Sound Asleep

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Introduction

Problem

Sleep is one of the most critical components of human health, yet poor sleep is a growing issue worldwide. Lack of restorative sleep has been linked to an increased risk of mental health disorders, kidney disease, diabetes, and other chronic illnesses. A particularly important stage of sleep is slow-wave sleep (SWS), the deepest and most restorative phase of non-REM sleep. Research shows that slow-wave sleep declines with age, even though it is essential for immune system strengthening, memory consolidation, and emotional regulation.

Existing wearable sleep trackers can measure sleep stages but often fail to improve them. Some devices use EEG technology but are uncomfortable for overnight use. Others lack active stimulation mechanisms. Recent literature has demonstrated that auditory closed-loop stimulation—delivering sounds like pink noise at precise phases of slow waves—can increase both the duration and amplitude of SWS, improving memory performance and overall sleep quality. However, consumer-ready, comfortable, and effective devices remain limited.

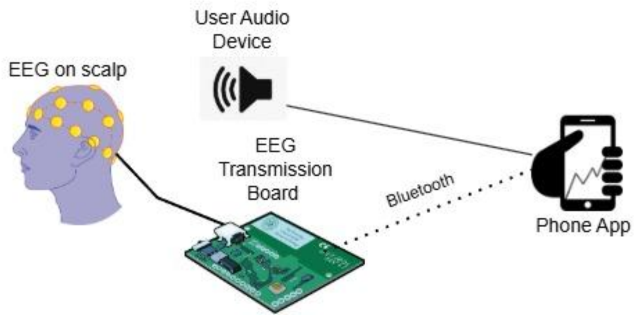
Solution

We propose **Sound Asleep**, a non-invasive wearable system designed to detect slow-wave sleep and deliver real-time auditory stimulation to enhance sleep quality.

The system combines a lightweight EEG headband for overnight wear with a companion mobile application. EEG signals will be wirelessly transmitted to the app, where real-time algorithms detect sleep stages and identify slow-wave activity. When a slow oscillation is detected, the app triggers auditory stimulation (e.g., pink noise bursts) delivered through the user's chosen Bluetooth audio device. Allowing users to select their own headphones or speakers increases comfort compared to proprietary hardware.

This closed-loop system leverages proven techniques from academic research while prioritizing usability and comfort for long-term adoption.

Visual Aid



High-Level Requirements

- The wearable must continuously record and transmit EEG signals overnight, with sufficient accuracy to distinguish between sleep stages, especially SWS.
- The processing system must detect slow-wave oscillations in real-time with a latency of less than 200 ms to ensure auditory stimuli align with ongoing brain rhythms.
- The system must successfully deliver auditory stimulation via Bluetooth to the user's device with timing precision of ±50 ms relative to slow-wave peaks.

Design

Block Diagram

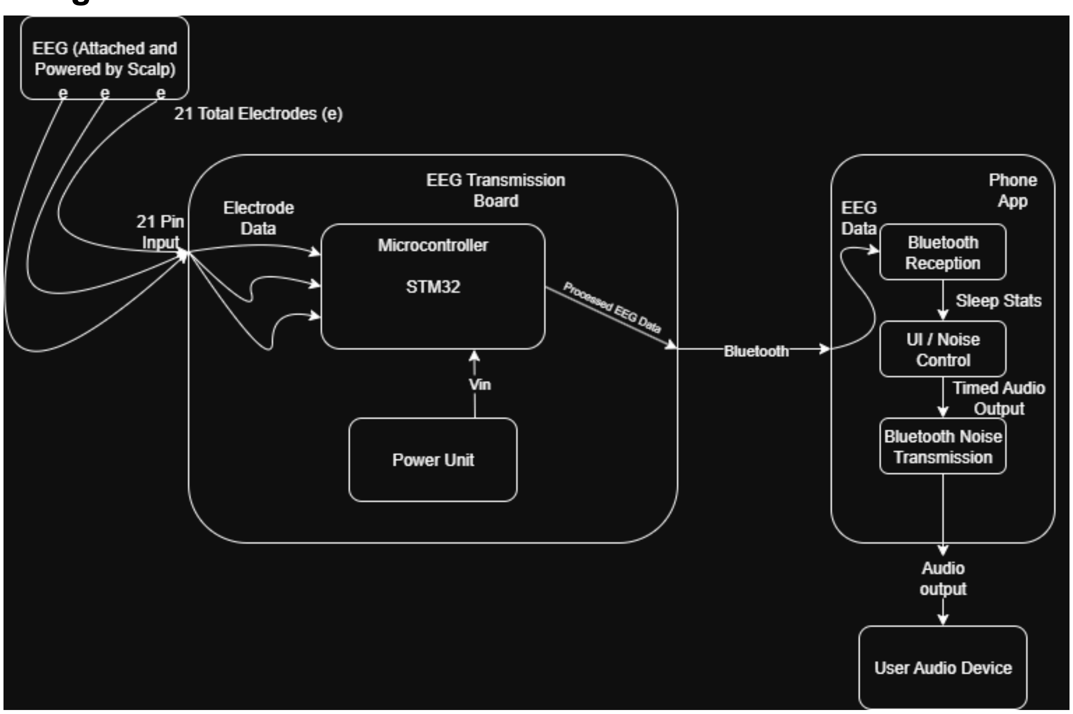


Figure 2. Block Diagram of Project.

Subsystem Overview

1. **EEG Acquisition + Wearable Hardware**
   - Records EEG signals using soft electrodes integrated into a headband or cap.
   - Includes low-noise amplification and filtering circuits to make signals suitable for processing.
   - Powered by a compact rechargeable battery designed for overnight operation.
   - Connects directly to the wireless transmission subsystem.

2. **Wireless Transmission + Power Management**
   - A microcontroller (STM32) digitizes EEG signals and transmits them via Bluetooth Low Energy (BLE) or Wi-Fi.
   - Implements a battery management system for safe charging and efficient overnight energy use.
   - Interfaces with the EEG hardware and the mobile app.

3. **Sleep Stage Classification + Signal Processing**
   - Mobile app processes EEG signals using algorithms for sleep staging and slow-wave detection.
   - Employs open-source libraries such as YASA and CoSleep as baselines.
   - Real-time detection ensures auditory cues are precisely timed to slow-wave oscillations.

4. **Auditory Stimulation Delivery + User Interface**
   - Companion app triggers auditory stimulation (pink noise bursts through the user's Bluetooth device.
   - Provides customization of sound characteristics (duration, intensity, frequency).
   - Displays nightly sleep summaries including time in SWS and number of stimulation events.

Subsystem Requirements

- **EEG Acquisition:** Must record EEG signals with at least 100 Hz sampling rate and <1 μV RMS noise.
- **Wireless Transmission:** Must maintain a continuous data stream with packet loss <1% for 8 hours.
- **Processing Algorithms:** Must classify sleep stages with >80% accuracy compared to baseline EEG scoring.
- **Auditory Stimulation:** Must deliver sounds within 50 ms of targeted slow-wave peaks and support user-adjustable volume.

- **Power System:** Must provide >8 hours of operation on a single charge at 3.3 V nominal battery voltage.

Tolerance Analysis

The most critical risk is **timing accuracy of auditory stimulation relative to slow-wave oscillations**. If stimulation occurs outside the proper phase, it may disrupt sleep rather than enhance it.

Analysis: Slow-wave oscillations occur at approximately 0.5–1 Hz. This means each cycle lasts about 1–2 seconds. The stimulation must align with the **up-phase** of the oscillation (±50 ms tolerance). Our proposed algorithms and wireless transmission pipeline must maintain end-to-end latency below 200 ms. To mitigate risks we have to employ buffering strategies, and efficient BLE protocols. Hardware testing will be performed to validate timing under real-world conditions.

Ethics and Safety

Ethics

In line with the IEEE Codes of Ethics, we are committed to protecting user health and privacy. Ethical considerations include:

- **Data Privacy:** EEG data contains sensitive health information. All data will be processed locally on the user's device whenever possible. If storage or sharing is necessary, it will be anonymized.
- **User Comfort and Safety:** The wearable must be designed for safe long-term use without causing discomfort.
- **Transparency:** Users will be informed about the purpose of auditory stimulation and data handling practices.

Safety

Relevant safety concerns include:

- **Electrical Safety:** The device must comply with standards for medical electrical equipment. This is to ensure safe operation at low voltages and proper battery isolation.
- **Wireless Communication:** BLE/Wi-Fi modules must comply with FCC regulations.
- **Sleep Disruption Risks:** Poorly timed auditory stimulation could negatively affect sleep. Robust algorithm testing and user controls will mitigate this risk.
- **Campus and Federal Regulations:** The device will be developed following UIUC ECE Senior Design Lab safety protocols and consumer electronic safety guidelines.

References

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- Bo-Lin Su et al. (2015). *Detecting slow wave sleep using a single EEG signal channel.*https://pubmed.ncbi.nlm.nih.gov/25637866/
- YASA Sleep Toolbox: https://github.com/raphaelvallat/yasa
- CoSleep Project: https://github.com/Frederik-D-Weber/cosleep