of irradiance, thermal stability, power consumption, and operational runtime at different intensity levels.

3.3 Proposed Solution

3.3.1 System Design

The Bioforge PTL consists of four major subsystems:

1. **Phototherapy Light Array:** A configuration of eight 10W blue LEDs (460–465 nm) arranged according to an optimized electrical topology ensuring uniform illumination and controllable intensity levels.

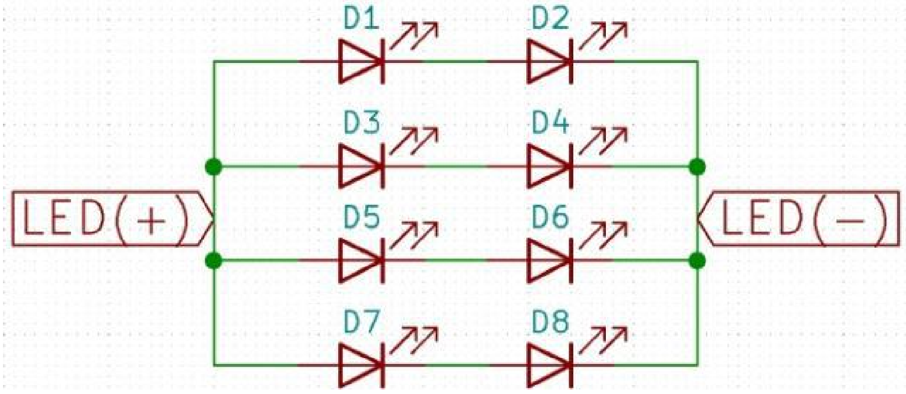


Figure 3.1: Electrical configuration of the phototherapy LED array.

2. **Power System:** A dual BMS-controlled battery pack of 25.6Ah capacity using 18650 Li-ion cells, supplemented with surge protection and step-up conversion to ensure stable 17V output for LED operation.

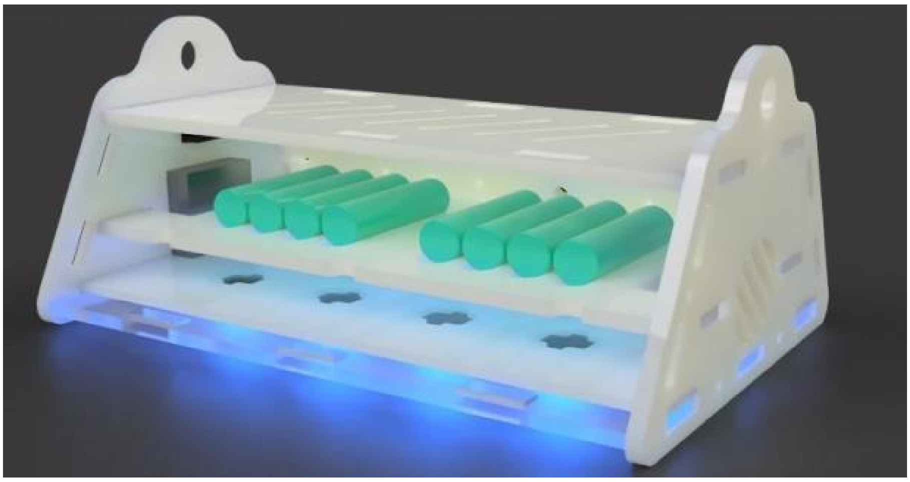


Figure 3.2: Battery pack arrangement using 18650 Li-ion cells.

3. **Control Electronics:** An ESP32 microcontroller generating PWM signals to adjust intensity levels, assisted by logic-level shifting and MOSFET gating. Temperature sensors ensure thermal safety by automatically shutting down LEDs if overheating is detected.

4. **IoT Integration:** The device transmits intensity level, average temperature, and therapy duration to a ThingsBoard cloud server at one-minute intervals, enabling remote monitoring via a web dashboard.

3.3.2 Data Collection

Three categories of operational data were recorded during development and testing:

- **Thermal Data:** Temperature readings from DS18B20 sensors mounted on the enclosure.

- **Operating State Data:** LED intensity level, PWM duty cycle, and battery state.

- **Therapy Duration Data:** Accumulated runtime for clinical tracking.

All data were transmitted to the IoT dashboard at fixed intervals for real-time review.

3.3.3 Data Analysis

Thermal data were analyzed to determine safe operational thresholds and the effectiveness of the cooling fans. Power consumption values at low, medium, and high intensity levels were used to calculate battery runtime and validate energy efficiency. IoT logs provided insight into long-duration performance patterns, detecting trends in temperature rise and system load.

Tables and plots summarizing these findings are included in later sections.

3.4 Hardware Design

3.4.1 Hardware Block Diagram

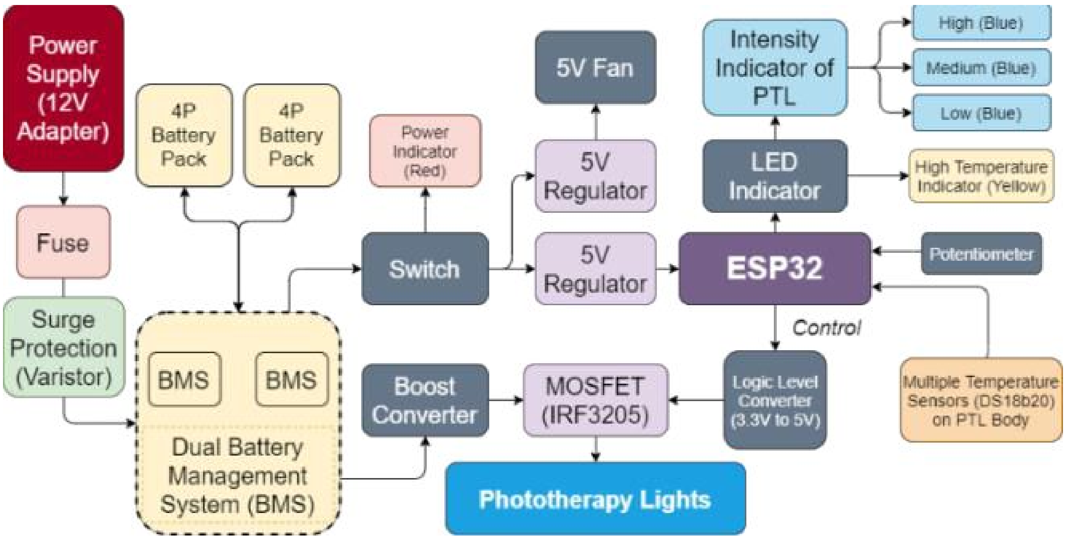


Figure 3.3: Electrical and electronic block diagram of the Bioforge PTL system.

A detailed block diagram describing the functional relationships between LED arrays, BMS modules, converters, fans, sensors, and ESP32 processing unit is shown in Fig. 3.3.

3.4.2 Components Used

- 10W 460–465 nm LEDs
- XR2681 boost converter
- Dual BMS modules
- 18650 Li-ion batteries (3200mAh each)
- ESP32 microcontroller

- IRF3205 MOSFET
- DS18B20 temperature sensors
- LM7805 regulators
- 5V cooling fans

3.4.3 Rationale for Component Selection

Components were selected based on:

- Availability in LMIC supply chains
- Low cost and ease of replacement
- Compatibility with battery-powered operation
- Proven thermal stability and efficiency

3.5 Design Overview

The enclosure consists of eight interlocking acrylic panels manufactured using laser cutting. This modular assembly allows flat-packing for transport and quick deployment in field conditions.

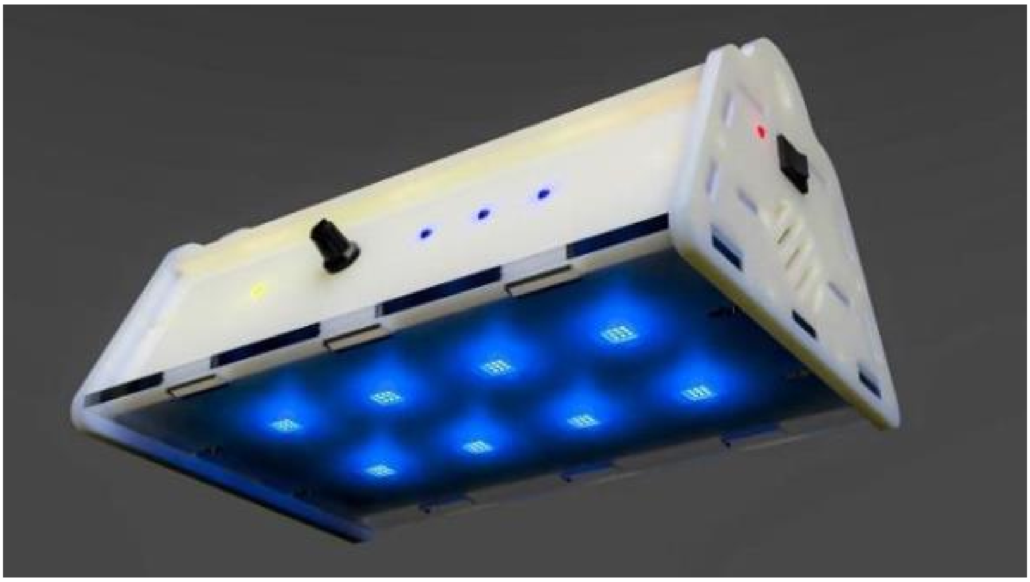


Figure 3.4: Acrylic-based enclosure supporting rapid assembly and stable heat management.

Two side holes support mounting on standard neonatal stands or improvised supports. Ventilation slots and dual fans ensure airflow around LEDs and battery packs.

3.6 Implementation

3.6.1 Hardware Implementation

Screw-based and interlocking joints were used for quick assembly. JST connectors allowed modular integration of sensors, LEDs, and power lines. The boost converter and BMS modules were mounted securely to withstand vibration or movement when deployed in mobile or emergency setups.

3.6.2 Software Implementation

The ESP32 firmware incorporated:

- PWM generation for LED control
- ADC reading of temperature sensor data
- Thermal cutoff algorithms
- Wi-Fi connectivity and MQTT/HTTP communication to ThingsBoard

3.7 Result Analysis

Figure 3.5: Fully assembled Bioforge PTL device.

Quantitative results include:

- Power consumption at three intensity levels

Figure 3.6: IoT dashboard for monitoring therapy duration and intensity.

- Battery runtime estimates
- Thermal stability during extended operation
- IoT logging performance

Table 3.1: Power consumption and runtime for different intensity levels.

Intensity Level	Power (W)	Runtime (hrs)
Low	2.80	33.83
Medium	5.90	16.05
High	16.40	5.78

A cost breakdown analysis demonstrated that the device can be manufactured locally at approximately 71 USD for the prototype configuration, far below commercial alternatives.

3.8 Findings and Challenges

The Bioforge PTL successfully meets clinical phototherapy requirements while maintaining affordability, portability, and rapid deployability. IoT integration improves oversight in settings where staffing is limited.

However, several challenges remain:

- Further ruggedization of the enclosure is needed for long-term field use.
- IoT features require reliable network connectivity, which may not always be available.
- Clinical trials are still required for full validation in hospital environments.

Future work includes enhanced IoT dashboards, improved thermal management, expanded alerting features, and clinical testing.

Chapter 4

A Cost-Effective Solution for Real-Time Remote Monitoring of Vital Signs in Patients

4.1 Problem Statement

The COVID-19 pandemic exposed critical weaknesses in healthcare systems worldwide, especially in low- and middle-income countries (LMICs). Overcrowded clinical facilities, shortages of trained personnel, and the high risk of infection for frontline workers make continuous bedside monitoring difficult and often unsafe. Conventional vital sign monitors (VSMs), though clinically effective, are expensive, lack remote monitoring capabilities, and generally support only one patient per device.

As a result, deterioration in patient health may go unnoticed, particularly during night hours or in emergency field hospitals where staff-to-patient ratios are unfavorable. The need for a low-cost, wearable, real-time VSM that operates inside and outside traditional clinical environments has become increasingly urgent.

The proposed VSM system addresses this need by enabling continuous remote monitoring of temperature, heart rate, ECG, and oxygen saturation, with data accessible through a bedside unit and a web-based dashboard. By leveraging low-cost sensors, microcontrollers, and open-source IoT infrastructure, the system aims to make patient monitoring safer, more scalable, and more affordable in resource-constrained settings.

4.2 Research Methodology

4.2.1 Motivation and Purpose

The primary motivation of this research is to design a vital monitoring system that:

- Reduces unnecessary physical interaction between patients and clinicians.

- Enables continuous and long-term monitoring in temporary hospitals, isolation centers, or home-care settings.
- Uses low-cost, locally available components.
- Provides real-time multi-patient visibility through a remote dashboard.
- Ensures physiological signals (ECG, SpO_2, temperature) are collected with sufficient accuracy for medical decision-making.

4.2.2 Methodological Approach

The methodology consisted of:

1. Prototyping the sensing module with necessary biosensors.
2. Developing firmware to filter and preprocess physiological signals.
3. Implementing Bluetooth/Wi-Fi-based communication.
4. Creating a bedside unit for local display.
5. Designing a cloud server backend and GUI for remote monitoring.
6. Experimentally validating the stability of long-duration recordings.

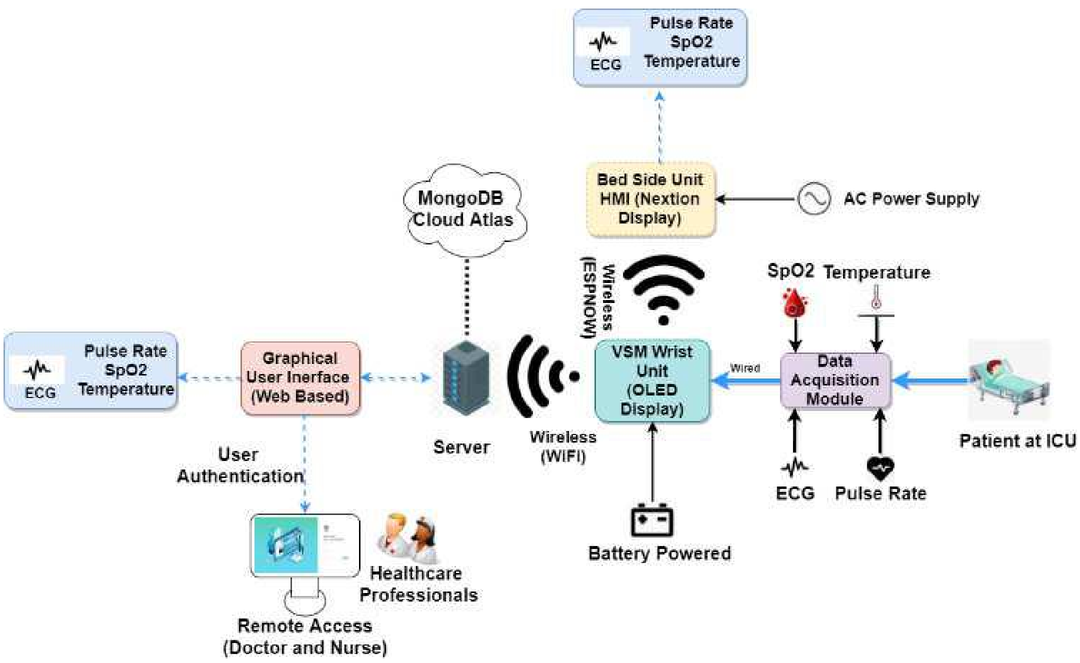


Figure 4.1: System architecture of the proposed VSM technology.

4.3 Proposed Solution

4.3.1 System Design

The complete VSM ecosystem consists of three integrated units:

1. **Wearable Wrist Unit** – acquires physiological data, displays basic vitals, and transmits data wirelessly.
2. **Bedside Unit** – receives and displays vitals continuously on a larger screen for clinical staff.
3. **Web-Based Dashboard** – provides real-time multi-patient monitoring remotely via any internet-connected device.

This layered design improves accessibility and allows deployment in both home-care and clinical environments.

4.3.2 Data Collection

Four key biological parameters are acquired:

- **Temperature (DS18B20)** – placed at the patient's axilla.
- **SpO_2 and Heart Rate (MAX30100)** – collected via optical pulse oximetry from the fingertip.
- **ECG (AD8232 module)** – single-lead ECG electrodes placed on the chest.

Data streams are captured at intervals suitable for real-time monitoring and transmitted via Wi-Fi or Bluetooth to the bedside unit and cloud server.

4.3.3 Data Analysis

Data processing includes:

- Digital ECG filtering using a running exponential filter.
- Removal of motion artifacts.
- Signal quality checks for SpO_2 and pulse readings.
- Timestamp alignment for database storage.

Filtered ECG signals and long-term stability of pulse/SpO_2 measurements were validated through continuous 48-hour recordings.

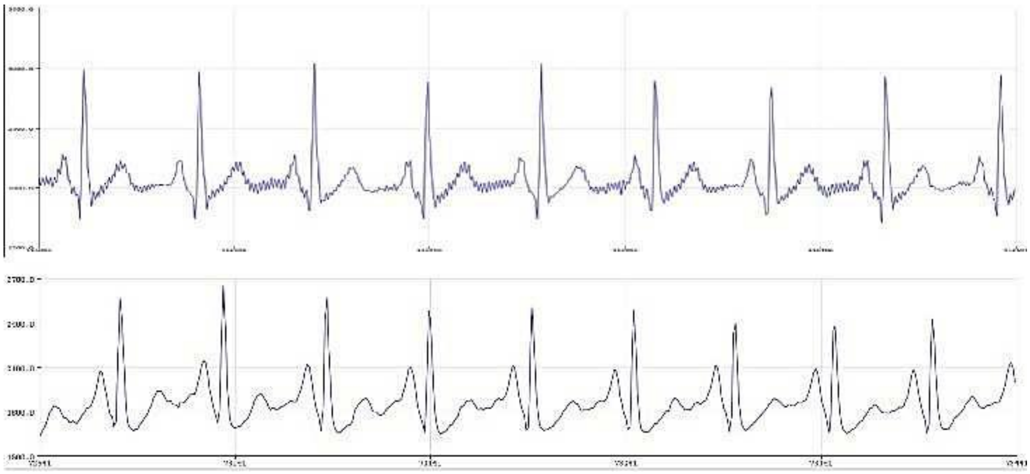


Figure 4.2: Comparison of unfiltered and filtered ECG signals.

4.4 Hardware Design

4.4.1 Hardware Block Diagram

The hardware integrates biosensors, a microcontroller, overcurrent protection, a display module, and communication layers. Fig. 4.3 illustrates the complete hardware flow.

4.4.2 Components Used

- ESP32 microcontroller (Wi-Fi/BLE)
- MAX30100 pulse oximetry sensor
- DS18B20 waterproof temperature sensor
- AD8232 ECG module
- OLED display for wrist unit
- Nextion touchscreen for bedside unit
- Overcurrent protection circuitry
- Rechargeable battery (3.3V)

4.4.3 Rationale for Component Selection

Components were selected based on:

- Power efficiency suitable for wearable devices.
- Open-source compatibility.
- High signal accuracy for physiological measurements.
- Cost-effectiveness ensuring replicability in LMIC contexts.

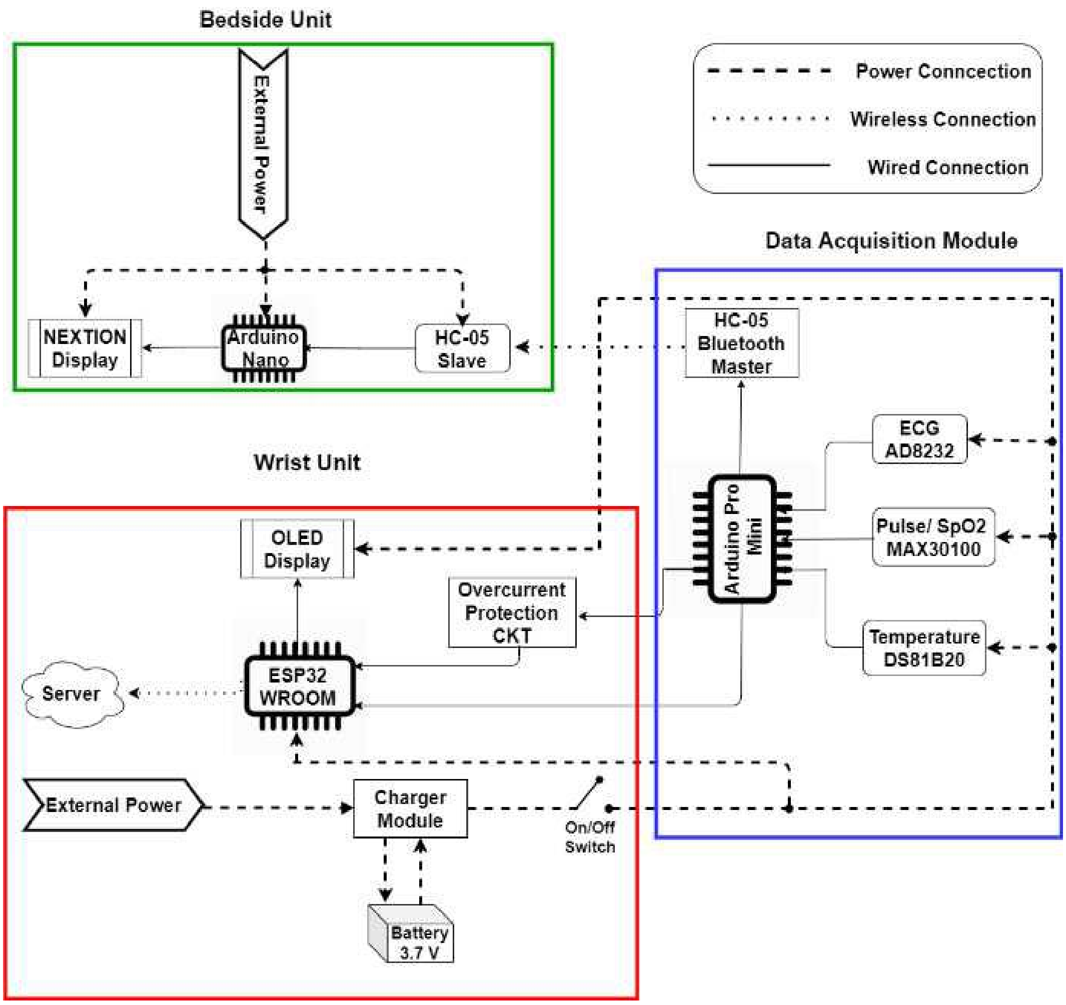


Figure 4.3: Block diagram of the VSM hardware design.

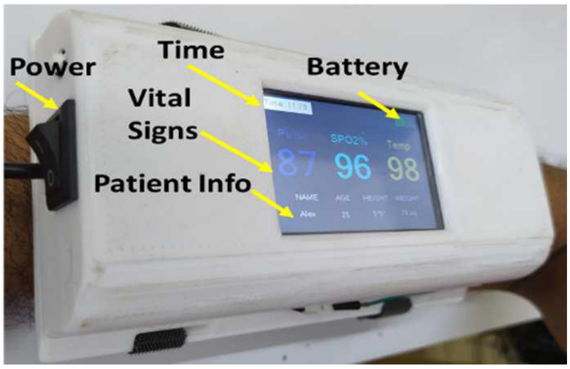
4.5 Design Overview

The wrist unit is designed for patient comfort and constant data acquisition. The bedside unit, using a larger Nextion display, is optimized for clinical readability and displays:

- Temperature
- Heart rate
- SpO_2
- Real-time ECG tracing
- Patient identification fields

The use of independent power sources for the wrist and bedside units enhances reliability.

(a) Bedside display unit



(b) Wearable wrist sensor module

Figure 4.4: (a) Bedside display unit; (b) Wearable wrist sensor module.

4.6 Implementation

4.6.1 Hardware Implementation

The sensing components were mounted inside a lightweight wrist-worn enclosure. The bedside unit was built using a Nextion display controlled by an ESP32. Overcurrent protection was added to ensure patient safety.

The ECG electrodes interface with the AD8232 module, and analog signals are digitized by the ESP32 for filtering and transmission.

4.6.2 Software Implementation

The software architecture features:

- ESP32 firmware handling sensor reading, filtering, and Wi-Fi transmission.
- A Node.js server managing incoming data via WebSockets and REST APIs.
- MongoDB Atlas cloud database for long-term storage.
- Web dashboard for clinicians, built for real-time multi-patient monitoring.

A Wi-Fi configuration manager enables setup without reflashing firmware.

4.7 Result Analysis

Testing was performed using real patient data across 48 hours.

4.7.1 Hardware Performance

Pulse and SpO_2 readings demonstrated operational stability, as shown in Fig. 4.6.
Temperature readings also remained stable and aligned with expected physiological ranges.
The ECG module successfully recorded clean single-lead ECG signals after filtering.

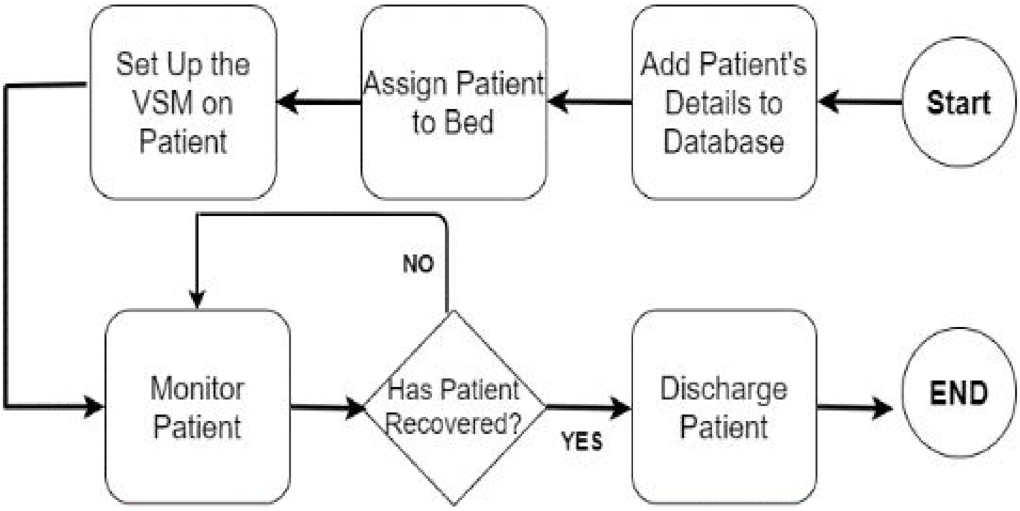


Figure 4.5: VSM software data flow diagram for real-time monitoring.

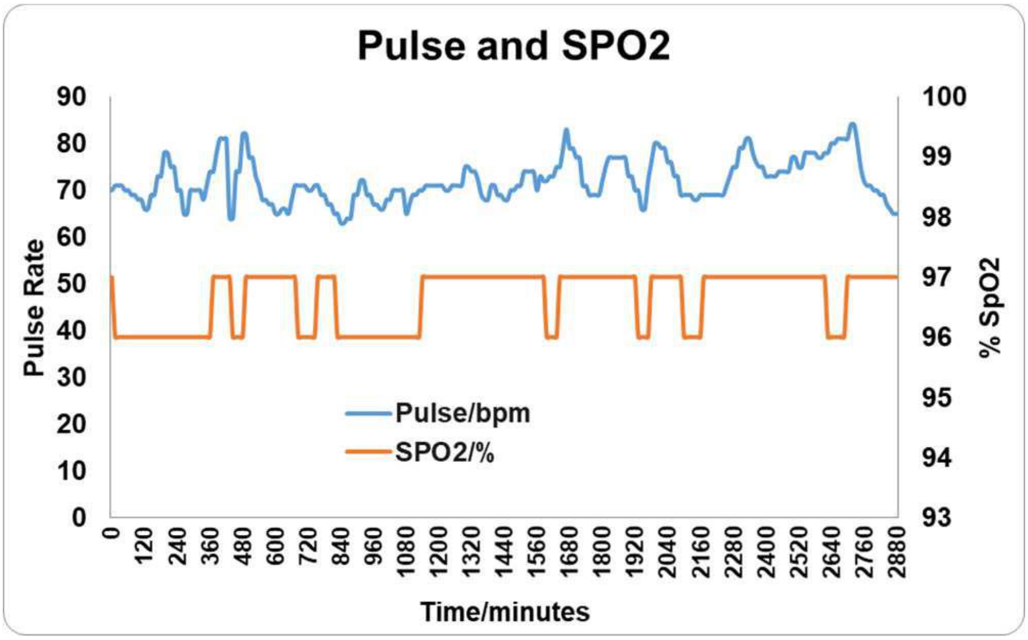


Figure 4.6: Continuous pulse and SpO_2 readings over 48 hours.

4.7.2 Software Performance

The dashboard allowed real-time visualization of all connected patients, triggering alerts when vital signs fell outside safe ranges.

4.8 Findings and Challenges

The VSM system provides an affordable, scalable solution for continuous and remote vital sign monitoring. It significantly reduces staff exposure to infectious patients and improves response time through centralized monitoring.

Key findings include:

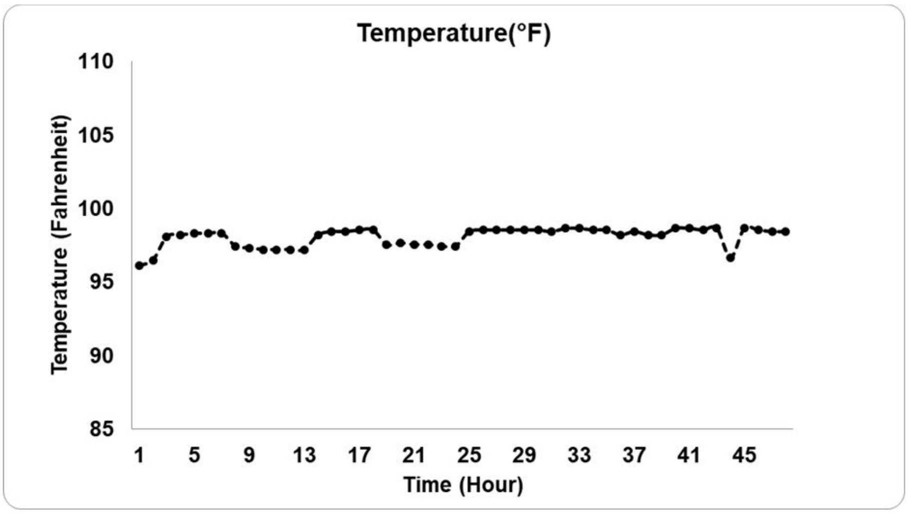


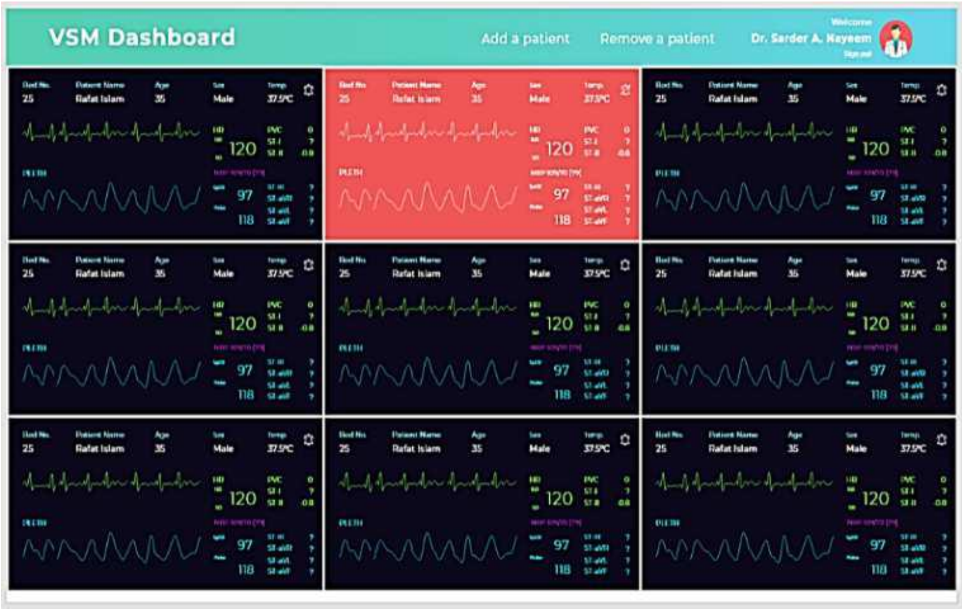
Figure 4.7: Continuous temperature readings over 48 hours.

- Stable acquisition of temperature, pulse, SpO_2, and ECG signals.
- Reliable end-to-end data transmission via Wi-Fi.
- Usable multi-patient dashboard suitable for clinical settings.

Challenges include:

- Motion artifacts affecting ECG and optical readings.
- Dependence on Wi-Fi networks for continuous operation.
- Device ergonomics requiring refinement for long-term comfort.

Future developments will include AI-based early-warning systems, improved signal denoising, and integration into larger IoMT ecosystems.



(a) Multi-patient dashboard

(b) Single-patient dashboard

Figure 4.8: Web dashboard for remote multi-patient and single-patient VSM monitoring.

Chapter 5

A Scalable IoMT Platform for Unified Medical Device Monitoring in Resource-Constrained Environments

5.1 Problem Statement

Digital healthcare ecosystems in low- and middle-income countries (LMICs) face persistent challenges in achieving unified, interoperable monitoring systems across medical devices. Existing Internet of Medical Things (IoMT) deployments often consist of isolated dashboards, vendor-specific ecosystems, and standalone monitoring units that cannot exchange or correlate data. This fragmentation leads to gaps in clinical insight, delayed responses to critical events, and an inability to support scalable, multi-device real-time monitoring.

Prior work by the authors on wearable vital sign monitors (VSM) and IoT-enabled phototherapy lights (PTL) demonstrated the local feasibility of low-cost biomedical devices. However, each device operated on separate software stacks, lacked unified data handling, and could not provide a complete clinical picture. Moreover, LMIC healthcare environments require systems that are low-cost, resilient to unstable network conditions, secure, scalable, and easy to maintain.

The problem addressed in this study is therefore twofold:

1. The absence of a unified IoMT framework capable of integrating heterogeneous medical devices onto a single monitoring platform.

2. The need for a scalable, low-cost, edge-enabled architecture optimized for resource-constrained environments.

5.2 Research Methodology

5.2.1 Motivation and Purpose

The central motivation of this work is to bridge the digital divide in LMIC healthcare settings by developing an IoMT platform that:

- Integrates multiple biomedical devices (VSM, PTL) under one system.
- Ensures low-latency, real-time monitoring of clinical data.
- Implements robust edge processing to minimize cloud dependence.
- Delivers actionable alerts to clinicians using ubiquitous channels such as WhatsApp.
- Supports scalable and modular expansion as new devices are added.

5.2.2 Methodological Approach

The development approach included:

1. Designing a multi-layer IoMT architecture with MQTT-based data ingestion.
2. Implementing a Node-RED gateway for edge parsing and rule evaluation.
3. Building a hybrid persistence model using MongoDB and MySQL.
4. Developing a backend orchestration layer for secure APIs and alert logic.
5. Designing a web dashboard for real-time multi-patient and multi-device monitoring.
6. Conducting performance evaluations under simulated device loads.

5.3 Proposed Solution

5.3.1 System Design

The proposed IoMT platform consists of the following main layers:

1. **Device Layer:** Biomedical devices such as VSM and PTL publish telemetry via MQTT.
2. **Edge Gateway (Node-RED):** Parses payloads, validates data, applies lightweight rules, and forwards processed messages.
3. **Backend Orchestration Layer:** A Node.js API server managing:
    - authentication,
    - business logic,

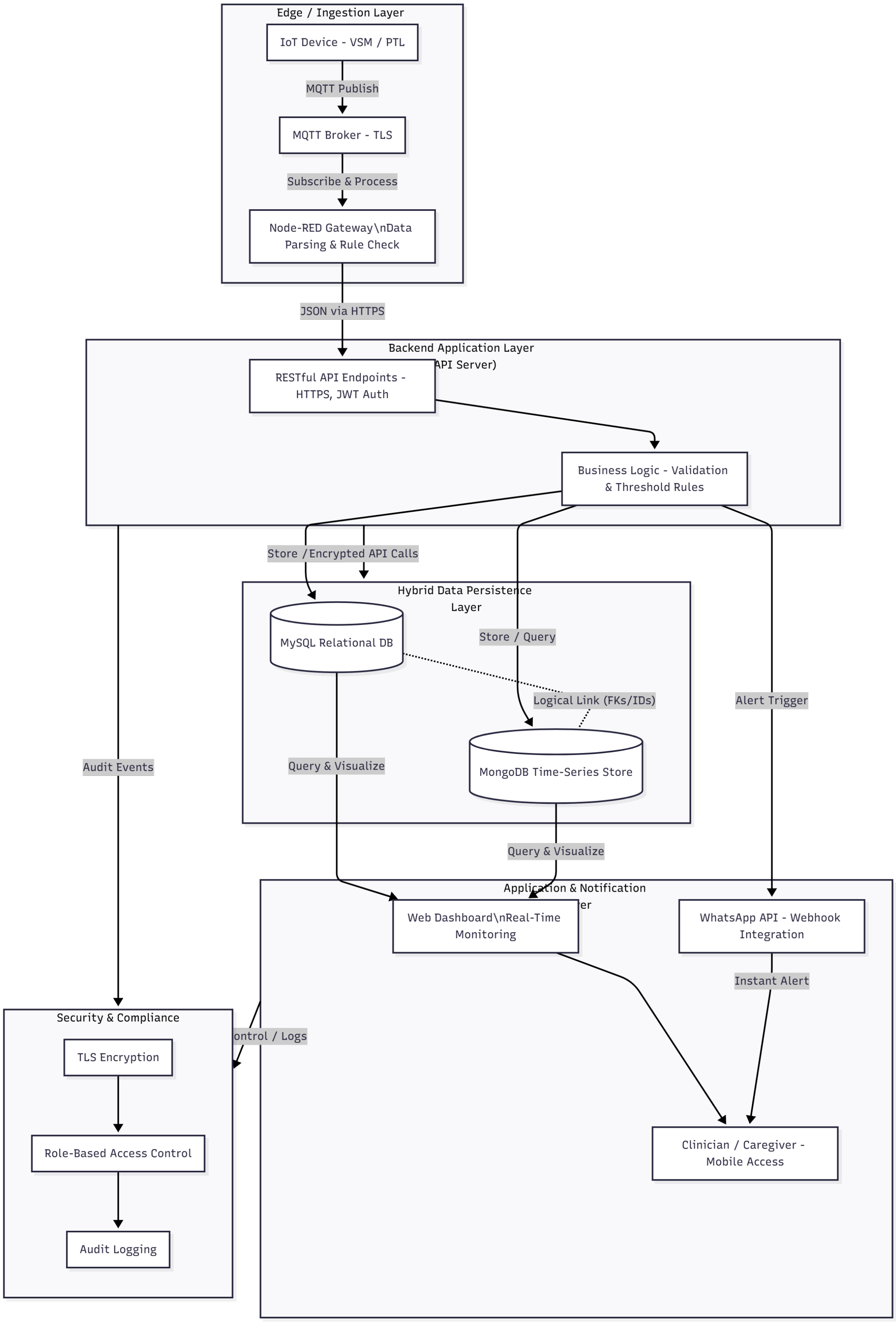


Figure 5.1: Overall IoMT system architecture illustrating edge processing, cloud orchestration, and real-time dashboards.

- unified device models,
- database communication.

4. **Hybrid Database Layer:**
   - MySQL for structured metadata (patients, devices, rules),
   - MongoDB for time-series sensor data.
5. **Application Layer:** Web dashboard and WhatsApp alert engine.

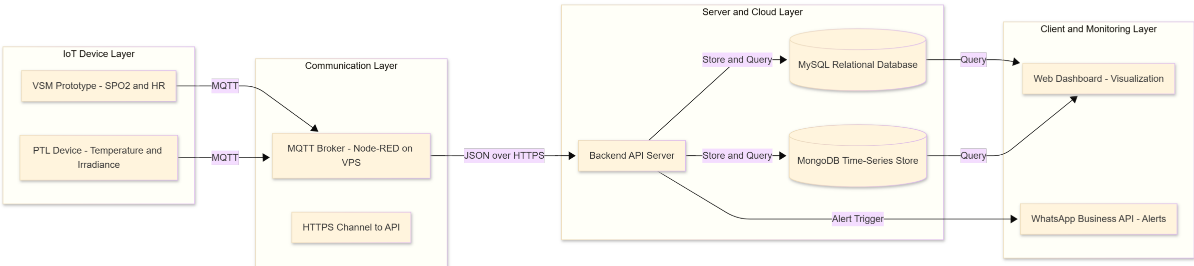


Figure 5.2: Multi-tier IoMT architecture with device, edge, backend, and application layers.

5.3.2 Data Collection

Telemetry captured from the VSM and PTL includes:

- Vital signs: temperature, SpO_2, heart rate, ECG waveform.
- Phototherapy device: LED intensity, therapy duration, enclosure temperature.
- Device health: uptime, connectivity state, error flags.

Data is formatted into standardized MQTT topics to support interoperability.

5.3.3 Data Analysis

Data analysis is performed through:

- Time-series trend extraction from MongoDB.
- Real-time rule evaluation at the backend for clinical alerts.
- Cross-device correlation (e.g., VSM vitals + PTL therapy duration).
- Performance benchmarking of latency and throughput.

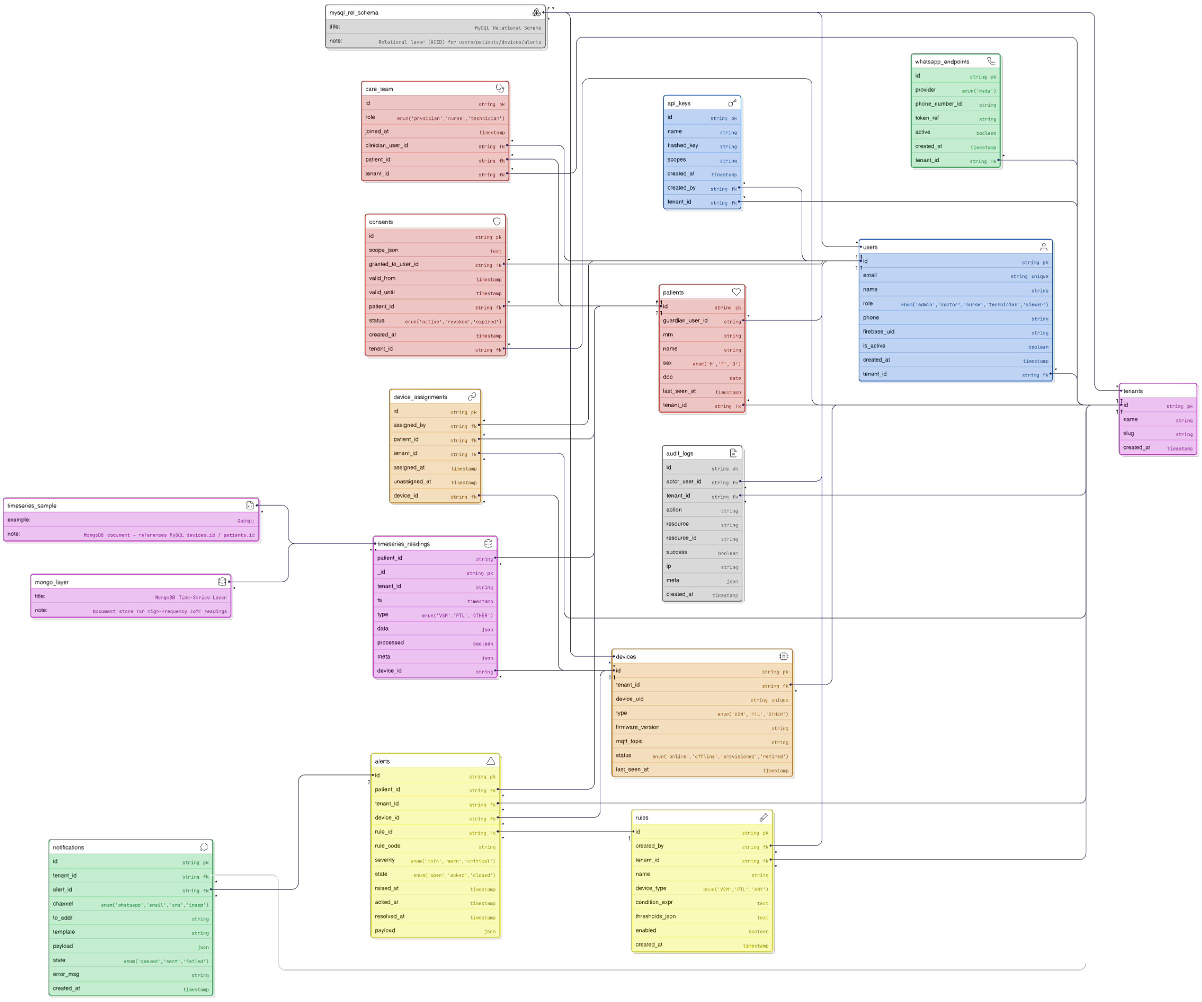


Figure 5.3: Hybrid persistence model combining MySQL and MongoDB.

5.4 Hardware Design

Although the IoMT platform is primarily a software-driven system, hardware integration is essential for uniform data ingestion. Each device includes:

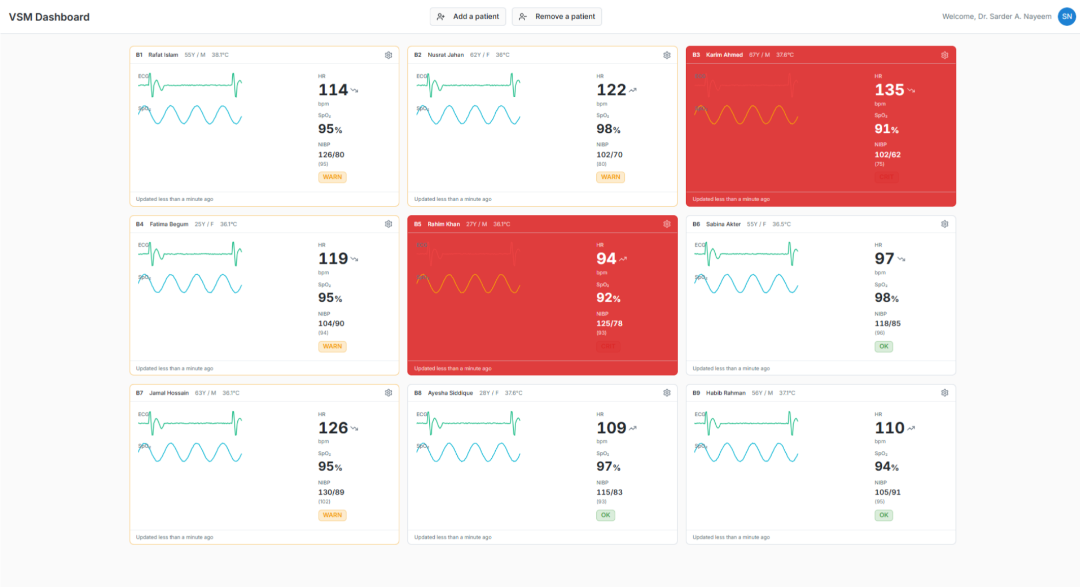
- ESP32 microcontrollers with Wi-Fi capability,
- standardized MQTT client firmware,
- unique device identifiers mapped to MySQL records,
- synchronized timestamps for multi-device correlation.

5.5 Design Overview

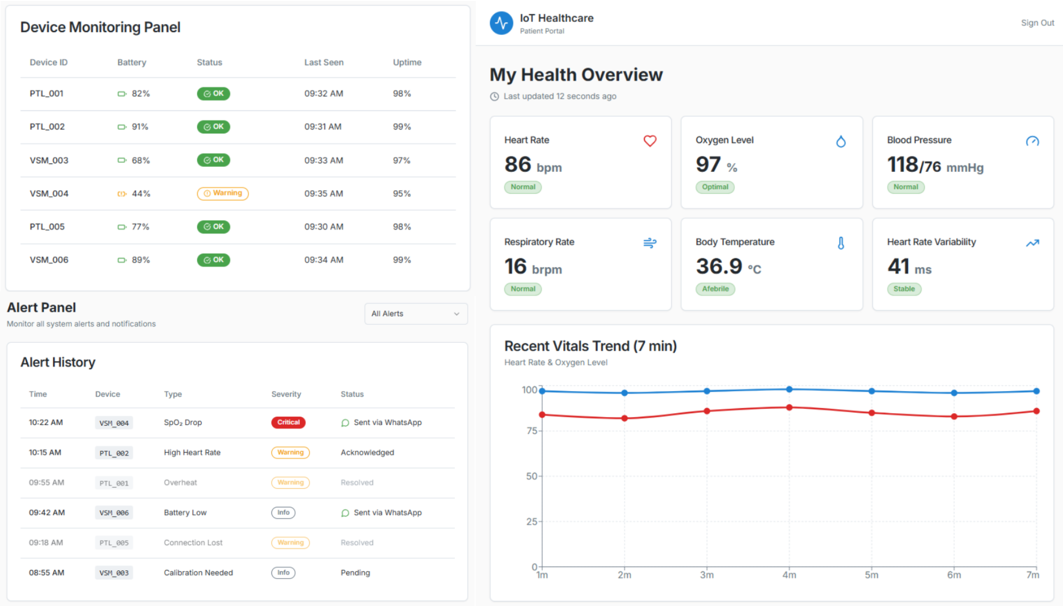
The platform supports:

- **Flow-based device onboarding** via Node-RED,

- **Standardized API endpoints** for device, user, and alert management,
- **Unified dashboard interfaces** for clinicians,
- **WhatsApp-based alert delivery** with structured clinical messages,
- **Distributed data storage** for scalability and resilience.



(a) Multi-patient ward dashboard



(b) Single-patient detailed view

Figure 5.4: Dashboard views

5.6 Implementation

5.6.1 Hardware Implementation

Each biomedical device publishes data via MQTT using:

- TLS encryption,
- lightweight JSON payloads,
- device registration tokens stored in MySQL.

Devices were tested under simulated loads equivalent to a small hospital ward.

5.6.2 Software Implementation

Key implementation details include:

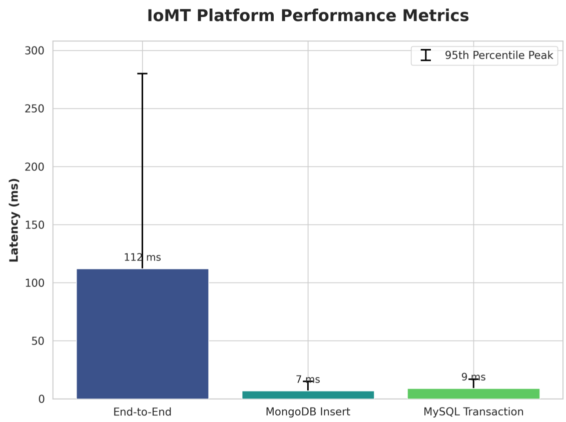
- Node-RED flows for ingestion, validation, and routing.
- Express.js backend for API routing, authentication, and alert orchestration.
- MongoDB for high-frequency sensor entries.
- MySQL for relational data and audit logs.
- WhatsApp Business API integration using webhooks.

5.7 Result Analysis

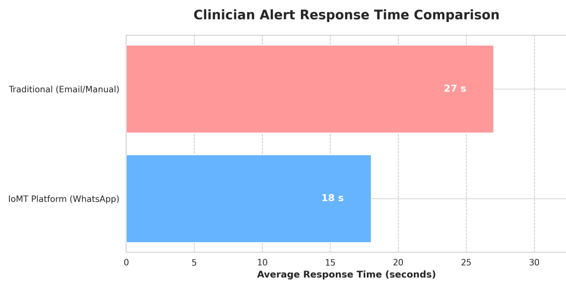
The IoMT platform was deployed on a cloud VPS (4 vCPU, 8 GB RAM) and tested with simulated loads of 50 devices transmitting once per minute.

5.7.1 System Performance

- Zero packet loss under nominal load.
- Mean end-to-end latency of 112 ms.
- MongoDB write latency: 7 ms.
- MySQL transaction latency: 9 ms.
- WhatsApp alert delivery time: 2.1 seconds on average.



(a) Latency and throughput



(b) Alert response times

Figure 5.5: System performance comparison for end-to-end latency, throughput, and alert response time.

5.7.2 Scalability and Fault Tolerance

Stress tests with 6× load demonstrated:

- Stable latency under 400 ms,
- No database bottlenecks due to separation of workloads,
- Automated failover for database replicas within 3–5 seconds,
- Linear CPU scaling supporting ¿200 simultaneous devices.

5.7.3 Clinical Workflow Improvements

WhatsApp-based alerting resulted in:

- A 35% reduction in clinician response time (18s vs. 27s),
- Faster triage decisions,
- Improved situational awareness in neonatal wards.

5.8 Findings and Challenges

The IoMT platform successfully integrates multiple medical devices into a unified, scalable ecosystem. Its use of open-source technologies and edge-driven processing makes it particularly suitable for LMIC clinical settings.

Key findings include:

- Robust real-time performance under realistic workloads.
- Significant improvement in clinical responsiveness.

- Flexible database model enabling heterogeneous device support.

Challenges identified:

- Internet dependency for cloud dashboard access.
- Need for enhanced security hardening for large-scale deployments.
- Occasional API throttling limits imposed by WhatsApp Cloud API.

Future work includes AI-driven predictive analytics, FHIR/HL7 interoperability, and deployment across multiple hospitals for clinical validation.

Chapter 6

Sustainability

This chapter evaluates the sustainability considerations associated with the integrated biomedical IoT ecosystem developed in this thesis. The system comprises three tightly connected components: (1) a rapidly deployable IoT-enabled phototherapy device (PTL), (2) a cost-effective remote vital sign monitoring (VSM) system, and (3) a scalable Internet of Medical Things (IoMT) platform that unifies device data into a centralized infrastructure for real-time clinical monitoring. Designed for low-resource healthcare settings, the combined system emphasizes longevity, maintainability, affordability, and responsible integration into clinical environments.

6.1 System Sustainability and Mitigation Plan

The overarching system architecture prioritizes long-term maintainability and modularity. All hardware subsystems—PTL, VSM, and IoMT gateways—are built on open, off-the-shelf microcontrollers (primarily ESP32) and replaceable sensor modules. This modularity reduces downtime and simplifies field repair in low- and middle-income countries (LMICs). Power resilience was a core design goal: the PTL incorporates high-capacity swappable battery packs for operation during outages, while the VSM includes on-device battery backup for uninterrupted monitoring.

To mitigate long-term risks:

- Firmware across all devices is version-controlled and documented to ensure future adaptability.
- Modular PCBs, JST connectors, and standardized components facilitate low-cost repair and replacement.
- IoMT backend services use open-source technologies (Node-RED, MQTT, MySQL, MongoDB), preventing vendor lock-in and ensuring sustainability.
- Temperature protection in PTL and overcurrent protection in VSM enhance hardware longevity.

The unified system thus ensures durability across clinical environments with constrained resources.

6.2 Social Effects Analysis and Mitigation Plan

Deployment in real-world clinical settings introduces important social considerations. The combined system affects clinicians, neonatal patients, and caregivers.

Key positive impacts:

- PTL expands access to neonatal jaundice treatment in underserved or disaster-hit regions.
- VSM reduces the need for frequent physical contact during infectious disease outbreaks, protecting healthcare workers.
- The IoMT dashboard improves workload distribution by providing remote, multi-patient visibility.

Identified risks and mitigations:

- **Perception of monitoring intrusiveness:** Clear communication ensures that only physiological and device metrics are collected; no audio or video is captured.
- **User comfort and safety:** VSM wrist and chest sensors were designed to be low-weight and non-irritating; PTL enclosure avoids sharp edges and overheating.
- **Training needs:** Short orientation sessions help nurses and caregivers understand device operation and alarms.

Social sustainability is strengthened by transparency, ease of use, and community engagement.

6.3 Environmental Effects Analysis and Mitigation Plan

Environmental sustainability was considered in terms of energy consumption, material usage, and lifecycle impact.

Low-power design:

- The PTL consumes only 16.4 W at its highest intensity, significantly lower than many commercial phototherapy units.
- VSM sensors and microcontrollers operate below 1 W during normal use.
- Node-RED edge processing minimizes cloud computation overhead.

Environmental mitigation measures:

- PTL supports renewable-energy charging (solar, wind) to extend usability in off-grid areas.
- Devices avoid single-use consumables; components are reusable or recyclable.
- Acrylic PTL enclosure can be flat-packed, reducing transportation footprint.

By leveraging energy-efficient hardware and recyclable materials, the system achieves a minimal ecological footprint.

6.4 Technical Sustainability Analysis and Mitigation Plan

Technical sustainability focuses on software maintainability, system scalability, interoperability, and long-term adaptability.

- The IoMT platform uses a hybrid persistence model (MySQL + MongoDB), enabling seamless scaling with high-frequency sensor data.
- MQTT-based device communication ensures interoperability and makes it easy to integrate future sensing devices.
- Modular firmware architectures in PTL and VSM simplify updates and accommodate new features or safety rules.
- TLS encryption, role-based access, and access-token authentication secure the system against long-term cybersecurity risks.

All components rely on well-supported open-source ecosystems, ensuring future compatibility even as technologies evolve.

6.5 Operational Sustainability Analysis and Mitigation Plan

Operational sustainability was evaluated through prolonged testing, simulated hospital workloads, and resilience to real-world constraints.

Operational strengths:

- The PTL's swappable battery pack enables continuous therapy during grid outages.
- The VSM maintained uninterrupted 48-hour signal acquisition during stress tests.

- IoMT simulations with up to 200 concurrent devices showed zero packet loss and sub-second latency.

Mitigation strategies:

- Watchdog timers reset devices on firmware freeze.
- Local buffering prevents data loss during temporary network failures.
- Default safe-state behaviors ensure patient protection (e.g., PTL thermal shutdown, VSM ECG filtering).

These safeguards ensure reliable operation even in unstable or resource-limited conditions.

6.6 Ethical Issues and Mitigation Plan

Ethical considerations are critical when designing systems for neonatal and clinical monitoring.

Ethical safeguards:

- Only non-identifiable physiological data are transmitted unless clinical workflows require metadata; all sensitive data are encrypted at rest and in transit.
- PTL implements thermal protection logic to prevent neonatal overheating, and LED irradiance remains within medically accepted ranges.
- VSM uses authenticated role-based dashboards to restrict access to patient information.
- The IoMT platform maintains audit logs for compliance and traceability.

These measures ensure patient safety, privacy, and compliance with ethical research standards.

6.7 Economic Sustainability and Mitigation Plan

A core objective of this thesis was to provide clinically meaningful technologies at costs suitable for LMIC healthcare systems.

Cost advantages of the integrated system:

- PTL prototype cost: $71; estimated production cost: $142, significantly lower than commercial devices costing $273–$395.
- VSM complete system cost: below $200, compared to $500–$5000 commercial monitors.
- IoMT software stack is entirely open-source, requiring no licensing fees.
- A single server instance can support dozens of devices with negligible recurring cost.

Systems are designed for local assembly, simple maintenance, and long operational lifespan, maximizing return on investment and reducing total cost of ownership.

6.8 Sustainability Summary Matrix

Table 6.1: Sustainability Risk vs. Mitigation Summary

Dimension	**Key Risks**	**Mitigation Strategies**
System	Hardware degradation; firmware obsolescence	Modular components; swappable sensors; version-controlled firmware; use of open-source platforms
Social	User misunderstanding; clinical adoption challenges	Orientation sessions; clear labeling; ergonomic device design
Environmental	Energy consumption; e-waste	Low-power devices; recyclable materials; renewable charging options
Technical	Interoperability issues; cybersecurity threats	MQTT communication; hybrid database; TLS, RBAC, authentication mechanisms
Operational	Power outages; network instability; device failure	Battery backup; watchdog timers; local data buffering; fault-tolerant IoMT routing
Ethical	Patient privacy; neonatal safety	Data encryption; access control; PTL thermal protection; ECG noise filtering
Economic	High cost of medical devices in LMICs	Low-cost BOM; open-source software; scalable IoMT infrastructure

This comprehensive sustainability analysis demonstrates that the combined system—integrating PTL, VSM, and IoMT components—is designed to be technically robust, socially responsible, environmentally efficient, ethically sound, operationally reliable, and economically accessible. Such characteristics make the system suitable for long-term deployment in resource-constrained healthcare environments while supporting the broader goal of improving real-time clinical monitoring through IoT-integrated medical technologies.

Chapter 7

Conclusion

7.1 Project Summary

This thesis presented the design, development, and integration of a low-cost, IoT-enabled biomedical ecosystem intended for real-time clinical monitoring in resource-constrained healthcare environments. The work addressed three critical clinical challenges in low- and middle-income countries (LMICs): the lack of accessible neonatal phototherapy units, the absence of affordable continuous vital sign monitoring systems, and the fragmentation of medical device dashboards that limit clinicians' ability to obtain a unified patient overview.

The first contribution was the development of the Bioforge PTL, a rapidly deployable phototherapy device for neonatal jaundice capable of operating on modular battery packs and transmitting operational data through an IoT interface. The second contribution was a wearable vital sign monitoring (VSM) platform capable of continuous acquisition of temperature, ECG, pulse rate, and SpO_2, supported by bedside and remote dashboards. The third contribution was a scalable Internet of Medical Things (IoMT) platform integrating PTL and VSM devices into a unified system using MQTT, Node-RED, hybrid database storage, and automated WhatsApp-based clinical alerts.

Performance evaluations demonstrated sub-second end-to-end latency, zero packet loss under nominal conditions, stable long-duration monitoring, and improved clinician response times. Together, these components form an affordable, interoperable, and scalable ecosystem capable of supporting neonatal therapy, continuous monitoring, and centralized clinical oversight within LMIC hospitals and emergency care settings.

7.2 Limitations

Despite the promising results, several limitations remain:

- **Clinical validation:** While hardware and software performance were extensively tested, full clinical trials have not yet been conducted for PTL, VSM, or the integrated IoMT system.

- **Network dependency:** Remote dashboards and alerting mechanisms require reliable internet connectivity. In low-resource settings, unstable networks may temporarily disrupt real-time monitoring.
- **Motion artifacts and noise:** ECG and optical sensors in the VSM system remain sensitive to patient movement, affecting signal accuracy in highly mobile patients.
- **Device durability:** The PTL's acrylic enclosure, while suitable for rapid deployment, may require further ruggedization for long-term use in harsh environments.
- **Scalability limits:** Although tested with simulated loads up to 200 devices, large-scale hospital deployments may require optimized microservices and distributed server architectures.

7.3 Ethical Considerations

The development and deployment of IoT-enabled biomedical devices require adherence to ethical principles related to patient safety, privacy, and data governance:

- **Data privacy and confidentiality:** All transmitted physiological and device data must be encrypted, securely stored, and accessed only by authenticated clinical personnel.
- **Informed usage:** Patients or guardians must be informed about the nature of remote monitoring, data collection, and storage practices to ensure transparency and consent.
- **Safe therapeutic operation:** The PTL device must maintain irradiance levels within clinically accepted limits and enforce thermal protection mechanisms to prevent harm to neonates.
- **Bias and accessibility:** Systems should be designed to avoid digital exclusion and must remain affordable and usable in low-resource communities.
- **Accountability:** Automated alerts and dashboards should support, not replace, clinical judgment. Final responsibility for decisions must remain with trained medical professionals.

7.4 Future Work

Building upon the work presented in this thesis, several promising directions can enhance the functionality, robustness, and clinical impact of the system:

- **Clinical Trials and Regulatory Approval:** Conduct formal clinical evaluations of the PTL and VSM devices, followed by regulatory approval under local and international medical device standards.

- **AI-Driven Early Warning Systems:** Integrate machine learning models for anomaly detection, predictive risk scoring, and automated triage based on continuous vital sign trends.
- **Expanded Device Ecosystem:** Add support for additional biomedical devices (e.g., blood pressure monitors, respiratory sensors, incubator telemetry) within the IoMT platform.
- **Enhanced Signal Processing:** Improve ECG and SpO_2 denoising algorithms to reduce motion artifacts and enhance signal reliability in active patients.
- **Offline-First Architecture:** Implement local caching, mesh networking, and Bluetooth-based fallback communication to improve resilience in regions with unstable internet access.
- **Ruggedization and Industrial Design:** Improve the physical robustness of the PTL enclosure and optimize ergonomics of the wearable VSM for long-term patient comfort.
- **FHIR/HL7 Integration:** Enable interoperability with hospital information systems to support electronic medical record (EMR) synchronization and large-scale deployments.

The results of this thesis demonstrate that IoT-integrated medical devices, when thoughtfully designed and deployed, can meaningfully enhance clinical capabilities in LMICs. With further research, refinement, and evaluation, the proposed biomedical ecosystem has the potential to contribute significantly to accessible, equitable, and data-driven healthcare.

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