IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 1, September 2026
Impact Factor: 8.2

# Design and Simulation of CMOS Operational Amplifiers: A Comprehensive Review of Architectures, Performance Trade-offs, and Emerging Design Methodologies

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**Abstract:** *The operational amplifier (Op-Amp) remains the fundamental building block in analog and mixed-signal integrated circuits, serving as the critical interface between the physical world and digital processing systems. This review paper provides a comprehensive examination of CMOS operational amplifier design and simulation methodologies, synthesizing findings from recent literature spanning 2023–2026. The review covers architectural evolution from basic two-stage topologies to advanced gain-boosting and compensation techniques, with particular emphasis on performance metrics including DC gain, gain-bandwidth product (GBW), phase margin, slew rate, and power efficiency. Through systematic analysis of simulation-based design approaches using Cadence Virtuoso, LTSpice, and emerging optimization algorithms such as the Bat Algorithm, this paper identifies key trade-offs between gain, bandwidth, stability, and power consumption. Comparative analysis reveals that Miller compensation with nulling resistors remains the dominant stability strategy, while optimization-based design methodologies demonstrate significant improvements—up to 39.1% power reduction and 20% gain enhancement over conventional approaches. The review also addresses emerging application domains including biomedical signal acquisition and ultra-low-power implantable devices, which impose stringent constraints on noise, power, and supply voltage. Future research directions are identified in the areas of automated design optimization, subthreshold operation, and technology scaling challenges.*

**Keywords** CMOS operational amplifier, Miller compensation, two-stage Op-Amp, simulation, gain-bandwidth product, phase margin

## I. INTRODUCTION

The operational amplifier stands as one of the most versatile and widely employed analog building blocks in modern electronics, finding applications spanning arithmetic circuits, active filters, data converters, biomedical instrumentation, and sensor interface circuits . As CMOS technology continues its relentless scaling trajectory into deep-submicron and nanoscale regimes, the design of high-performance operational amplifiers faces increasingly formidable challenges, including reduced voltage headroom, diminished intrinsic gain, elevated leakage currents, and heightened susceptibility to process, voltage, and temperature (PVT) variations .

The design and simulation of CMOS operational amplifiers constitute a multifaceted engineering problem requiring careful optimization across multiple, often conflicting performance dimensions. Gain, bandwidth, phase margin, slew rate, power consumption, and silicon area represent just a subset of the critical metrics that must be balanced against one another. The two-stage Miller-compensated architecture has historically dominated Op-Amp design due to its favorable balance of gain, output swing, and stability characteristics . However, contemporary applications—particularly those in the biomedical and Internet-of-Things (IoT) domains—demand increasingly aggressive power budgets and noise specifications that challenge conventional design approaches .


DOI: 10.48175/IJARSCT-38251

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This review synthesizes recent advances in CMOS operational amplifier design and simulation, drawing from a corpus of literature published between 2023 and 2026. The objectives are threefold: first, to provide a systematic overview of architectural topologies and their performance characteristics; second, to examine simulation methodologies and verification frameworks employed in contemporary design flows; and third, to analyze emerging optimization strategies and application-specific design considerations. Through this synthesis, the paper aims to identify enduring design principles, document state-of-the-art performance benchmarks, and illuminate future research trajectories.

## II. FUNDAMENTAL ARCHITECTURE AND DESIGN CONSIDERATIONS

### 2.1 Two-Stage CMOS Op-Amp Topology

The two-stage CMOS operational amplifier represents the canonical architecture for general-purpose analog amplification, offering a well-understood trade-off space between gain, bandwidth, and stability. The topology comprises a differential input stage followed by a common-source gain stage, with Miller compensation employed to ensure stability under feedback conditions .

The first stage, typically implemented as a differential pair with active current-mirror load, provides the bulk of the voltage gain while converting the differential input to a single-ended output. In the design documented by Eleanazeri, the first stage employs NMOS input transistors (M1, M2) with a PMOS current-mirror active load, biased at a tail current of approximately 13.2 µA per branch . The second stage, a common-source amplifier with current-source load, contributes additional gain and provides the output drive capability. Transistor sizing in this design ranges from W/L = 15 µm/2 µm for the tail current source to W/L = 50 µm/2 µm for the output stage driver, with all devices operating in saturation under nominal conditions .

A parallel implementation in TSMC 180nm technology documented by Sarma demonstrates similar architectural choices with distinct sizing for a 1.8 V supply . The input differential pair employs W/L = 6.5 µm/1 µm transistors biased at 30 µA each, while the second-stage common-source amplifier uses W/L = 60 µm/2 µm for the NMOS driver. The bias network utilizes a 10:1 mirror ratio from a 6 µA reference to establish the 60 µA tail current .

**Table 1: Comparative Transistor Sizing Across Two-Stage CMOS Op-Amp Implementations**

| Design Reference | Technology | Input Pair W/L (µm/µm) | Tail Current (µA) | Second Stage W/L (µm/µm) | Supply (V) |
|---|---|---|---|---|---|
| Eleanazeri | Not specified | 15/2 | 13.2 | 50/2 | — |
| Sarma | TSMC 180nm | 6.5/1 | 60 | 60/2 | 1.8 |
| EkagraM | TSMC 180nm | 4.348/0.5 | 67.15 | 50/0.5 | 1.8 |
| Sharma & Nath | 180nm | Not specified | — | — | 3.3 |

### 2.2 Compensation Strategies

Stability in multi-stage amplifiers is fundamentally challenged by the presence of multiple poles in the transfer function. Without compensation, the two-stage Op-Amp exhibits two dominant poles that can produce excessive phase shift at the unity-gain frequency, leading to oscillatory or unstable closed-loop behavior . Miller compensation addresses this challenge by introducing a capacitor (C_C) between the output of the first stage and the output of the second stage, creating a pole-splitting effect that pushes the dominant pole to lower frequencies while moving the non-dominant pole to higher frequencies .

The efficacy of Miller compensation is well-documented in the simulation results reported by Eleanazeri, where an initial Miller capacitance of approximately 1 pF yielded a phase margin of only 34.7°, failing to meet the 45° stability criterion . Doubling the compensation capacitance to 2 pF raised the phase margin to 50.68°, satisfying the specification while

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preserving a gain-bandwidth product of 6.685 MHz . This empirical relationship between compensation capacitance and phase margin underscores the critical trade-off between stability and bandwidth in Op-Amp design.

However, Miller compensation introduces a right-half-plane (RHP) zero due to the feedforward path through the compensation capacitor, which can degrade phase margin and stability. The nulling resistor technique, implemented by placing a resistor (R_z) in series with the Miller capacitor, addresses this issue by shifting the RHP zero to infinity or into the left-half-plane . In the design by Sarma, a 2.2 pF Miller capacitor with a 15 kΩ nulling resistor effectively eliminates the RHP zero while achieving stability . The design by EkagraM employs a similar strategy with C_c = 2.5 pF and R_z = 500 Ω, achieving a phase margin of 58.36° .

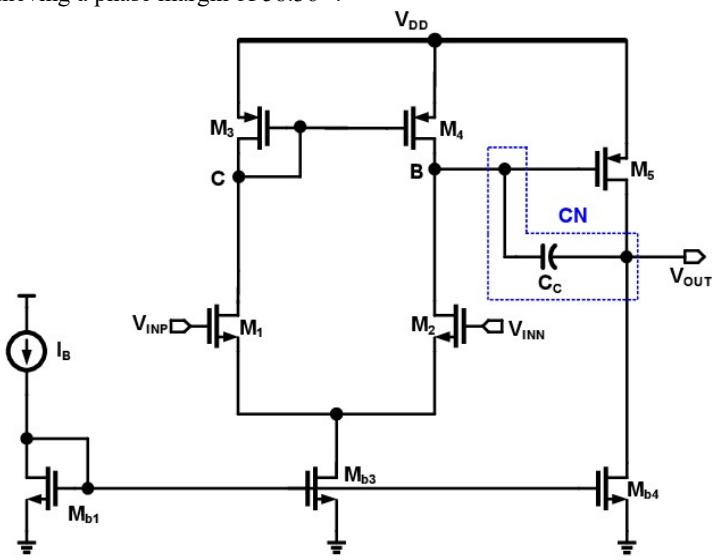


**Figure 1: Two-Stage Miller-Compensated CMOS Op-Amp Architecture**

### 2.3 Performance Metrics and Trade-offs

The performance characterization of CMOS operational amplifiers revolves around a core set of metrics that collectively define the amplifier's suitability for specific applications. DC open-loop gain determines the accuracy of closed-loop configurations and is fundamentally limited by the intrinsic gain (g_m·r_o) of the constituent transistors and the number of gain stages . Reported DC gains for two-stage architectures span 53.07 dB to 67.16 dB , with the variation attributable to differences in channel length, bias current, and technology node.

Gain-bandwidth product (GBW), representing the frequency at which the open-loop gain equals unity, is determined by the transconductance of the input stage and the compensation capacitance: GBW ≈ g_m1/(2πC_C). The designs surveyed demonstrate GBW values ranging from 6.685 MHz to 20.04 MHz , reflecting different optimization targets and technology capabilities.

Phase margin, the most critical stability metric, quantifies the margin against oscillation in closed-loop configurations. Values above 45° are generally considered acceptable, with 60° preferred for well-damped transient response. The designs examined achieve phase margins of 50.68° , 58.36° , and higher, demonstrating the efficacy of modern compensation techniques.

Slew rate, the maximum rate of output voltage change under large-signal conditions, is limited by the tail current and compensation capacitance: SR = I_tail/C_C. The design by Eleanazeri achieves 6.766 V/µs, exceeding its minimum specification by nearly sevenfold . Power consumption, increasingly critical for portable and implantable applications, ranges from 518.4 µW to sub-10 µW in subthreshold designs .

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**Table 2: Performance Comparison of CMOS Op-Amp Designs**

| Metric | Eleanazeri | Sarma | EkagraM | Subthreshold |
|---|---|---|---|---|
| DC Gain (dB) | 53.07 | ≥40 (target) | 67.16 | 60.1 |
| GBW (MHz) | 6.685 | — | 20.04 | 3.7 |
| Phase Margin (°) | 50.68 | — | 58.36 | — |
| Slew Rate (V/µs) | 6.766 | — | — | 2.0 |
| Power (µW) | ~145 | — | 518.4 | <10 |
| Supply (V) | — | 1.8 | 1.8 | — |

## III. SIMULATION METHODOLOGIES AND VERIFICATION FRAMEWORKS

### 3.1 Circuit Simulation Environments

Contemporary CMOS Op-Amp design relies on sophisticated electronic design automation (EDA) tools for simulation, verification, and optimization. Cadence Virtuoso, with its ADE L and ADE XL simulation environments, represents the industry-standard platform for analog IC design . The Virtuoso environment provides comprehensive capabilities for DC analysis (operating point verification, saturation checking), AC analysis (gain, phase, GBW extraction), transient analysis (slew rate, settling time), and specialized stability analysis (loop gain, phase margin via stb analysis) .

LTSpice, a freely available SPICE simulator, offers an accessible alternative for educational and preliminary design activities . The design by EkagraM demonstrates that LTSpice, combined with foundry-provided process design kits (PDKs), can achieve simulation results competitive with commercial tools, reporting a DC gain of 67.16 dB and phase margin of 58.36° for a TSMC 180nm implementation . PSPICE, another SPICE variant, has been employed for Op-Amp optimization studies, with simulations conducted using version 17.4 .

### 3.2 Design Verification Protocol

A comprehensive verification protocol for CMOS Op-Amps encompasses multiple analysis domains. DC analysis verifies that all transistors operate in the saturation region under nominal bias conditions and confirms that total supply current remains within budget . In the design by Eleanazeri, DC analysis confirmed a total supply current of 48.12 µA, comfortably within the 50 µA budget, with all devices verified in saturation .

AC analysis extracts the open-loop frequency response, from which DC gain, GBW, phase margin, and unity-gain frequency are derived. The stability (stb) analysis in Cadence Virtuoso provides an alternative method for phase margin extraction by directly measuring loop gain in closed-loop configurations, avoiding the need to break the feedback loop .

Transient analysis characterizes large-signal behavior, including slew rate and settling time. The unity-gain feedback configuration with a full-swing pulse input (0 V to 1 V) is commonly employed for slew rate measurement. The design by Eleanazeri achieved a slew rate of 6.766 V/µs under these conditions .

PVT (process, voltage, temperature) corner analysis and Monte Carlo simulation assess design robustness against manufacturing variations and environmental conditions. The design flow documented by Eleanazeri explicitly includes PVT corner verification and Monte Carlo analysis as part of the validation protocol .


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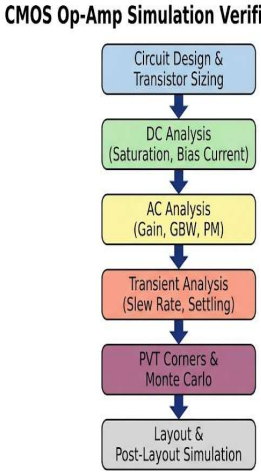


**Figure 2: Simulation Verification Flow for CMOS Op-Amp Design**

### 3.3 Optimization-Based Design Approaches

Traditional knowledge-based design methodologies, while effective, require substantial designer expertise and iterative manual tuning to achieve optimal performance. Recent research has explored optimization-based approaches that frame Op-Amp design as a constrained optimization problem amenable to automated solution . The synthesis process typically comprises two modules: an optimization-driven search module and a performance evaluation module that assesses circuit behavior at each iteration .

The Bat Algorithm (BA), a metaheuristic optimization technique inspired by bat echolocation behavior, has demonstrated significant promise for Op-Amp design optimization. In the study by Mohammed Rasheed and Motlak, BA-optimized design of a two-stage CMOS Op-Amp in 0.18 µm TSMC technology achieved dramatic performance improvements compared to conventional design: unity gain bandwidth doubled, voltage gain increased by 20%, power consumption decreased by 39.1%, and common-mode rejection ratio (CMRR) improved by 20% . These results underscore the potential of metaheuristic optimization to navigate the complex, multi-dimensional trade-off space of analog circuit design more effectively than manual approaches.

Evolutionary computation techniques more broadly have attracted attention for analog circuit synthesis. The Memetic Single-Objective Evolutionary Algorithm (MSOEA) combines conventional evolutionary operators with local search capabilities to handle the numerous complex design constraints characteristic of analog circuits . The successful application of such techniques to Op-Amp sizing suggests a pathway toward greater design automation in analog IC development.

**Table 3: Impact of Bat Algorithm Optimization on Op-Amp Performance**

| Metric | Conventional Design | BA-Optimized Design | Improvement |
|---|---|---|---|
| Voltage Gain | Baseline | +20% | 20% increase |
| Unity Gain BW | Baseline | 2× | 100% increase |
| Power Consumption | Baseline | −39.1% | 39.1% reduction |
| CMRR | Baseline | +20% | 20% increase |


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## IV. APPLICATION-SPECIFIC DESIGN CONSIDERATIONS

### 4.1 Biomedical and Bio-Potential Applications

The design of CMOS operational amplifiers for biomedical applications imposes unique constraints that fundamentally shape architectural and biasing choices. Bio-potential signals—including electrocardiogram (ECG), electroencephalogram (EEG), and electromyogram (EMG)—are characterized by low amplitude (typically 10 µV to 5 mV), low frequency content (0.1 Hz to 1 kHz for ECG, up to several kHz for EMG), and exposure to significant common-mode interference from power lines and other sources .

These signal characteristics drive several critical design requirements: high gain to amplify weak signals above noise floor, low input-referred noise to preserve signal fidelity, high common-mode rejection ratio (CMRR) to suppress interference, and high input impedance to avoid signal attenuation at the electrode-tissue interface . Additionally, the need to capture very-low-frequency signal components (sub-1 Hz for some ECG applications) places stringent demands on the amplifier's low-frequency gain and flicker noise performance.

The comprehensive review by Sharma and Nath surveys Op-Amp design methodologies specifically targeting industrial and biopotential applications . Their proposed design, implemented in 180nm CMOS with a 3.3 V supply, achieves 62.9449 dB gain, 92.8079 dB CMRR, and 33 MHz unity-gain bandwidth while occupying only 0.001476 µm² of layout area . The use of an active load resistor (MOS transistor) in place of conventional biasing circuitry simplifies the layout and reduces both area and power consumption .

For ultra-low-power implantable applications, subthreshold operation offers a pathway to dramatic power reduction at the cost of reduced bandwidth and increased sensitivity to process variations. A 45nm subthreshold CMOS Op-Amp with adaptive biasing achieves power consumption below 10 µW while maintaining 60.1 dB open-loop gain, 3.7 MHz gain-bandwidth, and 2.0 V/µs slew rate . Dynamic tail-current boosting ensures fast transient response while conserving power during idle periods—a critical capability for duty-cycled biomedical monitoring systems .

### 4.2 Arithmetic and Filtering Applications

Operational amplifiers employed in arithmetic processing units and active filters must satisfy a distinct set of performance criteria. Arithmetic applications—including analog multipliers, dividers, and weighted summers—demand high linearity and precise gain matching, while active filters require well-controlled frequency response and phase characteristics . The high-performance CMOS Op-Amp design reported by the 2026 IEEE conference paper addresses these requirements through systematic transistor-level optimization in Cadence Virtuoso, emphasizing device sizing, compensation strategies, and bias current selection .

## V. ADVANCED TECHNIQUES FOR PERFORMANCE ENHANCEMENT

### 5.1 Gain Boosting

The intrinsic gain of a single CMOS transistor, limited by channel-length modulation and short-channel effects, is often insufficient for high-precision applications requiring gains exceeding 80–90 dB. Gain-boosting techniques address this limitation by increasing the effective output impedance of the amplifier through auxiliary feedback loops .

Cascode gain boosting employs an auxiliary amplifier to regulate the gate voltage of a cascode transistor, maintaining the drain voltage of the input transistor at a constant value despite output voltage variations. This regulation dramatically increases the output impedance by a factor equal to the auxiliary amplifier's gain . The folded-cascode architecture with fully differential boosters described in the TU Delft work achieves high gain while maintaining adequate output swing through careful management of voltage headroom .

The auxiliary gain-boosting amplifiers introduce their own poles into the system, potentially degrading phase margin. The source-gate capacitances of the boosted transistors form Miller capacitances that can reduce the second pole frequency . Careful design of the auxiliary amplifier bandwidth and the addition of compensation capacitors at the auxiliary amplifier outputs can mitigate these effects .

An alternative gain enhancement approach employs negative resistance elements implemented as cross-coupled CMOS inverters placed between differential output nodes . This technique cancels the amplifier's output resistance, providing

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gain enhancement in excess of 40 dB with full output swing and minimal circuit area and power overhead . The simplicity of the cross-coupled inverter implementation makes this approach attractive for area-constrained designs.

### 5.2 Offset Compensation

Input offset voltage—the differential input voltage required to produce zero output—remains a persistent non-ideality in CMOS Op-Amps, arising from random mismatch in transistor parameters and systematic asymmetries in the circuit topology. For precision applications, offset voltages in the millivolt range can be unacceptable.

Conventional offset compensation techniques include autozeroing, which samples and subtracts the offset during a calibration phase, and chopper stabilization, which modulates the signal to a higher frequency where offset and flicker noise are less significant. However, these switched techniques introduce non-idealities including charge injection, clock feedthrough, and limited bandwidth .

A continuous-time offset compensation architecture based on quasi-infinite resistors and ultra-low-frequency analog feedback loops has been proposed to eliminate switches, modulation signals, and high-gain auxiliary amplifiers from the compensation path . This approach preserves the bandwidth of the main signal path while avoiding switching-induced artifacts. Experimental validation in ON Semiconductor 0.5 µm CMOS demonstrates 76° phase margin, 4.5 µA supply current, and 0.19 mm² die area with 1.4 mW power consumption .

## VI. CHALLENGES AND FUTURE DIRECTIONS

### 6.1 Technology Scaling Challenges

The continued scaling of CMOS technology into the nanometer regime introduces fundamental challenges for analog design. Reduced supply voltages limit signal swing and voltage headroom, while transistor intrinsic gain ($g_m \cdot r_o$) degrades due to short-channel effects and increased output conductance . Process variations become more pronounced at smaller geometries, increasing the spread of critical parameters and demanding more conservative design margins or sophisticated calibration techniques.

The design of operational amplifiers in deeply scaled technologies may require a departure from conventional architectural approaches. Gain-boosting and multi-stage topologies become increasingly necessary to achieve adequate gain, while compensation becomes more challenging due to the reduced ratio between transit frequency ($f_T$) and required bandwidth. Digital-assisted analog techniques, in which digital calibration corrects for analog non-idealities, represent a promising direction for maintaining performance in scaled technologies.

### 6.2 Design Automation and Optimization

The gap between the complexity of analog design problems and the effectiveness of available automation tools remains a significant bottleneck in analog IC development. While digital design has benefited enormously from synthesis and place-and-route automation, analog design continues to rely heavily on expert intuition and iterative manual optimization .

Optimization-based design methodologies, including metaheuristic algorithms such as the Bat Algorithm and evolutionary approaches like MSOEA, offer a pathway toward greater automation . However, these techniques face challenges in handling the full complexity of analog design problems, including multiple conflicting objectives, discrete and continuous design variables, and stringent constraint satisfaction. Future research should focus on developing more efficient optimization algorithms, improving the integration of simulation engines with optimization frameworks, and creating knowledge-based systems that capture and leverage designer expertise.

### 6.3 Emerging Application Domains

The proliferation of IoT devices, wearable sensors, and implantable medical devices is creating new and demanding requirements for CMOS operational amplifiers. Ultra-low-power operation, often in the subthreshold regime, becomes essential for battery-powered or energy-harvesting systems . Robustness to supply voltage variations and temperature fluctuations is critical for reliable operation in uncontrolled environments.

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Biomedical applications demand not only low power but also low noise, high input impedance, and safety compliance for direct patient contact. The integration of Op-Amps with sensors, analog-to-digital converters, and digital processing on a single chip raises additional challenges related to substrate noise, crosstalk, and thermal management.

## VII. CONCLUSION

This review has examined the design and simulation of CMOS operational amplifiers, synthesizing recent advances across architectural topologies, compensation techniques, optimization methodologies, and application-specific considerations. The two-stage Miller-compensated architecture remains the workhorse of general-purpose analog amplification, with documented designs achieving DC gains of 53–67 dB, GBW of 6.7–20 MHz, phase margins exceeding 50°, and slew rates of approximately 7 V/μs . The critical role of compensation capacitance in determining stability has been empirically demonstrated, with phase margin improvements from 34.7° to 50.68° achieved through doubling of the Miller capacitor .

Optimization-based design approaches, exemplified by Bat Algorithm application, demonstrate substantial potential for performance enhancement, with reported improvements including 100% increase in unity-gain bandwidth, 20% gain enhancement, and 39.1% power reduction . These results suggest that metaheuristic optimization can effectively navigate the complex trade-off space of analog circuit design.

Application-specific requirements drive architectural divergence. Biomedical signal acquisition demands high CMRR, low noise, and high input impedance, with subthreshold designs achieving sub-10 μW power consumption at the cost of reduced bandwidth . Gain-boosting techniques extend the achievable gain of cascode architectures, while continuous-time offset compensation eliminates the non-idealities of switched approaches .

Future research directions should address technology scaling challenges, improve design automation through advanced optimization and knowledge-based systems, and develop application-optimized architectures for emerging domains. The integration of machine learning techniques with analog design methodologies represents a particularly promising avenue for addressing the complexity of modern analog IC design.

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