16-Channel EEG Monitor – Cortex Design Hardware Design Challenge Final Submission

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1.0 INTRODUCTION

The advent of home-based health monitoring systems has opened new vistas for patient care, offering unprecedented convenience and empowerment to users managing neurological conditions. This document presents a detailed proposal for an innovative 16-channel EEG monitoring device, specifically engineered for home use without compromising on the clinical quality of EEG data. By leveraging cutting-edge technology to ensure secure and efficient transmission of raw EEG data to cloud platforms, our device is designed to meet the stringent demands of modern healthcare. Furthermore, it addresses crucial aspects such as cost-effectiveness, user experience, and reliability. Through a holistic approach to design and functionality, I aim to deliver a solution that not only fulfills clinical needs but also enhances the overall user journey, ensuring that advanced neurological monitoring is both accessible and practical for everyday use.

2.0 SYTEM DIAGRAM

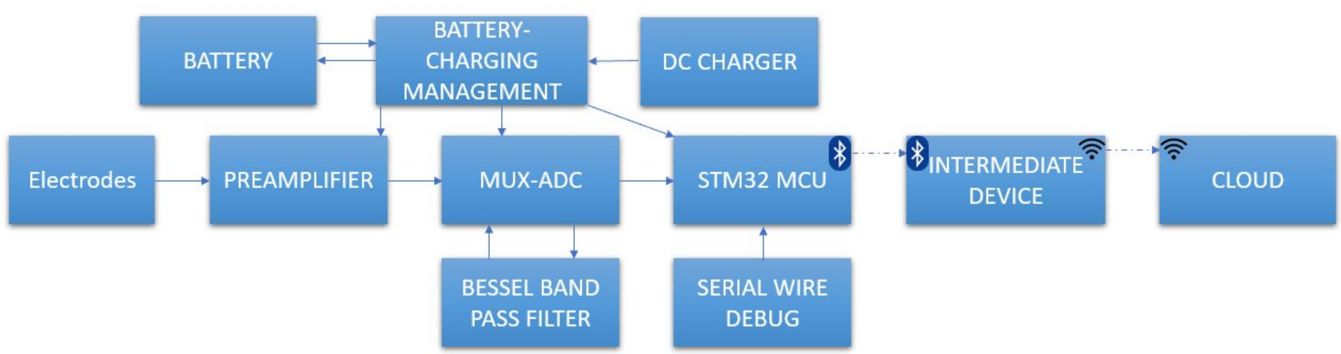

Figure 1: System Diagram

The system diagram delineates the flow of EEG data collection and processing in the 16-channel EEG monitor designed for home use. Initially, signals are captured by dry sintered electrodes, chosen for their convenience and clinical-quality signal acquisition without the need for gels or extensive preparation. These raw signals are then immediately amplified by a dedicated preamplifier for each electrode, ensuring the integrity and amplification of the low-amplitude EEG signals ranging from 0.1 Hz to 100 Hz. Subsequently, the amplified signals are directed to a MUX-ADC unit. This unit integrates a multiplexer (MUX) and an analog-to-digital converter (ADC), alongside a Bessel band-pass filter, to selectively condition, digitize, and filter the EEG signals, allowing for precise extraction of the relevant frequency components. The processed data is then relayed to an STM32 microcontroller unit (MCU) equipped with integrated Bluetooth 5.3 technology, enabling efficient and secure wireless transmission to an intermediate device, such as a smartphone or a workstation. This intermediate device performs additional data cleaning and analysis before securely uploading the refined EEG data to the cloud platform for storage and further analysis. This system design prioritizes cost-effectiveness, signal integrity, and user experience, making clinical-grade EEG monitoring accessible for home users.

3.0 DECISION RATIONALE

3.1 Cost

- **Dry Sintered Electrodes**: Chosen for their user-friendliness and comfort, making them ideal for home use. They require no gel or skin preparation, reducing setup time and improving user experience. Their high-quality material and construction provide reliable signal quality, essential for clinical-grade EEG readings.
- **One Preamplifier per Electrode**: Necessary to boost the EEG signals, which are inherently low in amplitude (0.1 Hz to 100 Hz), right at the source. This minimizes noise and interference before the signal travels through the system, ensuring the fidelity and cleanliness of the EEG data for accurate analysis.
- **MUX-Integrated ADC**: A cost-saving strategy without sacrificing functionality. This integrated approach reduces the need for separate multiplexer (MUX) and analog-to-digital converter (ADC) components, lowering both the cost and complexity of the circuit. It efficiently handles multiple channels of EEG data, facilitating the selection and conversion of these signals in a seamless manner.
- **Shared Active Band Pass Filter**: To maintain budget constraints while still ensuring quality data, a shared active band-pass filter strategy was implemented. Positioned after the MUX but before the ADC, this design choice allows for signal conditioning of all channels without the need for individual filters per electrode, balancing cost and data integrity.
- **STM32 MCU with Integrated Bluetooth 5.3**: Selected for its cost-effectiveness and robust features that support clean and secure data transmission. The integrated Bluetooth provides a high-bandwidth link to an intermediate device, eliminating the need for direct cloud connection hardware and further reducing costs.
- **Intermediate Device for Data Post-Processing**: Utilizes a mobile or workstation application for additional data cleaning and secure cloud transmission. This step ensures that the EEG data is both accurate and protected, enhancing user trust and data reliability. It allows for sophisticated processing that can be updated or changed without altering the hardware, adding flexibility to adapt to future needs.

This configuration has been carefully chosen to strike a balance between cost efficiency, user convenience, and the need for reliable, clean, clinical-grade EEG data in a home-use production and process with post-processing to clean the data even more before sending the data to a cloud platform. The final cost of the device comes to **184.40 USD** (before tax), below the required cost of 200 USD.

3.2 Data integrity

- **Dry Electrodes**: Selection based on reducing cost and complexity. Dry electrodes eliminate the need for conductive gels or pastes, streamlining the setup process and enhancing user comfort for home use. Despite their simplicity and lower cost, they are designed to maintain sufficient signal quality, minimizing noise and artifacts that could compromise data integrity. This choice aligns with the goal of making clinical-grade EEG monitoring more accessible and less burdensome for users.
- **Analog Front End (AFE) Design**: Incorporating a carefully designed AFE that includes preamplifiers, active Bessel band-pass filters, and a high-resolution ADC.
  - **Preamplifiers**: Essential for boosting the EEG signals right at their source, as these signals are characteristically low in amplitude (0.1 Hz to 100 Hz). Amplifying the signals before they traverse through any significant length of the system helps minimize the potential for noise insertion and signal degradation, ensuring the captured signals remain as clean as possible.
  - **Active Bessel Band-Pass Filter**: Selected for its phase-linear characteristics, minimizing phase distortion across the EEG signal's frequency spectrum (crucial for maintaining the wave shape of EEG signals). This choice supports the clinical requirement for unaltered, clean EEG waveforms, allowing for accurate diagnosis and analysis. The active filter design also offers flexibility in tuning the filter characteristics to precisely match the EEG signal bandwidth, effectively reducing unwanted frequency components outside the interest range.
- **MUX-Integrated ADC**: By integrating the multiplexer (MUX) with the ADC, the design not only saves space and cost but also reduces the complexity of the signal pathway. This integration facilitates efficient channel switching and signal conversion, allowing for high-resolution digitization of multiple EEG channels without the need for separate components. A high-resolution ADC ensures that the EEG signals are sampled accurately, preserving the fidelity of the signals for clinical analysis.
- **Shielded Cabling for Electrodes**: Implementing shielded cabling minimizes electromagnetic interference (EMI) and environmental noise that could corrupt the EEG signals as they are transmitted from the electrodes to the AFE. This practice is key in maintaining the signal integrity of low-amplitude EEG signals over the physical connection distance.
- **Differential Signal Acquisition**: Utilizing differential signal acquisition techniques on the PCB design serves to further enhance noise resistance. By measuring the difference between two closely related signals (one being the inverse of the other), common-mode noise — which affects both signals similarly — can be effectively canceled out. This technique is invaluable in preserving the quality of EEG signals amidst the potential for electrical noise within the device environment or from external sources.

These decisions collectively contribute to a system designed to meet the dual objectives of cost-effectiveness and adherence to clinical standards for EEG data. By thoughtfully selecting each component and technique, the design prioritizes data integrity and user experience, ensuring that users receive accurate and reliable EEG monitoring in a home setting. This approach not only makes advanced neurological monitoring more accessible but also stands as a testament to the feasibility of achieving medical-grade data acquisition within constrained budgets.

3.3 Usability

- **Wearable Design for Home Use**: The device's wearable format ensures ease of use and flexibility for the user, allowing continuous monitoring without restricting daily activities. This design choice reflects an understanding of the importance of user convenience and the need to integrate seamlessly into the user's lifestyle, making it ideal for home use.
- **Dry Electrodes**: Chosen to reduce setup complexity and enhance user comfort, dry electrodes do not require conductive gel or skin preparation, significantly simplifying the application process. Their use maintains data integrity, ensuring the device collects clinically relevant EEG data while prioritizing user experience by eliminating the messiness and discomfort associated with gel-based electrodes.
- **Battery Powered**: By designing the device to be battery-powered, users are freed from the constraint of being tethered to a wall outlet, enhancing mobility and convenience. This consideration is crucial for a device intended for continuous, long-term monitoring, as it allows users to engage in their daily activities unimpeded by cables, ensuring consistent data collection.
- **Compact and Lightweight**: The compactness and light weight of the device contribute significantly to wearability and comfort, crucial factors for a device designed for prolonged use. A non-intrusive, comfortable device is more likely to be used consistently, improving data collection quality and user compliance.
- **Simple Interface with Single Button Operation**: A simplistic user interface, featuring just a single button for turning on and initiating Bluetooth connection, minimizes the learning curve and potential user frustration. This design decision caters to a broad user base, ensuring ease of use regardless of technological proficiency.
- **Bluetooth Connectivity**: The inclusion of Bluetooth for data transmission allows for the seamless transfer of data to an external mobile device or workstation. This wireless connectivity enhances user convenience, enabling real-time monitoring and analysis of EEG data without the need for physical cables and enabling users to easily share data with healthcare providers.

- **Rigorous Power Supply Safety Regulations**: Adhering to stringent safety regulations for the power supply, including proper insulation, voltage, and current limits, ensures the device operates within safe parameters. This not only protects the user from potential electrical hazards but also underscores the device's reliability and trustworthiness as a medical-grade tool for home use.

Each of these design decisions has been made with the dual goals of ensuring user safety and enhancing the overall usability of the device. By focusing on wearability, simplicity, and safety, the device is positioned as a user-friendly, effective solution for home-based EEG monitoring, promising to deliver clinical-grade data with convenience.

3.4 Data transmission protocol

- **High Data Volume from 16 EEG Channels**: The system is designed to collect data from 16 EEG channels simultaneously, with each channel sampled at 250 samples per second. With a resolution of 24 bits per sample, this setup generates a substantial amount of data, totaling 96,000 bits per second (96 kbps). This high data volume necessitates a robust data transmission protocol capable of handling such bandwidth efficiently and reliably.
- **Bandwidth Requirements Met by STM32WB55xx MCU**: After analyzing the data bandwidth requirements, the STM32WB55xx MCU was identified as the optimal choice. This MCU, with its support for Bluetooth Low Energy (BLE) 5.3, provides a maximum theoretical data transmission rate of up to 2 Mbps. In practical applications, even after accounting for protocol overheads and real-world conditions, an effective data rate of 1 Mbps is achievable. This capability far surpasses the 96 kbps needed to transmit the raw EEG data from 16 channels, ensuring that the system can handle the required data volume with ease.
- **Advantages of BLE 5.3 for EEG Data Transmission**: BLE 5.3 was chosen for several compelling reasons:
    - **Low Energy Consumption**: Critical for wearable devices, especially those intended for continuous health monitoring, the low energy profile of BLE 5.3 ensures that the device can operate for extended periods on a single battery charge. This aspect is crucial for user compliance and uninterrupted data collection.
    - **High Data Rate Capacity**: The ability of BLE 5.3 to support data rates effectively up to 1 Mbps allows for the transmission of high-fidelity EEG data in real-time. This ensures that detailed neural activity is captured and transmitted without loss of information, vital for accurate clinical analysis.
    - **Secure Data Communication**: Given the sensitivity of EEG data, BLE 5.3's enhanced security features, including encryption and secure connections, protect against unauthorized access and ensure patient data privacy.

  - **Reliable Connectivity**: BLE 5.3 incorporates mechanisms such as adaptive frequency hopping to minimize interference from other wireless devices in the environment, promoting stable and reliable connections. This reliability is essential for medical devices where continuous data collection is critical.
- **Compatibility with Consumer Devices**: The widespread support for BLE across modern smartphones, tablets, and computers means that the EEG data collected by the device can be easily transferred to and visualized on these platforms. This compatibility facilitates seamless integration with existing user devices, enhancing the overall user experience by allowing for straightforward monitoring, analysis, and sharing of health data with healthcare providers.

The choice of the STM32WB55xx MCU and BLE 5.3 for this application succinctly addresses the challenges of transmitting multiple channels of EEG data in a wearable context. It strikes an optimal balance between bandwidth, energy efficiency, security, and user convenience, thereby ensuring that the device not only meets but exceeds the requirements for home-based clinical EEG monitoring.

3.5 Data security

Data security listed below is a strategy to enhance product cyber security and not implemented on the hardware but in the firmware.

- **Integrated AES-256 Encryption**: For data at rest and in transit, Advanced Encryption Standard (AES) with a 256-bit key is implemented. This level of encryption ensures that EEG data is protected by one of the most secure encryption standards available, making it virtually impervious to brute force attacks while maintaining a balance between security and performance.
- **End-to-End Encryption (E2EE)**: From the device to the cloud, data is encrypted end-to-end. This means that data is encrypted at the source (the EEG device) and remains encrypted as it travels through and arrives at the destination (cloud storage or healthcare providers), ensuring that only authorized parties can decrypt and access the sensitive EEG data.
- **Secure Key Exchange using ECDH (Elliptic Curve Diffie-Hellman)**: For setting up secure communication channels, ECDH is used for key exchange. This method allows both the sender and receiver to securely generate a shared secret key for encryption and decryption, preventing man-in-the-middle attacks during the initial handshake and key exchange process.
- **Periodic Key Rotation Policy**: To further enhance the security posture, a periodic key rotation policy is implemented. This policy ensures that encryption keys are changed and updated at regular intervals, reducing the window of opportunity for potential unauthorized access and keeping the data security dynamic and robust.
- **Regular Firmware Updates and Security Patches**: The device supports over-the-air (OTA) firmware updates to ensure that the latest security patches and enhancements can be applied

promptly. Regular updates help in safeguarding against emerging vulnerabilities and maintaining the device's defense against new threats.

- **Compliance with Health Data Protection Regulations**: The design and implementation of the data security strategy comply with relevant health data protection regulations such as HIPAA (Health Insurance Portability and Accountability Act) in the U.S., or GDPR (General Data Protection Regulation) in the EU, ensuring legal adherence in handling sensitive health data.

These strategic decisions in data security are aimed at ensuring the highest level of protection for EEG data collected by the device. While focusing on strong encryption and secure data handling practices, the approach remains mindful of the need for system performance and user experience, providing a secure yet efficient solution for home-based EEG monitoring.

3.6 User experience

Leveraging an intermediate device, such as a mobile phone, tablet, or PC, for user interaction with the EEG monitor presents several advantages that enhance user experience while adhering to cost and usability requirements. This approach is driven by the following considerations:

- **Superior Computing Power**: Mobile devices typically possess higher processing capabilities compared to standalone EEG monitors, especially within the constraints of a low-cost, home-use device. By offloading data processing, visualization, and analysis tasks to the mobile device, users can benefit from more sophisticated and responsive applications, enhancing the quality of interaction and overall experience.
- **Intuitive User Interfaces**: Modern mobile devices offer rich, intuitive user interfaces and are equipped with advanced display technologies. This makes them ideal platforms for developing user-friendly applications that can display complex EEG data in an accessible and understandable manner. Utilizing these devices for user interaction allows for the creation of more engaging and visually appealing applications without the need to incorporate expensive display components on the EEG monitor itself.
- **Enhanced Connectivity Options**: Mobile devices offer comprehensive connectivity options, including cellular data, Wi-Fi, and Bluetooth, facilitating seamless data synchronization and sharing. This connectivity enables easy and secure uploading of EEG data to cloud platforms for storage, further analysis, or sharing with healthcare providers. It also supports remote monitoring capabilities, allowing users or healthcare providers to access EEG data in real-time from any location.
- **Cost Efficiency**: By shifting the burden of user interaction to mobile devices, the EEG monitor can remain focused on its core function of accurate and reliable data collection, without the need for expensive hardware upgrades to support advanced user interface features. This

decision significantly contributes to keeping the overall device cost within the targeted budget, making the technology more accessible to a wider range of users.

- **Ecosystem and Compatibility**: Mobile devices operate within well-established ecosystems offering a wealth of development tools, libraries, and support. Developing applications within these ecosystems facilitates faster development cycles, better security, and ensures compatibility across different devices and operating systems, offering a flexible solution that can adapt to the user's preference of the intermediate device.
- **Scalability and Updates**: Software applications on mobile devices can be easily updated to introduce new features, improve performance, or fix bugs. This scalability ensures that the EEG monitoring system can evolve over time, improving user experience and adding functionalities without the need for hardware modifications.
- **Personalized Experience**: Mobile applications can be designed to offer personalized settings, reminders, and insights based on the user's interaction and data, providing a tailored experience that can better engage and motivate users in their health monitoring activities.

Overall, integrating an intermediate mobile device into the EEG monitoring system offers a pragmatic and effective solution to enhance user experience, ensure cost-effectiveness, and leverage the advanced capabilities of current consumer technology. This strategy effectively bridges the gap between the need for affordable, home-use EEG monitoring and the desire for a sophisticated, user-friendly interface.

3.7 Method of Functional Verification

Verifying the performance and integrity of an EEG device is crucial to ensure that it reliably captures and transmits accurate EEG data suitable for clinical or health-monitoring purposes. Here's a detailed rationale for the verification strategies mentioned:

- **Oscilloscope for Signal Verification**:
  - **Why**: An oscilloscope is an essential tool for visualizing and analyzing the electrical signals as they pass through various components of the EEG device. It allows engineers to observe the waveform characteristics of the EEG signal in real-time, making it possible to identify any distortion, noise, or signal loss that occurs throughout the signal conditioning process (including amplification, filtering, and digitization stages).
  - **How**: By probing different points in the signal path, from the electrode inputs through the analog front end (AFE), and up to the output of the microcontroller unit (MCU), engineers can ensure each subsystem performs as expected. This includes verifying the efficacy of the analog-digital conversion process and the integrity of the signal post-conditioning.
- **Software Testing for Data Transmission**:

  - **Why**: Once the EEG signal is processed and ready to be transmitted, software tests play a critical role in ensuring that the digital signal is accurately sent from the MCU to the intermediate device without data loss. This step is critical for maintaining the integrity and reliability of the EEG data.
  - **How**: Automated software tests can simulate the sending and receiving of data packets, measuring packet integrity, verifying data rates, and confirming the reassembly of the signal on the receiving end. This helps in detecting any discrepancies or errors in the data transmission process, ensuring that the system meets its requirements for data fidelity and transmission latency.
- **Cybersecurity Verification**:
  - **Why**: Given the sensitive nature of EEG data, ensuring the security of data transmission is paramount. Cybersecurity verification methods, such as penetration testing or conducting man-in-the-middle (MITM) attack simulations, are critical for identifying vulnerabilities in the device's security mechanisms.
  - **How**:
    - **Penetration Testing**: Ethical hackers simulate attacks on the device and its communication channels to identify potential vulnerabilities that could be exploited by malicious entities. This helps in strengthening the device's defenses against unauthorized access and data breaches.
    - **Man-in-the-Middle Testing**: Simulating MITM attacks specifically tests the security protocols and encryption methods used during data transmission. Verifying that these attacks are successfully thwarted confirms the effectiveness of the device's encryption and secure communication protocols.

By combining these verification strategies, developers can ensure the EEG device operates accurately, reliably, and securely. The oscilloscope allows for a detailed examination of the signal integrity at a hardware level, software testing confirms the robustness of data transmission algorithms, and cybersecurity verification methods ensure the protection of sensitive data against digital threats. Together, these approaches provide a comprehensive verification framework that underpins the device's suitability for its intended health monitoring or clinical application.

4.0 BILL OF MATERIAL

The Bill of Material can be found in the attached Excel worksheet.

5.0 PCB DESIGN AND SCHEMATIC

PCB design and Schematic can be found in the attached folder, under:

- 16-CHANNEL-EEG-SCH.pdf
- 16-CHANNEL-PCB.pdf

There are other PCB files worth checking out as well such as the 3D PCB file. Here are the preview of the files:

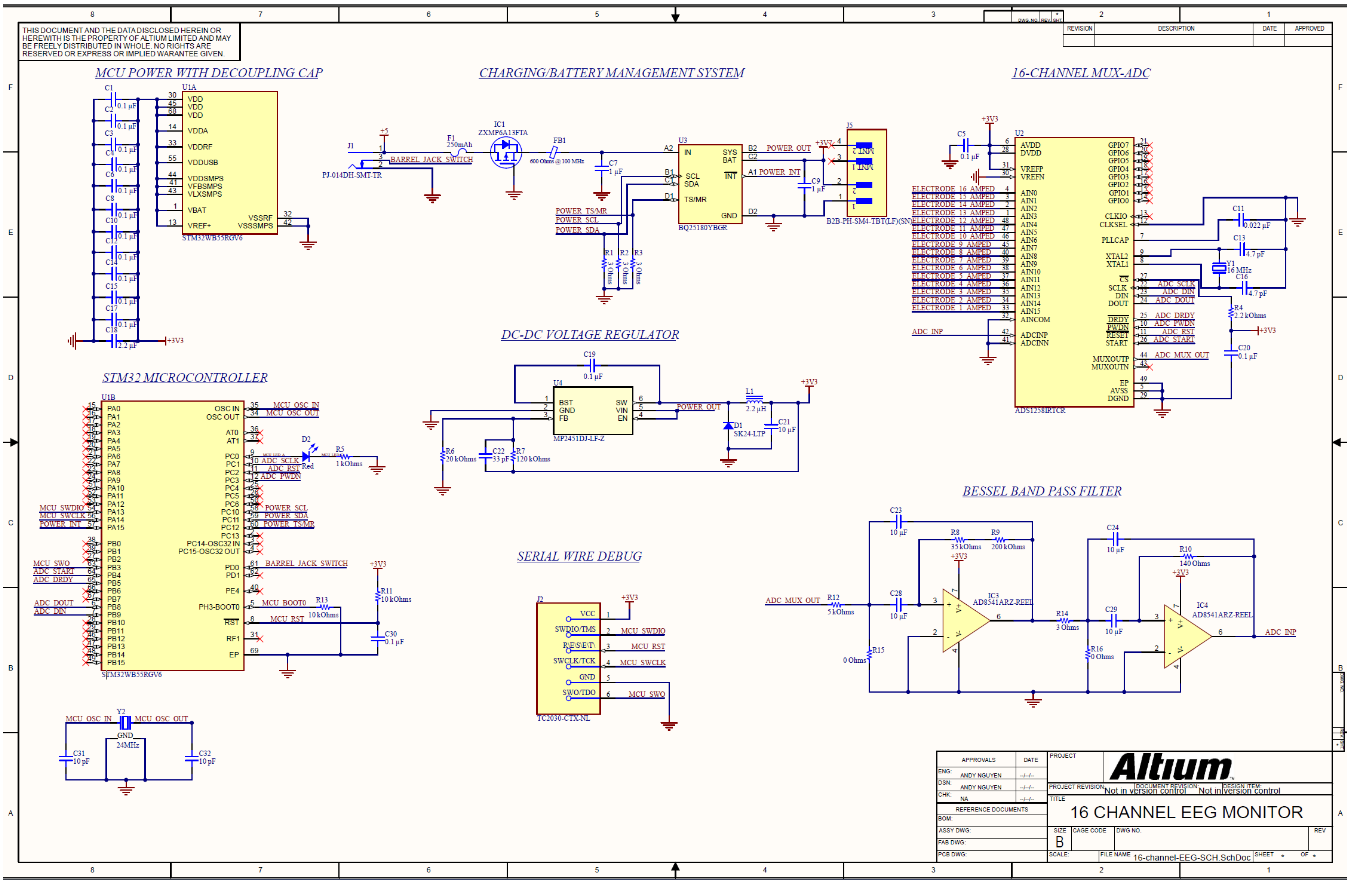

Figure 2: System Schematic - sheet 1

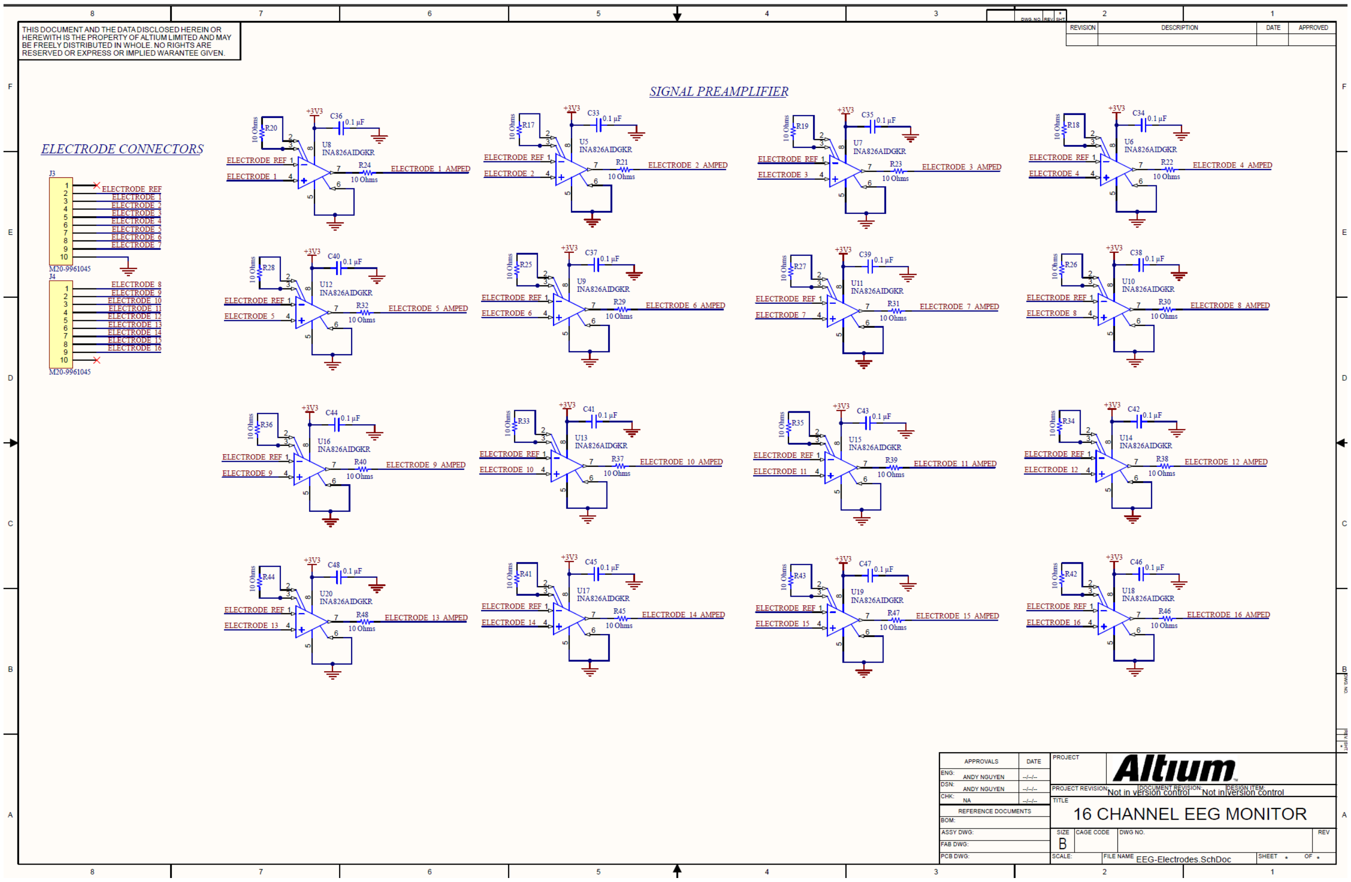

Figure 3: System Schematic - sheet 2

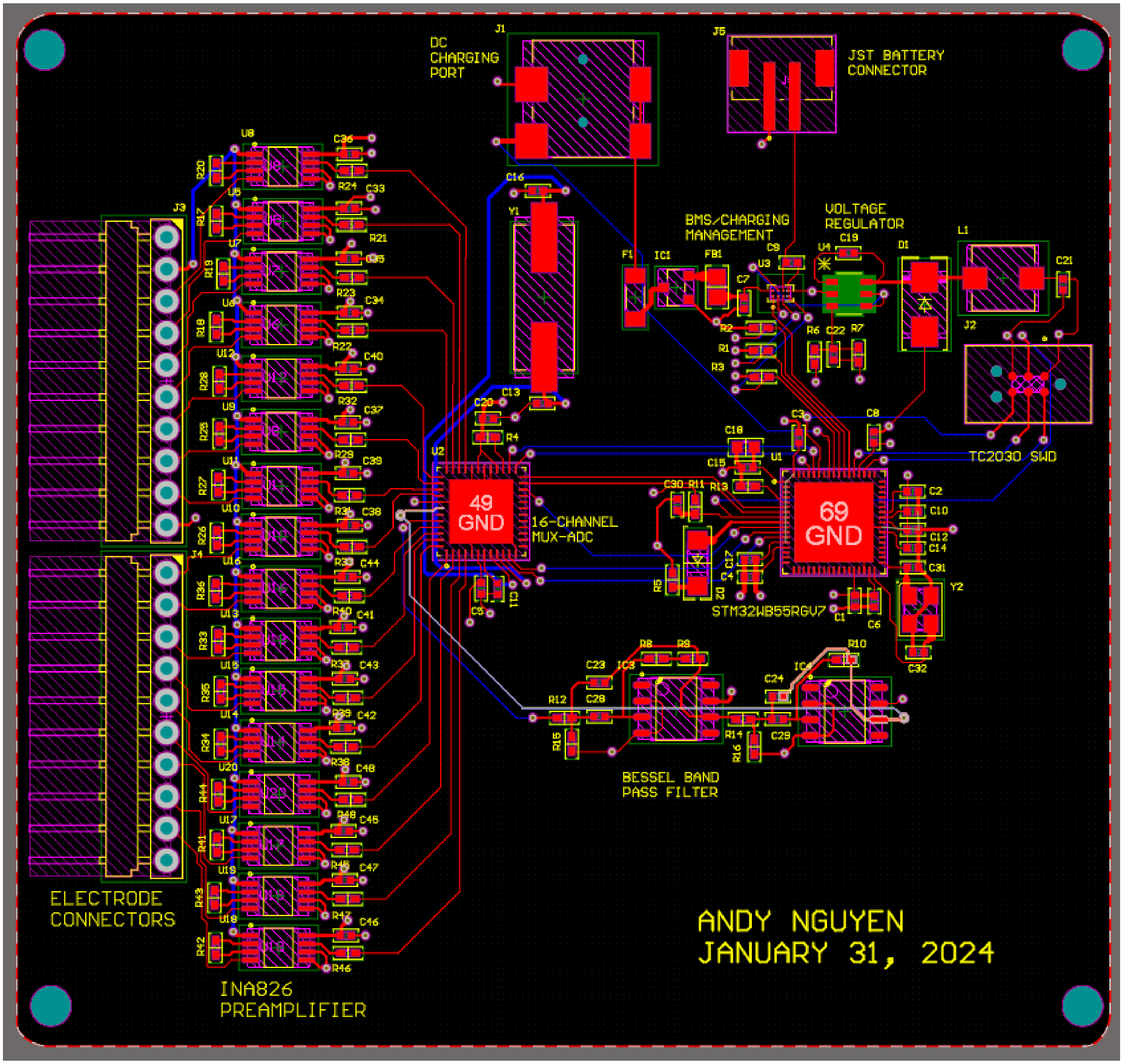

Figure 4: System PCB routing details preview

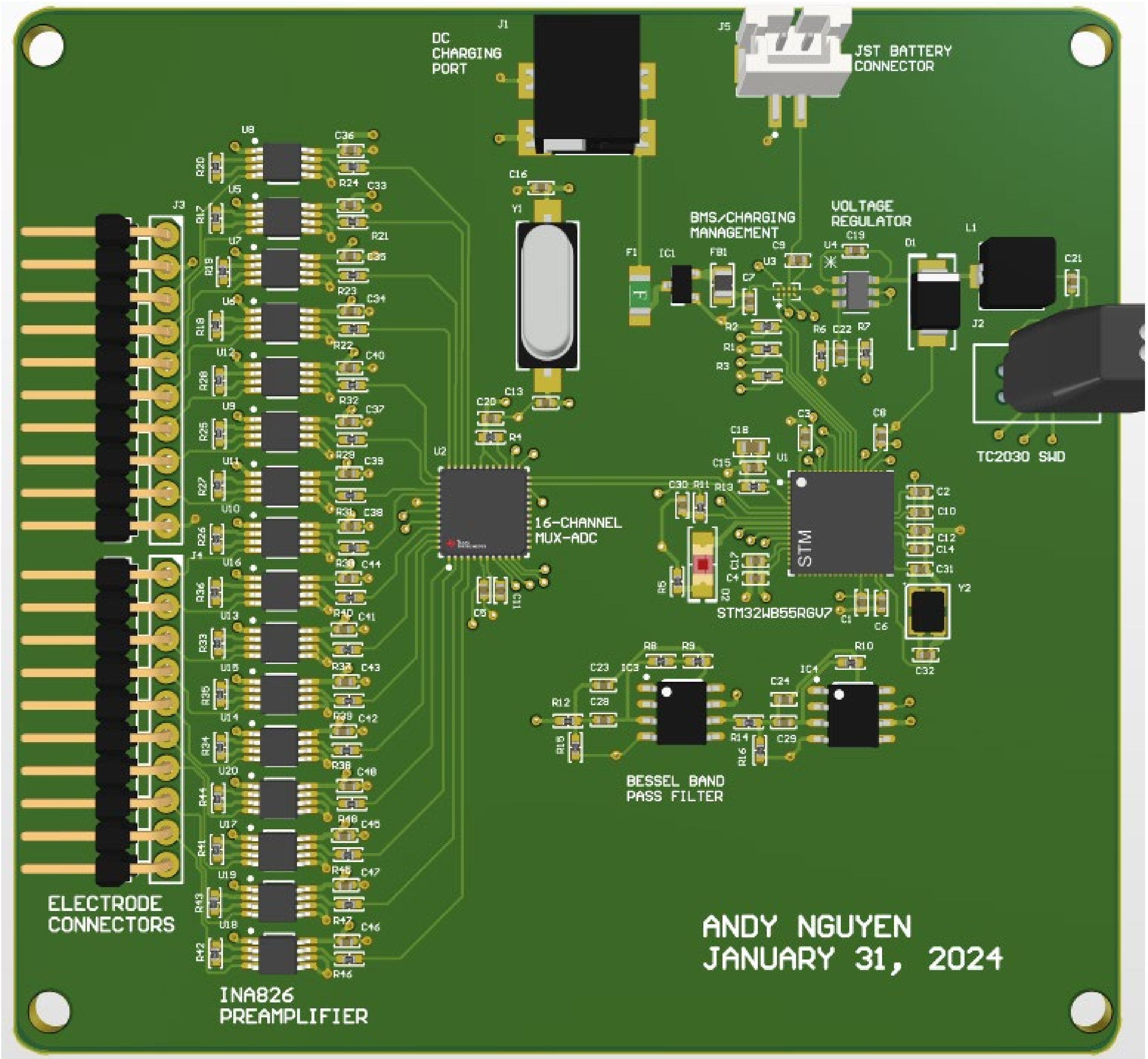

Figure 5: System 3D PCB preview

6.0 FIRMWARE ARCHITECTURE

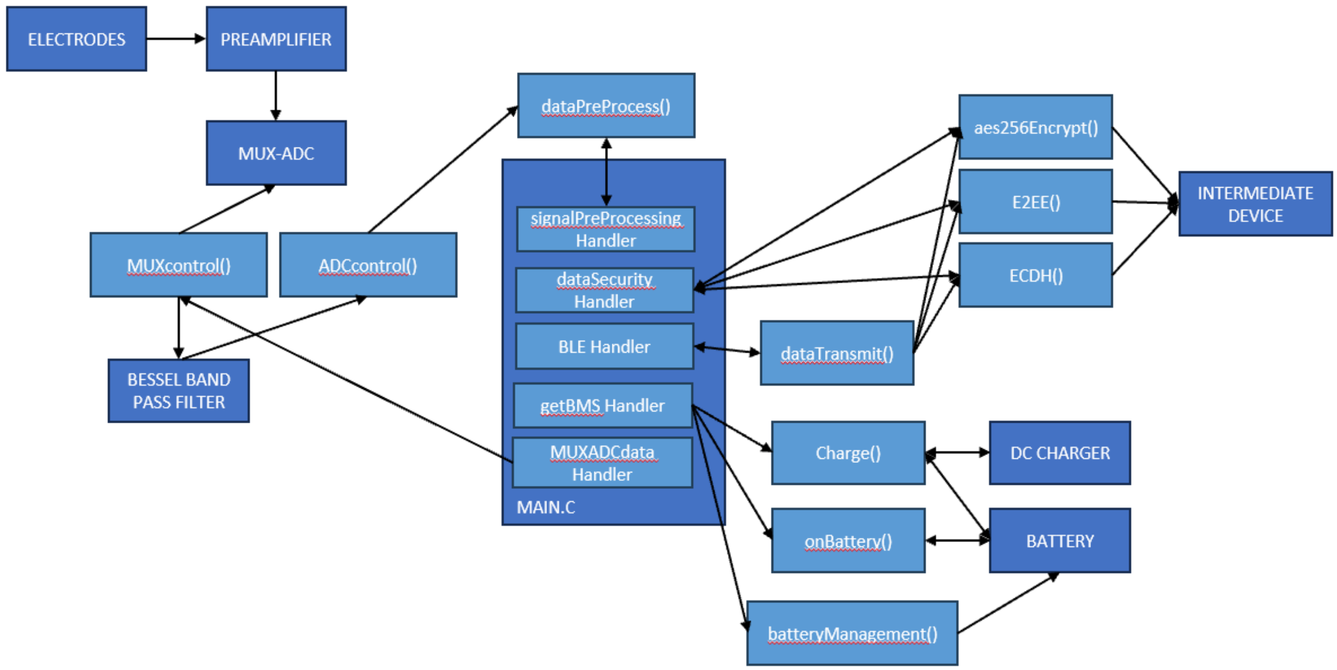

Figure 6: System Firmware Architecture

The proposed firmware architecture for this device is designed to ensure optimal performance, security, and user experience. The architecture encompasses several key modules, each tailored to meet the specific needs of a sophisticated EEG monitoring system:

- **Signal Processing Module:** This crucial module is responsible for the real-time processing of EEG signals. It employs algorithms for filtering, amplification, and artifact rejection, ensuring that the output data meets clinical standards. The focus is on accuracy and integrity, crucial for reliable EEG analysis.
- **Data Security Module:** In recognition of the sensitivity of EEG data, this module provides robust security measures. It features encryption methodologies to secure data both in transit and at rest, adhering to global data protection standards.
- **Bluetooth Data Transmission Control Module:** This component manages the transmission of EEG data to external devices through Bluetooth connectivity. Optimized for efficiency, it ensures data is sent reliably while conserving battery life. It supports real-time data sharing with minimal latency, enhancing the device's usability in clinical and home settings.
- **Battery-Charger Management System:** Understanding the importance of device autonomy, this system oversees battery status and charging processes. It ensures the device remains powered

and operational, integrating smart energy management strategies to prolong battery life without compromising performance.

- **MUX-ADC Control Module:** Central to data acquisition, this module controls the Multiplexer (MUX) and Analog-to-Digital Converter (ADC), crucial for converting analog EEG signals into digital form. Its precise operation guarantees high-fidelity signal capture, a cornerstone of accurate EEG monitoring.
- **Integration with FreeRTOS:** At the core of the firmware lies FreeRTOS, a leading real-time operating system chosen for its reliability and flexibility. FreeRTOS facilitates efficient task management, event scheduling, and resource allocation, ensuring smooth operation of concurrent processes. This integration enhances the device's responsiveness and scalability, accommodating future enhancements effortlessly.

7.0 Conclusion

In conclusion, I am profoundly grateful for this opportunity to showcase my skill set and expand my knowledge in the realm of EEG monitoring devices. The journey through this challenge has been immensely educational, providing me with valuable insights into the complexities and nuances of developing a state-of-the-art EEG monitoring system. I have learned a great deal about the intricate balance between technology, user experience, and data security, further enriching my expertise in this field. This experience has not only allowed me to apply my existing skills but has also spurred me on to explore new areas of research and development in EEG technology.