

BioListener: a methodological framework for precision biosignal acquisition using general-purpose ADC architecture*

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Abstract

The rapid development of biosensing technologies necessitates accessible tools that combine microvolt-level precision with low cost. Despite significant progress, modern biosensing systems are bifurcated into expensive clinical devices and unvalidated hobbyist solutions. This paper presents BioListener, a multi-channel platform that bridges this gap through a novel design methodology. The scientific novelty of this work lies in validating the concept of replacing specialized medical analog front-ends (AFEs) with precision 24-bit general-purpose analog-to-digital converters (ADCs), the AD7771 and ADS131M08, combined with a "floating ground" topology. The proposed architecture is based on dual-core processing using the ESP32 microcontroller, in which sampling is driven by the ADC data-ready interrupt on a dedicated core, so network activity cannot delay ADC reads. The validation methodology, aligned with the IEC 60601-2-26 standard, confirms input-referred noise of 1.99 μVpp and 5.68 μVpp for the two variants, below the 6 μVpp limit, and common-mode rejection above 114 dB and 104 dB balanced, 87 dB imbalanced, without active right-leg drive circuits. Integration with the BrainFlow library transforms BioListener into an open ecosystem for real-time signal processing. The platform reaches this performance at a BOM cost under \$35, making it a scalable tool for research and educational use.

Keywords

Biosensing platform, BioListener, ESP32, 24-bit ADC, bioelectric signals, open-source hardware, neurorehabilitation, BrainFlow, signal validation, low-cost

1. Introduction

The rapid integration of biosensing technologies into clinical diagnostics, consumer electronics, and neurorehabilitation creates a critical need for instrumentation that is not only high-performing but also affordable, portable, and open-source. Currently, the biosensing systems market is bifurcated: professional devices offer high precision but are prohibitively expensive, while low-cost hobbyist alternatives often lack proper signal validation. In the context of Ukraine's post-war recovery, the development of accessible biomedical tools is of particular importance, especially for neurorehabilitation and the treatment of motor disorders under resource-constrained conditions [3, 22]. The aim of the study is to design, implement, and validate BioListener – an affordable, portable, multi-channel biosensing platform capable of providing high-quality bio-signal registration using low-cost components. Parts of this work were first reported in [11]. To achieve this goal, the work develops a modular hardware platform based on the ESP32 microcontroller and versatile 24-bit analog-to-digital converters (AD7771 and ADS131M08), optimizes engineering solutions to reduce device cost without compromising safety or signal quality, and integrates the firmware with the

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BrainFlow library to ensure compatibility with various programming languages and simplify data acquisition. The device is then evaluated against the signal-quality limits of IEC 60601-2-26 across key performance indicators (noise, frequency response, SNR, and CMRR), and its effectiveness is demonstrated during real-time acquisition of electroencephalography (EEG), electromyography (EMG) and electrocardiography (ECG) signals.

Scientific novelty of the research lies in the development and substantiation of a biosensing platform architecture that eliminates reliance on specialized and expensive medical analog front-ends (such as ADS1299). A combination of general-purpose precision ADCs with a dual-core ESP32 microcontroller and the open BrainFlow ecosystem is proposed, together with a published validation dataset. This approach achieves noise down to $1.99 \mu V_{pp}$ and balanced CMRR over 100 dB while significantly reducing the Bill of Materials (BOM) cost to under \$35 USD. Passive electrodes were used for all recordings, supported by the input impedance and floating ground topology; no comparison with active electrodes was made.

2. Problem Statement

The problem addressed here is whether a front end built from general-purpose ADCs, without a dedicated medical AFE or an active right-leg drive, can meet the signal-quality limits of IEC 60601-2-26. Bioelectric signals are ionic potentials generated by the electrochemical activity of excitable cells [16].

EEG represents the aggregate electrical activity of the brain: these signals are extremely weak (1 μV to 150 μV) with a bandwidth of 0.5 Hz to 100 Hz, and capturing them requires exceptionally low input noise ($< 6 \mu V_{pp}$) [14]. EMG is generated by muscle contraction, ranging from 50 μV to 5 mV with frequency content up to 2000 Hz, and ECG by cardiac depolarization (1 mV to 5 mV).

BioListener is designed to support passive electrode configurations. Unlike active electrodes, which place an amplifier directly at the sensing site to buffer the signal, passive electrodes connect directly to the ADC inputs via shielded or unshielded cables [17]. While active electrodes offer better noise immunity, they significantly increase cost and complexity. By engineering a printed circuit board (PCB) with superior noise performance and high input impedance, BioListener enables the use of low-cost passive wet (gel-based) or dry electrodes without sacrificing signal quality.

The core processing unit is the Espressif ESP32 (Wemos D1 Mini module) [18]. The ESP32 was selected for its dual-core Xtensa 32-bit LX6 architecture. This dual-core design is fundamental to the system's stability:

- Core 1 (Real-Time Core): Dedicated to high-priority, deterministic tasks. It handles the Serial Peripheral Interface (SPI) communication with the ADC, reading data samples at precise intervals triggered by hardware interrupts.
- Core 0 (Protocol Core): Manages the Wi-Fi/Bluetooth stack and TCP/IP communications. By offloading these non-deterministic tasks to a separate core, network latency and connection handshakes do not delay the acquisition interrupt.

To increase supply chain resilience, two distinct PCB variants were developed based on different general-purpose 24-bit ADCs. The AD7771 (Analog Devices) is a high-performance Sigma-Delta ADC with a Programmable Gain Amplifier (PGA) of up to 8x and input impedance above 10 M Ω , making it suitable for EEG, EMG and ECG with dry electrodes [19]. The ADS131M08 (Texas Instruments) is a cost-effective Sigma-Delta ADC with a PGA of up to 128x and input impedance of 330 k Ω (gain 1-4) or 1.25–1.5 M Ω (gain ≥ 8), more suitable for wet-electrode recordings [20].

The mathematical formulation for the development and validation of the BioListener platform can be defined as a technical compliance problem within the field of biomedical engineering.

The object is the process of registering low-amplitude bioelectric signals (EEG, EMG, ECG) under resource-constrained conditions.

Let $S(t)$ be the useful bioelectric signal, characterized by the following properties depending on the type:

- EEG: Amplitude $A_{EEG} \in [1, 150] \mu V$, frequency band $f_{EEG} \in [0.5, 100] \text{ Hz}$.
- EMG: Amplitude $A_{EMG} \in [50, 5000] \mu V$, frequency band f_{EMG} up to 2000 Hz.

ECG: Amplitude $A_{ECG} \in [1, 5] \text{ mV}$.

The design is stated as requirements with validation criteria rather than an optimization. The goal is to minimize the system cost C_{BOM} subject to the following limits:

1. Cost: $C_{BOM} \leq \$35$ per unit.

Input Referred Noise (IRN): $IRN = 6\sigma_{noise} < 6 \mu V_{pp}$ (per IEC 60601-2-26).

Common-Mode Rejection Ratio (CMRR): $CMRR > 100 \text{ dB}$.

Frequency Response: Gain deviation $\Delta G < 1.1 \text{ dB}$ within the $[0.5, 100] \text{ Hz}$ band.

To achieve the objective, the system must maintain the following mathematical indicators:

- Signal-to-Noise Ratio (SNR) (1):

$$SNR = 10 \log_{10} (P_{signal} / P_{noise}) \geq SNR_{target}, \quad (1)$$

where SNR_{target} is set by the application; for a $10 \mu V_{pp}$ alpha rhythm on the AD7771 variant it is 14 dB. Signal Sampling: according to the Nyquist-Shannon sampling theorem, the sampling frequency f_s must satisfy (2):

$$F_s > 2 \cdot f_{max}, \quad (2)$$

where f_{max} is the maximum frequency of the biosignal. The use of 24-bit ADCs (AD7771 or ADS131M08) provides the necessary resolution to minimize quantization noise.

3. Related Work

The trajectory of technological development in the 21st century has been substantially defined by the miniaturization of electronics and their widespread integration into the biomedical domain. What once required racks of stationary, high-power equipment in specialized clinical environments can now be accomplished by battery-powered devices that fit in a pocket [1, 2, 3]. Modern electronic systems are capable of capturing fundamental human biosignals – such as electroencephalograms (EEG), electromyograms (EMG), and electrocardiograms (ECG) – with increasing reliability and fidelity.

This shift from stationary to portable instrumentation has catalyzed a revolution in diagnostics and assistive technology. Beyond rapid medical assessment, these tools enable the creation of Brain-Computer Interfaces (BCIs) that allow immobilized individuals to control external appliances via bioelectric signals [2]. Furthermore, neuro-interfaces are increasingly used to support sensory

function and are finding expanded utility in neurorehabilitation, cognitive training, personalized neurofeedback devices and monitoring systems, and gaming applications [3, 4, 5, 6].

However, a significant paradox persists in the field. While the theoretical capabilities of biosensing have expanded, practical access remains constrained by high barriers to entry. Commercial and semi-commercial solutions, such as those from established manufacturers [7], are often expensive due to reliance on specialized, low-volume components or rigorous medical certification costs. Conversely, the open-source landscape is frequently populated by projects that lack necessary documentation or fail to validate their signal quality against established standards [8, 9]. This leaves a "missing middle": a reliable, affordable, and validated platform suitable for serious education and research.

The theoretical and practical foundations of biosensors were established in the mid-20th century. Leland Clark is credited as the father of the biosensor concept, having developed the first enzyme-based sensors [15]. In the 1980s, Tompkins and Webster's definitive work formalized the architecture of digital medical devices, emphasizing the critical interface between sensors, analog-to-digital converters (ADCs), and microprocessors [16].

The landscape of portable biosensing changed dramatically with the introduction of the OpenBCI project in 2013. The OpenBCI Cyton board set a new standard for accessibility, utilizing the TI ADS1299 ADC to provide research-grade EEG data to the open-source community [7]. However, its price point remains a significant barrier.

Several recent academic efforts have attempted to reduce costs further. Earley et al. (2024) developed a platform for EMG/ECG/EEG acquisition, yet it retained reliance on the costly ADS1299 [3]. Other initiatives, such as "FreeEEG32" [8] and "nRF5x-Biosensing-Boards" [9], attempted to utilize general-purpose ADCs but faced limitations regarding wireless connectivity or software integration.

BioListener specifically targets the gaps identified in these studies: it combines the low cost of general-purpose ADCs with the wireless versatility of the ESP32 and the software robustness of the BrainFlow ecosystem.

4. Materials and Methods

The evaluation methodology followed an applied research approach, combining laboratory measurements of technical parameters and real-world biosignal acquisition tests – a hybrid approach recommended for emerging biomedical devices and an accepted practice among the studies covering the device validation part [1, 3]. This dual strategy ensures both compliance with biosensing standards and practical usability validation.

Laboratory tests quantified the critical analog front-end (AFE) characteristics. Input Referred Noise (IRN) defines baseline sensitivity, Frequency Response ensures faithful signal reproduction across the target physiological bandwidth, Signal-to-Noise Ratio (SNR) distinguishes meaningful biosignals from background interference, Common Mode Rejection Ratio (CMRR) determining environmental noise resilience, Input Impedance affecting electrode compatibility and application areas of the device, and Breakdown Voltage (BV) Testing to ensure operational safety margin (overvoltage tolerance) and as a simplified test of robustness against electrostatic discharge at ADC inputs. Real-world demonstrations then contextualized these metrics through the devices' functionality validation for electromyography, electrocardiography, and electroencephalography applications.

The methodology aligns with IEC 60601-2-26:2019 for electroencephalographs and IEEE Standard 1241 for ADC testing [14, 23]. It ensures reproducibility without requiring large-scale comparative studies with commercial devices, and large-scale onhuman trials by instead verifying absolute performance against biomedical standards and additionally validating the performance for the specific device application area through real-world demonstrations.

It should be noted that various IEC 60601-2-XX standards have different requirements for the specific device parameters, though general test setups are common among different biosensing devices [14]. In our case, the primary focus on the noninvasive EEG validation has been made, which has one of the strictest requirements regarding device performance and hence covers most of the other standards among non-invasive bioelectric sensing devices. Researchers are free to evaluate the specific needs for the device performance with the standard they need to ensure compliance.

All the tests are considered for non-invasive electrode usage with the device. BioListener is a research and educational instrument, not a certified medical device; the IEC 60601-2-26 limits are used as reference targets for signal quality. The device is not intended to be used with invasive electrodes.

The data has been collected for each experiment with the specific experimental setup according to the particular requirements and is available in the repository dedicated to device validation. Python scripts automated signal processing and data analysis to eliminate human bias, with Jupyter Notebook providing reproducible processing and visualization pipelines for all parameter evaluation experiments that included data collection.

The laboratory tests and real-world evaluation can be replicated with any other biosensing device integrated into the BrainFlow library, with over 60 most common biosensing boards supported by the BrainFlow now, without the need for any changes in the code except for the device initialization [13]. Some experiments have even simpler testing setups when data recording is not required to measure the parameters.

5. Experiments and Results

The BioListener platform was designed as a modular, dual-board architecture to isolate sensitive analog circuitry from high-speed digital processing and wireless transmission. This separation is crucial for minimizing noise coupling in a compact, mixed-signal device.

A critical design decision in the BioListener architecture was the omission of the Right Leg Drive (RLD) circuit. In traditional mains-powered (plug-in) medical instrumentation, RLD is essential to actively cancel common-mode interference and improve the Common Mode Rejection Ratio (CMRR). However, BioListener is designed exclusively as a battery-powered, floating-ground device. Because the system is isolated from earth ground, there is no closed loop for mains current to flow through the subject to the device ground. The "ground" reference of the BioListener floats with the subject's body potential. Consequently, the common-mode voltage relative to the ADC inputs is significantly reduced compared to mains-referenced systems. Validation tests showed that the native CMRR of the selected ADCs, combined with the floating topology, provides sufficient noise rejection without the added complexity of an active RLD loop. This simplification also reduces the component count, further lowering the barrier to entry [10]. Motion artifacts and dry-electrode operation were not evaluated.

To ensure robustness, the design relies on the smart overvoltage and Electrostatic Discharge (ESD) protection circuits integrated into the AD7771 and ADS131M08 chips. As confirmed by breakdown-voltage testing, these internal diode-clamping structures provide sufficient protection

against static discharge and overvoltage events typical in research environments, eliminating the need for bulky external TVS diode arrays.

A central feature of BioListener is its integration with BrainFlow, a hardware-agnostic biosensing library [13]. By developing a custom BrainFlow board definition, BioListener becomes compatible with a vast ecosystem of existing software. Users can utilize Python, C++, Java, C#, or other APIs to stream data, apply digital filters, and execute machine learning classifiers without writing low-level hardware code. This integration also provides general compatibility with the OpenBCI GUI, offering a powerful visualization tool for real-time analysis [21]. The resulting firmware task flow and data path are shown in Figure 1.

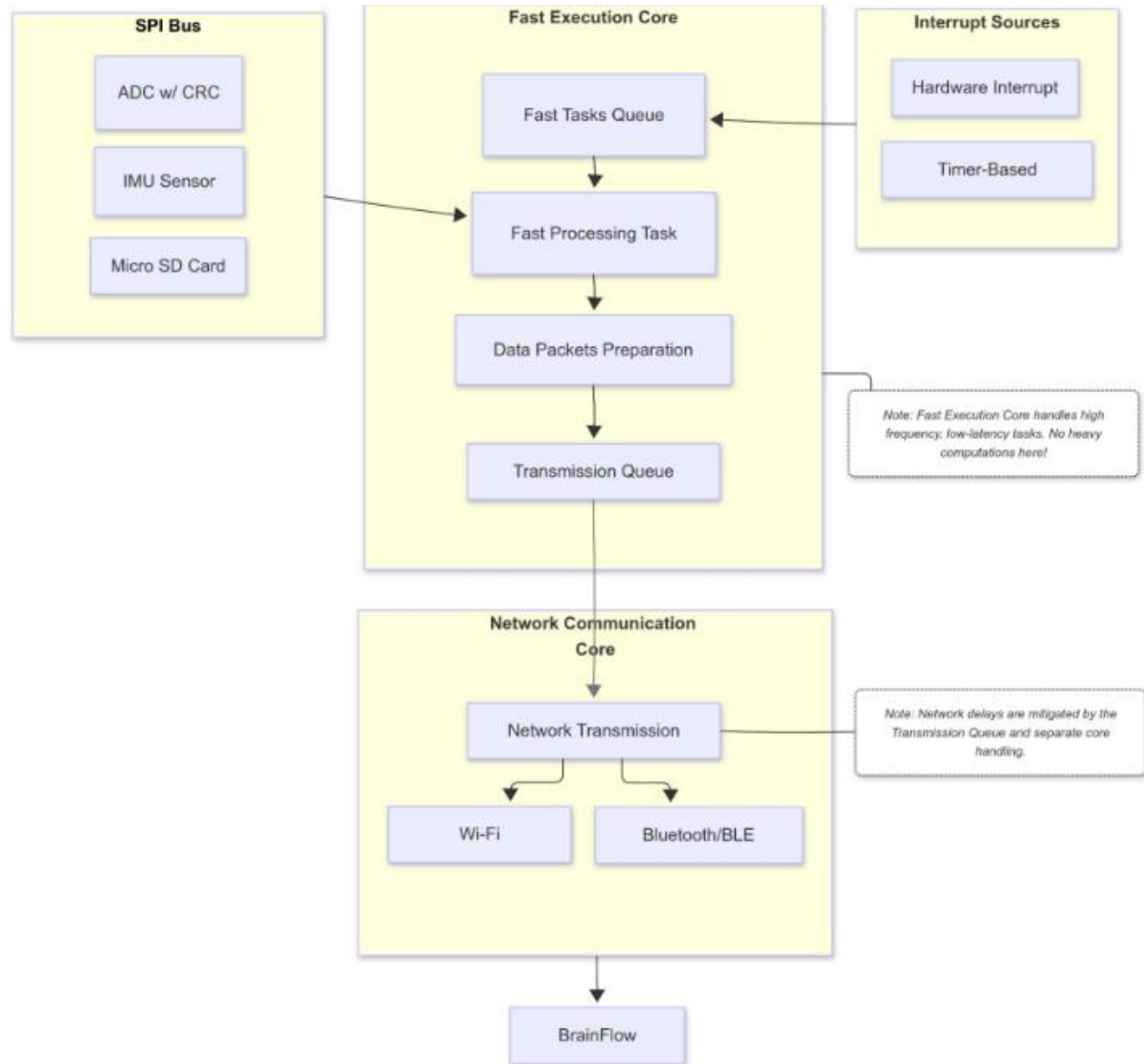


Figure 1: Firmware Task Flow and Data Path for the BioListener Device.

To characterize the acquisition performance of BioListener, a comprehensive evaluation was conducted in accordance with IEC 60601-2-26:2019 (Particular requirements for the basic safety and essential performance of electroencephalographs) [14].

Input Referred Noise is the critical metric defining the smallest detectable signal. Tests were conducted by shorting the ADC inputs to the device ground and recording the baseline noise floor for 10 seconds. IRN was calculated using the standard deviation approximation ($IRN = 6\sigma$) as per industry practice.

The AD7771 variant achieved an IRN of 1.99 μV peak-to-peak, while the ADS131M08 variant achieved 5.68 μV peak-to-peak. Both devices meet the IEC 60601-2-26 requirement of $< 6 \mu\text{V}_{pp}$ for clinical EEG devices, satisfying requirement 2. The AD7771's superior noise performance makes it the ideal choice for high-fidelity EEG, while the ADS131M08 is more suitable for higher-amplitude signals like EMG and ECG.

Both board variants demonstrated a flat frequency response across the bandwidth (0.5 Hz to 100 Hz), with maximum deviation of 1.08 dB (AD7771) and 0.60 dB (ADS131M08) relative to a 5 Hz baseline. This ensures no spectral distortion of brainwave bands (Delta through Gamma). The evaluation results plots are available in Figure 2 for Frequency Response.

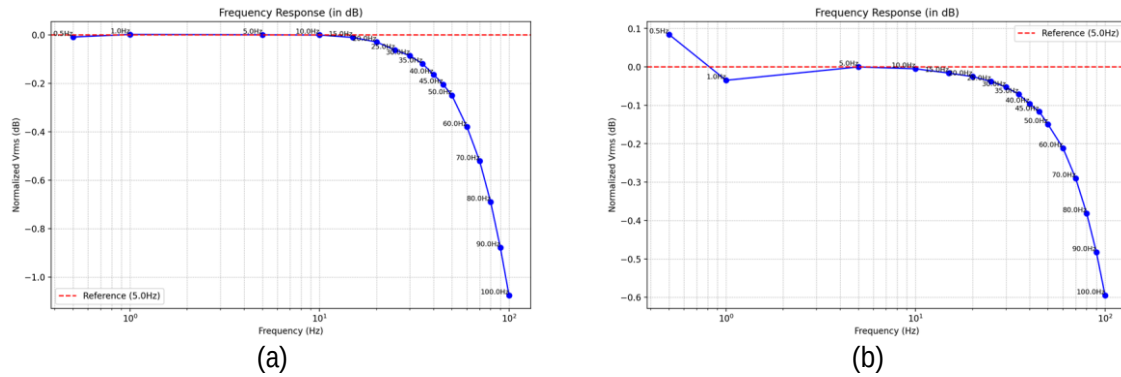


Figure 2: Evaluation plots for Parameter Evaluation: Frequency Response, where (a) is AD7771 and (b) is ADS131M08.

The Signal-to-Noise Ratio (SNR) was calculated using Fast Fourier Transform (FFT) analysis on a standard sine wave input, in accordance with IEEE Standard 1241-2010. The excitation was set to biosignal amplitudes rather than the near-full-scale level of IEEE Std 1241, so the values apply to the device in its operating regime: 17 dB to 33 dB (AD7771) and 17 dB to 35 dB (ADS131M08). The variation in Figure 3 follows from that choice, since at microvolt level the result depends on spectral bin alignment and narrowband interference at each test frequency, while the amplitude response of Figure 2 varies by at most 1.1 dB. The evaluation results plots are available in Figure 3 for SNR.

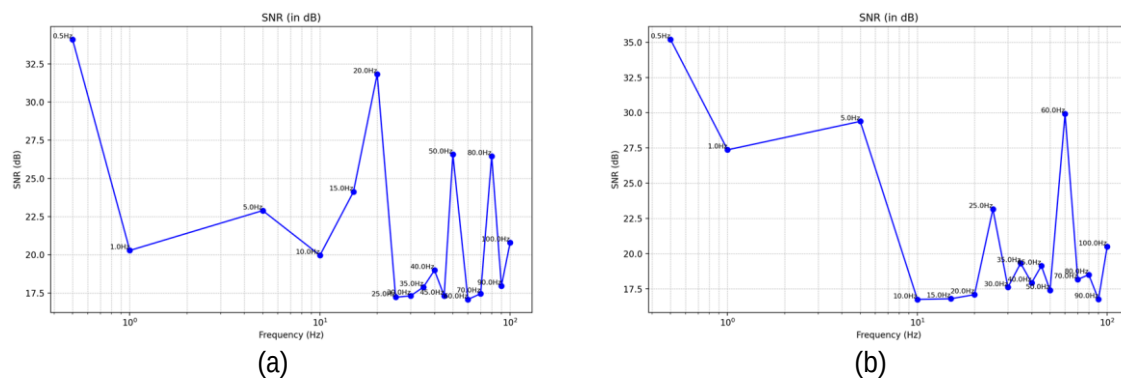


Figure 3: Evaluation plots for Parameter Evaluation: SNR, where (a) is AD7771 and (b) is ADS131M08.

CMRR describes the device's ability to reject common-mode interference on both inputs. The human body acts as an antenna, picking up 50/60 Hz interference from power lines. The differential amplifier must have a high CMRR to reject this common signal.

Testing involved both "Balanced" (ideal) and "Imbalanced" (simulating electrode mismatch) configurations.

Balanced CMRR: The AD7771 achieved > 114 dB, and the ADS131M08 achieved > 104 dB.

Imbalanced CMRR: Even with a resistor-capacitor imbalance network (simulating real-world skin impedance mismatch), both devices maintained a CMRR of > 87 dB. These results confirm the platform's robustness against electromagnetic interference, a crucial feature for non-shielded environments. The evaluation results plots are available in Figure 4 for the CMRR Balance Test and in Figure 5 for the CMRR Imbalance Test.

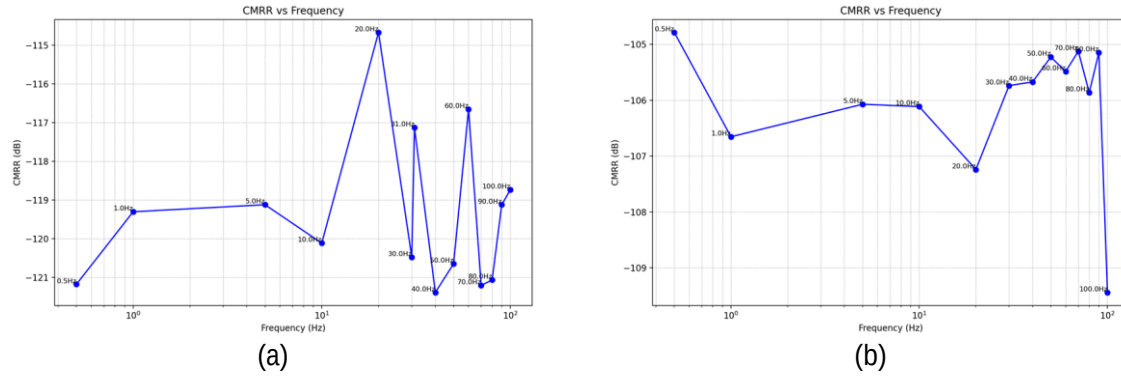


Figure 4: Evaluation plots for Parameter Evaluation: CMRR Balance test, where (a) is AD7771 and (b) is ADS131M08. CMRR is the magnitude of the plotted quantity.

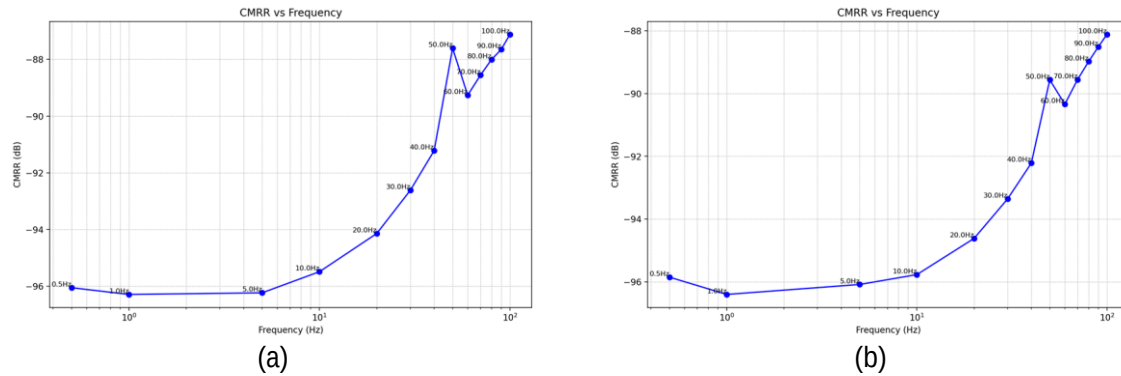


Figure 5: Evaluation plots for Parameter Evaluation: CMRR Imbalance test, where (a) is AD7771 and (b) is ADS131M08. CMRR is the magnitude of the plotted quantity.

High input impedance is critical for biosensing to prevent signal attenuation caused by the voltage divider effect formed between the ADC input and the skin-electrode interface, particularly when using high-resistance dry electrodes. To validate this parameter, a 1 V_{pp} AC sinusoidal signal was applied to the device input via a high-resistance series resistor, and the impedance was calculated based on the resulting voltage drop. The AD7771 variant demonstrated an input impedance exceeding 10 MΩ, suitable for dry silicone and silver-woven fabric electrodes, which were not tested here. In contrast, the ADS131M08 variant measured between 1.25 MΩ and 1.5 MΩ at maximum gain, which is sufficient for standard clinical Ag/AgCl wet electrodes but less suitable for high-impedance dry sensor applications.

The following on-person recordings demonstrate function; measurement performance is established by the standards-referenced validation above. Standard wet passive electrodes were used.

Electrodes were placed on the flexor digitorum muscle of the forearm. The subject performed intermittent fist clenches. The resulting time-series data showed distinct, high-amplitude bursts coincident with muscle contraction, returning to a quiet baseline during relaxation. This confirms that the system's transient response and dynamic range are suitable for muscle-computer interfaces. The evaluation plots for EMG: Fist Clenching real-world demonstrations are presented in Figure 6.

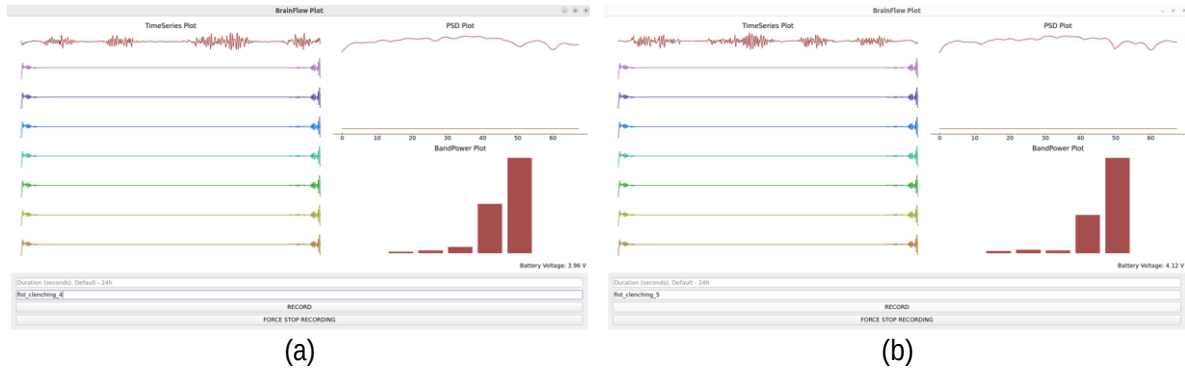


Figure 6: Real-World Demonstrations. EMG: Fist Clenching Plot, where (a) is AD7771 and (b) is ADS131M08.

Using a standard 3-lead Einthoven configuration, the device captured clean cardiac waveforms. The P-wave, QRS complex, and T-wave were clearly resolvable without aggressive software filtering. A 5-lead configuration was also successfully tested, demonstrating the system's capacity for multi-lead monitoring. The evaluation plots for ECG: 5-Lead Plot real-world demonstrations are presented in Figure 7.

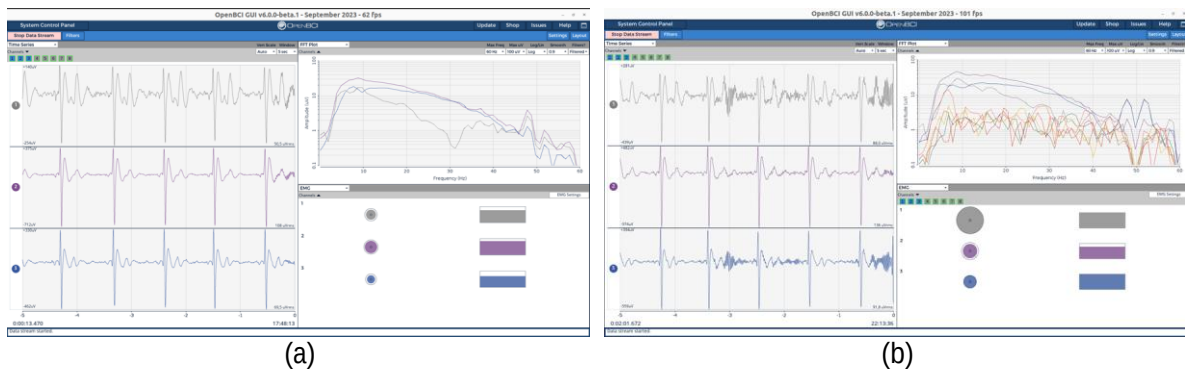


Figure 7: Real-World Demonstrations. ECG: 5-Lead Plot, where (a) is AD7771 and (b) is ADS131M08.

To test EEG sensitivity, electrodes were placed at O1 (occipital) and Fp2 (frontal) positions.

Alpha Wave Detection: The subject was instructed to close their eyes for 10 seconds. The real-time FFT visualization showed a sharp increase in power in the 8–12 Hz (Alpha) band at the occipital electrode, a classic neurological signature of visual cortex idling.

Eye Blink Artifacts: Voluntary eye blinks produced characteristic high-amplitude, low-frequency artifacts in the frontal electrode (Fp2), confirming the system's stability and bandwidth.

The evaluation plots for real-world demonstrations of EEG and EMG: Alpha Brain Wave and Eye Blink Detection are presented in Figure 8.

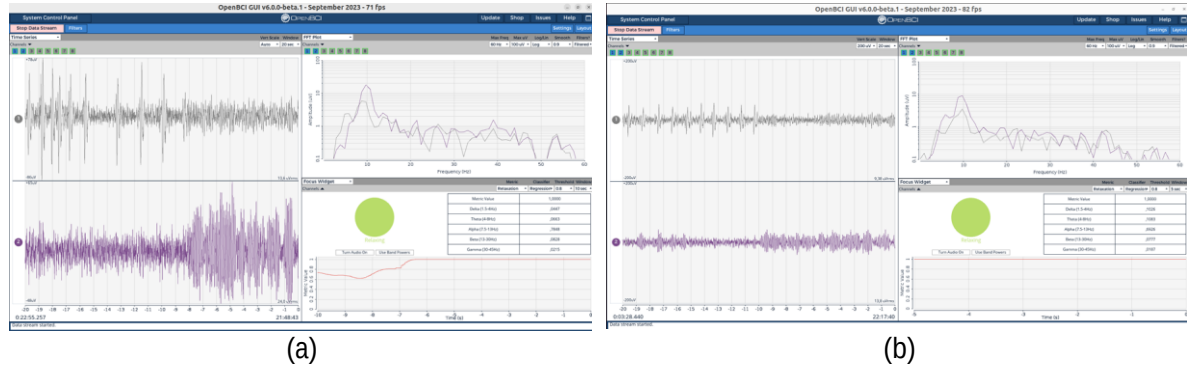


Figure 8: Real-World Demonstrations. EMG and EEG: Eye Blink Detection and Alpha Brain Wave Plot, where (a) is AD7771 and (b) is ADS131M08.

The comprehensive evaluation confirmed both developed devices meet or exceed biosensing standards. Real-world tests confirmed EMG, ECG, and EEG functionality, with the expected physiological features resolvable in each modality. No side-by-side comparison with a commercial instrument was performed. Physiological activity, artifacts and external noise were visually separable in the recordings, demonstrating the platform's potential for research, educational applications, and future advancements in bioelectric signal analysis.

The AD7771 performed best in low-noise applications, while the ADS131M08 offers higher configurability of the gain for specific research.

The analog frontend evaluation results have been combined into Table 1 Performance Evaluation, Key Specifications, and Cost Comparison. Reference projects are also included, with parameters taken from the relevant papers. Because these values come from different studies and test conditions, and a single reference column may aggregate results reported for several devices built on the same front end, the table places BioListener in the same performance class rather than constituting a controlled comparison. The AD7771 variant matches the ADS1299 in noise at a third of the chip cost, while the ADS1299 retains an advantage in input impedance and imbalanced CMRR.

By rigorously verifying all parameters that directly impact signal quality and achieving consistent results across metrics – this evaluation provides sufficient evidence of functionality without requiring mass comparative trials. The Python-based scripts ensure that any researcher can replicate results using the published Jupyter Notebook and datasets, a rare case with other studies.

All datasets, scripts, configurations, schematics and test procedures are available in the project repository [12]. The results of the performance testing and comparative analysis of various Analog Front-Ends (AFE) confirm the effectiveness of the proposed methodology, which advocates for the use of high-precision, general-purpose ADCs over specialized medical-grade integrated circuits.

The BioListener variant based on the AD7771 demonstrated an input-referred noise (IRN) level of 1.99 μV , compared with the 2.58 μV reported for the specialized ADS1299 medical chip used in industry-standard systems like OpenBCI Cyton. These values come from different studies, so this indicates that general-purpose components in a "floating ground" topology reach a comparable noise class rather than outperform domain-specific standards.

The Common-Mode Rejection Ratio (CMRR) for the AD7771 (> 114 dB) and ADS131M08 (> 104 dB) in balanced tests fully satisfies the requirements for precision instrumentation. Performance in unbalanced load tests (CMRR > 87 dB) indicates that native rejection is not the limiting factor when the active Right Leg Drive (RLD) circuit is omitted. No RLD variant was built, so the benefit forgone is not quantified.

Table 1

Comparative Analysis of Analog Frontend Chips: Performance Evaluation, Key Specifications, and Cost Comparison

Analog frontend	AD7771	ADS131M08	ADS1299	RHA2216 + ADC AD7980	KS1092 + ADC AD7682
Manufacturer	Analog devices	Texas Instruments	Texas Instruments	Intan + Analog Devices	Shenzhen Kingsense + Analog Devices
Devices built around analog frontend	BioListener, FreeEEG32	BioListener, nRF5x-Biosensing-Boards	OpenBCI Cyton, ADS_BP, Device by E. Mastinu at al., MiSMT	Dedicated evaluation research by E. Mastinu at al.	NeuroVista by Z. Yu a, S. Guo
Number of differential input channels	8	8	8	16	1
PGA Gain	Up to 8	Up to 128	Up to 24	200	360 to 2720
Resolution, bits	24	24	24	16	16
Sampling Rate max supported by chip, kSPS	128	32	16	1000	250
Differential Full-Scale Input Voltage Range	±2.5V/Gain	±1.2V/Gain	±2.5V/Gain	±0.4V	±1.8V/Gain
IRN, μV_{pp}	1,99	5,68	2,58	9,58	2,68
Frequency Response test	PASS	PASS	PASS	PASS	PASS
SNR, dB	17 to 33	17 to 35	20,94	21,45	No data
CMRR balance test, dB	> 114	> 104	> 116	> 84	> 96
CMRR imbalance test, dB	> 87	> 88	> 135	> 84	> 96
Input Impedance	> 10MΩ	330 kΩ (gain 1-4); 1.25–1.5 MΩ (gain ≥ 8)	> 0.5GΩ	13 Mohm to 1.3 Gohm	20 MΩ with bias network, 5 GΩ no bias network
Breakdown Voltage Test	PASS	PASS	PASS	No data	No data
ESD protection	Yes	Yes	Yes	Yes	Yes
Analog frontend chips price per set USD	15	6	53	218	15

The high input impedance of the AD7771 (> 10 MΩ) allows the platform to be used effectively with both wet and "dry" electrodes without signal degradation. Meanwhile, the budget-friendly ADS131M08 chip, despite its lower input impedance, remains a methodologically optimal "price-to-performance" solution for standard clinical Ag/AgCl electrodes.

The data in Table 1 indicate that a shift in design emphasis – moving from high-cost, narrow-focus components toward an intelligent combination of budget hardware and dual-core software

processing – enables instrumentation meeting the IEC 60601-2-26 signal-quality limits at a significantly lower cost.

6. Discussion

The contribution of this research is to re-examine a common design assumption in biomedical systems. Traditionally, it has been assumed that recording weak biological signals (in the microvolt range) necessitates the use of specialized, expensive "Analog Front-Ends" (AFE) that are often inaccessible to mainstream researchers or constrained by proprietary barriers.

This study provides experimental justification for the concept that adequate metrological precision can be achieved by shifting complexity from the analog hardware to a software-controlled digital core. A key contribution is the demonstration that general-purpose 24-bit Analog-to-Digital Converters (ADCs) possess sufficiently low intrinsic noise and high linearity to replace medical-grade chips, provided they are integrated within a specific "floating ground" topology.

Furthermore, the research proposes a methodology for replacing active Right Leg Drive (RLD) circuits with passive common-mode stabilization. This simplifies the hardware architecture without sacrificing the ability to filter power-line interference (50/60 Hz), indicating that passive referencing can meet the adopted CMRR limit in battery-powered, isolated systems.

The architectural implementation of BioListener is based on three fundamental improvements that distinguish it from existing open-source solutions:

1. A major challenge for portable Wi-Fi-based systems is the interruption of data acquisition by the network stack. The BioListener architecture implements a rigid functional separation: one core of the ESP32 microcontroller acts as a "real-time engine," dedicated solely to handling SPI data streams from the ADC, while the second core manages all communication logic. This decouples sample timing from network activity, which is critical for the precise analysis of EEG rhythms. Residual jitter and packet loss under wireless load were not quantified here.
2. By utilizing the Programmable Gain Amplifiers (PGA) integrated directly within the ADC die, the architecture minimizes the number of external components. This shortens the analog signal path, reducing the "antenna effect" for electromagnetic interference (EMI). The 24-bit resolution allows for the removal of complex hardware filter stages, shifting filtering into the digital domain without losing signal fidelity or dynamic range.
3. Unlike closed-source proprietary systems, the BioListener architecture was designed from the ground up for compatibility with the BrainFlow library. This creates a universal methodological bridge between physical hardware and high-level programming languages (Python, MATLAB, C++). Researchers can perform real-time data analysis using professional frameworks without the overhead of developing custom drivers.

The methodological advancement lies in the creation of an open, scalable standard. The developed platform offers a pathway to microvolt-level precision at the price of a hobbyist device, enabling applications such as low-cost prosthetics with myoelectric control and neurofeedback systems in university laboratories.

In conclusion, BioListener serves not merely as another device, but as a methodological foundation for the rapid deployment of high-precision biosensor networks in challenging economic or resource-limited environments.

7. Conclusion

This study presents the BioListener platform, the development of which allowed for the formulation and validation of an updated methodology for creating affordable, high-precision biosignal registration systems. The study proves the viability of a new approach to hardware selection, moving away from specialized medical Analog Front-Ends (AFE) in favor of high-resolution (24-bit) general-purpose ADCs. Experimental data confirms that this methodology achieves metrological performance (noise $< 2 \mu V_{pp}$ for the AD7771 variant) below the limit of IEC 60601-2-26, while significantly reducing system costs. A methodology of "deterministic core separation" based on the ESP32 microcontroller is proposed and implemented. Isolating the critical real-time data acquisition cycle from power-intensive communication stacks (Wi-Fi/Bluetooth) addresses temporal jitter, which is crucial for accurate phase and spectral analysis of EEG signals.

The paper reports recording without active Right Leg Drive (RLD) circuits. It is demonstrated that the combination of autonomous power supply, differential topology, and the high intrinsic CMRR (> 100 dB) of modern ADCs allows the acquisition of the expected physiological features (Alpha rhythms, P-QRS-T complexes) even in unshielded environments, simplifying the design of end-user devices.

Finally, a methodology for integration via the open-source BrainFlow library was implemented, providing a hardware abstraction layer. This allows researchers to focus on data processing algorithms (Machine Learning, DSP) in standard environments (Python, MATLAB), eliminating the need for low-level driver programming for each new device iteration.

In summary, the research confirms that the intelligent combination of affordable hardware with an advanced embedded software architecture enables the creation of a new generation of research tools whose measured parameters fall within the ranges reported for commercial systems.

Authors' contributions

Conceptualization, N.B.; methodology, S.M. and L.L.; software, S.M.; validation, L.L.; formal analysis, N.B.; data curation, L.L.; writing – original draft preparation L.L.; writing-review and editing, N.B.; visualization, S.M. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Declaration on Generative AI

The authors have not employed any Generative AI tools.

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