# PERFORMANCE AND YIELD OPTIMIZATION OF ELECTRONIC DEVICES AND CIRCUITS

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## Abstract

We review our recent work in performance and yield optimization (design centering) of electronic devices and circuits. While the problem formulations are usually nonlinear, we have used algorithms employing trust regions and linear programming for the minimax and $\ell_1$ formulations. The algorithms are implemented in the software system OSA90/hope™. OSA90/hope is a general purpose design optimization system oriented towards the optimization of high frequency analog electrical circuits. Optimization applications include electronic device modeling and parameter extraction, and performance- and yield-driven design of microwave integrated circuits. Features such as arbitrary nonlinear topology, symbolic subcircuit definitions, high-speed interaction with users' programs and the ability to define optimization problems in a versatile manner using expressions enhance the user-friendly optimization environment. In particular, results are presented of interfacing OSA90/hope with external simulators such as electromagnetic field simulators, for direct inclusion of these simulators into the circuit optimization process.

## Summary

Yield-driven design is recognized as effective, not only for massively manufactured circuits, but also to ensure first-pass success in any design where the prototype development is lengthy and expensive [1,2]. The complexity of calculations involved in yield optimization requires special numerical techniques. With the increasing availability of electromagnetic simulators it is very tempting to include them into performance-driven and even yield-driven circuit optimization. However, direct utilization of electromagnetic simulation for yield optimization or sensitivity analysis might seem to be computationally prohibitive [2].

Electromagnetic simulators, though computationally intensive, are regarded as accurate for microwave circuit analysis and validation, extending the validity of device models to higher operating frequencies, including millimeter-wave frequencies, and cover wider parameter ranges. The electromagnetic simulators, whether stand-alone or incorporated into CAD frameworks, will not realize their full potential to the designer (whose task is to come up with the best parameter values satisfying design specifications) unless they are driven by optimization routines to automatically adjust designable parameters.

In a recent paper [3], we reported results on minimax microwave filter design with electromagnetic simulations driven directly by a gradient based minimax optimization algorithm [4]. Challenges of efficiency, discretization of geometrical dimensions, and continuity of optimization variables are reconciled by a three stage attack: (1) efficient on-line response interpolation w.r.t. geometrical dimensions of microstrip device structures simulated with fixed grid sizes, (2) smooth and exact gradient evaluation for use in conjunction with the proposed interpolation, and (3) storing the results of expensive electromagnetic simulations in a dynamically updated data base. Design optimization of a double folded stop-band filter and of a millimeter-wave 26-40 GHz interdigital capacitor band-pass microstrip filter illustrates the technique [3]. Our concepts have been implemented in Empipe™ [5], an interface suitable for an electromagnetic simulator to be driven by OSA90/hope [6].

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We have developed a sophisticated hierarchical multidimensional response surface modeling system for efficient yield-driven design [7]. Our scheme dynamically integrates models and data base updating in real optimization time. The method facilitates a seamless, smart optimization-ready interface. It has been specially designed to handle circuits containing complex subcircuits or components whose simulation requires significant computational effort. This approach makes it possible to perform direct gradient-based yield optimization of circuits with components or subcircuits simulated by an electromagnetic simulator.

Efficiency and accuracy of our technique are demonstrated by yield optimization of a three-stage microstrip impedance transformer and a small-signal microwave amplifier. For the three-stage microstrip transformer we additionally perform yield sensitivity analyses and investigate different sets of optimization variables. Optimization was performed by OSA90/hope with Empipe. We employed the OSA90/hope one-sided $\ell_1$ algorithm [8] for yield optimization.

Engineering designers are often concerned with the robustness of numerical optimization techniques, and rightly so, knowing that engineering data is, with few exceptions, contaminated by model/measurement/statistical errors. The classical least-squares ($\ell_2$) method is well known for its vulnerability to gross errors: a few wild data points can alter the least-squares solution significantly. The $\ell_1$ method is robust against gross errors [9,10,11]. When data contains many small errors (such as statistical variations), the $\ell_1$ solution can be undesirably biased toward a subset of the data points.

We have implemented an approach to "robustizing" circuit optimization using Huber functions [12,13,14,15]. Advantages of the Huber functions for optimization in the presence of faults, large and small measurement errors, bad starting points and statistical uncertainties have been investigated [16]. In this context, comparisons were made with optimization using $\ell_1$, $\ell_2$ and minimax objective functions. A wide range of significant applications is illustrated, including device statistical modeling, microwave multiplexer optimization, analog fault location [17] and data fitting. (The analog fault location problem is a particularly interesting one in its own right as an application area for linear programming techniques [17,18,19]).

For large-scale problems, systematic decomposition techniques are employed to reduce computational time and prevent potential convergence problems [20]. In practice, a designer often attempts, by intuition, a "preliminary" optimization with a small number of dominant variables. A full-scale optimization is performed if and when a "reasonably good" point is obtained.

With a temporarily reduced number of optimization variables, an optimization algorithm may not be able to adequately reduce all error functions at the same time. For instance, a design specification may be violated more severely at some sample points than at the others. In such situations, a minimax method is preoccupied with the worst-case errors and therefore becomes ineffective or inefficient. We extended the Huber concept by introducing a "one-sided" Huber function for large-scale optimization [16]. We demonstrated, through microwave multiplexer optimization, that the one-sided Huber function can be more effective and efficient than minimax in overcoming a poor starting point.

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