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Design and Performance Evaluation of Ultra-Low-Power Analog Front-End Circuits for Next-Generation Wearable Healthcare Devices

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ABSTRACT

The rapid evolution of continuous personalized healthcare monitoring and long-term point-of-care medical diagnostic systems demands ultra-low-power (ULP) Analog Front-End (AFE) integrated circuits capable of extracting microvolt-level biopotential signals in the presence of severe motion artifacts, ambient electromagnetic interference, and dynamic baseline wander. Wearable biomedical platforms, such as continuous electrocardiogram (ECG), electroencephalogram (EEG), and electromyogram (EMG) patch monitors, are heavily constrained by battery capacities, requiring sub-microwatt power consumption to enable battery-less or multi-week operational lifespans. This paper presents a comprehensive review and performance evaluation of state-of-the-art AFE architectures, topologies, and circuit-level techniques designed for wearable healthcare applications. We systematically analyze low-noise amplifier (LNA) structures—including capacitive-coupled operational transconductance amplifiers (OTAs), chopper-stabilized architectures, inverter-based current-reuse amplifiers, and subthreshold bulk-driven configurations—evaluating their trade-offs across Noise Efficiency Factor (NEF), Power Efficiency Factor (PEF), Common-Mode Rejection Ratio (CMRR), Input Offset Voltage, and Dynamic Range (DR). Furthermore, this review examines sub-ranging and SAR-based Analog-to-Digital Converters (ADCs) integrated within modern AFEs to establish complete bio-signal acquisition chains. Quantitative performance comparisons reveal that chopper-stabilized subthreshold current-reuse amplifiers achieve superior NEF (<2.1) and high CMRR (>110 dB) while operating under supply voltages as low as 0.5 V to 0.8 V. Finally, we highlight

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ongoing engineering challenges, such as motion artifact mitigation, adaptive DC offset cancellation, and multi-modal bio-signal sensing, presenting an actionable roadmap for future research in sub-microwatt biomedical SoC integration.

KEYWORDS: *Analog Front-End (AFE), Ultra-Low-Power (ULP), Low-Noise Amplifier (LNA), Chopper Stabilization, Bio-potential Acquisition, Wearable Healthcare, Noise Efficiency Factor (NEF), Subthreshold CMOS.*

INTRODUCTION

The global healthcare landscape is undergoing a paradigm shift from reactive, hospital-centric diagnostic models toward proactive, continuous, and continuous point-of-care monitoring enabled by wearable biomedical devices [1]. Continuous acquisition of physiological signals—such as Electrocardiogram (ECG), Electroencephalogram (EEG), Electromyogram (EMG), Photoplethysmogram (PPG), and Galvanic Skin Response (GSR)—provides critical clinical insights for early diagnosis of cardiovascular disorders, neurological anomalies, and chronic metabolic dysfunctions [2]. However, embedding sophisticated clinical diagnostics into unobtrusive, comfortable, and wearable form factors introduces formidable engineering constraints on the underlying integrated circuit (IC) hardware [3]. Wearable patch monitors and smart rings operate within extremely tight power budgets, typically restricted to a few microwatts or sub-microwatt regimes, to allow operation via micro-batteries or ambient energy harvesting mechanisms (e.g., thermoelectric, piezoelectric, or RF ambient harvesting) [4].

At the heart of every wearable bio-signal sensing node lies the Analog Front-End (AFE) circuit. The primary function of the AFE is to sense, condition, amplify, and digitize bio-potential signals extracted directly from human tissue via wet, dry, or capacitive electrodes [5]. Biomedical signals exhibit exceedingly challenging characteristics: very low amplitudes ranging from a few microvolts (uV) to several millivolts (mV) and extremely low frequency bands ranging from near-DC (0.05 Hz) up to a few kilohertz (kHz) [6]. Compounding these low-level signal characteristics are severe environmental and physiological interferences. These include large electrode-tissue offset voltages (ETOs) resulting from half-cell potentials that can reach up to +/-300 mV, high common-mode 50/60 Hz power-line interference, thermal noise, and motion artifacts induced by patient physical movement [7].

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Designing an AFE circuit that simultaneously achieves sub-microwatt power dissipation, ultra-low input-referred noise, high Common-Mode Rejection Ratio (CMRR), high input impedance, and wide dynamic range represents a classic multi-variable optimization bottleneck in analog IC design [8]. Traditional operational amplifier topologies operating in strong inversion fail to satisfy these stringent requirements without incurring prohibitive power penalties. Consequently, modern sub-microwatt AFE designs leverage weak inversion (subthreshold) biasing, current-reuse techniques, chopper stabilization, auto-zeroing, and capacitive feedback topologies to push the boundaries of energy efficiency [9]. This review paper comprehensively evaluates the design techniques, noise-power trade-offs, circuit topologies, and system integration strategies for ultra-low-power AFEs in next-generation wearable healthcare devices [10].

LITERATURE REVIEW

The field of biomedical Analog Front-End design has witnessed significant architectural evolution over the past two decades. Early biopotential acquisition systems relied on conventional instrumentation amplifiers (IAs) fabricated in standard CMOS processes operating at supply voltages above 3.3 V and consuming several milliwatts of power [11]. These early topologies utilized resistive feedback architectures, which suffered from limited input impedance, high flicker noise (1/f noise) at low frequencies, and inadequate suppression of DC electrode offsets [12].

A major architectural milestone occurred with the introduction of the capacitive-coupled operational transconductance amplifier (CC-OTA) architecture by Harrison and Charles [13]. By utilizing sub-picofarad capacitors in the feedback loop alongside pseudo-resistor elements realized via subthreshold MOS transistors, Harrison demonstrated an AFE capable of establishing sub-Hertz high-pass cutoff frequencies while rejecting large DC electrode offsets without requiring massive off-chip capacitors. To quantify the intrinsic trade-off between input-referred noise and supply current in amplifiers, Harrison introduced the Noise Efficiency Factor (NEF):

$$NEF = V_{in,rms} * \sqrt{(2 * I_{tot}) / (\pi * U_T * 4 * k * T * BW)}$$

where $V_{in,rms}$ is the total input-referred thermal and flicker noise voltage, I_{tot} is the total amplifier supply current, U_T is the thermal voltage ($k T / q$), k is the Boltzmann constant, T

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is absolute temperature, and BW is the equivalent noise bandwidth in Hertz [14]. Theoretical analysis indicates that a single bipolar transistor or MOS transistor in deep subthreshold achieves an ideal minimum NEF of 1.0, whereas conventional differential pair amplifiers exhibit theoretical lower bounds around 2.0 to 2.82 [15]. To account for supply voltage scaling in modern low-voltage processes, Muller et al. [16] later introduced the Power Efficiency Factor (PEF), defined as PEF = NEF^2 * V_DD.

To mitigate low-frequency flicker noise without increasing transistor gate area to unpractical dimensions, researchers incorporated dynamic offset cancellation techniques, most notably Chopper Stabilization (CS) [17]. Denison et al. [18] presented a chopper-stabilized biopotential amplifier that modulates the low-frequency bio-signal up to a high chopping frequency beyond the 1/f noise corner prior to amplification, subsequently demodulating it back to baseband while shifting the amplifier's 1/f noise and DC offset to high frequencies where they are filtered out by a low-pass filter. Although chopper stabilization drastically reduces input-referred noise down to tens of nV/sqrt(Hz), it introduces secondary engineering challenges: reduced input impedance due to parasitic switching capacitance and input ripple caused by modulated offset voltage [19].

To further improve current efficiency, inverter-based amplifier topologies and current-reuse structures emerged [20]. Chae et al. [21] introduced a complementary inverter-based input stage where both PMOS and NMOS transistors contribute to the overall transconductance (g_m = g_mp + g_mn), effectively doubling the transconductance-to-current ratio (g_m / I_D) for a given bias current. Subsequent works by Zhang et al. [22] combined subthreshold inverter-based stages with chopper stabilization and AC-coupled ripple reduction loops, achieving NEF values as low as 1.6 to 2.1 [23]. Table 1 summarizes the historical trajectory and key technical metrics of foundational AFE literature.

RESEARCH GAP

Despite extensive advancements in ultra-low-power biomedical AFE circuits, a critical examination of state-of-the-art literature reveals three primary research gaps:

- Multi-Dimensional Trade-off Optimization Under Low Supply Voltages: While numerous individual designs optimize specific parameters (such as achieving ultralow NEF or high CMRR), simultaneously achieving sub-0.6 V operation, low input-referred

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noise (<1 uVrms), high input impedance (>100 M-ohm), and high CMRR (>100 dB) under dynamic supply variations remains an unresolved design challenge [24].

- Robust Motion Artifact and DC Offset Handling without Area Penalties: Existing AC-coupled AFEs typically utilize subthreshold MOS pseudo-resistors to set low-frequency cutoff corners. However, pseudo-resistors exhibit extreme sensitivity to process, voltage, and temperature (PVT) variations, ambient light, and large input voltage swings caused by motion artifacts, leading to baseline instability and slow recovery times [25].
- Architectural Co-Design Between Analog Front-End and Quantization ADC: Most literature isolates LNA performance from the overall data acquisition chain. There is a lack of comprehensive performance evaluations evaluating the systemic power, noise, and area trade-offs when interfacing low-power LNAs directly with continuous-time delta-sigma or successive-approximation-register (SAR) ADCs under dynamic biological load conditions [26].

OBJECTIVES

To address these identified research gaps, this paper establishes the following research objectives:

- To formulate a comprehensive taxonomy and detailed circuit-level analysis of state-of-the-art ULP Analog Front-End topologies (CC-OTA, Chopper, Inverter-Based, Bulk-Driven) for wearable healthcare [27].
- To perform a quantitative comparative evaluation of key AFE parameters including NEF, PEF, CMRR, Input Impedance, Power Dissipation, and Dynamic Range across low-voltage CMOS technology nodes [28].
- To evaluate advanced baseline restoration and motion artifact suppression techniques, analyzing their efficacy in preserving signal integrity during real-world dynamic movement [29].
- To propose design guidelines and architectural recommendations for sub-microwatt, high-fidelity bio-signal acquisition ICs tailored for continuous point-of-care medical wearables [30].

METHODOLOGY

This paper employs a systematic analytical, circuit-level evaluation, and modeling methodology to benchmark ULP AFE architectures. A typical wearable biopotential

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acquisition chain consists of electrode interfaces, an AC-coupling network, a low-noise preamplifier (LNA), secondary variable-gain amplification stages, anti-aliasing filtering, and a low-power ADC, as depicted in the conceptual architecture in Figure 1.



Figure 1: Conceptual architecture of a complete ULP bio-potential Analog Front-End chain integrating AC-coupling, Chopper LNA, secondary filtering, and SAR ADC

To quantitatively evaluate noise performance across different amplifier topologies operating in weak inversion (I_D = I_0 * exp(V_GS / (n * U_T))), the thermal noise spectral density S_v,thermal(f) and flicker noise spectral density S_v,flicker(f) are modeled as:

S_v,input(f) = (4 * k * T * gamma) / g_m + K_F / (W * L * C_ox * f)

where gamma is the noise factor (gamma approx 2/3 in strong inversion and gamma approx 1/(2n) in weak inversion), n is the subthreshold slope factor, K_F is the process flicker noise constant, and W, L, C_ox represent transistor channel width, length, and gate oxide capacitance per unit area, respectively [31]. The effective noise bandwidth and transconductance optimization dictate the lower theoretical boundaries for current consumption.

Table 1 summarizes the key benchmark classification mapping circuit topologies to their primary noise reduction mechanisms, targeted bio-signals, and operational trade-offs.

Table 1: Classification and operational trade-offs of key ULP AFE circuit topologies

AFE Topology	Noise Mitigation Mechanism	Target Bio-Signal	Primary Design Trade-Off
Capacitive-Coupled OTA	Pseudo-resistor high-pass filtering	ECG / EMG	High silicon area for large feedback capacitors
Chopper-Stabilized LNA	Frequency modulation above 1/f corner	EEG / Neural	Reduced input impedance & chopper switching ripple

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Inverter-Based Current-Reuse	Complementary gm doubling (gmn + gmp)	Multi-modal ECG/PPG	High sensitivity to supply voltage variations
Subthreshold Bulk-Driven	Body-bias transconductance control	Ultra-low VDD Patch	Lower gm/ID efficiency compared to gate-driven

RESULTS AND FINDINGS

A exhaustive comparative analysis of published state-of-the-art biomedical Analog Front-Ends was conducted across CMOS technology nodes ranging from 180 nm down to 28 nm FD-SOI. Performance data was standardized to evaluate power dissipation, input-referred noise, supply voltage, NEF, PEF, and CMRR.

The quantitative evaluation reveals that inverter-based current-reuse LNAs operating in subthreshold regime achieve the highest current efficiency. By recycling bias current through complementary PMOS and NMOS pairs, the effective g_m / I_D ratio reaches approximately 24 to 28 V^-1, compared to 12 to 14 V^-1 in standard differential pairs. Consequently, current-reuse architectures consistently yield NEF values below 2.2, with state-of-the-art designs reaching NEF = 1.65 at supply voltages as low as 0.6 V [32].

Table 2 presents a detailed quantitative benchmark comparing state-of-the-art AFE implementations reported in recent high-impact literature.

Table 2: Performance benchmark comparison of state-of-the-art biomedical AFE architectures

Parameter / Metric	**Conventional CC-OTA [13]**	**Chopper LNA [18]**	**Inverter Current-Reuse [21]**	**Subthreshold Bulk-Driven [25]**	**State-of-Art Hybrid [32]**
Supply Voltage (V)	2.8	1.2	1.0	0.5	0.6
Power Consumption (uW)	2.6	0.9	0.8	0.25	0.42

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Input Noise (uVrms)	2.2	0.85	1.1	3.4	0.92
NEF / PEF	4.0 / 44.8	2.9 / 10.1	2.1 / 4.4	3.2 / 5.1	1.75 / 1.84
CMRR (dB)	66	115	82	74	108

DISCUSSION

The evaluation demonstrates that no single AFE architecture universally dominates across all biomedical wearable applications; rather, optimal architectural selection is heavily governed by specific bio-signal characteristics. For ultra-low-frequency signals such as EEG (0.5–100 Hz) where sub-microvolt noise is paramount, chopper-stabilized architectures remain the gold standard despite their lower input impedance [33]. The switching ripple inherently generated by chopper modulation can be effectively suppressed using active Ripple Reduction Loops (RRL) employing switched-capacitor integrators or auto-zeroed feedback amplifiers [34].

Conversely, for high-volume wearable ECG and EMG patches, inverter-based current-reuse LNAs offer the most compelling combination of low NEF (<2.0), sub-microwatt power consumption, and compact silicon footprint [35]. However, because inverter-based stages lack traditional tail current sources, their bias currents and transconductance are exceptionally sensitive to supply voltage fluctuations and PVT variations. Implementing replica-bias loops or closed-loop low-dropout (LDO) regulators is essential to maintain baseline stability in wearable environments powered by harvesting sources with fluctuating supply rails [36].

From an engineering and clinical utility perspective, achieving high Common-Mode Rejection Ratio (CMRR > 100 dB) is critical to eliminate 50/60 Hz power-line interference without relying on heavy digital notch filtering, which can distort ECG ST-segment waveforms. AC-coupled capacitive feedback networks naturally provide high DC CMRR, but AC CMRR is limited by mismatch in input coupling capacitors (Delta C / C). Employing active Right-Leg Drive (RLD) circuits or dynamic element matching (DEM) in input capacitor arrays mitigates mismatch effects, elevating operational CMRR beyond 110 dB under real-world skin-electrode impedance imbalances [37].

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LIMITATIONS

While this review provides comprehensive insights into ULP AFE circuit design, several inherent limitations should be noted:

- Measurement Standardization Differences: Published literature exhibits variations in test conditions, such as differing noise bandwidth integrations (e.g., 0.5–100 Hz vs. 0.1–1 kHz) and electrode source impedance models, which can slightly distort direct empirical comparisons [38].
- Physical Validation Constraints: The analysis relies primarily on published silicone-proven prototype measurements and analytical physical models; extended multi-patient clinical trial data evaluating long-term motion artifact suppression across diverse physical activity routines remains limited in literature [39].
- Focus on Electrical Bio-Potentials: The core detailed circuit models focus primarily on biopotential signals (ECG/EEG/EMG), while optical (PPG) and electrochemical bio-sensing AFEs involve distinct transimpedance amplifier (TIA) constraints that were addressed only secondary [40].

FUTURE SCOPE

To advance the state-of-the-art in wearable healthcare AFEs, future research should focus on the following promising directions:

- Machine-Learning-Assisted Adaptive AFEs: Integrating light-weight, edge AI hardware engines directly within the AFE to dynamically adjust bias currents, amplifier bandwidth, and chopper frequencies based on real-time signal-to-noise ratio (SNR) and detected patient activity levels [41].
- Ultra-High Impedance Non-Contact Capacitive Sensing: Developing sub-femtofarad parasitic input capacitance AFEs utilizing active bootstrapped shielding to enable high-fidelity bio-potential sensing through clothing or non-adhesive dry interfaces [42].
- Multi-Modal Monolithic Bio-SoC Integration: Designing unified, reconfigurable AFEs capable of simultaneously acquiring bio-potentials, optical PPG, bio-impedance, and electrochemical sweat biomarkers on a single single-chip SoC powered entirely by ambient energy harvesting [43].

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CONCLUSION

This paper presented a rigorous review and performance evaluation of ultra-low-power Analog Front-End (AFE) circuits designed for next-generation wearable healthcare devices. By systematically analyzing capacitive-coupled, chopper-stabilized, inverter-based, and subthreshold bulk-driven amplifier topologies, we highlighted critical multi-variable trade-offs between noise, power, CMRR, supply voltage, and input impedance. Quantitative benchmark analysis confirms that chopper-stabilized subthreshold current-reuse amplifiers offer superior energy efficiency (NEF < 2.1, PEF < 4.5) while maintaining exceptional common-mode rejection (>108 dB) under sub-1V power supplies. As wearable healthcare devices transition toward continuous, battery-less, point-of-care diagnostics, the design paradigms, circuit techniques, and architectural guidelines synthesized in this work provide an essential foundation for realizing sub-microwatt, clinical-grade biomedical SoCs.

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