LINEAR/NONLINEAR/STATISTICAL MODELING FOR COMPUTER-AIDED ENGINEERING OF MICROWAVE INTEGRATED CIRCUITS

Final Report

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1. Title of the Project

LINEAR/NONLINEAR/STATISTICAL MODELING FOR COMPUTER-AIDED ENGINEERING OF MICROWAVE INTEGRATED CIRCUITS

2. IRAP Project Code

CAEMICMOD 8-5145-M-15

3. IRAP Funding

June 18, 1989 - March 31, 1990:	$45,000.00
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TOTAL IRAP FUNDING	$60,000.00

4. Project Team

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P2.	R.M. Biernacki	Project Consultant
P3.	S.H. Chen	Project Co-Leader
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5. Project Objectives

The purpose of the project was to research the area of microwave device modeling including extraction of small-signal and large-signal model parameters in the presence of device statistics. Based on the results of the research to develop a new software system for parameter extraction of linear/nonlinear statistical models of microwave devices.

6. Achievement of Project Objectives

The ultimate goal of the project was to develop a software system for device parameter extraction and modeling including statistics. This goal has been achieved. The first version of the software system is now being released.

The news of the release of the product has been enthusiastically received by the leading advertising journals in the field, namely *Microwave Journal* and *Microwave & RF Engineering*. Both have invited OSA to provide feature articles to appear in the coming issues, at no cost to OSA. A copy of one of the articles is included in the Appendix.

We decided that the system consist of two components: a master program organizing and processing statistical information, and a parameter extractor that will be invoked by the master program as many times as the number of statistical outcomes being processed. For the latter we adapted and expanded our existing software HarPE. For marketing purposes the system is released under the established name "HarPE". The statistical features are available to the user as an add-on module to be purchased as an option to HarPE. To this end both the master program for statistical modeling and the parameter extractor have been integrated into one system called HarPE Version 1.4+S. The basic version of the parameter extractor for non-statistical modeling, enhanced by some of the modules developed within the scope of this project, is released separately as HarPE Version 1.4.

Research and development carried out within the framework of the project are outlined in the following subsections.

Research towards Parameter Extraction and Statistical Modeling System

(a) Study special aspects of GaAs FET integrated circuit devices related to statistical modeling.

We studied the subject of GaAs FET modeling both at the equivalent circuit level and using physical parameters. The system can handle the following equivalent circuit FET models: the Curtice and Ettenberg model, the Materka and Kacprzak model and the Raytheon model. We initiated research on a physics-based FET model by Khatibzadeh and Trew. This is a large-signal analytic model derived from basic semiconductor equations, especially suitable for process-oriented simulation, pre-fabrication design optimization and modeling. User-specified parameters include gate length and width, channel thickness, doping density and profile, dielectric coefficient, saturation velocity, low-field mobility, high-field diffusion coefficient, and gate Schottky voltage.

(b) Develop theory for an optimization approach to statistical modeling.

The optimization approach to statistical modeling that emerged from this research can be described as a multi-device optimization and postprocessing method. Measurement data (large-signal power spectra, small-signal S-parameters, and/or DC IV data) is collected from a sample of (typically 100 to 300) devices. From the measured data, multiple device models are extracted through repeated optimization. A robust ℓ_1 optimization technique is employed, and reliability and speed of the extraction process are enhanced by taking as the starting point for successive optimizations the solution points of the preceding optimizations. This approach is well justified for typical statistical spreads of microwave device parameters. The sample of extracted model parameters is postprocessed to generate a consolidated statistical model.

(c) Implement and test the optimization approach to statistical modeling.

The optimization approach described in (b) was implemented an thoroughly tested. The overall efficiency turned out to be significantly better than originally expected. This was a decisive factor for the final integration of HarPE and the new statistical modeling system. It turned out to be feasible to perform statistical modeling in real time without the necessity to run long batch, for instance, overnight, jobs.

(d) Develop a framework for a comprehensive statistical modeling system for monolithic integrated microwave devices.

We studied various congruential random number generators and means to break sequential correlations. As a result we selected a generator for implementation within the system. We studied the suitability of mathematical eigenvalue algorithms for multidimensional distributions. A multidimensional normal random number generator was developed.

We investigated ways to employ a data base software system for processing large quantities of measurement data. We developed our own syntax and parser for accepting measurement data from external files in almost any format. Two specific formats used in industry, namely Cascade Microtech's MicroCAT™ Test Executive system format and the MDIF format are directly supported.

(e) Apply statistical modeling techniques to such devices reflecting fabrication parameters and response measurements.

We have used the physics based Khatibzadeh and Trew model to generate synthetic measurement data reflecting assumed statistical spreads of FET geometrical dimensions and doping density. This data was then used to extract statistics of small-signal FET model parameters such as the transconductance g_m, time delay τ, the capacitance C_{DS}. The resulting statistical model allowed us to investigate correlations between the equivalent circuit model parameters and the basic fabrication parameters.

(f) Interact with process and fabrication engineers for measurement data and process information.

We established contacts and interaction with a few leading companies including Cascade Microtech, TriQuint Semiconductor, and Plessey. We studied the output data format from the automated wafer probe and measurement system MicroCAT from Cascade Microtech. We studied the file compatibility aspects with Measurement Data Interchange Format (MDIF) by EEsof and Cascade Microtech.

(g) Test statistical modeling using real measurement data.

We have tested our system using real measurement data obtained from Cascade Microtech. The data contained S-parameter measurements taken at 6 frequencies and 2 bias points, for a sample of 30 devices. The Materka and Kacprzak FET model was used and its statistical parameters were extracted. This statistical modeling took only 20 minutes on the Apollo DN3500 workstation, in contrast to several hours initially expected.

Modules for Parameter Extraction and Statistical Modeling System

(a) User Interface and Command Processor.

We designed the overall product architecture including global modules, modular interface and interlanguage specifications, and global data structure. We developed the input file syntax for statistical variables including one-dimensional uniform, normal, exponential and lognormal distributions, and multidimensional normal distributions with correlations. We also developed the input syntax for sets of statistical data.

We designed a complete user interface layout including menus and windows. A "point-and-click" mouse-driven pull-down menu driver was implemented. We developed a version of HarPE suitable for background batch execution which may be used for processing large sets of measurement data while performing other jobs on the workstation.

(b) File Parser.

We worked on model description and element parameters, preprocessor for file blocks, "include file" handler, comment lines, expression parser and evaluator, and on handling user-defined labels and optimizable variables. We developed modules for parsing element statistics, parsing multi-device measurement data, and for parsing a sample of multi-device model parameters. In fact, the syntax for the latter allows the user to process any user-supplied raw statistical data.

(c) Editor.

HarPE's screen editor was adapted.

(d) Memory Manager.

We implemented data structure definitions: data deposit, retrieval and memory management. Also, a structured description of circuit topology, parameters and variables, including optimizable variables and parameter statistics, are incorporated.

(e) Circuit Element Library.

We developed modules for the library of linear elements allowing the user to create the linear device environment with no restriction on circuit topology. This includes modules handling transmission lines, resistors, capacitors, series and parallel connections of resistors, inductors and capacitors. Also, we developed a module for handling a generic "black-box" n-terminal element, thus enabling the user to import measurement or simulation data for whole subcircuits.

(f) Linear Simulator.

We developed a general linear simulator, including programming, testing and debugging. It has the capability of handling arbitrary topology allowing the user to define his own linear device environment reflecting measurement setup, and parasitic and packaging effects. General complex, frequency dependent and user-defined terminations, as well as user-defined reference resistance for S-parameter calculations are accommodated. We developed modules for calculation of the stability factor and maximum available gain.

(g) Harmonic Balance Simulator.

HarPE's harmonic balance simulator was adapted with modifications of the convergence criteria for the nonlinear solver.

(h) Optimizers.

In addition to HarPE's ℓ_1 and ℓ_2 optimizers we incorporated a state-of-the-art minimax optimizer.

(i) Library of Parasitic and Packaging Models.

Specialized linear simulators for extrinsic device parasitic models were developed. In addition to HarPE's Extrinsic1 and Extrinsic2 we implemented two new specialized simulators. All these simulators are optimized for speed, especially important for statistical modeling. Also, all of these parasitic models are available in the form of connectable elements within the general circuit topology, which together with the transmission lines provides the means to model packaging effects.

(j) Library of Intrinsic Device Models.

In addition to HarPE's FET models (the Curtice and Ettenberg model, the Materka and Kacprzak model, and the Raytheon model) we implemented the Khatibzadeh and Trew physics based FET model. Also, the Gummel and Poon models of NPN and PNP bipolar transistors and a semiconductor diode model are added.

(k) Drivers for Multi-Circuit Simulation and Error Functions for Modeling.

HarPE's drivers were adapted.

(l) Statistical Processor of Extracted Parameters.

We developed the drivers processing the measurement data and the extracted model parameters for histograms, run charts and scatter diagrams. We also developed modules to calculate statistical estimates of the means, standard deviations and correlations from a sample of outcomes.

As the most important module processing the extracted model parameters we developed a postprocessor generating a consolidated statistical model consistent with the syntax for describing element statistics. Parameter correlations are automatically estimated and included in the multidimensional normal (Gaussian) distribution model. For parameters exhibiting substantially non-Gaussian distributions the histograms, available for viewing, can be opted as discrete approximations of the marginal density functions.

(m) Interface to Measurement Equipment.

We implemented data entry compatibility with MicroCAT™ by Cascade Microtech and MDIF by Cascade Microtech and EEsof. Measurement data files in these formats are accepted without any modification.

(n) Output Data Processor.

We developed postprocessing capability allowing the user to define arbitrary response functions for both graphical and numerical output. We developed modules to output the results of the multi-device parameter extraction process, the first step in statistical modeling. A sample of device models in the form of a sample of extracted model parameters is created as a SAMPLE block in the circuit file. This block is then postprocessed into a concise statistical description.

(o) Graphics Interface.

We implemented graphics modules for plotting histograms, run charts and scatter diagrams to graphically illustrate statistical distributions and correlations of user selected parameters. We implemented graphics hardcopy capabilities and investigated the compatibility of graphics libraries for Apollo, Hewlett-Packard and Sun workstations.

We expanded HarPE's graphical display and numerical output to include conventional small-signal parameters (such as the transconductance g_m) analytically linearized from the nonlinear (large-signal) model at selected bias points. We added a graphical display of parameter sensitivities and made some other improvements to the graphics, such as VG-ID curves, and Smith chart and polar plots on a single display.

7. Protection of Technology

All title and rights to the technology resulting from this project will be retained by OSA. In particular, ownership of the statistical modeling system will not be passed on to any OSA's customers. Following the common practice of other CAD software vendors the customers will be licensed by OSA only to use the product, and no ownership or other rights will be given to them.

No patents arising from this projects are envisaged. The technology will be protected by distributing executable code only. No customer will be given access to the source code. In addition to respective clauses in the licensing agreement, the product is protected against copying by means of a built-in security module checking the site details, whether authorized by OSA or not.

8. Follow-up Technical Activities

Several areas of follow-up technical activities are clear at the point of completion of this project. The first one is yield optimization and statistical design centering. This is the ultimate use of statistical modeling now available due to this project. Equally important is physics based device modeling, just initiated within this project. It requires substantial research effort to make such models robust and efficient enough for integrated simulation and optimization, especially yield optimization to be feasible.

Another important direction is the development of a general purpose software system capable of handling multi-device and multi-tone harmonic balance simulations and optimizations, and time-domain simulation and optimization of nonlinear circuits. OSA has the necessary know-how and, more importantly, a novel software architecture for such a development. If created, OSA's general purpose CAE system would significantly outperform all products of other vendors. An essential part of such a system would be layout oriented, field-theoretic based treatment of microstrip distributed components of microwave circuits.

Among other follow-up technical activities we recognize a need for further development of bipolar transistor oriented features in HarPE. This will enlarge our market to industries such as VLSI and other integrated circuit and device manufacturers and users, as well as the currently addressed microwave industry.

Also, market response to the first release of the product and customer feedback will play an important role in future developments.

9. Expected Benefits

It is expected that this project will substantially contribute to profitability and development of OSA. Consequently, the growth of the company will generate jobs in Canada, for example, to create a technical support department for customers of OSA products. Also, the algorithms and software modules developed for this project will be extremely valuable in future products, thus reducing their development cost.

The marketing of the product developed within the framework of this project should contribute to Canadian competitiveness in the microwave CAE arena and in the high-tech industry in general, thus far dominated by the Americans.

10. Impact of Support

OSA had the technical expertise for the proposed project. IRAP funding was crucial for our ability to devote the necessary effort, time and resources to research and development needed for completion of the project, and thus it helped the project to be carried out.

11. Technical Description of the Product

This section provides technical description of the statistical modeling system developed within this project. As was mentioned in Section 6, the system will be marketed as an add-on module to HarPE. The module consists of two complementary parts: statistical modeling and statistical (Monte Carlo) analysis, the latter developed outside of the scope of this project.

Summary

The advanced features of statistical modeling and analysis are available as an add-on module for HarPE. These features are based on OSA's research work and are consistent with the multi-circuit, optimization-oriented approach used by HarPE.

The capability to extract statistical models of nonlinear devices from measurements is a prerequisite for yield and cost analysis and optimization of (M)MIC circuits. HarPE implements a multi-device optimization and postprocessing method for statistical modeling. Suitable measurements (large-signal power spectra, small-signal S-parameters, and/or DC IV data) is collected from a sample of (typically 100 to 300) devices. This may be automated by some measurement systems (such as Cascade Microtech's MicroCAT™ Test Executive system which is supported by HarPE). From the measured data, multiple device models are extracted through repeated optimization.

The sample of extracted model parameters is postprocessed to generate a consolidated statistical model, which is then back annotated to produce a HarPE circuit file immediately suitable for Monte Carlo analysis. Parameter correlations are automatically estimated and included in the multidimensional normal (Gaussian) distribution model. For parameters exhibiting substantially non-Gaussian distributions, the user can choose to keep the histograms as discrete approximations of the marginal density functions. This combined discrete/normal approach developed by OSA preserves the means, standard deviations, correlations and marginal distributions derived from the sample. It provides enhanced accuracy of the model while retaining the simplicity of the normal distribution.

Histograms of the measured data and the extracted model parameters can be displayed. Parameter correlations can also be shown graphically as scatter diagrams.

The statistical postprocessor can also be applied to user-supplied arbitrary raw data. The statistics (means, standard deviations and correlations) of such data can be analyzed, and the corresponding histograms and scatter diagrams can be displayed.

Menu Options

The HarPE menu for statistical options is illustrated in Fig. 1 and described in Table 1. A limited discussion of how the statistical variables are to be defined for statistical (Monte Carlo) analysis will be presented first to illustrate the ultimate output of statistical modeling. Then, the measurement data and statistical modeling operations are described in detail.

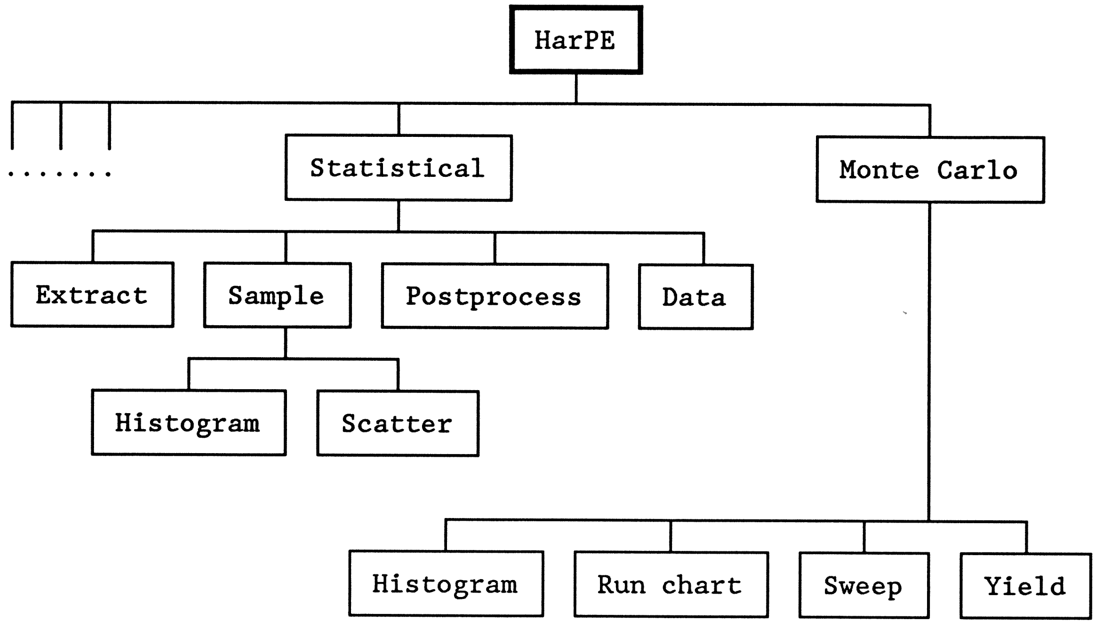

Fig. 1 Statistical menu options

TABLE 1 STATISTICAL MENU OPTIONS

Menu Option	**Function**
HarPE.Statistical	statistical modeling
HarPE.MonteCarlo	statistical (Monte Carlo) analysis
HarPE.Statistical.Extract	extracts multiple device models from measurements
HarPE.Statistical.Sample	plots statistical diagrams from the SAMPLE Block
HarPE.Statistical.Postprocess	postprocesses extracted statistical model
HarPE.Statistical.Data	plots histograms of the measured data
HarPE.MonteCarlo.Histogram	plots histogram of a single response
HarPE.MonteCarlo.RunChart	plots run chart of a single response
HarPE.MonteCarlo.Sweep	plots multiple sweep curves
HarPE.MonteCarlo.Yield	displays yield estimated by Monte Carlo analysis
HarPE.Statistical.Sample.Histogram	histogram of a single statistical variable
HarPE.Statistical.Sample.Scatter	scatter diagram between two statistical variables

Defining Statistical Variables

The menu option HarPE.MonteCarlo requires a suitable statistical model. This section describes the syntax for defining statistical variables in the circuit file. The models produced by the HarPE.Statistical option are consistent with this syntax.

A statistical variable, i.e., a parameter which is subject to statistical variations, is defined in the circuit file as

```
name = nominal { statistical distribution }
```

where "name" represents a keyword or a label, and "nominal" is the nominal (mean) value. Enclosed in a pair of curly braces is the definition of the distribution type, tolerance, correlation, etc., using the keywords listed in Table 2.

TABLE 2 STATISTICAL KEYWORDS

Distribution Type	Required Keyword	Optional Keywords
UNIFORM	TOL	HIGH, LOW
NORMAL	SIGMA	HIGH, LOW, CORRELATION, DDF
EXPONENT	TOL	HIGH, LOW
LOGNORMAL	TOL	HIGH, LOW

Statistical variables can be defined in the MODEL block (a block in the circuit file used to specify circuit components, their values, connections, etc.) by following a parameter keyword, for example

```
CAP  1  2   C = 5PF {UNIFORM TOL=1PF};
```

This defines a uniform distribution for the capacitance with a nominal value of 5PF and a tolerance of 1PF. The element "CAP" is connected between nodes 1 and 2. The parameter keyword to which the statistical description applies is the capacitance "C".

Statistical variables can also be defined in the EXPRESSION block (a block in the circuit file allowing the user to define his/her own variables, or labels, and equations) as a label, for example

```
VAR1: 50 {NORMAL SIGMA=10%};
```

This defines a normal distribution for the label VAR1 with a nominal value of 50 and a standard deviation of 10 percent of the nominal.

The nominal value can be defined by a constant, an optimizable variable, or a label, as illustrated by the following examples.

```
C = 5PF   {UNIFORM TOL=1PF};        ! nominal is a constant
C = ?5PF? {UNIFORM TOL=1PF};        ! nominal is optimizable
C = VAR1  {UNIFORM TOL=1PF};        ! nominal is a label
```

During the Monte Carlo analysis, statistically perturbed values are generated for each and every statistical variable defined in the circuit file. The process of generating the statistically perturbed values is described as follows.

First, HarPE generates *normalized deviates* (statistical perturbations) according to the distribution type specified (UNIFORM, NORMAL, etc.). These normalized deviates have a zero mean value and a unit tolerance. If truncation limits are specified using the LOW and HIGH keywords, the normalized deviates are truncated to be within the interval [LOW, HIGH]. These are called the *truncated deviates*. Then, the deviates are scaled by the tolerance specified by the TOL or SIGMA keyword. These are called *scaled deviates*. Finally, the nominal value is taken into account to produce an *outcome*, as

```
outcome = nominal + scaled_deviate
```

for an absolute tolerance, or

```
outcome = nominal + nominal * scaled_deviate
```

for a relative tolerance, that is, if the percent sign follows the TOL or SIGMA keyword.

The process of generating the statistical outcomes can be illustrated by the following simple example of a uniformly distributed capacitance value, defined as

```
C = 5PF { UNIFORM  TOL=10%  LOW=-0.5  HIGH=0.7 }
```

The following steps are involved:

(1) generating normalized deviates from the uniform distribution [-1, +1];

(2) truncating the deviates to the interval [-0.5, +0.7];

(3) scaling the deviates by the tolerance, the scaled interval is [-5%, +7%];

(4) including the nominal value, the outcome interval is [4.75PF, 5.35PF].

Applicable to the normal distributions only, parameter correlations can be defined through the use of the STATISTICS block in the circuit file and the keyword CORRELATION specified for the variable statistics. The STATISTICS block in the circuit file contains correlation matrices. It is structured as

```
STATISTICS

    correlation matrix
    ...
    correlation matrix

END
```

Each matrix defines the correlations among a group of statistical variables. It must have the header

```
CORRELATION: name  DIMENSION = n  [FORMAT = format];
```

where "name" is an arbitrary character string which uniquely identifies the correlation matrix. The DIMENSION keyword must be followed by a positive integer which specifies the number of rows (columns) of the matrix. The dimension is equal to the number of statistical variables whose correlations are defined by the matrix.

The elements in the correlation matrix are the correlation coefficients. The element at the position (i,j) is the correlation coefficient between the ith and the jth variables. The value of the coefficients must be between -1 and +1. The matrix must be symmetrical and all the diagonal elements must be 1. The entries can be organized in one of the four available formats, namely, FULL, UPPER, LOWER and SPARSE. In the FULL format, the complete matrix is entered. In the UPPER format, the upper-right triangular portion of the matrix, *including the diagonal*, is entered. In the LOWER format, the lower-left triangular portion of the matrix, *including the diagonal*, is entered. In the SPARSE format, only the nonzero and off-diagonal values need to be entered, together with their position indices. This is best illustrated through an example. The same matrix is shown in four different formats.

```
CORRELATION: ABCDE  DIMENSION=4  FORMAT=FULL;
    1.0   0.2   0.4   0.6
    0.2   1.0   0.8   0.0
    0.4   0.8   1.0   0.1
    0.6   0.0   0.1   1.0

CORRELATION: ABCDE  DIMENSION=4  FORMAT=UPPER;
    1.0   0.2   0.4   0.6
          1.0   0.8   0.0
                1.0   0.1
                      1.0

CORRELATION: ABCDE  DIMENSION=4  FORMAT=LOWER;
    1.0
    0.2   1.0
    0.4   0.8   1.0
    0.6   0.0   0.1   1.0

CORRELATION: ABCDE  DIMENSION=4  FORMAT=SPARSE;
    1  2  0.2
    1  3  0.4
    1  4  0.6
    2  3  0.8
    3  4  0.1
```

Once defined in the STATISTICS block, the correlation matrices can be referred to by any statistical variable using the CORRELATION keyword:

```
{ NORMAL SIGMA=xx  CORRELATION = name[k] }
```

where "name" must refer to the character string identifier of a correlation matrix (such as the string "ABCDE" in the above example), and "k" is a positive integer index not greater than the dimension of the correlation matrix. For example,

```
VAR1: 10.0 {NORMAL SIGMA=10%  CORRELATION=ABCDE[2]};
VAR2:  0.1 {NORMAL SIGMA=5%   CORRELATION=ABCDE[3]};
```

This indicates that the correlation coefficients of VAR1 and VAR2 are given by the 2nd and 3rd rows (columns), respectively, of the correlation matrix ABCDE. The correlation coefficient between VAR1 and VAR2, is the element at position (2,3), as well as (3,2).

For the normal distribution, the optional keyword DDF specifies a histogram to be used to map the outcomes into a discrete distribution. This feature is primarily intended for the statistical modeling option, where the postprocessor allows the user to choose a histogram as an approximation of the marginal density function to compensate for non-Gaussian distributions.

The DDF is a numeric record of the histogram. The value range of a statistical sample is divided into N subintervals (*bins*), where N is typically 10 to 20. The number of outcomes which fall into each subinterval (bin) is recorded. Then DDF is defined as

{ NORMAL SIGMA=x DDF = K_1 K_2 ... K_N }

where K_i is the count of outcomes in the *i*th subinterval (bin). During the Monte Carlo analysis, outcomes are first generated from a normal distribution with the specified mean, standard deviation and, possibly, correlations. Then the outcomes are mapped to the discrete distribution represented by the DDF.

Finally it should be pointed out that using HarPE's unique EXPRESSION block, the user can create sophisticated statistical definitions beyond the built-in capabilities. The user can define statistical variables which are computed through arbitrary functional forms from the basic distributions. For example,

```
EXPRESSION
   Normal_Deviate: 0 {NORMAL SIGMA=1};
   Transformed_Deviate: exp(Uniform_Var);
   Var: 50 + Transformed_Deviate;
End
```

where "Normal_Deviate" specifies a normal distribution with a zero mean and unit standard deviation. "Transformed_Deviate" is defined to have a standard lognormal distribution, and "Var" is a statistical variable with a nominal value of 50 and a lognormal distribution. Although the lognormal distribution is available as a built-in feature, this example serves as an illustration.

Measurement Data for Statistical Modeling

Statistical modeling requires measurement data taken on a sufficiently large sample of devices produced by the same process. Typically, a sample of 100 to 300 devices is deemed sufficiently large. In the current version, the maximum number of devices is 512. Such measurement data shall be referred to as *multi-device measurements*.

Measurement data is supplied in the DATA block of the circuit file. The measurements may include large-signal power spectra, small-signal S-parameters and DC IV data. Data can be entered directly in the DATA block, or contained in separate files which are linked to the circuit file using the "#include" statement. The DATA block is structured as

```
DATA
    PARAMETER  keyword = value ... keyword = value;  ⎫
    FORMAT     keyword(unit)   ... keyword(unit);    ⎪
          data data data ...                         ⎬ data set
          ...                                        ⎪
          data data data ...                         ⎭
    ...
    ...

    PARAMETER  keyword = value ... keyword = value;  ⎫
    FORMAT     keyword(unit)   ... keyword(unit);    ⎪
          data data data ...                         ⎬ data set
          ...                                        ⎪
          data data data ...                         ⎭
END
```

The PARAMETER and the FORMAT statements allow the user to enter his or her data in any format. The values specified in the PARAMETER statement are fixed for the whole data set. The FORMAT statement, on the other hand, instructs the program what data is being supplied in the respective columns of the data set, and the values supplied may differ from one row to another. Normally, different data sets represent measurement sets for different bias conditions, different frequency ranges, etc. For statistical modeling, additionally, measurements from multiple devices must be supplied.

The keyword INDEX is used to identify the measurement data from different devices. It must be specified in the PARAMETER statement for each data set, and must be assigned an integer value. The integer value can be arbitrary, but the data set(s) from each device must have a unique INDEX. The simplest way is to use integers 1, 2, 3, ..., N, where N is the total number of devices measured. The other allowable keywords are common for both statistical and non-statistical operations and are used to refer to parameters such as frequency, input power, magnitude of S_{11}, DC component of the drain current (FREQ, PIN, MS11, ID0), etc. The following is an example of a few data sets.

```
PARAMETER INDEX=1 VG=-1.74V VD=4V;
FORMAT FREQ S2RI;
    2  0.7815 -0.5718 -2.87    1.754  0.01673  0.03549  0.5183 -0.2733
    6 -0.0363 -0.8518 -0.5194 2.372  0.07108  0.04199  0.2542 -0.4683
   10 -0.4835 -0.6226  0.621  1.605  0.09085  0.01503  0.0227 -0.5372
   14 -0.6747 -0.365   0.9452 0.8582 0.0879  -0.00667 -0.19   -0.5467
   18 -0.7532 -0.1425  0.9245 0.3272 0.07678 -0.01788 -0.3916 -0.4998
PARAMETER INDEX=1 VG=-3.1V VD=4V;
FORMAT FREQ S2RI;
    2  0.6483 -0.7165 0.00148 0.00723 0.00148 0.00723 -0.8093 0.04526
    6 -0.328  -0.8011 0.00697 0.01679 0.00697 0.01679 -0.8003 0.1368
   10 -0.6873 -0.4572 0.01229 0.02409 0.01229 0.02409 -0.7823 0.226
   14 -0.7944 -0.1724 0.01842 0.03039 0.01842 0.03039 -0.7559 0.3119
   18 -0.8094  0.0476 0.02551 0.03538 0.02551 0.03538 -0.7219 0.3935
PARAMETER INDEX=2 VG=-1.74V VD=4V;
FORMAT FREQ S2RI;
    2  0.7851 -0.5705 -2.768   1.616  0.01642  0.03588  0.5309 -0.2561
    6 -0.0351 -0.86   -0.6142 2.256  0.07139  0.04453  0.2928 -0.4427
   10 -0.4912 -0.628   0.4863 1.599  0.09341  0.01832  0.0801 -0.519
   14 -0.684  -0.3636  0.8418 0.9255 0.09253 -0.00415 -0.1193 -0.543
   18 -0.7595 -0.1365  0.872  0.4269 0.08269 -0.01703 -0.3145 -0.5158
PARAMETER INDEX=2 VG=-3.1V VD=4V;
FORMAT FREQ S2RI;
    2  0.6483 -0.7165 0.00148 0.00723 0.00148 0.00723 -0.8093 0.04549
    6 -0.328  -0.8011 0.00697 0.0168  0.00697 0.0168  -0.8001 0.1375
   10 -0.6873 -0.4572 0.0123  0.02412 0.0123  0.02412 -0.7818 0.2271
```

```
    14 -0.7944 -0.1724 0.01843 0.03042 0.01843 0.03042 -0.7551 0.3133
    18 -0.8094  0.0476 0.02554 0.03541 0.02554 0.03541 -0.7207 0.395
PARAMETER INDEX=3 VG=-1.74V VD=4V;
FORMAT FREQ S2RI;
     2  0.7847 -0.5697 -2.74   1.646  0.01661  0.03573  0.5271 -0.2657
     6 -0.0324 -0.8565 -0.535  2.26   0.07148  0.04317  0.2754 -0.4599
    10 -0.4851 -0.6276  0.5619 1.556  0.0923   0.01623  0.0501 -0.5349
    14 -0.6785 -0.3669  0.8889 0.8534 0.09005 -0.00605 -0.1601 -0.5517
    18 -0.7565 -0.1419  0.8853 0.3466 0.0792  -0.01803 -0.3622 -0.5126
PARAMETER INDEX=3 VG=-3.1V VD=4V;
FORMAT FREQ S2RI;
     2  0.6483 -0.7165 0.00148 0.0072 0.00148 0.00723 -0.8093 0.04535
     6 -0.328  -0.8011 0.00697 0.0168 0.00697 0.0168  -0.8002 0.1371
    10 -0.6873 -0.4572 0.0123  0.0241 0.0123  0.0241  -0.7821 0.2265
    14 -0.7944 -0.1724 0.01842 0.0304 0.01842 0.0304  -0.7556 0.3125
    18 -0.8094  0.0476 0.02552 0.0353 0.02552 0.03539 -0.7214 0.3941
PARAMETER INDEX=4 VG=-1.74V VD=4V;
FORMAT FREQ S2RI;
     2  0.7796 -0.5746 -3.009  1.801 0.01665  0.03543  0.515  -0.271
     6 -0.0428 -0.8527 -0.6089 2.454 0.07078  0.04217  0.2529 -0.4623
    10 -0.4899 -0.6195  0.5684 1.696 0.09068  0.01563  0.0254 -0.5287
    14 -0.6791 -0.3595  0.9234 0.951 0.08814 -0.00585 -0.1825 -0.5381
    18 -0.755  -0.1362  0.9303 0.414 0.07749 -0.01713 -0.3797 -0.4934
PARAMETER INDEX=4 VG=-3.1V VD=4V;
FORMAT FREQ S2RI;
     2  0.6483 -0.7165 0.00148 0.00723 0.00148 0.00723 -0.8093 0.04531
     6 -0.328  -0.8011 0.00697 0.01679 0.00697 0.01679 -0.8002 0.137
    10 -0.6873 -0.4572 0.01229 0.0241  0.01229 0.0241  -0.7822 0.2263
    14 -0.7944 -0.1724 0.01842 0.03039 0.01842 0.03039 -0.7557 0.3122
    18 -0.8094  0.0476 0.02551 0.03539 0.02551 0.03539 -0.7216 0.3938
```

In this example, measured two-port S-parameters in the rectangular matrix form (the keyword S2RI) are supplied for four devices which are identified by four different INDEXes (1,2,3,4). Notice that more than one data set may be supplied for each device. In this example, two data sets for two different bias points are supplied for each device.

In addition to the formatted data described above, measurement data from Cascade Microtech's MicroCAT Test Executive system can be directly accepted by HarPE. Its data files can be directly included in the DATA block as

```
#include "file_name"  source = cascade
```

The directive "source =" indicates that the data file comes from an external source and is not in HarPE format. The keyword "cascade" identifies the source of the data file as Cascade Microtech's MicroCAT Test Executive system. The following is an example of a MicroCAT data file.

```
NOTE MicroCAT sample data file.
NAME MicroCAT test run
DATE 31-JAN-89
SITE 5.000 0.000
BIAS Vds=3.000
BIAS Ids=0.0210
BIAS Vgs=0.000
S2RITABLE 6
45.000E6 1.0050 -0.0194 -3.662720 0.040894 -0.000080 0.000970 0.7965 -0.0076
 5.336E9 0.1462 -0.8846 -1.238892 2.359375 0.053711 0.051359 0.6062 -0.3692
10.627E9 -0.3997 -0.7135 0.280334 1.669678 0.089882 0.032745 0.4051 -0.5222
15.918E9 -0.5872 -0.5211 0.700195 0.978119 0.096882 0.012543 0.2379 -0.6282
21.209E9 -0.6796 -0.3917 0.756439 0.492950 0.096874 0.000851 0.0750 -0.7027
26.500E9 -0.7203 -0.3161 0.686371 0.204041 0.089085 -0.000854 -0.0869 -0.7499
ENDTABLE
SITE 4.000 1.000
SUBSITE 220 775
BIAS Vds=3.000
BIAS Ids=0.0394
BIAS Vgs=0.000
S2RITABLE 6
45.000E6 1.0041 -0.0181 -3.826660 0.048096 0.000105 0.000278 0.8454 -0.0050
```

```
 5.336E9 0.1950 -0.8993 -1.423218 2.491699 0.031494 0.034666 0.7165 -0.3345
10.627E9 -0.4012 -0.7502 0.282349 1.854736 0.058233 0.025927 0.5421 -0.5294
15.918E9 -0.6143 -0.5454 0.778137 1.085999 0.062037 0.013163 0.3824 -0.6673
21.209E9 -0.7236 -0.3884 0.869995 0.517761 0.064667 0.006695 0.2167 -0.7726
26.500E9 -0.7646 -0.2987 0.780518 0.180756 0.047050 0.013371 0.0516 -0.8484
ENDTABLE
SITE 3.000 2.000
SUBSITE 220 775
BIAS Vds=3.000
BIAS Ids=0.0464
BIAS Vgs=0.000
S2RITABLE 6
45.000E6 1.0040 -0.0170 -3.844971 0.035034 0.000180 0.000485 0.8460 -0.0059
 5.336E9 0.2629 -0.8913 -1.619507 2.518066 0.029911 0.034388 0.7216 -0.3345
10.627E9 -0.3558 -0.7808 0.193970 1.995117 0.057085 0.026552 0.5448 -0.5289
15.918E9 -0.5966 -0.5757 0.773621 1.211670 0.061361 0.013147 0.3797 -0.6645
21.209E9 -0.7109 -0.4142 0.917053 0.609497 0.063061 0.003658 0.2176 -0.7643
26.500E9 -0.7625 -0.3196 0.845215 0.249634 0.049517 0.011354 0.0548 -0.8461
ENDTABLE
```

From the information contained in a MicroCAT file, HarPE picks up the bias data, namely Vds, Vgs and Ids, and the S-parameters. The different devices are identified by the SITE data. The SITE data given by MicroCAT has the form

```
SITE  X  Y
```

HarPE combines the X and Y indices into a single INDEX = 1000 * X + Y. In the above example, three different devices (SITEs) have been measured. The respective (X,Y) indices (5,0), (4,1) and (3,2) are converted into INDEXes 5000, 4001 and 3002.

Statistical Modeling

The first step in statistical modeling is to supply multi-device measurements in the DATA block of the circuit file, as was described in the previous subsection. The next step is to designate optimizable model parameters in the circuit file by enclosing their values within a pair of question marks.

The designated parameters will be optimized to match the measurements from each of the devices. The optimization will be repeated for every device, resulting in a sample of optimized models which consist of as many individual models as the number of different devices. The results can then be postprocessed into a single statistical model.

The error functions to be minimized in the extraction process must be defined in the SPECIFICATION block of the circuit file. Usually, the measured data (e.g., MS11, PS11, ID) is to be matched directly. But the user can also specify user-defined expressions, in which the measured data is transformed, weighted, or otherwise manipulated, as optimization goals.

The multi-device parameter extraction process is invoked by the user by selecting the menu option: HarPE.Statistical.Extract (see Fig. 1), after the circuit file is correctly parsed by the file editor. This starts the automated multi-device optimization process. A message is displayed in the upper-left-hand corner of the screen:

```
Optimization ...  Press any key to interrupt
```

and a graphical indicator is also displayed to signal that the optimization is in progress:

■ ■ ■ ■ ■ ■ ■ ■

On the first line of the screen, the INDEX of the device currently being matched by the optimization is displayed:

```
Statistical Modeling INDEX=kkk
```

where "kkk" is the current INDEX value. Following this line, at each iteration, the following information is displayed, as the parameter extraction progresses:

```
Iteration  xxx/30  L1 Error=yyy
```

where "xxx" represents the current iteration count, and "yyy" is the value of the ℓ_1 error function at the current iteration. The iteration count is reset to 1 for each device (each different INDEX), and the number of iterations is internally limited to 30 per device.

The optimization process can be interrupted at any point by pressing any key on the keyboard. The user is then prompted with the following message:

```
Terminate Operation (Y/<N>)?
```

Pressing <Y> will force the termination of the optimization process, or pressing any other key will resume the optimization process.

A SAMPLE block is automatically created in the circuit file to store the optimized parameter values. There will be as many sets of optimized parameter values as the number of different devices (INDEXes). Each line in the SAMPLE block corresponds to one of the devices and stores the set of parameter values extracted from the measurement data for that device. The INDEX of that particular device is also stored on the same line as an identifier. If the optimization process is interrupted, then the SAMPLE block will contain only those sets of values that have been completed by the time of interruption. The SAMPLE block is structured as

```
SAMPLE
    FORMAT  INDEX  name1  name2  ... nameN;
            kkk    xxxx   xxxx   ... xxxx
            kkk    xxxx   xxxx   ... xxxx

            ...
            ...

            kkk    xxxx   xxxx   ... xxxx
            kkk    xxxx   xxxx   ... xxxx
END
```

where "name1", ..., "nameN" represent the names of the optimizable parameters, "kkk" represents the INDEXes identifying the different devices, and "xxx" represents the optimized parameter values. For instance, if "VAR1", "CDS" and "T" are designated as optimizable parameters in the circuit file, and measured data for 100 devices identified by INDEXes 1, 2, ... 100, is supplied, the SAMPLE block may look like this:

```
SAMPLE
   FORMAT  INDEX VAR1 CDS(PF) T(PS);
       1   32.2   0.1035    3.522
       2   29.7   0.1105    3.266

       ...
       ...

     100   34.1   0.0983    3.471
END
```

The menu option: HarPE.Statistical.Sample (see Fig. 1) allows the user to statistically examine the parameter values stored in the SAMPLE block of the circuit file. Histograms and scatter diagrams of the parameter values in the SAMPLE block can be examined. The histogram display is available through the HarPE.Statistical.Sample.Histogram menu option. It provides a graphical display of the marginal distribution of a parameter. A pop-up window allows the user to select any one of the parameters contained in the SAMPLE block. The number of bins can also be selected. The mean value and standard deviation of the selected parameter are displayed.

Scatter diagrams are available through the HarPE.Statistical.Sample.Scatter menu option. Scatter diagrams display graphically the correlation between two parameters. A pop-up window allows the user to select separately any two of the parameters contained in the SAMPLE block. The correlation coefficient of the pair is also displayed.

Normally, the creation and processing of the SAMPLE block is transparent to the user. However, he or she can edit the contents of the SAMPLE block if so desired. For instance, after a visual inspection of the parameter variations, it may be desirable to delete some of the points that seem to have "wild" values. Moreover, the user can create his/her own SAMPLE block. This is useful to utilize some but not all of the statistical capabilities of HarPE. In fact, a SAMPLE block may contain a sample of values (raw data) of any kind which the user wishes to analyze statistically.

The parameter values stored in the SAMPLE block after parameter extraction represent a sample of models. This statistical information can be further postprocessed to produce a single statistical model. The menu option for this task is HarPE.Statistical.Postprocess (see Fig. 1).

A multidimensional normal (Gaussian) distribution is used for the postprocessed statistical model. However, some of the parameters of the equivalent circuit model, such as the Curtice model, may exhibit substantially non-Gaussian sample distributions. For such parameters, the user may choose to keep the corresponding histograms as discrete approximations of the marginal density functions. Pioneered by OSA, this combined discrete/normal approach preserves the means, standard deviations, correlations and marginal distributions derived from the sample. It provides enhanced accuracy of the model while retaining the simplicity of the normal distribution.

How close a parameter's sample distribution is to a normal distribution can be assessed from its histogram. Once the HarPE.Statistical.Postprocess option is invoked, the histograms for all the parameters being postprocessed are sequentially displayed. Together with each histogram the following prompt is displayed:

```
Keep the histogram as an approximate DDF (Y/<N>):
```

Answering "Y" will result in creating the DDF option in the parameter statistics with the histogram values stored after the DDF keyword.

The final result of postprocessing is a back annotated circuit file containing a consolidated statistical model and immediately suitable for statistical (Monte Carlo) analysis. Parameters which are defined in the original circuit file as optimizable, as

```
name: ?...?;
```

and have corresponding sample of values in the SAMPLE block are redefined as statistical variables, as

```
name: x {Normal Sigma=y% Correlation=CORMAT[k]};
```

where "x" represents the mean value, "y" the standard deviation as a percentage of the mean value, "CORMAT" the default name of the correlation matrix, and "k" the index in the correlation matrix. For the following example,

```
    VAR1: ?30?;
    CDS: ?0.1PF?;
    T: ?3PS?;

...

SAMPLE
    FORMAT  INDEX VAR1 CDS(PF) T(PS);
        1   32.2   0.1035    3.522
        2   29.7   0.1105    3.266
        ...
        ...
      100   34.1   0.0983    3.471
END
```

the back annotated file may appear as follows:

```
    VAR1: 31.05 {Normal Sigma=4.3% Correlation=CORMAT[1]};
    CDS: 0.102PF {Normal Sigma=6.1% Correlation=CORMAT[2]};
    T: 3.47PF {Normal Sigma=8.44% Correlation=CORMAT[3]};

...

STATISTICS
    CORRELATION: CORMAT DIMENSION=3 FORMAT=FULL;
          1    0.4638       0.82
     0.4638         1     0.7997
       0.82    0.7997          1
END
```

where STATISTICS is a new circuit file block containing the correlation matrix. The dimension of the correlation matrix is equal to the number of statistical variables that are postprocessed. The correlation matrix contains the correlation coefficients between each and every pair of statistical variables.

If the histogram of a parameter is chosen as a discrete approximation of the marginal density function, then the statistical definition takes the form

```
name: x {Normal Sigma=y% Correlation=CORMAT[k] DDF=n1 n2 ... nN};
```

where keyword "DDF" stands for "discrete density function", and is followed by N integers. N is the number of bins in the histogram, and the integers are the numbers of values from the SAMPLE block which fall within the bins. For example:

```
VAR: 1 {Normal Sigma=5% Correlation=CORMAT[1] DDF=7 16 29 37 9 2};
```

The back annotated circuit file is automatically placed in the screen editor's buffer and the program switches into the editing mode. The file can be viewed and/or edited. However, the back annotated file is not automatically saved to the disk. It exists only in the memory buffer and will disappear upon exiting from the editor. It has to be explicitly saved to the disk if so desired. The back annotated file is in a separate memory buffer from the master circuit file (i.e., the file before postprocessing). Hence the editing performed on the back annotated file will not affect the master circuit file. After exiting from the editor, all the subsequent operations will be controlled by the master circuit file.

The DATA, SPECIFICATION and SAMPLE blocks are removed from the back annotated file. This is because they have served their purposes in the modeling stage and are no longer useful for statistical analysis.

Finally, the menu option: HarPE.Statistical.Data (see Fig. 1) allows the user to view the histograms of the measured data. From a pop-up window, he/she selects a particular bias point, frequency and/or input power level from those supplied in the DATA block. The user also selects a response from those available. For example, suppose that the measured data supplied is

```
PARAMETER INDEX=1 VG=-1.74V VD=4V;
FORMAT FREQ RS11 IS11 RS21 IS21 RS12 IS12 RS22 IS22;
    2  0.7815 -0.5718 -2.87    1.754  0.01673  0.03549  0.5183 -0.2733
    6 -0.0363 -0.8518 -0.5194 2.372  0.07108  0.04199  0.2542 -0.4683
   10 -0.4835 -0.6226  0.621   1.605  0.09085  0.01503  0.0227 -0.5372
   14 -0.6747 -0.365    0.9452 0.8582 0.0879  -0.00667 -0.19   -0.5467
   18 -0.7532 -0.1425  0.9245 0.3272 0.07678 -0.01788 -0.3916 -0.4998
PARAMETER INDEX=1 VG=-3.1V VD=4V;
FORMAT FREQ RS11 IS11 RS21 IS21 RS12 IS12 RS22 IS22;
    2  0.6483 -0.7165 0.00148 0.00723 0.00148 0.00723 -0.8093 0.04526
    6 -0.328   -0.8011 0.00697 0.01679 0.00697 0.01679 -0.8003 0.1368
   10 -0.6873 -0.4572 0.01229 0.02409 0.01229 0.02409 -0.7823 0.226
   14 -0.7944 -0.1724 0.01842 0.03039 0.01842 0.03039 -0.7559 0.3119
   18 -0.8094  0.0476 0.02551 0.03538 0.02551 0.03538 -0.7219 0.3935

...
```

The user can select any one of the 10 measurement points (i.e., two bias points and five frequencies per bias). Also, any response from the 8 responses available, namely, RS11, IS11, ..., RS22, IS22 can be selected. The mean value and standard deviation of the selected response are displayed together with the histogram.

12. Appendix

This appendix contains a copy of a feature article scheduled to appear in the August 1990 issue of *Microwave Journal*. It should be noted that acknowledgement of the NRC assistance is included in this publication. A similar article will appear in the July/August issue of *Microwave & RF Engineering*.

New CAD System for Statistical Modeling

Optimization Systems Associates Inc.

Dundas, Ontario, Canada

Introduction

Advanced features of statistical modeling and analysis are now available as an add-on module for HarPE. The package is released as HarPE Version 1.4+S, available immediately on Apollo, Hewlett-Packard and Sun workstations.

HarPE is a state-of-the-art software system for device modeling, simulation and optimization. It offers many of OSA's pioneering technologies, including integrated large-signal, small-signal and DC modeling, FAST sensitivities for harmonic-balance optimization, and user-created models using the EXPRESSION Block.

The new statistical features are derived from OSA's long-term, in-depth research work. As the microwave industry recognizes the importance of yield and cost analysis and optimization of (M)MIC circuits, the capability to extract statistical models from measurements becomes a CAD priority.

Multi-Device Modeling

HarPE Version 1.4+S implements a multi-device optimization and postprocessing approach to statistical modeling. Suitable measurements (large-signal power spectra, small-signal S-parameters, and/or DC IV data) are collected from a sample of devices. The size of the sample is determined by a trade-off between measurement cost and statistical estimation accuracy. Typically, a sample of 100 to 300 devices is used. A theoretical study by OSA on the relationship between statistical confidence level and sample size has indicated that, *if the distribution is indeed normal*, sufficient confidence can be achieved from a sample size as small as 20 to 50. Measurements on multiple devices may be automated by some systems, such as Cascade Microtech's MicroCAT Test Executive system which is supported by HarPE.

From the measured data, multiple device models are extracted through repeated optimization. OSA's gradient-based ℓ_1 optimizer provides a fast and reliable tool for the underlying parameter extraction. Execution times vary according to the model used, the sample size, and the amount of data per device. Our test examples show a typical run time for 100 devices, with S-parameter measurements at two bias points and five frequencies per bias, ranging from 45 minutes on an Apollo DN3500 to 15 minutes on a Sun SPARCstation 1.

Postprocessing

The sample of extracted models include all model parameters designated as optimizable in the HarPE circuit file, e.g.,

```
CDS: ?1PS?
```

The sample of these parameter values is automatically stored in the circuit file as the SAMPLE block. For example, with a sample size of 100, we may have

```
SAMPLE
   FORMAT  INDEX  CDS(PS)  ...  ...  ...;
              1    1.013   ...  ...  ...
              2    0.982   ...  ...  ...
             ...
            100    1.107   ...  ...  ...
END
```

Histograms showing parameter spreads and scatter diagrams showing parameter correlations are displayed. The sample of parameters can be postprocessed to generate a consolidated statistical model, which is then back annotated to produce a HarPE circuit file immediately suitable for Monte Carlo analysis. For example, the definition of optimizable CDS, as shown above, will be replaced by (back annotation),

```
CDS: 1.1PS {Normal Sigma=7.4%
            Correlation=CORMAT[1]}
```

where "1.1PS" is the estimated mean value, "Normal" indicates the distribution type, "Sigma" is followed by the standard deviation as a percentage of the mean, and "CORMAT[1]" points to indexed entries in the correlation matrix.

Parameter correlations are automatically estimated and included in the multidimensional normal (Gaussian) distribution model. For parameters exhibiting substantially non-Gaussian distributions, the user can choose to keep the histograms as discrete approximations of the marginal density functions. This combined discrete/normal approach developed by OSA preserves the means, standard deviations, correlations and marginal distributions derived from the sample. It provides enhanced accuracy of the model while retaining the simplicity of the normal distribution.

The statistical postprocessor in HarPE Version 1.4+S can also be applied to arbitrary raw data supplied by the user. The statistics (means, standard deviations and correlations) of such data can be analyzed, and histograms and scatter diagrams can be displayed.

Monte Carlo Analysis

The back annotated circuit file produced by the statistical modeling option can be used readily for statistical (Monte Carlo) analysis. HarPE Version 1.4+S features Monte Carlo analysis including large-signal, DC and small-signal simulations. Uniform, normal, exponential and lognormal distributions with absolute or relative tolerances can also be used in Monte Carlo analysis. Histograms, run charts, and sweep diagrams are displayed. Yield can be computed from specifications on spectra, S-parameters, DC currents and arbitrary user-defined functions. The statistical responses can also be saved as numerical data files.

Physics Based FET Model

The statistical features can be used with any of HarPE's built-in or user-created device models. Popular equivalent circuit models are supported, including the Materka model, Curtice model and Raytheon model for FET, bipolar models, and the diode model. Even more significantly, HarPE Version 1.4+S is the first commercial software system to offer a physics based FET model *together with* statistical modeling and analysis capabilities.

The physics based model in HarPE is a large-signal analytic model based on the work of Khatibzadeh and Trew. It describes the conduction and displacement currents of the FET as a function of instantaneous terminal voltages and their time derivatives. Model parameters include gate length, gate width, and channel thickness. Uniform doping and arbitrary doping profiles are accommodated. Physics based models enjoy a distinctive advantage in statistical modeling and analysis. Because such models directly relate to physical, geometrical and process parameters, their statistical distributions are closer to being normal (Gaussian). They may be either strongly or loosely correlated. Therefore, physics based statistical models should prove to be more accurate and reliable.

All these exciting new features are presented in HarPE's polished and user-friendly environment, which includes high-quality graphics, menu-driven operation, integrated full screen editor, clear file syntax, on-line help and Manual, and more.

Acknowledgement

The statistical modeling feature, featured in HarPE Version 1.4+S, was made possible in part by the National Research Council of Canada through its IRAP-M program.

For more information, contact **Optimization Systems Associates, Inc., Dundas, Ontario, Canada (416) 628-8228.**