IoT - Driven: Sleep Apnea Detection

Capstone Project Proposal

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BE Third Year- COE/ CSE

CPG No. 167

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Mentor Consent Form

I hereby agree to be the mentor of the following Capstone Project Team

Project Title: IoT - Driven: Sleep Apnea Detection

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Project Overview

Sleep apnea, a serious condition that repeatedly interrupts breathing during sleep, is linked to an increased risk of heart disease, diabetes, and cognitive decline. Traditional diagnosis relies on polysomnography (PSG), requiring an overnight stay at a specialized clinic with cumbersome and expensive equipment. This process is not only inconvenient but also limits access to timely diagnosis, leading to many undiagnosed and untreated cases.

To overcome these challenges, a smart wristband powered by IoT and AI is being developed to detect sleep apnea in real time. The device will monitor key physiological parameters, including heart rate, oxygen saturation, brain activity, and respiratory patterns, using non-invasive biosensors. AI-driven algorithms will process this data to detect apnea episodes and assess their severity. The collected information will be securely transmitted to a cloud-based system, allowing healthcare providers to remotely monitor patients and intervene when necessary.

Designed for comfort, affordability, and ease of use, this wearable technology aims to revolutionize sleep apnea diagnosis and management. By offering a non-invasive, real-time monitoring solution, it reduces dependence on clinical sleep studies and improves accessibility to early detection and treatment. The goal is to provide a practical, reliable, and user-friendly alternative that empowers individuals to take control of their sleep health while enabling better clinical outcomes.

Need Analysis

Sleep apnea is experienced by millions worldwide, with most cases remaining undiagnosed due to inaccessible diagnostic procedures. Polysomnography, recognized as the gold standard for diagnosis, is expensive and limited to controlled clinical settings, making daily monitoring impossible. Home-based diagnostic solutions, though available, lack accuracy and fail to provide real-time, automated analysis of apnea events.

Amid the rising prevalence of sleep apnea, an affordable, convenient, and efficient alternative is required to prevent serious health risks. Continuous monitoring is enabled by IoT-based wearable solutions, allowing early detection and timely medical interventions. The accuracy of disease detection is enhanced through AI-driven analytics, where real-time multi-sensor data processing eliminates manual analysis delays and inefficiencies.

The proposed system is further strengthened by multi-sensor fusion, AI-driven analytics, and cloud-based monitoring. Real-time insights into sleep health will be provided to users, while medical professionals will be granted remote access to patient data.

Literature Survey

Theory Associated with Sleep Apnea and its detection using IoT sensors and AI/ML

Sleep apnea detection systems are designed to identify and monitor apnea events using various IoT sensors and machine learning techniques. These systems are built upon several core technologies and concepts, including:

1. **Physiological Signal Analysis:**
   - ECG (Electrocardiogram): Heart rate variability (HRV), R-R intervals, ECG-derived respiration (EDR)
   - SpO_2 (Oxygen Saturation): Oxygen desaturation index (ODI), SpO_2 drop patterns
   - Respiratory Signals: Airflow waveform, breathing rate irregularities
   - Body Movement & Snoring Detection: Accelerometers, gyroscopes, and microphone-based sound analysis
2. **Feature Extraction and Spectrogram Analysis:**
   The extraction of physiological signal features is essential for accurate sleep apnea detection. Breathing variations are indicated by time-domain features such as HRV and SpO_2 fluctuations, while frequency-domain analysis of ECG and respiratory signals enables the differentiation of apnea-affected sleep stages.
3. **Machine Learning and Deep Learning Models:**
   Various Machine Learning and Deep Learning models, such as CNN, Transformers, Autoencoders, LSTM, Random Forest Classifier, KNN, and DBN, are applied to enhance the accuracy of sleep apnea detection.
4. **Real-Time Processing:**
   An IoT-based sleep apnea detection system is designed with wearable sensors, edge computing, and cloud storage for real-time monitoring. Physiological data is collected through IoT sensors and processed locally before being transmitted to the cloud for ML-based analysis. Results are displayed in apps and dashboards, providing real-time alerts and reports to users and healthcare professionals.

Existing System Solution:

Several sleep apnea detection methods are currently available.

1. **Polysomnography (PSG) in sleep labs**

   Polysomnography is considered the gold standard for sleep apnea detection, as multiple physiological signals, including EEG, ECG, SpO_2, airflow, respiratory effort, and muscle activity, are measured. However, several limitations exist, such as high costs ranging from Rs 5000 to Rs 20000 or more, the inconvenience of an overnight stay in a sleep lab, and the necessity of medical supervision by trained professionals, making it inaccessible for regular monitoring.

2. **CPAP (Continuous Positive Airway Pressure) Therapy**

   CPAP is considered the most effective treatment for Obstructive Sleep Apnea (OSA). A continuous stream of air is delivered through a mask to prevent airway collapse during sleep. However, discomfort, noise, and poor adherence remain key challenges for long-term use.

3. **Consumer Wearables (eg. Fitbit, Apple Watch, Oura Ring)**

   Parameters such as heart rate variability (HRV), blood oxygen saturation (SpO_2), and sleep patterns are monitored. Insights into sleep disturbances are provided, but direct apnea detection algorithms are lacking.

4. **Existing wearable solutions (eg. withings sleep analyzer, Go2Sleep**)

   More advanced than general wearables, these devices are equipped with under-mattress sensors or finger-worn technology.

   Withings Sleep Analyzer: Breathing disturbances, heart rate, and movement are tracked using a pneumatic sensor.

   Go2Sleep: SpO_2 fluctuations and HRV are monitored to estimate apnea risk.

While good accuracy is achieved, limited physiological parameters reduce reliability compared to PSG.

The effectiveness and challenges of sleep apnea detection using various ML techniques and sensors have been explored in several studies. Key research findings include:

Research Findings from the Provided Papers:

1. **Convolutional networks (CNN) on ECG signals**: A 1D-CNN was used to analyze ECG signals for sleep apnea classification. Temporal features were extracted, enabling the accurate classification of sleep apnea episodes.[1]
2. **Transformer-Based Models**: BERT-like transformer architectures have been utilized for the analysis of PSG time-series data. [6]
3. **Deep Belief Networks (DBNs) for Unsupervised Feature Learning:** The automated extraction of features from raw ECG and respiratory signals has been explored using DBNs. [2]
4. **LSTMs for detection**: Long Short-Term Memory Networks (LSTMs) based models process sequential physiological data such as respiration and oxygen saturation levels, to detect apnea patterns.[2]
5. **CNN on SpO2**: used 1D-CNN to analyze SpO2 signals and detect sleep apnea using polysomnographic St. Vincent UCD database. [3]
6. **Random Forest for feature-based sleep apnea classification** - applied random forest classifier to polysomnography features, such as ECG, SpO2 levels, heart rate variability etc. The model showed high accuracy well distinguishing apnea from normal breathing patterns.[2]
7. **Datasets**: The datasets used have been evaluated, and the best ones identified in our survey are listed as follows:
   - St. Vincent's University Hospital/ University College Dublin Sleep Apnea Database. https://physionet.org/content/ucddb/1.0.0/ [3]
   - MIT-BIH Polysomnographic Database https://www.physionet.org/content/slpdb/1.0.0/ [7]

Objectives

Table 1: Objectives

S. No.	Description
1	**An AI-driven, real-time sleep apnea detection system is developed**, where physiological signals are analyzed, apnea events are detected in real-time, and instant alerts are provided for timely intervention.
2	**Multi-sensor fusion is implemented** to enhance diagnostic accuracy by integrating data from multiple biosensors, improving accuracy, reducing false positives, and ensuring comprehensive sleep apnea detection.
3	**Cloud-based remote monitoring is enabled**, allowing sleep data to be securely transmitted to the cloud for remote access, real-time monitoring, and AI-driven insights by medical professionals.
4	**A cost-effective and non-intrusive design is implemented,** featuring a comfortable wearable with remote monitoring capabilities.

Methodology

1. **Dataset Selection and Training Data Preparation:**
    - ML models are trained using benchmark datasets (MIT-BIH, PhysioNet) with labeled apnea events.
    - Data preprocessing includes denoising, segmentation, and feature extraction.
2. **IoT Device Development and Sensor Integration**
    - A wearable device (wristband or chest band) is designed using ECG, SpO_2, airflow, and movement sensors for data collection.
    - Microcontrollers like ESP32 are selected, and Bluetooth (BLE) or WiFi modules are integrated for real-time communication.
    - Low-power optimization is implemented for extended battery life.
3. **Data Collection and IoT sensor Integration**
    - Wearable sensors collect real-time physiological data, with local data preprocessing handled by an IoT gateway device (ESP32).
4. **Data Preprocessing and Feature Extraction**
    - Filters and normalization are applied to remove noise, and key features are extracted from ECG (HRV), SpO_2 (ODI, drop rate), and airflow (breathing cycle irregularities).
5. **Machine Learning and Deep Learning Model Development**
    - ML models like Logistic Regression, SVM, XGBoost, and Random Forest are trained for sleep apnea detection. CNN, LSTM, and Hybrid CNN-LSTM models are implemented for raw signal analysis.
6. **Real Time processing and Mobile App Integration**
    - A React Native app is developed for real-time monitoring, apnea alerts, and sleep reports, with live data received from IoT sensors via Bluetooth or WiFi.
7. **Performance Evaluation and Validation**
    - Models are validated using accuracy, sensitivity, specificity, and F1-score. System results are compared with PSG data for clinical validation.

Work Plan

1. Phase 1: Research and Feasibility (Jan 2025 – Feb 2025)

- Existing diagnostic tools and sensor technologies are studied.
- Suitable biosensors and machine learning models are identified.

2. Phase 2: Hardware Development (Mar 2025 – Jun 2025)

- Sensors for ECG, SpO_2, HRV, and respiration are integrated.
- A comfortable and power-efficient prototype is developed.

3. Phase 3: Software and AI Integration (Jul 2025 – Aug 2025)

- Firmware for data collection and transmission is developed.
- AI-based apnea detection algorithms are implemented.
- A web or mobile-based monitoring dashboard is built.

4. Phase 4: Testing and Validation (Sep 2025 – Oct 2025)

- Trials on healthy individuals and apnea patients are conducted.
- Results are compared with polysomnography (PSG) data.

5. Phase 4: Optimization and Deployment (Nov 2025 – Dec 2025)

- Algorithm accuracy and power efficiency are improved.
- Regulatory compliance for medical use is ensured.

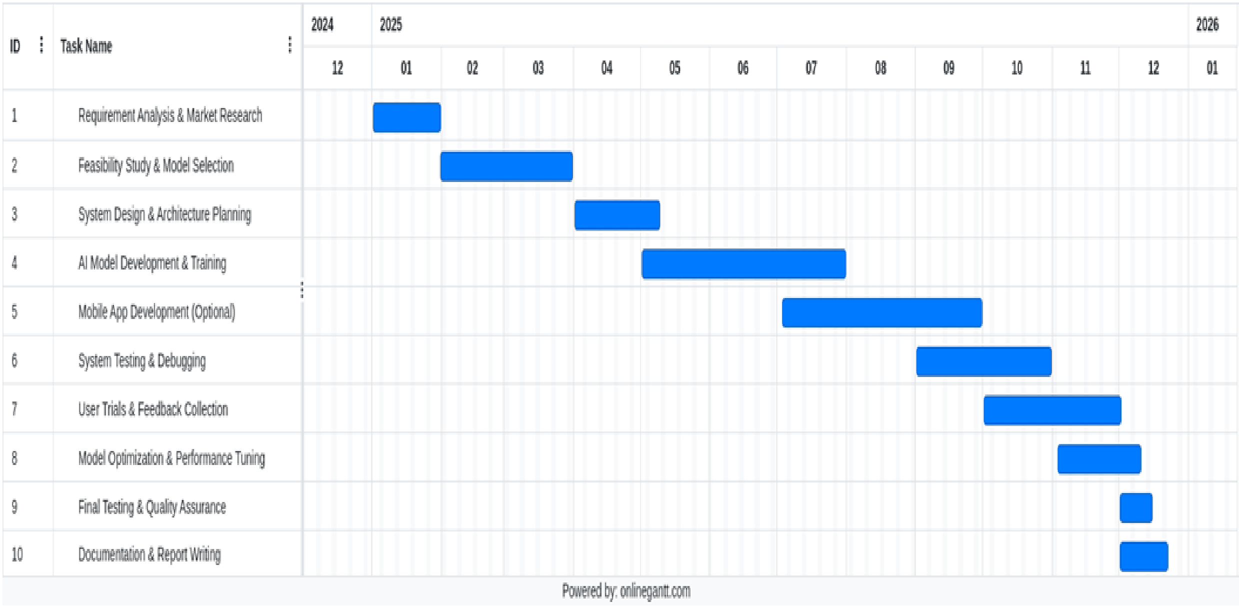

Figure 1: Gantt Chart for Work plan

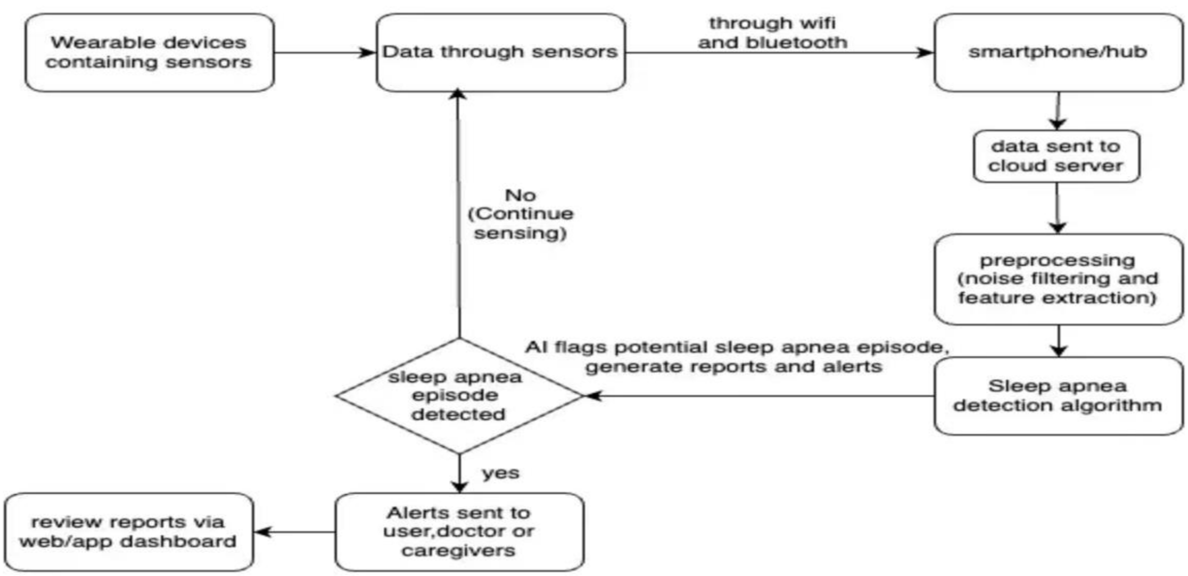

Figure 2: Workflow Diagram

Project Outcomes and Individual Roles

Outcomes

- A multi-sensor wristband is developed for data acquisition and functionality integration.
- Real-time AI-driven sleep apnea detection algorithms are implemented.
- A cloud-based remote monitoring dashboard is designed for patients.
- Continuous tracking is used to evaluate CPAP effectiveness.

Individual Roles

Table 2: The list of Individual roles

Name	Role	
Baneet Singh	Model Development	Documentation
Armaan Saini	Model Development	Frontend & Backend
Ramitdeep Kaur	Model Development	Frontend & Backend
Babandeep Kaur	IoT Integration	Documentation
Mehakdeep Kaur	IoT Integration	Frontend & Backend

Course Subjects

The following course subjects were instrumental in the successful execution of the IoT Driven Sleep Apnea Detection, covering various aspects of computer science and artificial intelligence:

- **Software Engineering (SE)**

  Developed and maintained a modular and scalable software infrastructure, incorporating UML diagrams.

- **Artificial Intelligence (AI)**

  AI-driven decision-making techniques implemented to analyze physiological signals, thereby enhancing the accuracy of apnea event detection and prediction through real-time monitoring.

- **Machine Learning (ML)**

  Trained and fine-tuned machine learning models on real-world sleep datasets, leveraging deep learning algorithms and feature extraction methods to detect irregular breathing patterns indicative of sleep apnea.

- **Biomedical Signal Processing**

  Processed and extracted key features from bio signals, including heart rate variability (HRV), SpO_2 levels, breathing rate, ECG, and movement patterns, enabling precise identification of apnea episodes.

- **Embedded Systems & IoT**

  Designed and integrated low-power, wearable hardware with real-time data transmission capabilities, ensuring continuous monitoring and seamless communication between the wristband and the mobile/web application.

- **Data Science & Time-Series Analysis**

  Analyzed large-scale sleep datasets using statistical and signal processing techniques, enabling the identification of apnea-related anomalies through advanced time-series analysis.

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