# Acoustic Stimulation to Improve Sleep

By

Bakry Abdalla

Sid Gurumurthi

John Ludeke

Final Report for ECE 445, Senior Design, Fall 2026

TA: Mingrui Liu

13 February 2026

Project No. 18

# Abstract

Poor sleep quality is a common problem often caused by not enough time spent in slow-wave sleep (SWS). Research has shown that closed-loop auditory stimulation can enhance SWS by amplifying the slow-wave oscillations. This project proposes a wearable, cost-effective sleep enhancement device that delivers precisely timed auditory stimulation during sleep. The system consists of an EEG headband with dry electrodes connected to a custom printed circuit board (PCB) integrating the EEG front-end, microcontroller, audio driver, and power management circuitry. The embedded processor continuously monitors brain activity for slow-wave oscillations in real time. Upon detection, the device delivers brief bursts of pink noise synchronized to the phase of the slow waves through an integrated speaker. A phone application is available to provide users with insights into their sleep patterns. We hope the system is able to successfully detect SWS in real time and improve sleep quality as reported by the user.

# Contents

# 1. Introduction

Poor sleep quality affects a large portion of the population, particularly older adults and individuals with sleep disorders, and can be caused by insufficient time spent in slow wave sleep (SWS). Slow waves are high-amplitude, low-frequency oscillations in cortical EEG activity that reflect synchronized neuronal firing and define the deepest stage of non-REM sleep. Slow wave sleep is critical for memory consolidation and cognitive health. While prior research has shown that closed-loop auditory stimulation can enhance SWS by reinforcing brain-produced slow wave oscillations, existing commercial and research-grade solutions remain costly, bulky, or inaccessible to the general public.

This project addresses the engineering challenge of designing a low-cost, wearable, closed-loop sleep enhancement system that reliably detects slow wave sleep using electroencephalography (EEG) and delivers precisely timed auditory stimulation to improve sleep quality. This system integrates an EEG headband, custom signal processing hardware, audio output circuitry, power management, and a user-facing application into a compact and comfortable form factor suitable for overnight use. The device performs real-time EEG acquisition and processing, identifies slow wave oscillations, and delivers short bursts of pink noise in phase with the detected brain activity, reinforcing the slow wave oscillations and sleep.

This report details the design, implementation, and verification of the proposed system. Chapter 2 details the overall system architecture and each subsystem, including the EEG front end, digital signal processing pipeline, audio output mechanism, power delivery circuitry, and user application. Chapter 3 describes methods to verify subsystem and system-level performance. Chapter 4 analyzes the cost of components and labor. Finally, Chapter 5 summarizes the project's goals and discusses considerations further. Overall, the project demonstrates the feasibility of a practical and affordable closed-loop auditory stimulation device for sleep enhancement.

## 1.1 Problem

Poor sleep quality affects a large portion of the population, particularly older adults and individuals with sleep disorders, and is often associated with insufficient time spent in slow wave sleep (SWS). Slow waves are high-amplitude, low-frequency oscillations observed in cortical EEG activity that reflect synchronized neuronal firing and define the deepest stage of non-REM sleep. Adequate time spent in slow wave sleep is critical for memory consolidation, cognitive performance, and overall neurological health.

Prior research has demonstrated that closed-loop auditory stimulation can enhance slow wave sleep by reinforcing endogenous slow wave oscillations through precisely timed acoustic stimuli. However, existing research-grade and commercial systems capable of performing closed-loop EEG-based stimulation are typically expensive, bulky, or require clinical-grade hardware, limiting their accessibility for at-home and long-term use. This creates a need for a wearable, user-friendly system that can perform real-time EEG monitoring and stimulation without the cost and complexity of current solutions.

## 1.2 Solution

This project proposes a wearable, closed-loop sleep enhancement system that detects slow wave sleep using EEG and delivers phase-aligned auditory stimulation to reinforce slow wave activity. The system consists of an EEG headband connected to a custom printed circuit board (PCB) that performs the core functionality of a commercial EEG acquisition platform while also supporting real-time audio output. EEG signals are acquired through dry electrodes, amplified and digitized on-board, and processed in real time to detect slow wave oscillations.

When slow wave activity is detected, the system generates short bursts of pink noise timed to the phase of the oscillation to reinforce it and enhance slow wave sleep. In addition to stimulation, digitized EEG data are transmitted wirelessly to a mobile application, where users can view sleep metrics and historical trends. The system is designed as an integrated, compact, and comfortable device suitable for overnight use, enabling closed-loop sleep modulation outside of a clinical setting.

## 1.3 Visual Aid

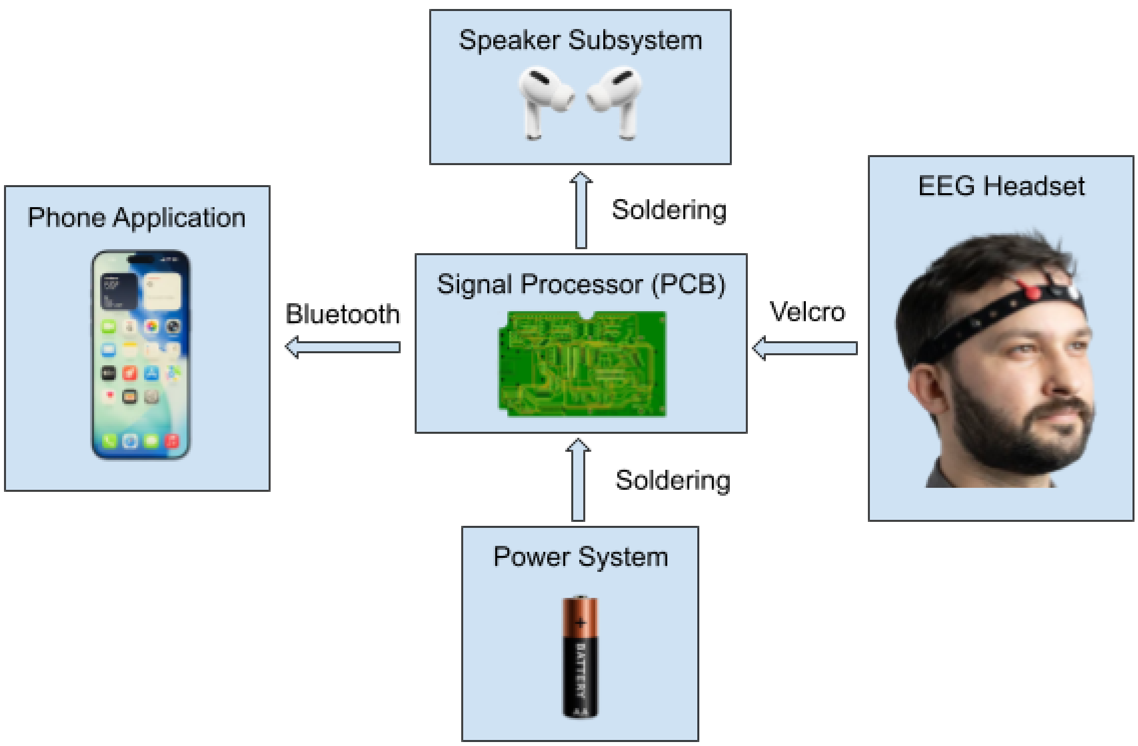


Figure 1. Pictorial representation of the acoustic stimulation system

## 1.4 High-Level Requirements List

The system shall detect slow wave activity in EEG signals in real time with sufficient temporal resolution to deliver phase-aligned auditory stimulation within 300ms.

The device shall operate continuously for a full night of sleep (at least 10 hours) while remaining comfortable and safe for overnight wear.

The system shall wirelessly transmit EEG-derived data to a mobile application, enabling users to view sleep stage information and historical sleep trends.

# 2 Design

## 2.1 Block Diagram

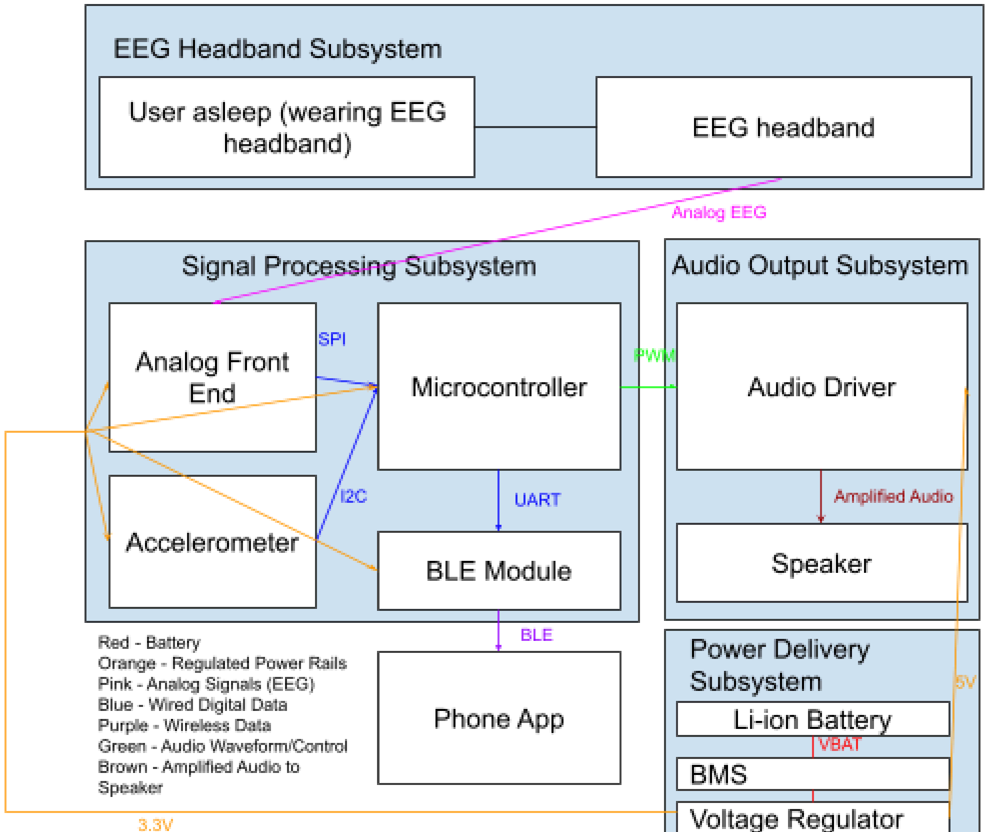


**Figure 2. Block diagram of the system**

## 2.2 Wearable Headband

### 2.2.1 EEG Headband

We will be using a commercially available EEG Headband, the OpenBCI EEG Headband Kit. This includes the headband, electrodes, and cables carrying the analog signal. It will be directly connected to the PCB which has the signal processor, audio system and power systems through velcro.

Requirements: The headband shall be comfortable for most users. Comfort will be evaluated through user testing in which multiple participants wear the device and report whether they would be willing to use it again based on comfort.

### 2.2.2 Signal Processor

The signal processing subsystem performs EEG acquisition, digitization, and real-time analysis, replicating the functional role of a commercial EEG interface such as the OpenBCI Cyton at reduced cost. Differential microvolt-level EEG signals from the headband electrodes, referenced to a common electrode, are first routed to the Texas Instruments ADS1299 analog front end. The ADS1299 provides programmable gain amplification, anti-alias filtering, and high-resolution analog-to-digital conversion. EEG signals are digitized at a minimum sampling rate of 250 Hz with at least 16-bit resolution and transmitted to the microcontroller via an SPI interface.

The microcontroller (PIC32MX250F128B) executes embedded firmware that performs digital signal processing, including bandpass filtering (0.5-4 Hz) to isolate slow-wave activity and notch filtering at 60 Hz to suppress power-line interference. Slow-wave detection and phase estimation are performed in real time to support closed-loop stimulation. Motion data from the LIS3DH accelerometer are acquired over an I2C interface and used to detect large motion artifacts, allowing contaminated EEG segments to be flagged or stimulation to be temporarily inhibited.

Processed EEG samples and extracted features are packetized and transmitted to the BLE module over a UART interface for wireless streaming to the mobile application.

Requirements: The signal processing subsystem must acquire differential EEG signals in the 1-100 µV range and digitize them at a sampling rate of at least 250Hz per channel. The subsystem shall perform real-time digital filtering and slow-wave detection with an end-to-end processing latency of within 300 ms from acquisition to detection output. The subsystem shall transmit EEG data and extracted features to the BLE module for wireless streaming while generating stimulation timing signals with a temporal resolution of ≤ 10 ms.

### 2.2.3 Audio System

The audio output subsystem converts stimulation timing decisions from the microcontroller into precisely timed audible pink noise delivered through a speaker. The microcontroller produces a low-power digital audio waveform (PWM-encoded pink noise) at the desired phase. An audio driver/amplifier stage converts the low-power waveform into a speaker-level signal with sufficient current and voltage swing. This subsystem enables the closed-loop functionality of the system through auditory stimulation.

Requirements: Output noise should be pink noise below 50 decibels.

### 2.2.4 Power system

To provide power for the entire system, a power circuit is integrated into the PCB. This circuit manages battery charging and voltage regulation while minimizing heat dissipation for user comfort.

Requirements: Must be able to supply enough current to the rest of the system continuously at a stable voltage of 5V +/- 0.1V.

## 2.3 Data analysis

### 2.3.1 User-facing Application

To improve usability, the User-Facing Application will give the end user insights into their sleep using standard sleep metrics. Specifically, it will tell the user their time spent not sleeping, in REM sleep, light sleep, and deep sleep.

We can use a React Native frontend for compatibility with Android and iOS. We can run a lightweight ML model on-device with Python to determine the state of sleep (using libraries like FFT and bandpower). For the backend, Firebase can be used to store our data, which will come in via Bluetooth.

The application will follow standard UI/UX practices common in 2026, prioritizing data visualizations for everyday users. Below is a

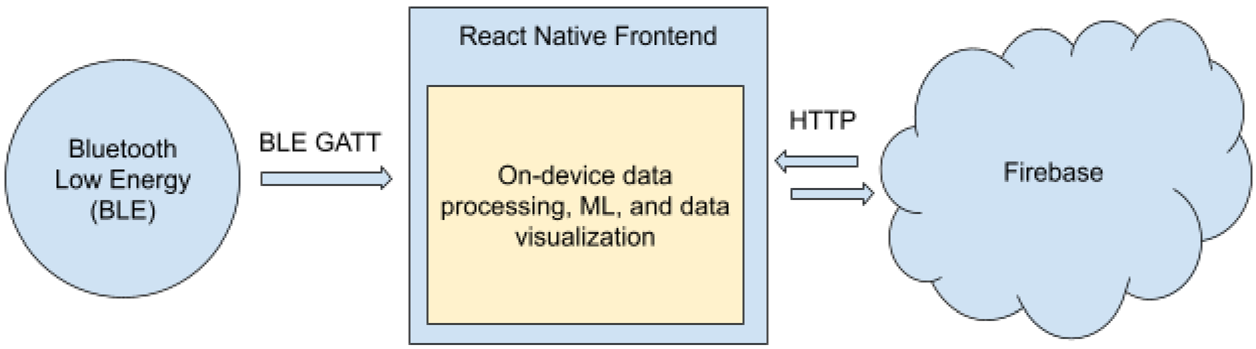


Figure 2 Block diagram of the mobile application.

Requirements: The application should be functional and receive the exact same data that is being collected through the headband.

## 2.4 Tolerance Analysis

The effectiveness of closed-loop auditory stimulation depends on delivering pink noise bursts at a specific phase of the slow-wave oscillation. Variations in signal processing latency, sampling rate, and computational delay may result in phase errors that reduce stimulation efficacy.

Slow-wave sleep oscillations typically occur for a frequency of about 1 Hz. With that assumption:

$$T = 1/f = 1s$$

To maintain effective phase locking, the stimulus must be delivered within ±45° of the target phase, corresponding to a timing tolerance of:

$$\Delta t = 45°/360° \times T = 0.125s$$

The estimated latency consists of EEG sampling delay (~10ms), signal processing (~40ms), microcontroller processing (~20ms) and audio driver latency (~10ms). This is ~80ms in total meaning this requirement should be feasible to satisfy.

# 3. Design Verification

To ensure the proposed system meets all requirements including functionality, performance, and reliability, the following design verification plan will be implemented. Each subsystem will be tested independently to validate correct operation under expected use conditions.

## 3.1 Wearable Headband

The fully integrated wearable headband, composed of the subsystems described below, will be evaluated to verify reliable EEG signal acquisition, correct algorithmic signal processing (see Reference 2), accurate audio delivery, sufficient power management, and overall user comfort.

### 3.1.1 EEG Headband

The EEG headband will be verified by measuring signal quality, electrode impedance, and noise levels under static and motion conditions. Recorded EEG data will be compared against known test signals and reference measurements to ensure accurate detection of brain activity.

### 3.1.2 Signal Processor

The signal processing subsystem will be tested using both simulated and recorded EEG waveforms and compared directly with a known, working signal processor, the OpenBCI Cyton board (see Reference 3).

### 3.1.3 Audio System

The audio subsystem will be verified by measuring output amplitude, frequency, and time delay of the delivered noise stimuli. This is to ensure it is within safe auditory limits, matches the frequency of pink noise, and that it can be delivered in under 300ms in combination with the algorithm that detects SWS. Verification that SWS is detected correctly will be done via comparison with real life data.

### 3.1.4 Power system

The power system will be tested for voltage regulation, current consumption, and battery life under normal operating conditions. Specifically, tests will ensure the voltage remains stable for a minimum of 10 hours and that battery life lasts that amount of time.

## 3.2 Data analysis

### 3.2.1 User-facing Application

The user-facing application will be tested to verify accurate data transfer by comparing with signals collected on the field. Functional testing will ensure correct display of sleep insights and reliable user interaction.

# 4. Costs

## 4.1 Parts

**Table 2 Electronics Parts Costs**

| Part | Manufacturer | Retail Cost ($) | Bulk Purchase Cost ($) | Actual Cost ($) |
|---|---|---|---|---|
| OpenBCI EEG Headband Kit | OpenBCI | 349.99 | 349.99 | 0.00 |
| ADS1299 AFE | Texas Instruments | 47.91 | 32.00 | 47.91 |
| PIC32MX250F128B | Microchip | 5.22 | 3.80 | 5.22 |
| RN4871 BLE module | Microchip | 9.24 | 8.45 | 9.24 |
| LIS3DH Accelerometer | STMicroelectronics | 0.97 | 0.97 | 0.97 |
| TL082CP Op-Amp | Texas Instruments | 1.55 | 1.55 | 1.55 |
| 2.048 MHz Oscillator (C3291-2.048) | Citizen | 2.30 | 1.58 | 2.30 |
| Resistor Pack (COM-10969) | SparkFun | 9.95 | 9.95 | 2.00 |
| Capacitor (75-562R5HKD10) | Vishay | 2.47 | 0.89 | 2.00 |
| Capacitors (330820) | Kemet | 0.14 | 0.07 | 2.00 |
| Speaker AST03008MRR | PUI Audio | 3.67 | 1.86 | 3.67 |
| LM350T Regulator | Texas Instruments | 1.75 | 0.78 | 1.75 |
| AAA Batteries | Energizer | 0.62 | 0.34 | 0.62 |
| On/Off Switch 1MS3T1B1M1QE | Multicomp | 2.85 | 2.10 | 2.85 |
| Power Jack PJ-002A | Same Sky | 0.47 | 0.27 | 0.47 |
| **Total** | | **439.10** | **414.60** | **82.55** |

**Table 3 Software Components Costs**

| Part | Manufacturer | Retail Cost ($) | Bulk Purchase Cost ($) | Actual Cost ($) |
|---|---|---|---|---|
| React Native | Same Sky | 0.00 | 0.00 | 0.00 |
| Firebase | Google | 0.00 | 0.00 | 0.00 |
| FFT / ML Libraries | Open source | 0.00 | 0.00 | 0.00 |
| **Total** | | **0.00** | **0.00** | **0.00** |

## 4.2 Labor

The cost of labor for this project is technically zero dollars, despite the engineering efforts being on-par with the current industry. Rather than being paid a salary with benefits, the students building this project are instead provided with “academic enrichment”.

A *potential* cost of labor which is included in our university tuition could be the faculty in the ECE Department including professors, TAs, CAs, as well as those who maintain the various ECE shops (e.g., machine shop) and oversee ECE supplies.

# 5. Conclusion

## 5.1 Uncertainties

Possible uncertainties include the EEG headband not being seated correctly, durability during sleep, and function of each subcomponent.

## 5.2 Ethical considerations

This project involves a wearable EEG-based device that monitors brain activity and delivers auditory stimulation during sleep. Because it interacts with users' physiological signals and sleep behavior, ethical considerations related to safety, privacy, transparency, and responsible use are important.

### 5.2.1 User Safety and Welfare

The system is designed to be non-invasive and low-risk, using dry EEG electrodes and low-voltage battery-powered electronics. Audio stimulation levels are constrained to remain within safe listening thresholds to avoid hearing damage or negative sleep disturbance. The device is not intended to diagnose or treat medical conditions, and all documentation and user-facing materials will clearly state that it is a prototype research device and not a certified medical product. This avoids misleading users or encouraging unsafe medical reliance.

### 5.2.2 Data Privacy and Security

The device collects EEG-derived data and sleep metrics, which qualify as sensitive biometric information. Ethical handling of this data requires minimizing collection to only what is necessary, using secure wireless transmission, and storing data in protected application storage. If cloud services are used, access controls and encryption should be enabled. Users should be informed what data is collected and how it is used. No data should be shared with third parties without explicit consent.

### 5.2.3 Transparency and Informed Use

Consistent with IEEE and ACM ethical principles, the system should be described accurately with no exaggerated claims about performance or health benefits. Users must be informed about limitations in sleep-stage detection accuracy and stimulation effectiveness. Known uncertainties and error rates should be disclosed so users can make informed decisions about use.

### 5.2.4 Bias and Performance Limitations

Sleep detection algorithms may perform differently across users due to physiological variability, electrode placement, or noise. Ethical deployment requires acknowledging that performance may not generalize equally to all users and avoiding claims of universal effectiveness. Future validation across diverse users is recommended.

### 5.2.5 Standards and Professional Responsibility

The design approach follows general IEEE and ACM codes of ethics by prioritizing user safety, honest reporting of results, protection of user data, and clear communication of limitations. Electrical design practices follow low-voltage wearable device norms and standard PCB safety practices to reduce risk of shock, overheating, or short circuits.

## 5.3 Future work

While the current version is expected to cost just about $400 (80% of which comes from the OpenBCI EEG Headband Kit). We reasonably believe that this headband could be made from scratch with commercially available materials for at least 50% the cost, especially since we aren’t using the full kit. This would also allow for more custom integration of our PCB into the headband, making the product more comfortable to wear as well.

## References


[1] OPENBCI EEG HeadBand Kit. Available at: https://shop.openbci.com/products/openbci-eeg-headband-kit

[2] B. L. Su, Y. Luo, C. Y. Hong, M. L. Nagurka, and C. W. Yen, “Detecting slow wave sleep using a single EEG signal channel,” Journal of Neuroscience Methods, vol. 243, pp. 47–52, Mar. 2015, doi: 10.1016/j.jneumeth.2015.01.023.

[3] OPENBCI CYTON Board. Available at: https://shop.openbci.com/collections/frontpage/products/cyton-biosensing-board-8-channel?variant=38958638542&_gl=1*133cm45*_gcl_au*MTg1NjQ1ODIxOC4xNzY5NTU4NDE5*_ga*NjMyODg4MTYzLjE3Njk1NTg0MTk.*_ga_HVMLC0ZWWS*czE3NzAzNTAwMzEkbzQkZzEkdDE3NzAzNTAwNDMkajQ4JGwwJGgw

[4] IEEE, IEEE Code of Ethics, Institute of Electrical and Electronics Engineers. Available: https://ieee-cas.org/about/ieee-code-ethics.

[5] ACM, ACM Code of Ethics and Professional Conduct, Association for Computing Machinery. Available: https://www.acm.org/code-of-ethics.