A synopsis report on

Analog/RF Circuit Optimization using Adjoint Network Sensitivity Analysis and Metaheuristics

submitted by

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1 Introduction

The development of system-on-chip, consisting of analog and digital circuits, have become a crucial area of research due to the ever-increasing demand for miniaturization and compact devices. The induction of Internet-of-things (IoT) devices has made analog circuit design more challenging due to low power requirement. In the modern era, the design specifications of analog circuit are becoming more demanding with the advancements in IC fabrication techniques. Analog circuits consume a significant part of resources (knowledge intensive design efforts) and time, during a system design process. Therefore, the automation of analog circuit design is gaining importance to achieve time-to-market goals. The design methodology for analog and RF circuit sizing has evolved from "pen and paper" approach to an optimization scheme via simulation-based approach. In general, analog circuit designers derive design equations for circuit design (sizing) and solve them for a given set of specifications. Recently, various numerical simulation methods [1] have been presented to study circuit performance. With the advent of new methodologies, development of efficient circuit simulators has become essential for analog design process-flow. The performance evaluation of analog circuits, which undergoes a complicated design process, empowers circuit simulators to iteratively modify design variables through the use of optimization techniques [2]. With the scaling down od technology, analysis and design of analog circuits become more complex and it becomes vital to analyze tradeoffs among various design specifications *simultaneously* to meet a certain process yield. Hence, there is a growing need for efficient optimization methodologies in automated design process environment as circuit sizing tools.

2 Brief Review of Literature

Sizing of a circuit is carried out by using either topology specific fixed design plan [3, 4] or performing random numerical simulations during optimization [5]. Fixed design plan emphasizes on solving a set of equations for a given set of design variables representing both performance and characteristics of circuit. In order to facilitate the process of optimization, sometimes first order expressions are considered neglecting the higher order terms. Although the computational effort is less, omitting higher order terms during cost function formulation leads to issues related to reliability and robustness. On the other hand, taking random numerical steps in a nature-inspired pattern [3, 4, 6] with associative features (advanced device models) to carry out optimization introduces flexibility in exploring design space to preserve diversity and in achieving the optimum solution with minimum computational effort.

Further, with more than one cost functions are to be analyzed simultaneously, the design space becomes more diversified with multiple design variables bounded by constraints and the complexity increases with increase in their number [7]. As two cost functions are competing to achieve optimality, transforming the problem into single objective optimization problem is complicated and finding an optimal solution is rather difficult [8]. To address this issue, several methods have

been suggested for modeling design space [6, 9]. These models aim to capture the prominent functionalities of circuits to speed up the process of optimization. Both stochastic and deterministic approaches are employed in literature to generate a class of macromodels [9, 10]. However, with the reduction in feature size, the effect of design parameters has become more pronounced, and design of an efficient macromodel of a circuit became quite challenging. Therefore, it is necessary to have an efficient system-level design methodology with adequate functionalities (macromodel) to capture the optimum performance of a circuit.

Various efforts on stochastic search algorithms especially nature-inspired algorithms, have been made to optimize the design of analog/RF circuits. Genetic algorithm (GA) is one of the popular optimization method, which has been employed for analog circuit optimization in both industry and academia [3, 4]. With different circuits, other nature-inspired algorithms, e.g., particle swarm optimization (PSO) [11], simulated annealing (SA) [12], ant colony optimization (ACO) [13] etc., have also been applied in the form of design space boundary exploration techniques. For example, these techniques have been applied for optimization of different digital filters [14, 15]. Several variants of GAs have been employed to design CMOS operational amplifier circuits with constrained topologies. Genetic programming is used as an analog synthesis tool in several filter designs and circuit synthesis problems [4].

However, different methods have been presented for analog circuit sizing, there is need to develop techniques aimed towards superior performance in terms of efficiency, accuracy and applicability. With the increased number of components in an analog circuit, the interdependency of design variables increases resulting in a more complex optimization problem. To handle such problems, development of robust as well as scalable methods has always been an active research interest among circuit designers' community.

3 Thesis Motivation and Objective

In analog circuit optimization, sensitivity analysis plays an important role in determining the critical design parameters. Sensitivity analysis can be viewed as a mathematical measure of variations in the performance metrics due to infinitesimally small perturbations of circuit parameters [16]. The main advantage of adjoint network based sensitivity analysis approach is low computation cost (i.e., the order of (N+1)). The CPU-time of adjoint sensitivity analysis is significantly low in comparison with direct forward/backward finite-difference sensitivity approximations [17]. This approach has been demonstrated by applications in microwave circuits [17–19]. The application of this methods for analog circuits is rarely reported. Hence, in this work, the extension of this method for the optimization of analog circuits is aimed.

Further, due to the flexibility in the application, nature-inspired algorithms have become popular among analog circuit designers. The concept of *survival of the fittest* enables a detailed selection process for complete exploration of performance space to obtain optimal solutions. The cost func-

tions can be optimized by using nature-inspired algorithms subject to a set of conditions or constraints. Although particle swarm optimization (PSO) has been an popular method used for finding optimum solutions, it has a disadvantage of being trapped locally and having slow convergence. Simulated annealing has a tendency to reach local optimum based on a serial stochastic search strategy [20]. Therefore, to improve the search performance of PSO, a metaheuristic, combining both PSO and SA is aimed to optimize analog circuits.

As circuit modeling is often affected by uncertainties and errors at many levels, it is necessary to analyze tradeoffs among performance specifications to avoid inconsistent solutions during design. To overcome these problems, several multi-objective techniques have been proposed with an emphasis on nature-inspired algorithms because of their inherent ability and efficiency in handling uncertainty during circuit design flow. An efficient multi-objective optimization framework is required to be developed to generate Pareto fronts for analog/RF circuits.

The objective of this thesis is to develop optimization methods for analog/RF circuits by using sensitivity analysis and hybrid of evolutionary algorithms. In order to achieve these goals, key tasks, which need to be accomplished, are as follows:

- Design of a framework to compute sensitivity of analog circuit's response.
- Improvement of search strategy using the hybrid of PSO and SA.
- Formulation of temperature mapping scheme as an initialization scheme for SA in hybrid framework.
- Development of multi-objective optimization scheme using the PSO-SA hybrid.

4 Thesis Organization

The thesis is organized as follows:

Chapter 1: Introduction

Analog/RF circuit optimization, using sensitivity analysis and evolutionary algorithms, is introduced in this chapter. The motivation towards the proposed work is discussed along with the objectives and contributions of the thesis. Further, the highlights of subsequent chapters are presented as thesis organization.

Chapter 2: Fundamentals of Optimization Techniques in Analog Circuit Sizing

In this chapter, evolution of various optimization methods for analog/RF circuits is discussed. Different existing methodologies for the performance optimization of analog/RF circuits, are reviewed.

The fundamentals of problem formulation for analog/RF circuits along with the evolutionary algorithms are also discussed in this chapter.

Chapter 3: Sensitivity Analysis and Circuit Optimization

In this chapter, a gradient-based method for the optimization of analog circuits using adjoint network based sensitivity analysis (ANSA) is presented. By analyzing analog circuit and its adjoint transformation, sensitivities of the circuit response with respect to different parameters can be computed. The formulation of adjoint networks, calculation of sensitivity of circuit's response with respect to various design parameters and modification in the design parameters values in every iteration are described in this chapter. In order to verify the effectiveness of the proposed method it is employed to optimize the performance of a two-stage operational amplifier (OpAmp). Subsequently, the OpAmp circuit is simulated using Cadence Virtuoso for optimized parameters and the results are validated with post fabrication measurement results as well.

Chapter 4: Analog Circuit Optimization using Metaheuristics

This chapter presents the development of evolutionary algorithms for analog circuit optimization. A metaheuristic (HPSO) based on PSO and SA is presented to optimize analog/RF circuits subject to a variety of design constraints. Here, convergence of PSO is improved by advancing through local solutions using SA to achieve the global optimum solution. PSO is applied to construct initial solutions for SA and these initial solutions are used to decompose the entire search space into different annealing regions. The results obtained by proposed method are compared with standard optimization methods to show the performance of the proposed method in terms of optimization quality and robustness. Further, HPSO is extended (l-HPSO) by incorporating Lévy flight principle to improve the convergence. The proposed optimization scheme is implemented for common analog/RF circuit optimization and the obtained result are compared with the results generated by standard test functions.

Chapter 5: Multi-objective Optimization of Analog Circuits using Metaheuristics

This chapter presents a hybrid multi-objective optimization framework (MHPSO) by combining particle swarm optimization and simulated annealing. In order to reduce manual efforts in the process of circuit design, tradeoffs among performance specifications are need to be analyzed using multi-objective optimization methodologies. The framework emphasizes on preserving nondominated solutions in an external archive. The multi-dimensional space excluding the archive is divided into several sub-spaces according to a velocity-temperature mapping scheme. Further, the solutions in each sub-space are optimized using simulated annealing for generation of a Pareto front. The

framework is extended by incorporating crowding distance comparison operator (MHPSO-CD) to maintain nondominated solutions in the archive. The effectiveness of proposed methodologies is demonstrated for performance space exploration of three electronic circuits, namely, a two-stage operational amplifier, a folded cascode operational amplifier and a low noise amplifier with inductive source degeneration. Further, the performance of proposed algorithms (MHPSO, MHPSO-CD) are evaluated on various test functions and the results are compared with standard multi-objective evolutionary algorithms.

Chapter 6: Conclusions and Future Work

In this chapter, summary of the proposed works is presented. Future scope along with the different possible applications is discussed in this chapter.

5 Thesis Contributions

Different methodologies are proposed to produce optimized circuit parameters for the given performance. These methods are validated by optimizing basic analog circuits. The work can be classified into two broader parts. In the first part, circuit optimization method is developed by using adjoint network based sensitivity calculation. Whereas, hybrid evolutionary algorithms are developed for analog/RF circuit optimization in the second part. Further, a multi-objective framework is also developed by using hybrid evolutionary algorithms to analyze the performance space of circuits as an aid to circuit designers. The key contributions of the thesis are as follows:

- A method of analog circuit optimization using adjoint network based sensitivity analysis is developed.
- A metaheuristics, hybrid evolutionary algorithm based on PSO and SA, is developed for analog/RF circuit optimization. An extension of this metaheuristic is proposed based on an improved search strategy.
- A multi-objective hybrid evolutionary algorithm is developed to study tradeoffs of various parameters related to performance optimization in analog/RF circuit design.
- Experimental results are verified by comparing them with the state-of-art optimization techniques for different test circuits and standard test functions. We report significant improvement by proposed methods over various existing approaches in this thesis.

An overview of the contribution made in different chapters is as follows:

- **Chapter 3**
  The analytical model or equation-based problem formulation of an analog circuit optimization problem is evaluated via classical optimization scheme. The essence of proposed method

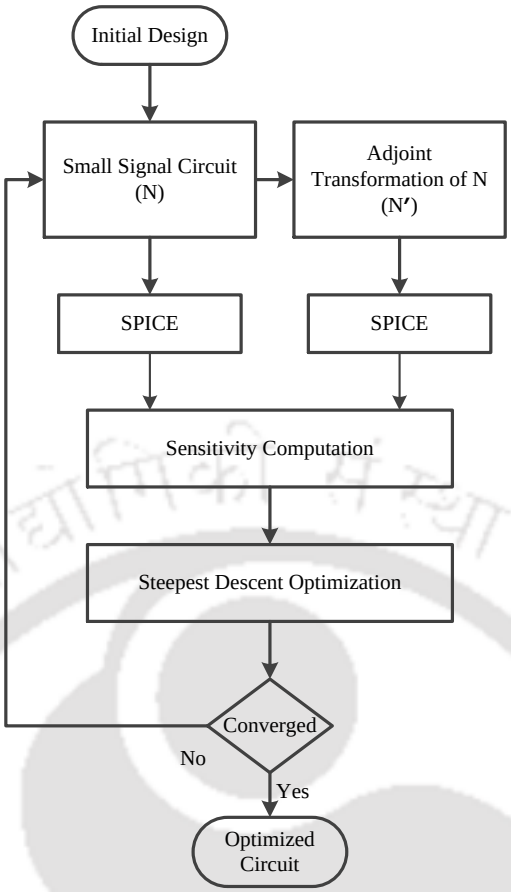

Figure 1: Optimization Flow of ANSA

is the reduction in computation cost of gradient calculation. The gradient of a cost function defines the direction of minimum cost and is calculated in steepest descent method. Sensitivities of circuits response with respect to circuit elements are simultaneously calculated by solving the original circuit and its adjoint transformation. These sensitivities provide the gradient vector of the cost function. This gradient can be used as an optimal direction in steepest descent optimization method. The optimization process flow using ANSA is presented in Figure 1.

The applicability and effectiveness of the proposed method are demonstrated by designing the basic analog circuits, cascode amplifier and two-stage operational amplifier, and the results are verified by employing commercial EDA tool provided by Mentor Graphics. Further, a two-stage operational amplifier is designed using ANSA and fabricated with 180 nm CMOS bulk technology. The post fabrication measurement results of two-stage OpAmp are compared with the simulation results of optimal circuit obtained using the proposed method.

- **Chapter 4**

  A combination of PSO and SA, HPSO and its extension l-HPSO, employing Lévy flight mechanism to improve the search capability of PSO, are proposed in this chapter. The effectiveness and applicability of the proposed methods are validated by optimizing basic ana-

log/RF circuits and comparing the results with existing standard methods in literature.

In Table 1, gain and noise figure are presented with the number of function evaluations. The smaller number of function evaluation indicates faster convergence of a particular algorithm. Therefore the smaller number of function evaluation and better value of cost function (larger gain or smaller NF) denote the superior performance. Further, the proposed methods are tested on standard benchmark functions.

Table 1: Comparison of Proposed HPSO and l-HPSO with different algorithms (Values shown are in format of cost of objective function (function evaluation))

Algorithms	Two-stage opamp	Folded cascode opamp	LNA
	Gain(dB)	Gain(dB)	NF(dB)
gGA	67.02(1200)	73(1000)	0.27(1220)
SADE	68(890)	73.01(800)	0.43(1150)
SPSO	68.96(1022)	73(1010)	0.35(1200)
CRPSO	68.99(1020)	73.56(1000)	0.38(1200)
LPSO	69.85(800)	72.85(750)	0.72(800)
ALCPSO	42.06(300)	75.04(220)	0.62(210)
HPSO	73.12(230)	**75.66(220)**	0.62(210)
***l*-HPSO**	**75.12(220)**	75.03(220)	**0.67(200)**

- **Chapter 5**

  The multiobjective optimization methods (MHPSO and MHPSO-CD) are developed for analog/RF circuit optimization. The proposed method provides a set of optimized solution (also known as Pareto fronts) subject to performance tradeoffs. Pareto fronts generated by the proposed methods are assessed qualitatively based on the hypervolume quality indicator (as shown in Table 2). Pareto fronts with higher hypervolume represent better quality of optimized solutions in terms of diversity of solutions. MHPSO and MHPSO-CD provide superior hypervolume for all three test circuits. In Table 2, b/e/w presents the number of test functions where MHPSO and/or MHPSO-CD are better, equal to, or worse than the other cited methods with the significance level of 0.05, respectively. It may be noted that the proposed algorithms have produced better Pareto fronts for analog and RF circuits, in terms of diversity and density of nondominated solutions in the objective space. Further, the proposed methods are also validated for the standard test functions.

Table 2: Hypervolume values for analog circuit optimization problems.

Algorithm	Two-stage opamp	Folded cascode opamp	LNA
NSGA-II	0.6045	0.8371	0.6012
NSGA-II-DE	0.6980	0.8461	0.6421
MOEA/D-DE	0.6494	0.7021	0.7256
PESA-II	0.5996	0.7433	0.5982
SPEA-II	0.6079	0.7312	0.6085
DMOPSO	0.6081	0.6086	0.5912
OMOPSO	0.7080	0.7997	0.7134
SMPSO	0.8029	0.8200	0.7465
MHPSO	0.8345	0.8361	0.7496
MHPSO-CD	**0.8556**	**0.8472**	**0.7782**
b/e/w	8/0/0	8/0/0	8/0/0

List of Publications

Journal Publications:

- **Deepak Joshi**, Satyabrata Dash, HS Jatana, Ratnajit Bhattacharjee and Gaurav Trivedi, "Analog circuit optimization using adjoint network based sensitivity analysis", in *AEU - International Journal of Electronics and Communications*, Volume 82, 2017, Pages 221-225, ISSN 1434-8411, https://doi.org/10.1016/j.aeue.2017.08.053.

Conference Publications:

- **Deepak Joshi**, Satyabrata Dash, Ayush Malhotra, Pulimi Venkata Sai, Rahul Das, Dikshit Sharma and Gaurav Trivedi, "Optimization of 2.4 GHz CMOS Low Noise Amplifier using Hybrid Particle Swarm Optimization with Lévy Flight", *30th International Conference on VLSI Design*, Hyderabad, 2017.

- **Deepak Joshi**, Satyabrata Dash, Ujjawal Agarwal, Ratnajit Bhattacharjee and Gaurav Trivedi, "Analog Circuit Optimization Based on Hybrid Particle Swarm Optimization", *International Conference on Computational Science and Computational Intelligence*, Las Vegas, 2015.

- **Deepak Joshi**, Satyabrata Dash, Ratnajit Bhattacharjee, Gaurav Trivedi, "A method of analog circuit optimization using adjoint sensitivity analysis", *25th International Conference on Radioelektronika*, CZ, 2015. (Student Best Oral Paper Award)

Manuscripts Under Review

- **Deepak Joshi**, Satyabrata Dash, Y. Sushanth Reddy, M. Rahul Reddy, and Gaurav Trivedi, "Multi-objective Hybrid Particle Swarm Optimization and its Application to Analog and RF Circuit Optimization ", in *IEEE Transactions on Cybernetics* (under review)

Manuscripts Under Preparation

- **Deepak Joshi**, Satyabrata Dash, and Gaurav Trivedi, "Hybrid Particle Swarm Optimization with Aging Leader and Challengers and its Application to Analog and RF Circuit Optimization ", *Under Preparation*
- **Deepak Joshi**, Satyabrata Dash, and Gaurav Trivedi, "Hybrid Particle Swarm Optimization with Heterogeneous Strategy and its Application to Analog and RF Circuit Optimization ", *Under Preparation*

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