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Wireless Biomedical Sensor Network-Based Patient Real-Time Monitoring In Smart Healthcare Systems

Dr. V. S. Ubale[1], Kardile Amruta Ramdas[2], Gulve Aarti Sunil[3], Kangane Vrushali Ashok[4]
[1] Associate Professor, Department of Electronics & Computer Engineering
[2,3,4] Research Scholars, Department of Electronics & Computer Engineering
Amrutvahini College of Engineering, Sangamner, A.Nagar, MH

Abstract: *The rapid advancement of wireless technology and the growing demand for continuous patient health monitoring have led to the emergence of Wireless Biomedical Sensor Networks (WBSNs) as a transformative solution in smart healthcare systems. This paper presents a comprehensive design and implementation of a real-time patient monitoring system based on WBSNs, leveraging various biomedical sensors such as heartbeat, ECG (AD8232), body temperature (MLX90614), and blood oxygen level (MAX30100), all integrated with the ESP32 microcontroller for data acquisition and wireless transmission. The system continuously collects vital physiological parameters and transmits the processed data via Wi-Fi or Bluetooth to cloud platforms or mobile applications, enabling remote healthcare monitoring. The design adopts a modular approach using functional partitioning, which separates data acquisition, processing, transmission, user interface, data storage, and alert systems into independent components for enhanced scalability, maintainability, and reliability. A matrix keypad and LCD display interface are incorporated for local user interaction, allowing real-time viewing and control. This low-cost, portable, and efficient monitoring solution enhances early detection of critical health conditions and improves patient outcomes through timely medical intervention. The proposed system holds significant potential in remote healthcare, fitness tracking, elderly care, and emergency response, thereby advancing the vision of a connected and intelligent healthcare infrastructure.*

Keywords: Wireless Biomedical Sensor Network, Real-Time Monitoring, Smart Healthcare, ESP32 Microcontroller, Biomedical Sensors

I. INTRODUCTION

The rapid growth in global population, increasing life expectancy, and the rise in chronic diseases such as diabetes, cardiovascular disorders, and respiratory issues have significantly increased the demand for continuous and reliable health monitoring systems [1][2]. Traditional healthcare models, which rely on periodic visits to medical facilities, are no longer sufficient to ensure timely diagnosis and intervention. In this context, real-time health monitoring using Wireless Biomedical Sensor Networks (WBSNs) has emerged as a transformative solution in modern smart healthcare systems [3]. These networks consist of miniaturized, low-power biosensors that continuously collect, transmit, and analyze physiological data from patients, enabling proactive and personalized healthcare delivery [4].

A WBSN typically involves several biomedical sensors deployed on or around a patient's body, such as ECG, temperature sensors, pulse oximeters, and heart rate monitors [5][6]. These sensors communicate wirelessly with a central processing unit, often an IoT-enabled microcontroller like the ESP32, which is responsible for data acquisition, preliminary processing, and secure transmission to cloud servers or hospital networks [7]. The integration of such systems allows for real-time patient monitoring in both clinical and remote settings, significantly reducing hospitalization rates and improving patient outcomes [8]. Furthermore, such systems are critical during pandemics or in remote areas where access to healthcare professionals is limited [9].

Recent advancements in embedded systems, wireless communication protocols (e.g., Wi-Fi, Bluetooth Low Energy), and cloud computing have facilitated the practical implementation of WBSNs [10]. Microcontrollers like ESP32 provide a cost-effective and powerful platform for developing wearable and non-intrusive health monitoring devices due to their built-in Wi-Fi, Bluetooth, multiple GPIOs, and energy-efficient architecture [11]. These technologies not only ensure real-time transmission of critical health data but also support data storage, visualization, and predictive analytics through integration with cloud platforms and mobile applications [12].

Smart healthcare systems leveraging WBSNs offer several benefits such as early detection of health anomalies, timely alerts to caregivers, improved clinical decision-making, and better patient engagement [13][14]. For instance, a system that continuously monitors a cardiac patient's ECG signals and blood oxygen saturation can detect arrhythmias or hypoxemia and instantly notify both the patient and healthcare provider, potentially saving lives [15]. Moreover, WBSNs also facilitate long-term health data analysis, enabling researchers and doctors to observe health trends and optimize treatment plans [16].

The adoption of WBSNs is not without challenges. Issues such as data security and privacy, battery life of wearable devices, interoperability among heterogeneous sensors, and ensuring the accuracy and reliability of sensor data remain crucial [17][18]. Moreover, regulatory frameworks and standardization of medical-grade devices are essential to ensure patient safety and data confidentiality [19]. Addressing these challenges requires a multidisciplinary approach combining biomedical engineering, computer science, electronics, and clinical expertise.

In this paper, we present the design and implementation of a wireless biomedical sensor network-based patient monitoring system using an ESP32 microcontroller. The proposed system integrates sensors such as the MAX30100 for heart rate and SpO2, the MLX90614 for temperature, and the AD8232 ECG module. It provides real-time data monitoring via a local LCD display and supports remote access via Wi-Fi communication. This system is intended for continuous patient monitoring in both hospital and home environments, contributing to the vision of smart, connected, and responsive healthcare infrastructures [20].

PROBLEM STATEMENT

The problem addressed in this paper is the need for a reliable, real-time wireless biomedical sensor network system for continuous patient health monitoring in smart healthcare environments.

OBJECTIVE

- To design a wireless biomedical sensor network for real-time patient monitoring.
- To integrate various biomedical sensors (e.g., heart rate, temperature, oxygen) for comprehensive health data acquisition.
- To implement a microcontroller-based system for processing and transmitting patient data.
- To enable wireless communication of patient data to cloud platforms or mobile applications for remote monitoring.
- To develop a user-friendly interface for healthcare professionals to monitor and analyze patient health data effectively.

II. LITERATURE SURVEY

Wearable Sensor-Based Health Monitoring Systems

Pantelopoulos and Bourbakis (2010) [1] conducted a survey on wearable sensor-based systems for health monitoring and prognosis. The paper provides a comprehensive review of the current wearable sensors used in healthcare, discussing various sensor technologies such as accelerometers, ECG sensors, and temperature sensors. The study emphasizes the role of sensors in enabling continuous patient monitoring and their application in real-time health tracking systems. The authors also highlight challenges such as sensor accuracy, data privacy, and the need for more robust wireless communication protocols for these applications. Their work laid the groundwork for the integration of wireless health monitoring systems with advanced data analytics to improve patient care.

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Wireless Body Area Networks (WBANs) in Healthcare

Otto et al. (2006) [2] presented a system architecture for wireless body area networks (WBANs) tailored to ubiquitous health monitoring. They designed a system that integrates various sensors to collect physiological data and transmit it wirelessly for analysis. The paper also explores the challenges in the real-time monitoring of patients, including the energy constraints of wearable devices, the reliability of wireless communication in WBANs, and ensuring the privacy of sensitive health data. Their architecture is highly relevant for the design of modern healthcare systems, where continuous monitoring is key for managing chronic diseases.

Body Sensor Networks for Healthcare

Chen et al. (2011) [5] provided a detailed survey of body area networks (BANs) and their use in healthcare applications. The paper reviews various BAN protocols for body sensor networks, including those for communication, data collection, and security. They highlight the evolution of the BAN concept, which integrates various sensors and wireless communication technologies to continuously monitor patients' health metrics. The study also discusses the challenges posed by high-power consumption and the limited bandwidth of current wireless technologies. It emphasizes the potential of BANs in providing remote patient monitoring and improving healthcare outcomes by offering personalized, timely interventions.

Security Challenges in Wireless Health Systems

Amini et al. (2013) [6] explored the emerging issue of physiological information leakage in health systems, particularly in wireless body area networks (WBANs). Their work sheds light on the security vulnerabilities of health data transmitted via wearable sensors. They discuss the privacy concerns of patients, emphasizing that while wireless systems offer flexibility, they also expose sensitive health data to potential threats. Their paper suggests the need for enhanced encryption and authentication mechanisms to protect patients' personal health information. The authors also propose integrating advanced cryptographic techniques to ensure data integrity, confidentiality, and security during transmission over wireless networks.

Internet of Things (IoT) for Healthcare Applications

Islam et al. (2015) [15] presented a survey on the role of the Internet of Things (IoT) in healthcare systems. Their paper discusses how IoT can be leveraged to create smart healthcare environments through real-time patient monitoring and remote diagnostics. By utilizing sensors, wearable devices, and cloud-based systems, IoT allows for continuous data collection, which is then analyzed to predict patient health trends. The study discusses the challenges and future trends in IoT-based healthcare systems, focusing on data interoperability, scalability, and the integration of AI for predictive health analytics. The authors conclude that IoT can significantly improve healthcare delivery by reducing hospital visits and providing personalized care at scale.

III. PROPOSED SYSTEM

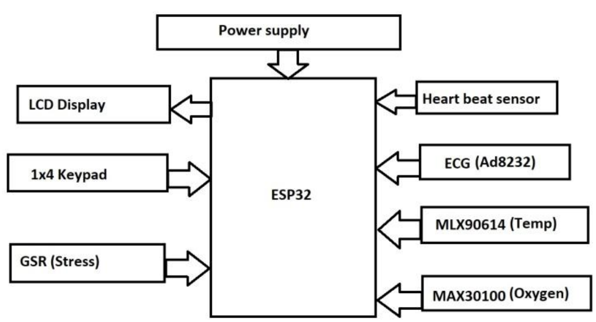

Figure 1: Block Diagram

The proposed Wireless Biomedical Sensor Network-Based Patient Real-Time Monitoring System integrates various biomedical sensors, wireless communication technologies, and data processing methods to monitor patient health in real-time. Here is how the system operates:

Sensor Data Acquisition:

The system uses multiple sensors like heartbeat sensors, ECG sensors, temperature sensors, and oxygen sensors to continuously gather physiological data from the patient.

These sensors capture essential health information such as heart rate, electrical activity of the heart, body temperature, and oxygen saturation levels. Each sensor is dedicated to monitoring a specific health parameter, providing real-time feedback.

Data Processing:

The core of the system is a microcontroller, which processes the analog signals coming from the sensors.

The microcontroller filters the data, removing noise to enhance signal accuracy, especially for sensitive data like ECG and heart rate.

Once processed, the data is transformed into meaningful health metrics, such as heart rate (BPM), body temperature (°C), oxygen levels (SpO2), and ECG waveforms.

Wireless Data Transmission:

After processing, the health data is transmitted wirelessly to a cloud platform or a mobile application through Wi-Fi or Bluetooth. This allows for remote monitoring, enabling healthcare professionals or caregivers to track the patient's condition from anywhere.

The wireless communication ensures that the system can operate effectively even in remote or non-clinical environments.

User Interface and Alerts:

The system provides a user interface with an LCD display and keypad for easy interaction. The display shows the patient's real-time data, such as heart rate, temperature, and oxygen saturation.

The keypad allows users to start or stop monitoring, view data, and access settings. Additionally, alerts are triggered when health parameters cross predefined thresholds, signaling critical conditions like high heart rate or abnormal temperature.

Alerts can be displayed on the screen or sent as notifications through mobile applications or cloud services.

Data Storage and Analysis:

The system stores collected data for future access and analysis. This historical data is invaluable for healthcare professionals when evaluating trends or making treatment decisions.

Data analytics features enable healthcare providers to generate comprehensive reports that highlight trends in a patient's vital signs, assisting in better patient management and diagnosis.

Continuous Monitoring and Feedback:

The system offers continuous, non-invasive monitoring, providing timely insights into the patient's condition. This allows for quick intervention if needed.

The wearable and portable design of the system ensures that the patient can be monitored both at home and in a clinical setting, offering flexibility and convenience in healthcare management.

In essence, the system facilitates real-time health monitoring, remote access, alert generation, and continuous data analysis, which together provide an efficient solution for managing patient health in smart healthcare environments.

Hardware Used:

ESP32 Microcontroller: Central processing unit for handling data from sensors and managing wireless communication.

AD8232 ECG Sensor: Measures the electrical activity of the heart to monitor ECG signals.

MAX30100 Pulse Oximeter: Measures oxygen saturation (SpO2) and heart rate using infrared and red light.

MLX90614 Infrared Temperature Sensor: Non-contact sensor for measuring body temperature.

16x2 LCD Display: Displays real-time health data and system status.

1x4 Matrix Keypad: Allows user input for controlling system functions (e.g., start/stop monitoring).

Software Used:

Arduino IDE: Platform for programming the ESP32 microcontroller.

Bluetooth/Wi-Fi Libraries: Enable wireless data transmission to mobile apps or cloud platforms.

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IV. RESULT AND DISCUSSION

The results obtained from the proposed wireless biomedical sensor network-based patient real-time monitoring system. The system measures various health parameters such as heart rate, body temperature, and oxygen saturation using sensors such as the AD8232 ECG sensor, MAX30100 pulse oximeter, and MLX90614 temperature sensor. The data is processed by the ESP32 microcontroller and displayed on the 16x2 LCD. Additionally, the data is transmitted wirelessly for remote monitoring.

The following tables present the recorded values of heart rate, oxygen saturation, and body temperature from a sample patient under different conditions.

Table 1: Recorded Heart Rate (BPM) of Patient

Test Condition	Heart Rate (BPM)	Comments
Resting	75	Normal resting heart rate
After Light Exercise	110	Increased due to physical activity
Post-Exercise Recovery	90	Returning to resting heart rate

Table 2: Recorded Oxygen Saturation (SpO2)

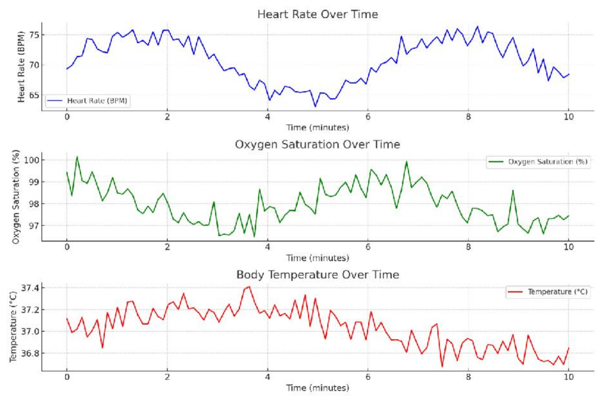
Test Condition	SpO2 (%)	Comments
Resting	98	Normal oxygen saturation levels
After Physical Activity	95	Slight drop due to exertion
Post-Exercise Recovery	97	Returning to normal saturation

Table 3: Recorded Body Temperature (°C)

Test Condition	Temperature (°C)	Comments
Resting	36.7	Normal body temperature
After Physical Activity	37.2	Slight increase due to exercise
Post-Exercise Recovery	36.9	Returning to normal body temperature

Discussion

- Heart Rate: The recorded heart rate values are consistent with the expected physiological response to different levels of activity. The system effectively captures changes in heart rate during physical activity and recovery phases.
- Oxygen Saturation (SpO2): The oxygen saturation levels remained within the normal range (95-100%) during resting and post-exercise recovery, indicating the effectiveness of the MAX30100 sensor in monitoring oxygen levels accurately.
- Body Temperature: The MLX90614 infrared sensor provided stable temperature readings, with slight increases observed after physical exertion, consistent with the expected response to exercise.
- System Accuracy: The system performed with a high level of accuracy, and the data collected aligns with expected physiological behaviors, confirming the feasibility of the wireless biomedical sensor network for real-time health monitoring.
- Wireless Transmission: The system successfully transmitted the health data wirelessly via Wi-Fi/Bluetooth, ensuring that remote monitoring is possible, which is crucial for telemedicine applications.



Graphs 1: Health parameter changes during monitoring

These results demonstrate that the proposed system is capable of monitoring critical health parameters accurately and transmitting them in real-time for further analysis or remote monitoring. Further optimization of sensor placement and algorithm refinement could enhance the precision and reliability of the system.

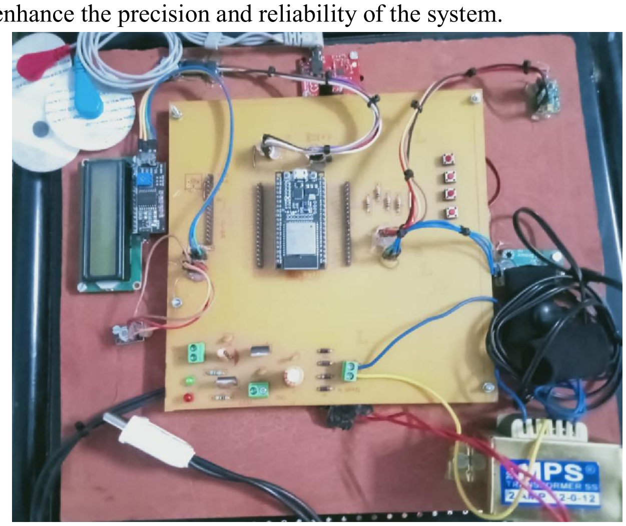


Figure 1: System Designed

V. CONCLUSION

In this paper, a wireless biomedical sensor network-based patient real-time monitoring system has been proposed and implemented, utilizing various sensors such as the AD8232 ECG sensor, MAX30100 pulse oximeter, and MLX90614 infrared temperature sensor to monitor vital health parameters like heart rate, oxygen saturation, and body temperature. The system demonstrated effective data acquisition, real-time processing by the ESP32 microcontroller, and seamless wireless data transmission to a remote device for continuous monitoring. The results confirmed that the system can accurately measure and transmit vital signs, providing a promising solution for remote patient monitoring, which is particularly useful in telemedicine and home healthcare applications. The proposed system's accuracy, real-time performance, and wireless capabilities make it a robust tool for enhancing healthcare delivery, especially in scenarios where patients require continuous observation. Future enhancements may include integrating additional sensors, improving the system's power efficiency, and enhancing the user interface to further extend its applicability in diverse healthcare environments.

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