Design and Implementation of a Heart Rate and Blood Oxygen Monitoring System Based on LoRa with Data Visualization on ThingsBoard and Interactive Leaflet Map

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Abstract— **In this study, we designed and implemented a vital signs monitoring system capable of measuring heart rate and blood oxygen saturation (SpO_2). The system employs the MAX30102 optical sensor and a Raspberry Pi Pico 2W microcontroller to acquire and preprocess physiological data. The data are transmitted to a receiver using the low-power, long-range LoRa communication technology. At the receiver, the data are decoded and forwarded to the IoT platform ThingsBoard via the lightweight MQTT protocol. These data are visualized in real time on a graphical dashboard and an interactive Leaflet map, enabling analysis, recording, alerting, long-term monitoring, and location tracking.**

Experimental evaluation demonstrated satisfactory accuracy in signal measurement, reliable data transmission, and low power consumption, with acceptable performance in terms of transmission success rate, effective range, stability, and latency. The system can serve as a practical prototype for remote health monitoring in environments without stable internet infrastructure.

Keywords: Internet of Things (IoT); Remote Health Monitoring; Heart Rate; Blood Oxygen Saturation (SpO_2); LoRa.

I. INTRODUCTION

Continuous monitoring of vital signs is recognized as one of the fundamental pillars of modern medical care. Among these parameters, heart rate and blood oxygen saturation (SpO_2) are particularly important, since abnormal variations in these values can indicate serious conditions such as cardiac disorders, respiratory diseases, or oxygen deficiency. Therefore, continuous recording and monitoring of these data play a crucial role in the early detection of critical conditions and the prevention of irreversible harm. With the growing elderly population, the rising prevalence of chronic diseases, and health crises such as the COVID-19 pandemic, the demand for intelligent health monitoring systems has become increasingly urgent [1].

Despite advancements in wearable sensors and optical technologies enabling the collection of vital signs in home-care settings without requiring hospital visits, wireless transmission of medical data still faces significant challenges. Conventional approaches such as Wi-Fi and Bluetooth are often unsuitable for many medical applications, especially in crisis situations, rural areas, or field hospitals, due to their high energy consumption, limited range, and dependency on stable infrastructure. This highlights the necessity of employing emerging communication technologies that feature low power consumption, long transmission range, and high stability[13],[14].

One such promising technology is LoRa, specifically developed for Internet of Things (IoT) applications, which allows low-data-rate transmission over long distances with minimal power usage. Complementing this, the open-source IoT platform ThingsBoard provides developers with robust capabilities for data collection, storage, visualization, and analysis using lightweight protocols such as MQTT. Moreover, data can be visualized on interactive maps using the Leaflet.js library, enabling advanced spatial tracking and geographical data analysis. This integration offers a comprehensive and practical solution for remote health monitoring systems, combining centralized data management and analytics through ThingsBoard with interactive and customizable spatial visualization provided by Leaflet.

In this research, a low-cost and portable system for measuring heart rate and blood oxygen saturation was designed and implemented. The vital signs are acquired using the MAX30102 sensor, preprocessed by the Raspberry Pi Pico 2W microcontroller, and transmitted to the receiver via a LoRa module. At the receiver side, the data are decoded, formatted in JSON, and sent to the ThingsBoard platform through the MQTT protocol. By providing real-time data visualization on a graphical dashboard and an interactive map, along with alerting capabilities for critical conditions, the proposed system can serve as a foundation for developing remote health monitoring solutions in home-care environments, healthcare facilities, and emergency situations .

II. RELATED WORK

Remote health monitoring has gained significant attention in recent years due to its potential to improve patient care, reduce hospital visits, and enable continuous observation of vital signs. Several studies have focused on wearable sensors for measuring heart rate and blood oxygen saturation (SpO_2). Optical sensors such as MAX30102 have been widely employed for noninvasive, real-time monitoring, demonstrating satisfactory accuracy in controlled environments [3] ,[4],[17].

The MAX30102 pulse oximeter sensor has been utilized in various studies to measure heart rate and blood oxygen saturation (SpO_2). MAX30102 sensor is used for accurate and reliable measurements of heartbeat pulse rate and oxygen concentration in blood.

Wireless transmission of physiological data has also been extensively explored. Traditional communication technologies, including Wi-Fi and Bluetooth, provide high data rates but are often limited by short transmission range and high energy consumption, making them less suitable for continuous monitoring in home-care or remote settings. To overcome these limitations, Low-Power Wide-Area Network (LPWAN) technologies such as **LoRa** have emerged as promising alternatives, offering long-range communication with minimal energy requirements. The performance of LoRa technology as a wireless platform in IoT health monitoring, is evaluated and its suitability is highlighted for healthcare applications [5],[6],[7].

In addition to data acquisition and transmission, visualization and analysis of collected data are crucial for effective health monitoring. IoT platforms like **ThingsBoard** have been employed to store, manage, and visualize physiological data, enabling real-time alerts and analytics. ThingsBoard, an open-source IoT platform, facilitates data collection, processing, visualization, and device management, and has been successfully utilized in various healthcare applications [8].

Furthermore, interactive mapping tools such as **Leaflet** allow geographical representation of user data, supporting location-based monitoring and spatial analysis. Leaflet.js, a leading open-source JavaScript library for creating mobile-friendly interactive maps, has been applied in several domains, including health service planning, to enhance the visualization and analysis of spatial data [9].

Despite these advancements, integrating low-cost wearable sensors,long-range communication,IoT-based data management, and interactive spatial visualization into a unified system remains limited. This motivates the development of comprehensive solutions that combine reliable physiological data acquisition, energy-efficient wireless transmission, cloud-based processing, and interactive visualization for practical remote health monitoring applications. For example, An Internet of Wearable Things-based Hybrid Healthcare Monitoring System (IoWT-HHMS) is designed and developed for smart medical applications, emphasizing the integration of multiple technologies to provide a comprehensive remote health monitoring solution [10],[15],[16].

III. PROPOSED METHOD

In this section, the design and implementation of the vital signs monitoring system are described. The proposed system consists of three main components: data acquisition, data transmission, and data visualization and analysis. Heart rate and blood oxygen saturation (SpO_2) data are collected using the **MAX30102** optical sensor and undergo initial processing in the **Raspberry Pi Pico 2W** microcontroller. The data are then transmitted to the receiver via **LoRa** technology, which provides long-range communication with low power consumption.

On the receiver side, the data are decoded and formatted in **JSON** and sent to the **ThingsBoard** IoT platform through the lightweight **MQTT** protocol. The data are displayed on the ThingsBoard graphical dashboard and simultaneously visualized on an interactive map using **Leaflet**, enabling user location tracking and geographical data analysis.

Subsequently, the hardware and software architecture, data flow, and algorithms for data processing and transmission are described in detail.

A.General System Architecture

The Figure below illustrates the general architecture of the vital signs monitoring system with GPS, LoRa, and ThingsBoard.

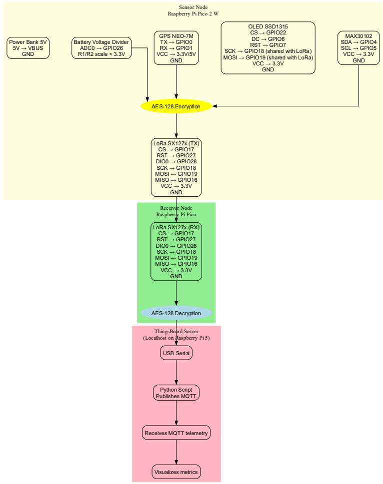

Figure 1. General Architecture of the Vital Signs Monitoring System

B. Hardware Architecture

The proposed system consists of three main components: the Sensor Node, the Receiver Node, and the ThingsBoard server. This architecture ensures reliable data acquisition, low-power long-range wireless communication, and accurate visualization of the collected information.

B.1 Sensor Node

The Sensor Node is built around the Raspberry Pi Pico 2W and integrates several peripheral modules for collecting, processing, and transmitting vital signals. The MAX30102 sensor is used to measure blood oxygen saturation (SpO_2) and heart rate through an optical sensing method. It is connected to the Pico via the I2C interface, with SDA connected to GPIO4 and SCL to GPIO5, which corresponds to the default I2C0 on the Pico. The sensor is powered by 3.3V from the Pico and shares a common ground with other modules.

An OLED SSD1315 display operates in SPI mode and provides local real-time visualization of sensor data. Its SPI connections include CS to GPIO22, DC to GPIO6, RST to GPIO7, SCK to GPIO18, and MOSI to GPIO19. The SCK and MOSI lines are shared with the LoRa module.

The LoRa SX127x module also operates in SPI mode, enabling low-power, long-range wireless communication. Its SPI connections include NSS/CS to GPIO17, RST to GPIO27, DIO0 to GPIO28, SCK to GPIO18, MOSI to GPIO19, and MISO to GPIO16. The SCK and MOSI lines are shared with the OLED display. The module is powered with 3.3V and shares a common ground with the other modules. All transmitted data is encrypted using AES-128.

The GPS NEO-7M module operates in UART mode and provides the user's geographic coordinates. The module's TX is connected to the Pico RX at GPIO0, and its RX is connected to the Pico TX at GPIO1. The GPS module is powered by 3.3V.

Battery voltage is monitored using a voltage divider circuit, which scales the battery voltage down to below 3.3V for safe reading by the Pico ADC at GPIO26 / ADC0. This enables real-time monitoring of the battery level.

Power is supplied via a 5V power bank capable of 1A and 2000mAh, connected to the Pico through the micro-USB port. The VBUS line is connected to 5V, and GND is shared across all modules. This design ensures a common ground for all modules and properly managed SPI/I2C lines, preventing signal interference.

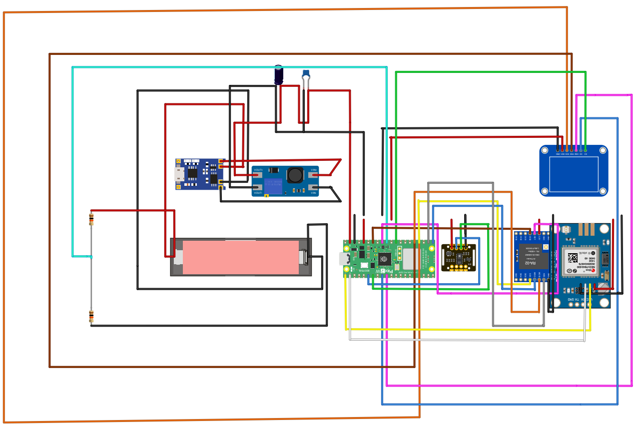

Figure 2. Sensor Node

B.2 Receiver Node

It uses a Raspberry Pi Pico along with the LoRa SX127x module. The LoRa module receives encrypted packets from the sensor Node. The Pico sends the received data to the host system via USB Serial.

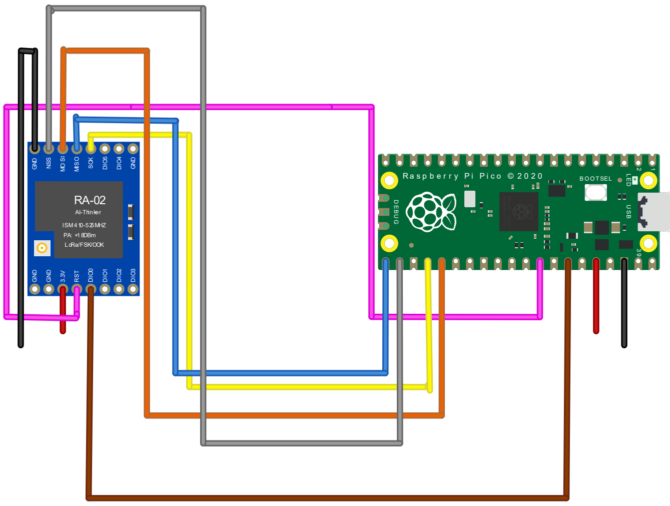

Figure 3. Receiver Node

B.3 ThingsBoard Server Node

A Raspberry Pi 5 is deployed as a local server running ThingsBoard. Data is received via the MQTT protocol. The visualization includes metrics such as heart rate, SpO_2, GPS coordinates, and battery voltage. Interactive maps using Leaflet are supported to display user locations.

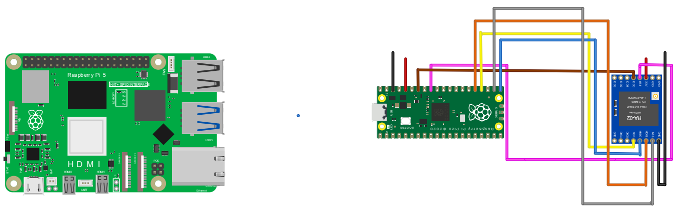

Figure 4. ThingsBoard Server Node

C. Software Architecture

The system's software architecture ensures data flow management, initial signal processing, encryption, and secure transmission to the server. This section comprises three main layers: the Sensor Node, the Receiver Node, and the ThingsBoard Server.

C.1 Sensor Node

Sensor data processing involves reading heart rate and SpO_2 data from the MAX30102 sensor via I2C. The data is preprocessed, and signal noise is removed using filters or DSP algorithms. Battery voltage is read via the ADC and appropriately scaled. GPS coordinates are obtained from the NEO-7M module and parsed.

Data encryption and packaging are performed by collecting all data, including heart rate, SpO_2, battery voltage, and GPS coordinates, in JSON format. For security, the data is encrypted using the AES-128 algorithm.

Data transmission to the receiver is carried out by sending the encrypted data using the LoRa SX127x module. LoRaWAN or LoRa P2P protocol is used to ensure low power consumption and long-range communication.

C.2 Receiver Node

Receiving LoRa Packets, where the LoRa module receives the encrypted packets and delivers them directly to the microcontroller for further processing.

Decryption and Conversion to JSON, in which the received data is decrypted using AES-128 and then converted into a JSON structure containing heart rate, SpO_2, GPS coordinates, and battery voltage.

Publishing Data to ThingsBoard, whereby the data is sent to the server using the lightweight MQTT protocol, and communication between the receiver and the server is established via TCP/IP or Wi-Fi.

C.3 Thingsboard Server Node

Data Reception and Storage involves receiving the JSON data from the receiver via MQTT and storing it in the internal ThingsBoard database.

Data Visualization and Analysis provides a graphical dashboard for real-time monitoring of vital signs, battery voltage, and location. An interactive map using Leaflet displays the users' positions based on GPS coordinates. The system also supports alert configuration under critical conditions and long-term data logging.

Advantages of the Software Architecture include the separation of the sensor, processing, and server layers, which facilitates system scalability and easier maintenance. The use of standard protocols such as MQTT, JSON, and AES ensures security, scalability, and flexibility of the system.

IV. EVALUATION

A. Evaluation of Transmitter Module Energy Consumption

Evaluation of Transmitter Module Energy Consumption shows that the average current in the baseline scenario, with a transmission interval of every 10 seconds and a TX duration of 0.2 seconds, is approximately 92.96 mA. With this current, the estimated operating time of a 2000 mAh battery is about 21.5 hours, and considering an efficiency of 90%, this time is reduced to approximately 19.4 hours [11].

TABLE I. AVERAGE CURRENT CONSUMPTION AND ESTIMATED BATTERY OPERATING TIME OF THE SYSTEM

Component / Parameter	Formula	Value (mA)
MAX30102	(0.6 + 1.6) / 2	1.1
OLED	(8 + 12) / 2	10
GPS	(25 + 30) / 2	27.5
Raspberry Pi Pico (Avg)	(45–55)	50
LoRa (Avg)	$I_{idle} \times (1 - duty) + I_{TX} \times duty$ duty=0.02 2×0.98+120×0.02	4.36
Total Current	50 + 1.1 + 10 + 27.5 + 4.36	92.96
Battery Time (2000 mAh)	T=2000/92.96	≈ 21.51 h
Effective Time (90% efficiency)	T_{eff}=2000×0.992.96	≈ 19.36 h

B. LoRa Module Performance Evaluation

TABLE II. LORA MODULE RANGE AND SIGNAL STRENGTH IN ENVIRONMENTAL CONDITIONS

Environment	Approx. Range	Reception Status
Open space (no obstacles)	3.5 km	RSSI ≈ -115 dBm
Semi-urban area	1.2 km	RSSI ≈ -105 dBm
Inside building	300 m	RSSI ≈ -95 dBm

This table presents the approximate range and signal strength (RSSI) of the LoRa SX1278 module under different environmental conditions.

In open outdoor areas without obstacles, the module can communicate up to 3.5 kilometers with an RSSI of about −115 dBm.

In semi-urban environments with some buildings or obstacles, the range decreases to about 1.2 kilometers with an RSSI of around −105 dBm.

Indoors, where walls and other barriers weaken the signal, the range is reduced to approximately 300 meters with an RSSI of about −95 dBm.

This table demonstrates that environmental conditions have a significant impact on the range and signal quality of LoRa communication.

C. Discussion and Analysis

Comparison with Similar Methods highlights that most related works rely solely on Wi-Fi or Bluetooth, which are limited to ranges of 10–100 meters. In contrast, the proposed system utilizes LoRa, which provides long-range communication in the order of kilometers and is highly beneficial for rural and emergency applications.

Advantages of the proposed system include relatively low energy consumption, which enables long-term battery operation. Data transmission security is ensured through AES-128 encryption at a high level, while the long range of LoRa allows monitoring from considerable distances. Moreover, real-time data visualization is supported through integration with ThingsBoard and Leaflet.

Limitations of the system lie in the fact that the low data rate of LoRa is suitable for vital signs but not appropriate for high-volume data such as full ECG signals. The use of GPS depends on sky visibility, making indoor operation challenging. In addition, battery life with sensors continuously powered is limited to several hours, requiring optimization of module duty cycles for long-term usage[12].

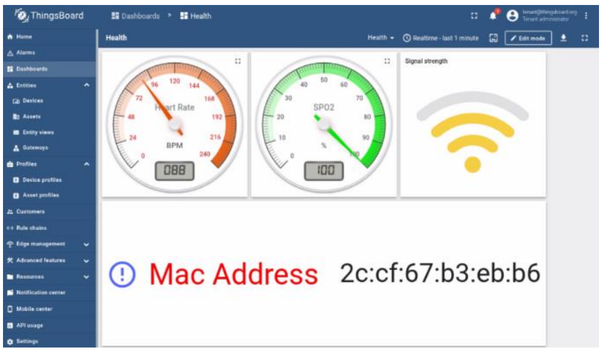

Figure 5. A view of the ThingsBoard dashboard for visualizing parameters including heart rate, Spo_2, received signal strength, and the MAC address of the transmitting device.

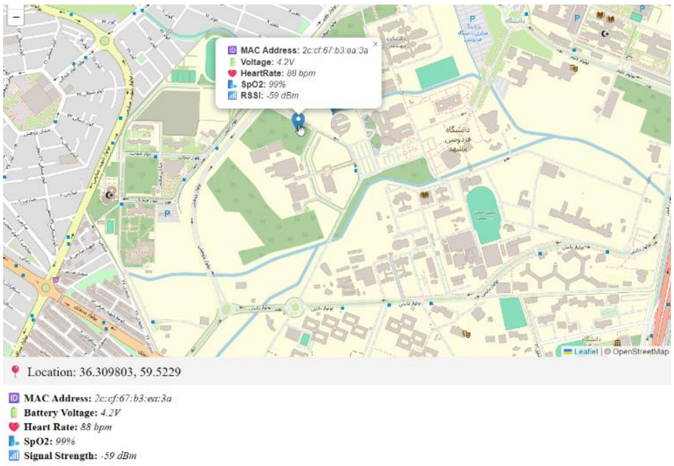

Figure 6. A view of the interactive map using Leaflet for visualizing parameters including heart rate, Spo_2, received signal strength, and the MAC address of the transmitting device.

V. FUTURE WORK

In Future work for the proposed wearable health monitoring system focuses on enhancing its functionality, scalability, and intelligence to better serve remote healthcare applications. One key direction is the integration of additional physiological sensors, such as blood pressure, respiratory rate, and body temperature, to provide a more comprehensive assessment of patient health. Combining multiple sensor modalities through data fusion techniques could further improve measurement accuracy and reduce noise, especially in real-world environments.

Another significant avenue is the incorporation of machine learning and artificial intelligence algorithms for predictive analysis. By analyzing historical trends in heart rate, SpO_2, and other vital parameters, the system could anticipate critical health events, such as arrhythmias or sudden drops in oxygen saturation, and generate early alerts. This would elevate the system from passive monitoring to proactive healthcare support.

Enhancing the communication layer is also crucial. Future iterations may explore hybrid LPWAN solutions, adaptive transmission protocols, and advanced encryption schemes to improve reliability, reduce energy consumption, and ensure data privacy. Alongside, the user interface can be further developed with advanced dashboards, interactive visual analytics, and real-time notifications for patients and healthcare providers.

Scalability represents another important consideration. Deploying a network of sensor nodes across multiple patients or healthcare facilities could enable population-level monitoring, while cloud-edge integration would minimize latency and support real-time decision-making. Finally, validation through clinical trials and comparison with standard medical devices will be essential to establish the system's accuracy, robustness, and usability in real-world healthcare scenarios.

Collectively, these enhancements aim to transform the current system into a comprehensive, intelligent, and scalable remote health monitoring platform, capable of supporting personalized, proactive, and reliable patient care in diverse environments.

VI. Conclusion

In this study, a health monitoring system based on the Raspberry Pi Pico 2W was designed and implemented, integrating multiple biomedical and communication modules. The proposed architecture provides real-time measurement of vital signs including SpO_2, heart rate, battery level, and geographic location (GPS), along with long-range, low-power communication (LoRa) and secure data transmission (AES-128) within a unified system.

Compared to conventional solutions based on Wi-Fi or Bluetooth, the proposed LoRa-based design significantly extends network coverage, reduces energy consumption, and offers greater stability in environments lacking communication infrastructure. Additionally, the ThingsBoard platform enables real-time data visualization, interactive map plotting with Leaflet, and scalable data management. These features make the proposed system highly suitable for remote health monitoring and IoT applications.

Overall, this study demonstrates that a lightweight, cost-effective, and energy-efficient architecture can provide reliable vital sign monitoring and accurate location tracking, offering a promising outlook for future applications in wearable health, emergency response, and smart IoT ecosystems[18].

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