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Supplementary Materials

A Novel Battery-Supplied AFE EEG Circuit Capable of Muscle Movement Artifact Suppression

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General Note

The References presented in supplementary materials has the same numbering sequence with the ones that are located in the main body of the article.

Supplementary Materials "SA"

This section provides supplemental information for an in-depth introduction to the domain of EEG circuit design techniques and requirements, the nature of the EEG signals and artifacts as well as additional information about the subcomponents of a Generic EEG circuit Template.

EEG plays a vital role in patient real-time monitoring due to its non-invasive nature in tracking brain activity. For the purpose of diagnosing neurological disorders, evaluating cerebral functioning, measuring the effectiveness of therapy, tracking the course of the disease, and providing prognostic insights, high temporal resolution is crucial. It additionally functions well as a monitoring tool during surgery and can be easily integrated with other methods such as fMRI and fNIRS.

The detail of classification of brainwave signal and their characteristics is presented in the Table SA.1

Table SA1. EEG Signals Categorization by Significance and Key Topics.

Frequency Band	Significance	Key Topics
Delta (0.5-4 Hz)	Deep Sleep, Unconsciousness	Basics and Beyond, Significance in Sleep and Memory, Methods, and Applications
Theta (4-8 Hz)	Creativity, Meditation, Drowsiness	Bridging Consciousness, Thalamic Origins, Practical Insights
Alpha (8-13 Hz)	Relaxation, Calmness, Decreased Attention	Indicators of Visual Activation, Enhancing Techniques and Benefits
Beta (13-30 Hz)	Active Thinking, Focus, Anxiety	Association with Alertness, Analysis to Application
Gamma (30-100 Hz)	Higher Mental Activity, Perception, Consciousness	Cognitive Functions, Exploring High-Frequency Bands

Table SA.2 provides an overview of the noises that contaminate the EEG signals and their characteristics, impact and mitigation measures [10, 11].

Table SA2. Noise Interference in EEG Signal Acquisition.

Type of Noise	Frequency Range	Source/Characteristics	Impact on EEG Signal	Mitigation Measures
Hardware Noise (DC)	0 Hz (DC)	Originates from wiring and electrical components of the recording system	Values up to a few μV	Use of special gear for noise reduction/isolation
Muscle Noise	0-200 Hz (1-50 Hz most impactful)	Caused by muscle activity, including minor movements like eye blinking	Values may exceed 100 mV	Careful electrode installation, skilled operators for reduction
Motion, Breath, Sweat and Cardiac Noise	0-1.2 Hz	Due to normal physical activities	Values may reach 10-80 μV	Proper installation and setup
Eye Motion & Electromagnetic Field Noise	0-16 Hz	Eye motion and intensity of electromagnetic fields	Values between 50-100 μV	Correct electrode placement, skilled operators
Electromagnetic Interference (EMI) & Circuit Noise	50 Hz (e.g. Greece), 60 Hz (e.g. USA)	From electrical power lines and nearby electronic devices	Significant distortion possible	Use of special filters for isolation

Table SA.3 presents a structured overview of the various components involved in EEG circuits, along with their respective functions [12,13,14].

Table SA3. Components involved in EEG Circuits Design (Generic).

Category	Subcomponent	Function Description
Filter	Notch Filter	Eliminates power line interference, typically at 50 or 60 Hz.
	Anti-Aliasing Filter	Prevents aliasing by removing high-frequency components before analog-to-digital conversion.
	High Pass Filter	Removes low-frequency components, typically below 0.1 Hz.
	Low Pass Filter	Cuts off frequencies higher than a certain threshold to remove high-frequency noise.
Circuit	Chopper Circuit	Reduces low-frequency noise and drift in DC amplifiers by modulating and demodulating the input signal.
	ESD Protection Circuit	Protects sensitive EEG electronics from static electricity.
Amplifier	Operational Amplifier (Op-Amp)	Amplifies the EEG signal with high gain and stability.
	Programmable Gain Amplifier	Allows for adjustment of the amplification level of the EEG signal.
	Instrumentation Amplifier with Integrated Filter	Provides high input impedance, and low noise, and includes integrated filters for signal conditioning.
Other Subcomponents	Analog Mux (Multiplexer)	Selects one of several input signals and forwards it into a single line in multi-channel EEG systems.
	Analog to Digital Converter (ADC)	Converts the analog EEG signal into a digital format for processing and analysis.
	Drive Right Leg Circuit	Reduces common-mode interference in biopotential amplifiers.

The technical distinctions in design specifications between medical-grade and research-grade EEG circuits [22] are illustrated in Table SA.4.

Table SA4. Comparison of the Key Technical Aspects of Medical-Grade & Research-Grade EEG Circuits.

Aspect	Medical-Grade EEG	Research-Grade EEG
Accuracy and Resolution	Higher accuracy and resolution for diagnostic purposes	Slightly lower resolution, suitable for studying brain patterns
Number of Electrodes	Higher number, standardized layouts (e.g., 10-20 system)	Fewer electrodes, focusing on specific brain regions
Signal Quality and Noise Reduction	Advanced noise reduction for highly accurate readings	Noise reduction present, but may prioritize flexibility in analysis
Regulatory Compliance and Certification	Must meet strict regulatory standards (e.g., FDA approval)	Not subjected to the same level of regulatory scrutiny
Durability and Robustness	Designed for frequent and sustained use, more durable	May not be as durable, focuses on flexibility for research

Supplementary Materials "SB"

This section provides an overview of the EEG circuit designs analyzed in this study. It delineates the requisite parameters and technical specifications for some of the circuits that are not part of the direct comparison with the proposed EEG Circuits and the distinct Case ''1'', Case ''2'', and Case''3'', as well as more details about Case ''1''[47], Case ''2''[48], and Case ''3''[50].

SB.1. Supplementary information for Case "1"

SB.1.1. Requirements and Specifications in the EEG Circuit: Case "1"

The given table outlines the exact requirements and specifications for this EEG circuit that include the following: Common Mode Rejection Ratio (CMRR) is greater than 120 dB; hence, high-performance proof in the minimization of noise and interference. Its bandwidth and frequency range are cut with a 3 dB passband from 0.3 to 40 Hz, tailor-made for EEG signals that include ensuring the major relevant frequencies of the brainwaves are effectively captured. This then becomes a demonstration of a low-cost effective circuit. The extracted signal level will be a big gain at low frequency and effectively extracted; this way, the quality of the extracted signal and the level of noise are highly diminished. Table SB1 shows the requirement and technical description in Case "1" [47] low cost designed EEG.

Table SB1. Comparison of the Key Technical Aspects of Medical-Grade & Research-Grade EEG Circuits.

Common Mode Rejection Ratio (CMRR)	Circuit Bandwidth	Signal Quality	Common Mode Rejection Ratio (CMRR)
>120 dB	0.3 to 40 Hz	▪ Gain: 25000 V/V ▪ Noise: absence of noise data ▪ Notch depth: 48 dB at 50 Hz	▪ Notch only at 50 Hz not 60 Hz, ▪ Not input test data provided ▪ No test for strong muscle artifacts ▪ No ESD protection ▪ Not test for compliance with the safety standards for current

B.1.2 Comparative Evaluation with EEG Generic Circuit Design

The comparison of the low-cost EEG circuit design with the aforementioned generic model in this study underscores the novel aspects of combining multiple filters and amplifier stages. This design is characterized by ease of implementation because advanced design techniques are avoided (e.g., chopping), robust anti-interference capabilities are achieved by the high-pass filters, and high signal amplification from the amplifier is guaranteed by two instead of one amplification stage.

B.1.3. Usage-Centric Justification for Design Differentiation: Case "1"

The definition of a low-cost EEG circuit design provides real-time, high-quality, and cost-effective signal processing specifically designed to support the development of advanced Brain-Computer Interface systems (BCI). It is very good in precisely enhancing and optimizing raw EEG signals. In addition, it could serve as a portable detector for EEG signals in a research or medical environment. These features have proved to be high input resistance, high CMRR, high gain, large gains, substantial, low noise, low drift currents, low drift currents, low-frequency response, and substantial estimated SNR.

B.1.4. Simulation - Experimental Results: Case "1"

These experimental results, therefore, indicate that the design of the low-cost EEG circuit can be used for signal extraction and amplification. This further will confirm that the design can maintain stability and performances of the circuits while enhancing the EEG signal, dropping the low frequency, and reducing the power line interference. According to the research of Case "1" [47], it is noted that this assessment is very important and significant, since it will emerge if the design of the project meets the requirements and, on top of that, it will reflect on the development of EEG circuits.

SB.2. Supplementary information for Case "2"

SB.2.1. Requirements and Specifications in EEG Circuit: Case "2"

The specific requirements and specifications of EEG Circuit set in [48] are supplemented with the technical characteristics of the AD8428 amplifier [49] for a thorough analysis. This circuit boasts a notable CMRR of 140 dB, effectively minimizing noise and interference by canceling out the common component of the two input signals. On the contrary, unlike the usual EEG frequency ranges, this circuit is specifically designed for a wide range of frequencies up to 3.5 MHz. Furthermore, the circuit is distinguished by its extremely low-cost design, achieved through the use of merely two components, thereby ensuring affordability. Moreover, the circuit excels in signal quality, with the Vpp noise from 0.1 Hz to 10 Hz being only 50 nV before amplification. Lastly, the circuit provides a variable gain up to 10580K V/V, a gain that is a strictly increasing function of frequency. The requirements and specifications for a battery-powered, low-noise EEG amplifier system are meticulously detailed in Table SB2.

Table SB2. Requirements and specifications in battery-powered, low-noise EEG amplifier system (Case "2").

Common Mode Rejection Ratio (CMRR)	Circuit Bandwidth	Signal Quality	Common Mode Rejection Ratio (CMRR)
140 dB	3.5 MHz	▪ Gain: variable 40.9K to 10580K V/V ▪ Noise: Vpp noise in 0.1 Hz to 10 Hz is 50nV before amplification ▪ Notch depth: -	▪ No Notch at 50 Hz or 60 Hz, ▪ No test for strong muscle artifacts ▪ No ESD protection ▪ Not test for compliance with the safety standards for current

SB.2.2. Comparative Evaluation with EEG Generic Circuit Design

This study demonstrated the uniqueness of the low-noise, battery-operated EEG amplifier system that has simple filtering in comparison with the Generic model. As a result, this system posts an exact instrumentation and inverting amplifier to come out with minimal design while consuming low power for sustainability and portability, since it's battery-operated. It also includes superior CMRR and SNR for accurate amplification and reliable readings, high input impedance to prevent signal distortion, and high gain for clear signal interpretation. While it has a low-pass filter to remove high-frequency noise, it deliberately lacks a notch filter. This is attributed to the fact that it is not connected to supply from the main grid, but still, a notch filter could have been of use for tackling EMI from the main grid . Consequently, it can be used to identify neurological irregularities, demonstrating its effectiveness in advanced neurological research.

SB.2.3. Usage-Centric Justification for Design Differentiation: Case "2"

Further, the design of this biomedical device is in consideration of low power consumption; as such, this design befits the requirement for use in most cases of research that will see a long time in practical use. Or even better, the quality of acquired EEG signals is even higher when using a battery to reduce noise from the electric grid and increase the strength of the device because it will, therefore, last longer. Therefore, this circuit is a fine candidate for use in setting up the research protocols where portability, low noise, and low cost of the device are the major issues to be considered.

SB.2.4. Simulation - Experimental Results: Case "2"

Results in this study supported and established the role of the tested device, the low-noise battery-powered amplifier, in signal isolation and amplification. In this context, the results validate the ability for accurate records of EEG signals and hence the usefulness of the device in ascertaining a number of research protocols. The asset of low energy usage, the minimally flexible design, and the portability of the BB-ESAS extend its applicability in both home-use and research settings. Nonetheless, the simulation was conducted only with EEG signals of one wave band at a time in the total absence of noise (a nonrealistic signal of brain physiology). This simulation setting makes the usage of this EEG circuit questionable when it is operated in high-EMI environments or in protocols with strong compound muscle movements. Last but not least, this system, though it removes noise from low-amplitude EEG signals, does not handle low-frequency drift and does not involve necessary ESD protection.

SB.3. Supplementary information for Case "3"

SB.3.1. Requirements and Specifications in EEG Circuit: Case "3"

The specific requirements and specifications for this EEG circuit are well articulated. Although the CMRR is estimated at 110 dB, the circuit's bandwidth is adeptly configured from 0.5 to 33.86 Hz, which is within the mostly studied EEG signal frequency spectrum between 0.1 and 100 Hz. This illustrates the system's capability of effectively handling the bandwidth requirements that are essential for EEG signal processing. In terms of signal quality, the pre-amplification error is a minimal 0.74%, rising slightly to 1.75% post-amplification, indicating a high level of signal fidelity. Subsequently, the circuit is a budget-friendly choice due to its low cost. The requirements and specifications for a double notch filter analog front end EEG circuit is meticulously detailed in Table SB3.

Table SB3. Requirements and specifications in Double Notch Filter Circuit Design of EEG (Case "3").

Common Mode Rejection Ratio (CMRR)	**Circuit Bandwidth**	**Signal Quality**	**Common Mode Rejection Ratio (CMRR)**
Estimated at 110 dB	0.5 to 33.86 Hz	▪ Gain: 64000 V/V ▪ Noise: pre-amplification error: 0.74% ▪ Post-amplification error: 1.75% ▪ Notch depth: absence of depth data	▪ Notch only at 50 Hz not 60 Hz, ▪ Not input test data provided ▪ No test for strong muscle artifacts ▪ No ESD protection ▪ Not test for compliance with the safety standards for current

SB.3.2. Comparative Evaluation with EEG Generic Circuit Design

The comparison between the dual-notch filter EEG circuit design and the generic one emphasizes the essential variables that contribute to Case ’’3’’ [50] circuit's superior performance. This design has the novelty of 1 pre-amplification and 2 amplification stages. In addition, the way in which electrodes are attached to the scalp provides a low-impedance path to achieve minimal common mode interference noise contained in the signal coming from the body. As a result, this eliminates the requirement for protective electric shielding when collecting EEG signals. Moreover, this circuit configuration employs a rare (unorthodox) engineering decision by using two-notch filters, which greatly improves the suppression of electromagnetic interference originating from the power grid.

SB.3.3. Usage-Centric Justification for Design Differentiation: Case "3"

First, it is applicable for the clinical diagnoses over fine monitoring of brain diseases with accuracy since it does not require electrical shielding technology, the EEG. The configuration is hence mandatory in the medical settings for proper diagnosis and treatment effectuality. This EEG technology has further important uses: in national defense and aerospace medicine. The industries served by the medical units require systems that are both sturdy and flexible. Most of these systems are easily prone to a host of electromagnetic interference (EMI) sources, including: The human body is biologically eliminated through the use of pre-amplification techniques, driven-right-leg circuits, and biomedical engineering. Such decisions in the design help the effective detection of the EEG signals in environments that lack proper shielding. This development, therefore, significantly eases the logistic problems the conventional methods of data collection in EEG have and, therefore, reduces these constraints for Case ’’3’’ [50], making them much more feasible and accessible for their implementation in a wide variety of contexts. A brain-computer interface (BCI) device retrieves the signals of EEG. As such, where accuracy of such brain activities is very much necessary, to assure reliability in the systems, this circuit would facilitate essential signal recording.

SB.3.4. Simulation - Experimental Results: Case "3"

The experimental output of this specific EEG signal amplifier is demonstrative of its utility to isolate noise and enhance signals effectively. The high CMRR of the main amplifier, the ability to eliminate high-frequency noise and 50 Hz frequency interference, and a gain of more than 60,000 V/V produce a low-noise, significantly amplified analog signal that is excellent for digital conversion. This EEG circuit design, by using the pre-amplifier and post-amplifier, along with high-performance filter sets (two low-pass filters and two 50 Hz traps), has high performance in effective amplification and extraction, which can be achieved in non-shielded environments, potentially expanding the range of applicability of EEG systems.

SB.4. Supplementary information for four other circuits of Related Works

The following Table SB4. succinctly presents key aspects of the Neonates-Specific EEG System [43], including the CMRR, signal bandwidth, gain, and filter characteristics:

Table SB4. Parameters and technical specifications in Neonates-Specific EEG System.

Feature	Description
Common Mode Rejection Ratio (CMRR)	The AD620 instrumentation amplifier used in the design has a high CMRR of 110 dB, crucial for minimizing noise and interference in EEG signals.
Signal Bandwidth/Frequency Range	Targets neonatal EEG signals, predominantly delta waves, with frequencies from 0.5 to 2 Hz, 100µV amplitude.
Gain	Total gain of 17776 V/V. Individual stage gains: ▪ 16 V/V (instrumentation amplifier), ▪ 101 V/V (second stage), ▪ 11 V/V (third stage).
Filter Characteristics	High pass and low pass filters with cutoff frequencies of 0.16 Hz and 50 Hz, respectively to remove DC offset and power line interference

The following Table SB5 provides a succinct overview of the compact amplifier and signal conditioning module designed for wireless EEG monitoring [44]. This kind of EEG design includes features, relate to variable gain, CMRR, power consumption, portability, components, cost, and signal quality metrics. The design prioritizes low power consumption and portability, utilizing readily available commercial components to achieve a cost-efficient and compact solution.

Table SB5. Wireless EEG Monitoring-Compatible Compact Amplifier and Signal Conditioning Module.

Feature	Description
Common Mode Rejection Ratio (CMRR)	High CMRR suitable for EEG applications
Signal Bandwidth	0.5 to 40 Hz
Variable Gain	Between 100 and 7000
Power Consumption	Low
Portability	Designed for portability
Components	Uses commercially available components
Cost	Cost-effective
Signal Quality Metrics	Detailed metrics not directly provided

The following Table SB6 systematically organizes the technical parameters of a Single-Chip EEG Signal Sampling Circuit [45], such as Common Mode Rejection Ratio (CMRR), Amplifier Gain, Pass-Band Frequency, and Input Impedance:

Table SB6. Single-Chip EEG Signal Sampling Circuit.

Feature	Description
Common Mode Rejection Ratio (CMRR)	102 dB, effective in reducing noise and interference from common-mode signal
Amplifier Gain	Variable, with options for 5000, 10000, 20000, or 30000 V/V
Pass-Band Frequency	Ranges from 0.12Hz to 35.4Hz, accommodating the typical frequency range of EEG signals
Input Impedance	113MΩ, ensuring that the circuit does not significantly load the signal source, preserving signal integrity

The following Table SB7 offers a concise summary of key BCI-Specific EEG [46,60] design elements, such as CMRR, amplifier gain, notch filter, etc. These elements highlight the circuit's ability to deliver accurate amplification and filtering of EEG signals, which are crucial for dependable monitoring of brain activity:

Table SB7. BCI-Specific EEG.

Feature	Description
Common Mode Rejection Ratio (CMRR)	100 dB for gains ≥ 100, aiming for effective common-mode noise rejection
Amplifier Gain	G≥100V/V
Modified High-Q Factor Active Twin-T Notch Filter	60 Hz and a rejection level of -38 dB.
PCB Size	Less than 5.5 cm^2