Optimization Methods In The Computer-Aided Design Of Microwave Non-Linear Active And Passive Circuits

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Abstract: -This paper presents the various types of optimization methods that are employed in the computer-aided design of microwave active and passive circuits. The optimizers also have different methods for error function formulation in order to arrive at the desired circuit response. It brings out the role and significance of these methods and their effect on the achievable performance parameters of the active and passive circuits. In the present paper, we concentrate on aspects that are relevant to and necessary for the continuing move to optimization of increasingly more complex microwave active and passive circuits, in particular non linear circuits like mixer, oscillator, etc.

INTRODUCTION

To Optimize design procedures for various types of microwave circuits to meet the given circuit or subsystem specifications successfully, a computer-aided design (CAD) approach becomes necessary. When the CAD approach is used, experimental modifications of the circuit (which are unavoidable in the conventional design procedure) are replaced by a computer-based simulation and optimization of the initial design. In communication amplifiers, any non-linearity in the phase and amplitude of the voltage-transfer characteristics must be minimized to preserve the shape and spectral content of the signal. As in the case of linear circuits, for nonlinear circuits also, it becomes necessary to adjust the various designable parameters to optimize the circuit performance. As most of the designable parameters are in the linear sub network part of the circuits, it becomes necessary to obtain repeated solutions for the linear sub network only. Optimization procedures involve iterative modifications of the initial design, followed by circuit analysis and comparison with the specified performance. There are two different ways of carrying out the modification of designable parameters in an optimization process. These are known as gradient methods and direct search methods of optimization. Gradient methods use information about the derivatives of the performance functions (with respect to designable parameters) for arriving at the modified set of parameters. This information is obtained from the sensitivity analysis. On the other hand, the direct search methods do not use gradient information, and searching for the optimum in a systematic manner carries out parameter modifications.

NOMINAL OPTIMIZATION

Nominal optimization, also known as performance optimization, is the process of modifying a set of parameter values to satisfy predetermined performance goals. Optimizers' compare computed and desired responses and modify design parameter values to bring the computed response closer to that desired. Nominal optimization can be performed in conjunction with any frequency-domain or time-domain Analog/RF systems simulation component as well as most signal processing components. For example:

a) To optimize the response of a low-pass filter, you can perform an S-parameter simulation or an AC simulation to calculate the output amplitude of the filter over a frequency range, then change filter parameter values to refine filter response shape.
b) To optimize the rise time of a pulse, you can perform a transient simulation to calculate the output voltage over a period of time, then change circuit parameter values to fine-tune the rise time of the pulse.
c) You can optimize the gain of a carrier recovery loop to achieve a desired lock time and residual loop error.
d) You can optimize a fixed-point bit-width parameter in a DSP design.

The steps required to perform nominal optimization include:

1) Running a simulation.
2) Comparing results with the goal.
3) Changing the circuit parameters to obtain results that are likely to be closer to the goal.
4) Running a simulation again with the new parameter values.

Types Of Optimizers

This section presents on the various optimizers and search methods available for performing nominal optimization as well as guidelines on error function formulation. The optimizers are differentiated by their search methods and error function formulations. The search method determines how the optimizer arrives at new parameter values, while the error function measures the difference between computed and desired responses. The smaller the value of the error function, the more closely the responses coincide. When optimizers execute their search method, they substitute new parameter values to effect a reduction in the error function value [2].

Search Methods

There are six search methods to arrive at new parameter values:

a) Random Search.
b) Gradient Search.
c) Quasi-Newton Search.
d) Gauss-Newton/Quasi-Newton Search.
e) Discrete Search.
f) Genetic Algorithm Search.

Optimization with Random Search is typically used initially. Optimization with Gradient search is generally used in later stages of optimization. Discrete optimization only affects discrete-valued variables. The genetic algorithm search is well suited to the discrete and mixed (continuous and discrete) problems.

Random Search

The optimizers using random search method (Random, Random Minimax, and Random Max optimizers) arrive at new parameter values by using a random-number generator, that is, by picking a number at random within a range, which is sometimes a slower process compared to the optimizers using gradient search methods. Optimization with random search method is a trial and error process. Starting from an initial set of parameter values for which the error function is known, a new set of values is obtained by perturbing each of the initial values, and the error function is re-evaluated. For optimization with random search method, a trial consists of two error function evaluations. Reversing the algebraic sign of each parameter value perturbation and re-evaluating the error function complete a trial performed by optimization with random search method. These two values, corresponding to positive and negative perturbations, are compared to the value at the initial point. If either value is less than the initial value, then the set of parameter values for which the error function has its least value becomes the initial point for the next trial. If neither value is less than the initial value, then the initial point remains the same for the next trial.

Gradient Search

The optimizers using gradient search method (Gradient and Gradient Minimax optimizers) find the gradient of the network's error function. These optimizers usually progress more quickly to a point where the error function is minimized, though it is possible for them to terminate in a local minimum. The optimizers find the gradient of the error function (i.e., the direction to move a set of parameter values in order to reduce the error function). Once the direction is determined, the set of parameter values is moved in that direction until the error function is minimized. Then the gradient is re-evaluated. This cycle is equals one iteration of the gradient optimizers. A design that is optimized by a gradient optimizer has the least sensitivity (more stable) to slight variations in its parameter values. A single iteration usually includes many function evaluations; therefore, iteration in optimization using gradient search method takes much longer than a trial in optimization using random search method.

Quasi-Newton Search

The optimizers using Quasi-Newton search method (Quasi-Newton and Least Pth optimizers) use second-order derivatives of the error function and the gradient to find a descending direction. The optimization routine using Quasi-Newton search method estimates the second-order derivatives using the Davidson-Fletcher-Powell (DFP) formula or its complement. Appropriately combined with the gradient, this information is used to find a direct and an inexact line-search is conducted. The optimization terminates when the gradient vanishes or the change ratio in the variables is small (less than 1.0e-5). It also stops when the number of iterations, that you have specified, is reached. The bounds imposed on the optimization variables are handled using a transformation of variables. Like the optimizers using gradient search method, iteration in the optimizers using Quasi-Newton search methods consists of many function evaluations, and takes longer than a trial in the optimizers using random search method.

Gauss-Newton/Quasi-Newton (minimax) Search

The minimax optimizer consists of two stages. In the first stage of the algorithm, the optimizer solves a minimax problem using a linear programming technique. In doing so, the status and potential of each individual error function component are analyzed. Its contribution to the minimax problem is mathematically assessed and taken into account during optimization. In the second stage, the optimizer works with a Quasi-Newton method using approximate second-order derivatives. Such extra effort becomes necessary for an accurate and efficient solution to certain ill-conditioned problems (i.e., singular problems). The minimax optimizer terminates when responses become optimally equal-ripple or the relative change in the variables is less than 0.05 percent. It also stops when the number of iterations is reached. Note that the bounds imposed on the variables are formulated and treated directly as linear constraints without having to resort to variable transformation; therefore, a source of nonlinearity is eliminated.

Discrete Search

Exclusively the discrete optimizer uses the exhaustive search method. This optimizer only affects parameter values specified as discrete-valued optimization variables. The discrete search method involves a comprehensive search for the combination of discrete values that results in the best design performance. Starting from an initial set of parameter values for which the error function is known, an update in the parameter values occurs upon an improvement in the error function. Because the parameter values that may change are not continuous variables, this search method is more a series of trials than iterations. Moreover, the number of trials required to attempt all combinations might often be prohibitive. To reduce optimization time, keep the number of discrete variables to a minimum and reduce the number of values the discrete variables may take on.

Genetic Algorithm Search

Genetic algorithms (GA's) provide another direct search optimization method. The basis of the procedure is a set of trial parameter sets, sometimes called chromosomes, which are allowed to evolve towards a set that gives progressively better performance. The key to the genetic optimization is the strategy of change in the parameter population, i.e., each generation of parameters; the performance given by the parameter population improves.

Error Function Formulation

The optimizers also have different methods for error function formulation.

Least-Squares error Function

Evaluating the error for each specified goal at each frequency/power point individually, then squaring the magnitudes of those errors calculate the least-squares error function. Then those squared magnitudes are averaged over frequency and/or power.

Minimax Error Function

The Minimax optimizer calculates the difference between the desired response and the actual response over the entire measurement parameter range of optimization. Then the optimizer tries to minimize the point that constitutes the greatest difference between actual response and desired response.

Least P^{th} Error Function

The least Path optimizer uses an error function formulation similar in makeup to the least squares method found in the random, gradient, and the quasi-Newton optimizers. But, instead of squaring the magnitudes of the individual errors at each frequency, it raises them to the P^{th} power, where p=2,4,8 or 16. The optimizer automatically increases p in that sequence. This emphasizes the errors that have high values much more strongly than those that have small values. As p increases, the Least P^{th} error function approaches the minimax error function. Least P^{th} allows the error function to become negative. That happens when you specify a performance window and the response moves inside that window. For example, there may be a minimum and maximum gain specification on an amplifier and the Least P^{th} optimizer can go beyond the specification and place the gain halfway between the two limits. The Least Pth optimization routine is the exponential sum of the error function, where the exponent p is not necessarily equal to 2. It can be a positive number, usually an integer.

Minimax L1 Error Function

Random Minimax and Gradient Minimax use the Minimax L1 error function. These optimizers calculate the difference between the desired response and the actual response over the entire measurement parameter range of optimization. Then the optimizers try to minimize the point that constitutes the greatest violation for the desired response. Compared with minimax error function, minimax L1 error cannot be less than zero. So that it only accounts for the most severely violated case.

OPTIMIZATION OF NONLINEAR CIRCUITS

Solid-state microwave components are all nonlinear to some degree. In communication amplifiers, any non-linearity in the phase and amplitude of the voltage-transfer characteristics must be minimized to preserve the shape and spectral content of the signal. However, components such as limiting amplifiers, oscillators, doublers, and mixers rely on device non-linearity for proper operation. In all cases, complete circuit analysis of these components requires a nonlinear device model and analytic means to extract the effect of device-circuit interactions from the model. A method, which weds frequency-domain linear circuit analysis to an arbitrary non-linear device model represented in the time domain, is the harmonic balance technique [3]. As in the case of linear circuits, for nonlinear circuits also, it becomes necessary to adjust the various designable parameters to optimize the circuit performance. As most of the designable parameters are in the linear sub network part of the circuits, it becomes necessary to obtain repeated solutions for the linear sub network only. The following are some of the common performance parameters of a non-linear circuit (for example mixer, oscillator and frequency multiplier etc.) that can be optimized using any one of the above mentioned optimization methods. They are

- Conversion Gain/Loss.
- Noise Figure.
- Gain Compression.
- Inter-modulation distortion and intercepts.
- Dynamic Range.
- Isolation between the ports (RF, IF and LO).
- Adjacent channel power.

CONCLUSIONS

A detailed overview of the various types of optimization methods present in the modern CAD packages is presented.

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