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Statistical Circuit Design:

History and Introduction

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The papers in this series describe the status of a continuing program at Bell Telephone Laboratories to apply computers to all phases of transmission circuit design. The process involves the same steps now that it has historically. Given a set of circuit objectives, the designer:

(*i*) Synthesizes a circuit, using known or assumed characterizations of the devices and components involved.
(*ii*) Analyzes circuit performance, either by measurements of laboratory samples or by calculations based on simulation or modeling.
(*iii*) Optimizes design performance and cost by changing topology or element values.
(*iv*) Examines the design for compliance with objectives under all expected conditions of manufacturing tolerances and the environment of application.
(*v*) Iterates some or all of these steps until a satisfactory, if not optimum, design is achieved.

The first large-scale application of a digital computer to the analysis of linear filter and equalizer designs came in 1950. The computer was the BTL Mod VI, an early version using telephone relays. As computers gained in speed and versatility and programmers developed new algorithms, strides were taken in synthesis and optimization.

Paralleling this work was a continuous effort to improve the frequency range, speed, precision, and accuracy of transmission measurements. A major milestone was reached in 1953 with the announcement by Thaddeus Slonczewski of the "micro-bel" technique. This achieved measurement accuracies of ±0.001 decibel by a method that can be applied over very wide frequency ranges.

In 1966, the important step was achieved of using a dedicated general-purpose computer to control the transmission measuring set, and also to process, collate, and output the data in various forms. The next step, of using this computer also to play a role in the iterative process used in design and production, is described in this series.

The advantages of modeling and simulation were recognized early. Both digital and analog computers were put to this task. In 1962, a hybrid interconnection of the two produced great flexibility in dealing with both linear and nonlinear systems.

An obvious requisite to useful modeling is an adequate characterization of the elements to be modeled. The computer-operated test sets have been used extensively in measurements characterizing transistors and other devices, coupled with efforts to relate the measurements to the physics and geometry of the device.

Most recently, algorithms and programs have been developed to use the computer in the process of analyzing the performance of networks under realistic conditions of manufacturing tolerances, variations of the environment, and manufacturing adjustments. The next step is to have the machine apply the results of this analysis in the iterative process to achieve something near an optimum design.

This brief history of two decades in computer-aided design in transmission development provides a useful perspective in viewing this series of papers dealing with statistical analysis. The notion of using statistical procedures was proposed[1] many years ago and successful applications have been reported[2] in the past in the analysis of logic circuits. The catalyst which has led to the present effectiveness on a wide class of circuits and systems, however, has its roots in this twenty-year-old effort in device characterization, development of algorithms for general-purpose programs, and the effort to improve the factory transmission measurement and adjustment capabilities. Consider what has occurred in the past several years of statistical analysis as described in this series.

During 1968 several versions of a general-purpose, statistical analysis program (TAP)[3, 4] were written and used effectively for a range of circuits from passive filter designs to highly nonlinear systems. In their original conception, the tolerance analysis procedures were visualized as a final step in the design process. They belonged to the class of computer aids that allows the computer to manipulate an analysis or simulation in a fashion similar to the general-purpose optimization programs. The computer-aided design process was viewed as consisting of the following three steps:

(*i*) *Analysis*—Components are modeled and the circuit is analyzed. Components and the network topology are changed until the circuit performance approaches the designer's expectations.

(*ii*) *Optimization*—The designer identifies a desired measure of performance and the analysis is embedded in a general-purpose optimization program. These optimization programs use various strategies to alter the circuit parameters to bring the performance within the desired bounds.

(*iii*) *Tolerance Analysis*—Using a similar measure of performance, the optimized model parameters are varied within their anticipated distributions with the appropriate correlation between parameters. The circuit performance is repetitively analyzed with these different parameters until a histogram of the performance measure can be interpreted with confidence.

Our experience in the past several years has shown that the use of statistical analysis is not the simple final step in the design process. Our present view is that this technique forms new bridges among design, manufacture, and field failure problems. These bridges carry information in both directions with a substantial impact on both design and manufacturing technologies.

Consider what occurs when the designer takes the first step into the use of tolerance analysis. If he is using the same performance measure as was used in the optimization procedure, he can build histograms as he accumulates the statistics of many designs. For this to be related to the manufacturing yield, however, he must include anticipated bench adjustments on selected components. These adjustments may be as simple as tuning inductors to resonance or as involved as anodizing resistors (a one-directional adjustment) while monitoring a complicated performance measure of some subsystem.

When he considers the manufacturability of the circuit in the factory environment, he faces the issue of relating factory testing procedures to his performance measures used for design. These are often only casually related to each other in spite of the increasing reliance on computer-operated measurement equipment. This factory test equipment can often be adapted to do "go/no-go" testing using the *same* performance criteria used in the tolerance analysis program.

To simplify the problem, let us presume that the same performance criteria are used for both design and manufacture. The bridge for information flow in both directions becomes critical. In his tolerance analysis, was the designer detecting failures discernible in manufacturing or in the field environment? Can he devise a set of conditions for factory testing (a particular temperature, bias supply voltage, etc.) that will detect most failures predicted for the field? Is there an alternate technique for component adjustment which will increase yield and decrease field failures? If so, should not this adjustment procedure be brought back into his optimization and tolerance analysis programs to see if he still has the optimum nominal values for his components?

Obviously, the answers to these questions depend on the specific circuit or system being designed. These questions, however, are not peripheral to the design process but often introduce overriding considerations which should be considered at every stage of the design process.

The first three papers in this series deal with the current capabilities in tolerance analysis. The first paper by J. Logan[5] introduces the characterization and modeling of components. This characterization capability enables the designer to analyze manufacturing yield (correlation between devices, adjustments, etc.) as separate from field failures (temperature effects, aging, etc.). The second paper by C. L. Semmelman, E. D. Walsh, and G. T. Daryanani[6] traces the development of a linear circuit analysis capability that allows the designer to specify the factory and field environments for a class of active circuits. The third paper by I. A. Cermak and Mrs. D. B. Kirby[7] describes the extension of these techniques to nonlinear circuits.

The fourth paper by G. D. Haynie and S. Yang[8] develops the relationships between the design process and the measurement and testing process. The next two papers by E. M. Butler[9] and B. J. Karafin[10] examine the question of using tolerance analysis for optimum design. The first deals with techniques to optimize the component sensitivity and the second to optimize cost.

The last three papers by L. A. O'Neill;[11] P. Balaban, et al.;[12] and R. G. Olsen[13] provide a view of these techniques as applied to the design of a complex linear circuit, a nonlinear hybrid integrated circuit, and finally a waveguide system analysis. In each of these cases the ability to extend the designer's capability past the traditional worst-case design estimate was an important factor in the successful design.

This series of papers documents the establishment of analytic bridges between design, manufacturing, and field environment problems. The effective use of these techniques places substantial demands on the design experience of the engineer. The designer must have insight into the factory capabilities and procedures and consider these effects at an early stage of design. This ability, however, to bring these manufacturing and field environments into the design process results in substantially more reliable and economical designs. Major advances still lie ahead, so that one cannot say the program has reached maturity: it is possible to see it as in sturdy adolescence.

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