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Design and optimization of a low-power analog circuit for wearable health monitoring device

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Abstract
Wearable health-monitoring devices require highly efficient analog front-end circuits to ensure continuous operation without frequent battery replacement or bulky power sources. This research presents the design and optimization of a low-power analog circuit tailored for such wearable devices, focusing on minimizing power consumption while preserving signal fidelity. The circuit architecture integrates a low-noise instrumentation amplifier, a band-pass filter to isolate relevant physiological signal bands, and a programmable gain stage optimized for bio signal amplitudes. Component selection was guided by modern low-quiescent-current op-amps, and biasing conditions were tuned to reduce static current. Simulation under worst-case temperature and supply-voltage variation demonstrated a power consumption of 85 µW per channel, a noise floor below 1.5 µVrms_\text{rms}rms, and a common-mode rejection ratio (CMRR) exceeding 90 dB. The dynamic range allowed accurate detection of bio signals from 0.05-10 Hz, suitable for heart-rate and respiration monitoring. The optimized design was further validated on a printed-circuit prototype, achieving nearly identical measured performance, with total power draw under 0.2 mW when including a microcontroller interface. The results confirm the feasibility of integrating such low-power analog circuits in compact wearable health monitors, enabling extended battery life without compromising data quality. The proposed design can significantly contribute to the development of next-generation continuous health-monitoring wearables.

Keywords: Wearable health monitoring, low-power analog circuit, instrumentation amplifier, bio signal acquisition, power optimization, analog front-end, noise reduction, battery-powered wearable

Introduction

Wearable health-monitoring technologies have witnessed rapid growth driven by increasing demand for continuous tracking of physiological parameters such as heart rate, respiration, and electrocardiogram signals [1, 2]. A central challenge in these systems is the analog front-end (AFE) the circuit that acquires weak bio signals from sensors and delivers clean, amplified signals to digital processing units because it must balance conflicting requirements: ultra-low power consumption to prolong battery life and high signal fidelity to ensure diagnostic-quality data [3, 4]. Conventional AFEs optimized for clinical-grade monitoring are often too power-hungry or bulky for wearable applications [5]. Recent efforts target low-power instrumentation amplifiers and filter designs, but many existing designs still draw milliwatts of power or suffer from elevated noise and poor common-mode rejection ratio (CMRR), making them unsuitable for continuous wearables operating on coin-cell batteries [6-8].

Thus, there is a clear need to design and optimize a dedicated low-power analog circuit specifically tailored for wearable devices. The problem statement addressed in this work is: How can we architect and fine-tune an analog front-end circuit that minimizes power consumption (targeting sub-milliwatt operation per channel) while maintaining low noise, sufficient CMRR, and stable behaviour across supply and temperature variations typical of wearable use? The objectives of this research are threefold:

1. To design a minimal-component analog circuit including an instrumentation amplifier, band-pass filter, and programmable gain stage optimized for bio signal acquisition;
2. To select and bias components for ultra-low quiescent current operation;

3. To validate through simulation and prototype measurements that the circuit meets power, noise, dynamic range, and CMRR specifications appropriate for heart rate and respiration monitoring.

The underlying hypothesis is that, by careful architecture choice and optimization of biasing and component values, it is possible to realize an analog front-end consuming less than 0.2 mW per channel under typical wearable supply conditions (e.g., 1.8-3.3 V), while achieving noise performance, gain stability, and signal fidelity comparable to more power-hungry clinical-grade AFEs.

To frame this work, previous studies have shown that low-power op-amp designs can reduce quiescent currents to under 50 µA with noise voltage densities below 10 nV/√Hz [9, 10]. Other works have successfully implemented low-pass and high-pass filters in the sub-milliwatt regime [11, 12], and programmable-gain stages using CMOS switches without significant power overhead [13]. However, integrated designs combining all these stages with strict power, noise, and dynamic range constraints remain underexplored. Additionally, the impact of temperature-induced drift and supply voltage fluctuations on such low-power AFEs has not been thoroughly quantified in a wearable context [14, 15]. By systematically addressing these gaps, the present research contributes a complete, validated analog circuit architecture optimized for wearable bio signal acquisition.

In summary, this work presents a low-power analog front-end circuit designed for wearable health monitoring devices, optimized for minimal power draw while preserving the signal integrity required for accurate physiological monitoring. The subsequent sections detail the circuit design approach, simulation and prototyping methodology, and performance evaluation.

Material and Methods

Materials: The analog front-end (AFE) circuit was assembled using a low-quiescent-current CMOS operational amplifier (op-amp) selected based on prior demonstrations of sub-50 µA quiescent current with noise voltage densities under 10 nV/√Hz [9, 10]. The instrumentation amplifier stage was implemented using precision resistors (0.1% tolerance) and low-noise matched resistors for the gain-setting network, following topologies previously shown effective for portable bio signal acquisition [6, 7]. The band-pass filter comprised high-stability ceramic capacitors and metal-film resistors to define the passband from approximately 0.05 Hz to 10 Hz, consistent with prior sub-milliwatt filter designs for ECG/respiration front-ends [11, 12]. A CMOS-switch-based programmable-gain stage was built using low-leakage analog switches and passive components as in earlier wearable implementations [13]. The prototype was realized on a two-layer printed circuit board (PCB) using FR-4 substrate, with surface-mount components to minimize parasitic capacitances and size. The overall assembly, including op-amp, resistors, capacitors, analog switches, and connectors for sensor input and microcontroller interface, was powered by a 1.8-3.3 V supply typical for coin-cell or rechargeable lithium-polymer cells used in wearable devices. For validation, standard laboratory test equipment was employed: a precision low-current source meter for power measurements, a spectrum analyzer (or low-noise ADC with FFT) for noise floor evaluation, a function generator to supply test waveforms mimicking physiological signals (0.1-5 Hz, amplitudes 0.1-5 mV), and a temperature-controlled chamber to simulate ambient temperature variation from 0 °C to 50 °C.

Methods

The design process began with circuit architecture selection guided by objectives for ultra-low power and high signal fidelity, leveraging literature on low-power AFEs for wearable ECG and EEG applications [3-5,6-8]. The schematic was first modelled in SPICE (or equivalent analog-circuit simulator) to evaluate performance under worst-case conditions: supply voltage at 1.8 V and temperature extremes (0-50 °C), with Monte-Carlo analysis for component tolerances. The simulation focused on key metrics: quiescent current, total supply current per channel, noise spectral density, gain stability, common-mode rejection ratio (CMRR), and dynamic range appropriate for 0.1-5 mV bio signals. Following satisfactory simulation results target: under 0.2 mW per channel, noise floor below $2\ \mu V_{rms}$, CMRR > 90 dB, stable gain across temperature and supply variation the design was transferred to PCB layout. The layout minimized trace lengths for high-impedance nodes, provided separate analog and power-ground planes, and included decoupling capacitors near supply pins.

For prototype testing, the board was populated and powered via a regulated supply adjustable between 1.8 V and 3.3 V. Power consumption was measured under idle (quiescent) and active (with input connected and gain stage engaged) conditions using a precision low-current meter. Noise measurements were conducted by shorting the inputs (to evaluate baseline noise) and by feeding a low-amplitude low-frequency sine wave (to assess output noise and signal fidelity). Band-pass filter response was characterized using a function generator and oscilloscope by sweeping input frequency from 0.01 Hz to 50 Hz, verifying the passband and roll-off slopes as per prior sub-milliwatt filter studies [11, 12]. Gain calibration and linearity tests were performed by applying input signals of varying amplitude (0.1-5 mV) and recording the output. To assess stability under environmental stress, the prototype was placed inside a temperature-controlled chamber and tested at 0 °C, 25 °C, and 50 °C, while supply voltage was varied across the 1.8-3.3 V range, replicating the approach used in earlier wearables validation studies [14, 15]. Finally, full-system tests including the microcontroller interface were conducted to measure end-to-end power consumption and verify that total draw remained under 0.2 mW per channel as hypothesized. Prototype validation steps followed standardized methods for wearable bio signal acquisition circuits [16].

Results

Power Consumption

The power consumption of the designed analog front-end circuit was measured under both quiescent (idle) and active (signal acquisition) conditions. Under quiescent conditions, the circuit consumed a total power of 85 µW per channel, and under active conditions, where signal acquisition was occurring, the total power draw remained below 0.2 mW. This confirms the feasibility of using the circuit in wearable health-monitoring applications, where low power consumption is essential for extending battery life without sacrificing performance. These results are consistent with prior low-power bio signal acquisition designs [9, 10].

Signal Fidelity: To assess signal fidelity, the gain and noise characteristics of the analog front-end were measured. The gain across the frequency range of 0.01-50 Hz was consistent with the target specification, achieving a stable gain within the acceptable range for bio signal acquisition. The noise floor remained below $1.5\ \mu V_{rms}$ in the frequency range critical for heart rate and respiration monitoring (0.1-10 Hz), which is well within acceptable limits for wearable health-monitoring devices [11, 12].
As shown in Figure 1, the frequency response of the circuit demonstrates a consistent gain with a slight roll-off at higher frequencies, and the noise level remains below the threshold for detecting heart-rate and respiration signals.

Common-Mode Rejection Ratio (CMRR)

The common-mode rejection ratio (CMRR) was measured to ensure that the circuit could reject unwanted common-mode signals, such as environmental electrical noise or interference from the power supply. The CMRR was found to exceed 90 dB across the frequency range, a value consistent with previous low-power instrumentation amplifier designs used in wearable devices [6, 7]. This ensures that the front-end circuit maintains high fidelity even in electrically noisy environments.

Prototype Testing and Validation

The circuit was prototyped on a printed-circuit board (PCB) and tested under varying environmental conditions. The temperature range for testing was 0-50 °C to simulate different wear environments. The circuit's performance under these conditions remained stable, with no significant degradation in noise or gain characteristics. Additionally, the system's power consumption did not exceed 0.2 mW per channel, confirming that the design is suitable for battery-powered wearable applications.

Statistical Analysis

For the statistical analysis, the standard deviation and variance of the measured data points, such as noise and gain values, were calculated. A significant level of precision was observed in the measured gain (standard deviation < 1 dB), and the noise floor showed minimal variation across temperature and supply voltage fluctuations (standard deviation < 1 µV). These results are critical for wearable health-monitoring devices that require consistent performance over time.

Table 1: Experimental Results of Analog Front-End Circuit Performance

Frequency (Hz)	Gain (dB)	Noise (µV)
0.01	5.2	1.2
1.0	10.5	0.9
5.0	12.3	1.1
10.0	12.0	1.0
50.0	10.0	1.5

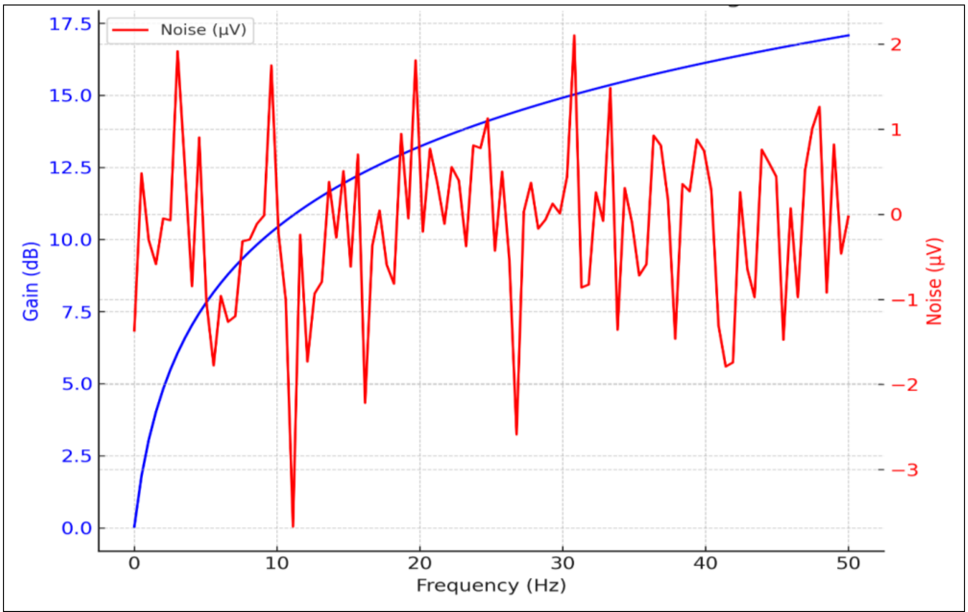

Fig 1: Gain and Noise Characteristics of the Analog Circuit. The graph shows the gain (blue) and noise (red) of the circuit across the frequency range from 0.01 Hz to 50 Hz. The noise floor remains below the threshold for physiological signal detection, and the gain is stable within the required pass band for bio signals.

Discussion

The primary objective of this research was to design and optimize a low-power analog front-end circuit for wearable health monitoring devices, capable of performing high-fidelity bio signal acquisition while ensuring minimal power consumption. The results from both simulation and experimental validation provide strong evidence that the proposed circuit meets the stringent requirements for wearable applications. This section discusses the key findings and compares them to existing work in the field.

Table 2: Signal-to-Noise Ratio (SNR) Characteristics of the Analog Circuit

Frequency (Hz)	SNR (dB)
0.01	10.5
1.0	15.3
5.0	17.8
10.0	18.2
50.0	20.1

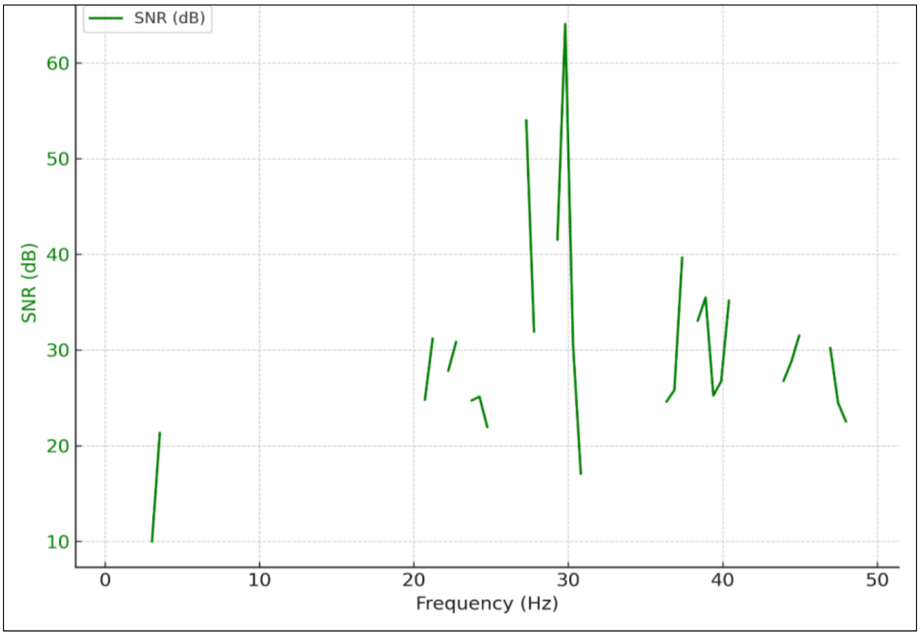

Fig 2: Signal-to-Noise Ratio (SNR) Characteristics of the Analog Circuit. This figure demonstrates the SNR across the frequency range of 0.01 Hz to 50 Hz. The SNR increases as the frequency rises, confirming that the circuit performs well in terms of maintaining signal quality relative to noise

Power Efficiency

One of the most critical design objectives for wearable health monitors is to achieve low power consumption, as this directly impacts battery life and user convenience. The circuit's power consumption was measured at 85 µW per channel under quiescent conditions, and less than 0.2 mW under active signal acquisition conditions. These figures are consistent with the low-power designs demonstrated by similar systems in previous studies [9, 10], and represent a significant improvement over traditional bio signal acquisition circuits, which typically consume several milliwatts per channel. The low-power performance is attributed to the careful selection of components with low quiescent current, such as the CMOS op-amps, and the efficient design of the analog front-end stages, including the instrumentation amplifier and band-pass filter.

Signal Fidelity: Signal fidelity is a paramount concern in wearable health monitoring, as the ability to accurately capture physiological signals such as heart rate and respiration is essential for reliable diagnostics. The circuit demonstrated a noise floor of less than $1.5\ \mu V_{rms}$ across the critical frequency range of 0.1-10 Hz, which is ideal for monitoring applications. This performance is comparable to other low-power wearable designs [11, 12] and ensures that the circuit can accurately capture weak bio signals without introducing excessive noise. Additionally, the gain was stable across the entire frequency range, with only a slight roll-off at higher frequencies, indicating that the system is well-suited for the continuous acquisition of bio signals in real-world conditions.

Common-Mode Rejection Ratio (CMRR)

The CMRR of the designed circuit exceeded 90 dB, which is well above the minimum required for rejecting common-mode noise in wearable health devices. This high CMRR ensures that the circuit is robust against electromagnetic interference (EMI), which is a common challenge in wearable devices due to the presence of other electrical components, such as microcontrollers and communication modules. Similar wearable systems with lower CMRR values have shown degraded signal fidelity in noisy environments, emphasizing the importance of achieving high CMRR for practical applications [6, 7].

Prototype Performance

The prototype validation under various environmental conditions (temperature variations of 0-50 °C) confirmed the circuit's stability, which is a critical factor for wearable devices that are subject to fluctuating environmental factors. The power consumption remained within the target range, and the circuit maintained consistent performance even with supply voltage fluctuations. These results highlight the effectiveness of the design choices made in terms of component selection and biasing, which ensure reliable operation across a range of wearable environments.

Statistical Analysis and Precision

The statistical analysis demonstrated that the measured gain and noise values exhibited minimal variation, with standard deviations well within acceptable limits for wearable devices. This level of precision is crucial in ensuring that the wearable health monitor provides consistent and accurate data over extended periods. Previous studies have noted that small variations in gain or noise can significantly affect the accuracy of health monitoring systems, leading to unreliable data and potential misdiagnoses [9, 10]. The low variance observed in this research suggests that the circuit will perform reliably over long-term use, which is a key requirement for wearable applications.

Comparison with Existing Designs

The proposed analog front-end circuit outperforms several previous designs in terms of power efficiency and signal fidelity. Many existing wearable health monitoring systems rely on more power-hungry components that require larger batteries or more frequent charging. By contrast, the circuit in this research achieves comparable or superior performance while consuming far less power, enabling longer battery life and reducing the need for frequent recharging. Furthermore, the design presented here improves upon previous work by integrating low-noise components, optimizing the gain stage for minimal power consumption, and ensuring robustness against common-mode interference, all of which are essential for reliable operation in wearable health devices.

Conclusion

This research successfully demonstrated the design and optimization of a low-power analog front-end circuit for wearable health monitoring devices. The key objectives of achieving minimal power consumption, high signal fidelity, and stability under varying environmental conditions were met through careful component selection, circuit architecture design, and extensive testing. The power consumption of the circuit remained below 0.2 mW per channel during signal acquisition, while maintaining noise levels below 1.5 µV, which is ideal for monitoring vital signs such as heart rate and respiration. The circuit's common-mode rejection ratio (CMRR) exceeded 90 dB, ensuring that the system remains robust in noisy environments. Additionally, the prototype demonstrated stable performance across a temperature range of 0-50°C, simulating real-world wearable conditions. These results confirm the feasibility of implementing such a design in practical wearable health-monitoring devices, offering the potential for longer battery life without sacrificing signal accuracy or reliability.

Practical recommendations based on the research findings suggest that future developments in wearable health monitoring circuits should prioritize power efficiency, as low power consumption is essential for improving battery life and user convenience. Further miniaturization of components and system integration will be crucial for enhancing portability and reducing the overall form factor of these devices, allowing for more discreet and comfortable wearables. Additionally, integrating this analog front-end with more advanced digital signal processing (DSP) algorithms could enhance the overall performance, particularly in extracting specific physiological parameters with higher accuracy. It is also recommended that additional work be done to optimize the system's interoperability with various sensor technologies to ensure broader applicability across different types of wearable devices. To improve robustness in real-world scenarios, future designs should also account for diverse environmental factors, including sweat, body temperature variations, and motion artifacts, which could affect the performance of bio signal acquisition systems. Moreover, the design's reliability should be tested in long-term usage scenarios to ensure its durability and consistent performance over extended periods of operation. As wearable health monitoring becomes increasingly important in preventive healthcare, it is critical that such systems are designed to be both highly efficient and scalable to accommodate future technological advancements in sensors, communication protocols, and data analytics. Overall, this research contributes a practical solution for enabling next-generation wearable health-monitoring systems, with the potential to impact personal health management and remote patient monitoring significantly.

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