

AI-Driven Capacitor Optimization for Advanced Power Integrity Analysis in Semiconductor Circuit Designs

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ABSTRACT

Capacitor selection and optimization are crucial for power integrity in high-speed electronic systems. However, finding the optimal combination of capacitor values, types, and placements while meeting performance goals is a complex task. This article introduces an AI-based capacitor optimizer that integrates machine learning techniques with circuit and electromagnetic simulators to tackle capacitor optimization more efficiently. The optimizer automates the iterative process of proposing capacitor schemes, simulating their performance, and learning from the results. This method significantly reduces time and costs by streamlining the optimization process. The AI system learns from previous simulations, improving the accuracy and efficiency of capacitor selection. This approach is applicable to various industries, including consumer, automotive, and telecommunications. The AI capacitor optimizer represents a significant advancement in capacitor selection and optimization, allowing engineers to achieve better results in less time and with fewer resources.

THE CHALLENGE OF POWER DELIVERY NETWORK INTEGRITY

The power delivery network (PDN) is crucial in modern electronic systems, transporting stable voltage from power sources to switching loads. Maintaining power integrity is increasingly important as semiconductor processing technologies scale down and system integration becomes complex. Excessive voltage noise and ripple can cause timing violations, performance degradation, and functional failure. PDN design is a critical and challenging aspect of system design.

DOI: 10.4018/407393

LITERATURE REVIEW

Research on Power Delivery Network (PDN) design has evolved from empirical capacitor-placement heuristics to advanced AI-driven optimization frameworks. Early studies (Choi & Swaminathan, 2011) employed analytical and finite-element modeling to minimize PDN impedance, but the process required extensive manual tuning and long simulation time. Later, metaheuristic algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Simulated Annealing (SA) were introduced to automate capacitor selection and placement. These methods provided flexibility in exploring design space but suffered from slow convergence and heavy reliance on repeated full-wave simulations.

To accelerate optimization, surrogate-assisted frameworks emerged. (Cecchetti et al. 2020) demonstrated that training an Artificial Neural Network (ANN) on PDN impedance data could approximate solver outputs with much lower runtime. This hybrid GA-ANN approach achieved nearly a 30× reduction in computation time, though its accuracy degraded for unseen topologies and high-frequency parasitic effects. Likewise, simplified cavity-resonance and reduced-order models (Wang et al., 2024) improved speed but lacked fidelity beyond 1 GHz, leaving a persistent trade-off between modeling precision and scalability.

Recent efforts have shifted toward Deep Reinforcement Learning (DRL) for intelligent capacitor placement. (Zhang et al. 2023) and (Jiang et al. 2024) framed PDN decoupling as a sequential decision problem solved via Proximal Policy Optimization (PPO) and Convolutional Neural Networks (CNNs). These DRL agents achieved comparable impedance targets using 30–40% fewer capacitors and one-tenth the runtime of conventional GA approaches. However, DRL adoption remains limited by its data-hungry training process, lack of manufacturability awareness, and minimal coupling with industrial EDA tools.

Identified gaps include:

- Incomplete integration of AI optimizers with commercial solvers (Cadence Sigrity, Keysight ADS).
- Absence of manufacturing, cost, and thermal constraints in optimization objectives.
- Poor interpretability of learned capacitor-placement strategies.
- Need for physics-informed hybrid models combining analytical equations with learning-based intelligence.

The current chapter addresses these deficiencies through an AI-assisted, physics-aware PDN optimization workflow that unites learning efficiency, manufacturability, and electromagnetic accuracy -bridging academic innovation with real-world hardware design.

THE ROLE OF DECOUPLING CAPACITORS

Decoupling capacitors are crucial in PDN noise mitigation, acting as local charge reservoirs to quickly provide transient current demands and dampen voltage fluctuations. They minimize impedance between power and ground planes, ensuring PDN impedance remains below a specific mask.

This target impedance is often determined by the permissible voltage fluctuation (ΔV) and the maximum anticipated change in current (ΔI), following the relationship:

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