STATISTICAL DESIGN, YIELD OPTIMIZATION

AND DEVICE MODELING FOR (M)MICs

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STATISTICAL DESIGN, YIELD OPTIMIZATION AND DEVICE MODELING FOR (M)MICs

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Abstract

The state-of-the-art in optimization oriented microwave CAD will be reviewed. In particular, optimization techniques suitable for simulation of nonlinear circuits, yield optimization, optimal tolerance assignment and cost optimization, worst-case design, and parameter extraction by optimization will be discussed. Specific objective function formulations and properties of ℓ_1, ℓ_2, least *p*th and minimax will be addressed together with the state-of-the-art algorithms for solving these problems. Usefulness of different optimization formulations for different design and modeling tasks will be given special attention. Commercially available software for CAD will be reviewed. Current research trends in statistical design and modeling will also be presented. This will include discussion on growing needs for an integrated software system capable of solving layout oriented complex (M)MIC designs and incorporating layout/process parameters, field theoretic simulation at the component level, circuit theoretic simulation at the system level, device modeling integrated with device and circuit simulations, statistical device processing integrated with statistical design centering, etc.

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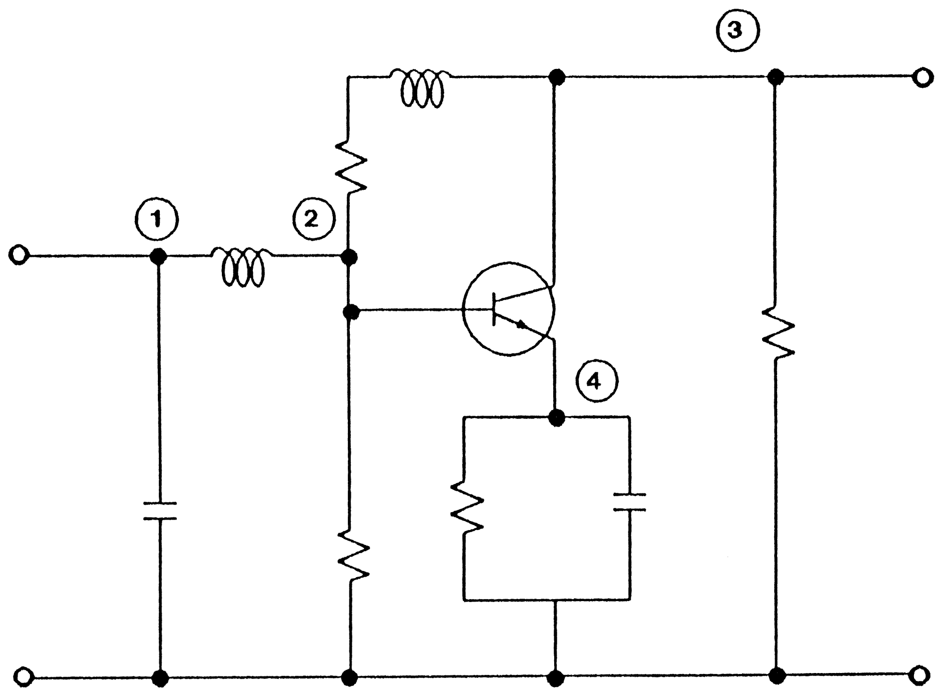
Statistical Analysis and Yield-Driven Design
Input File Example

```
*
* DESIGN CENTERING EXAMPLE: FILE CEN01.DAT
*
BLK
  CAP       1     0    C  4PF      #ND  5%#
  IND 1     2          L  ?8NH?    #UD  15%#
  RES       2          R  550
  TWO       2  3  4    Q1
  PRC       4          R  5        #ND  5%#       C  ?14PF?
  SRL2      3          R  ?154?    #ND  10%#      L  ?24NH?
  RES       3          R  300
A:2POR      1     3
END
FREQ
  10MHZ  STEP  250MHZ  1000MHZ  250MHZ
END
OPT
  A  MS11  -8.0DB  LT  MS22  -8.0DB  LT  MS21  9DB  10DB  + W  2
END
STAT
  A  MS11  -8.0DB  LT  MS22  -8.0DB  LT  MS21  9DB  10DB
END
.
(data section for Q1)
.
.
```



Small-signal amplifier

Statistical Analysis and Yield-Driven Design
Command Level Example

CMD > CEN
Number of outcomes <20> : 15
Gradient, Random or Quit? (G/R/Q): G
..
Initial Variables and Gradients

Variables			Gradients	
(1):	8.0000	NH	(1):	2.2392
(2):	14.000	PF	(2):	24.992
(3):	154.00		(3):	-203.40
(4):	24.000	NH	(4):	72.516

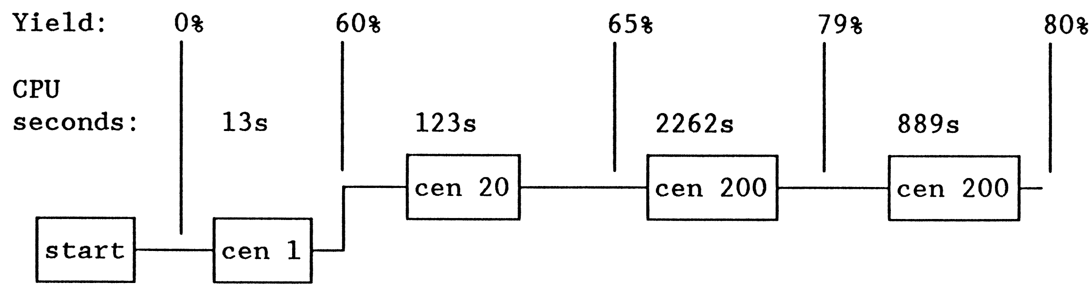
Obj. F.= 7.00000 Yield Est.= 53.33%
----****----
..
Number of iterations? (x/<0>): 50 N
..
CMD > STAT NH
Number of trials? (n/<0>): 300
..
Number of additional trials? (n/<0>): <RET>

Statistical Analysis and Yield-Driven Design
Results of Optimization

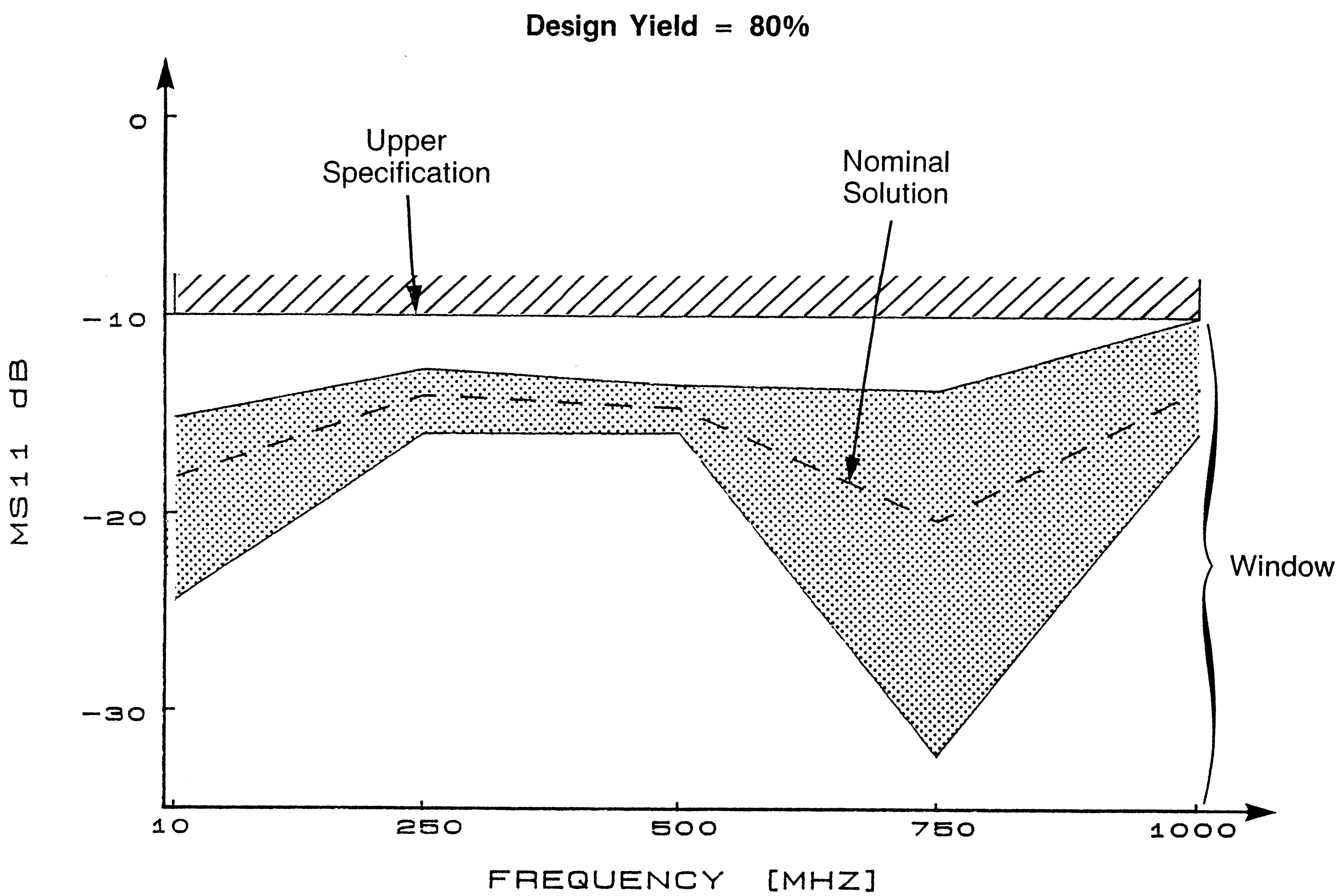
.

.

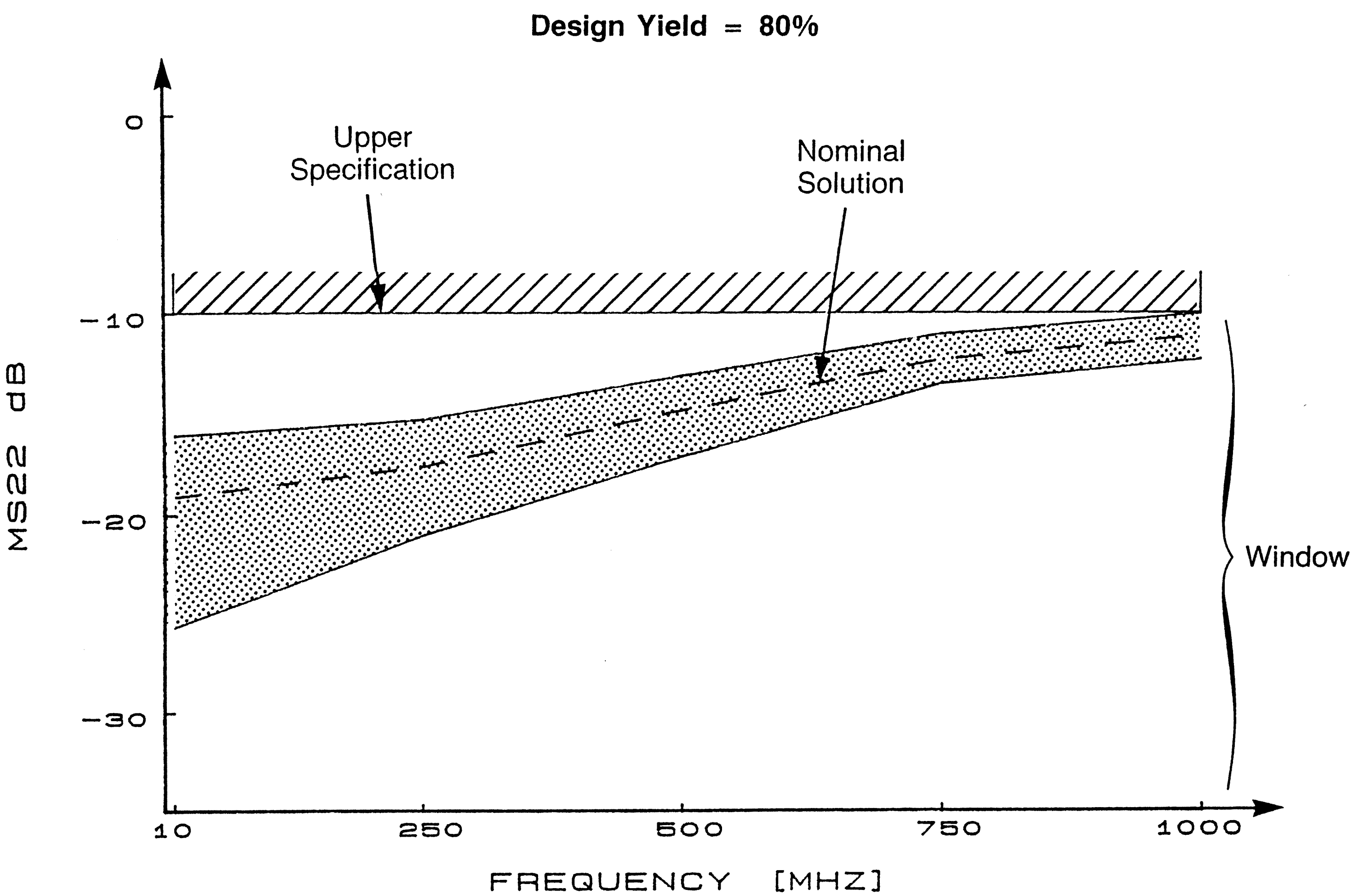
```
( 1):  9.6931    NH        ( 1):  65.828
( 2):  5.1598    PF        ( 2): -33.352
( 3):  311.56              ( 3): -119.50
( 4):  59.748    NH        ( 4): -163.99
       .
       .
       .
( 15/ 50)  Obj. F.=  29.4900 Yield Est.=  80.50%
       ----****----
 Local minimum -- gradient search cannot improve
 CPU time = 2261.85 Secs.    28000 Function evaluations
```



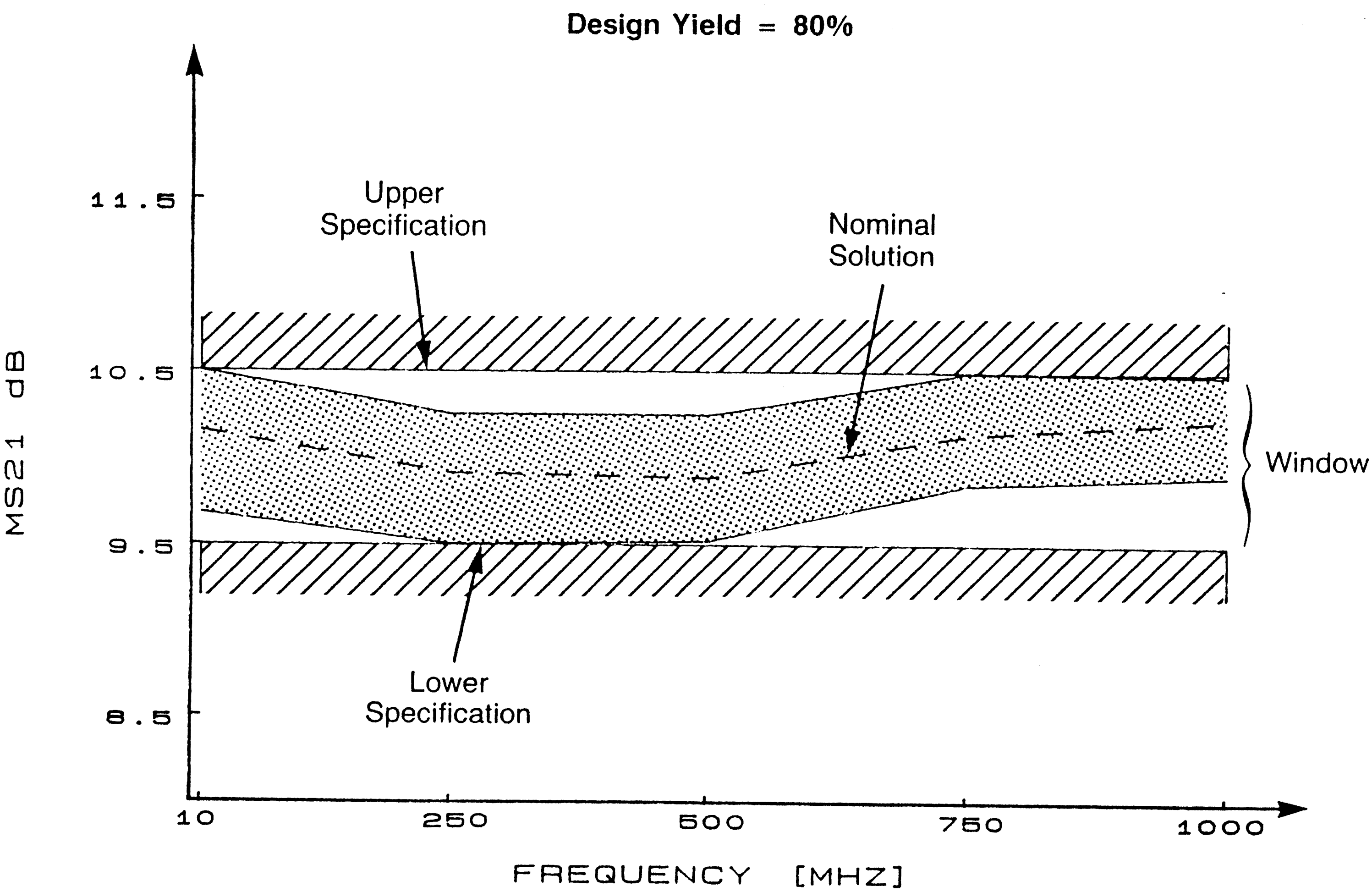
Multistage yield optimization



Envelope diagram for the magnitude of S_{11} for centered design of small-signal amplifier



Envelope diagram for the magnitude of S_{22}
for centered design of small-signal amplifier



Envelope diagram for the magnitude of S_{21} for centered design of small-signal amplifier

Yield Optimization of a 5-Channel Multiplexer

5-channel 12 GHz contiguous band microwave multiplexer, consisting of multicavity filters distributed along a waveguide manifold (*Bandler, Daijavad and Zhang* 1986)

scale of the problem

- 124 nonlinear constraint functions for each outcome
- total of 75 toleranced design variables
- up to 200 outcomes uniformly distributed between tolerance extremes

specifications for the original design

- 20dB for the common port return loss and 20dB for the individual channel stopband insertion losses

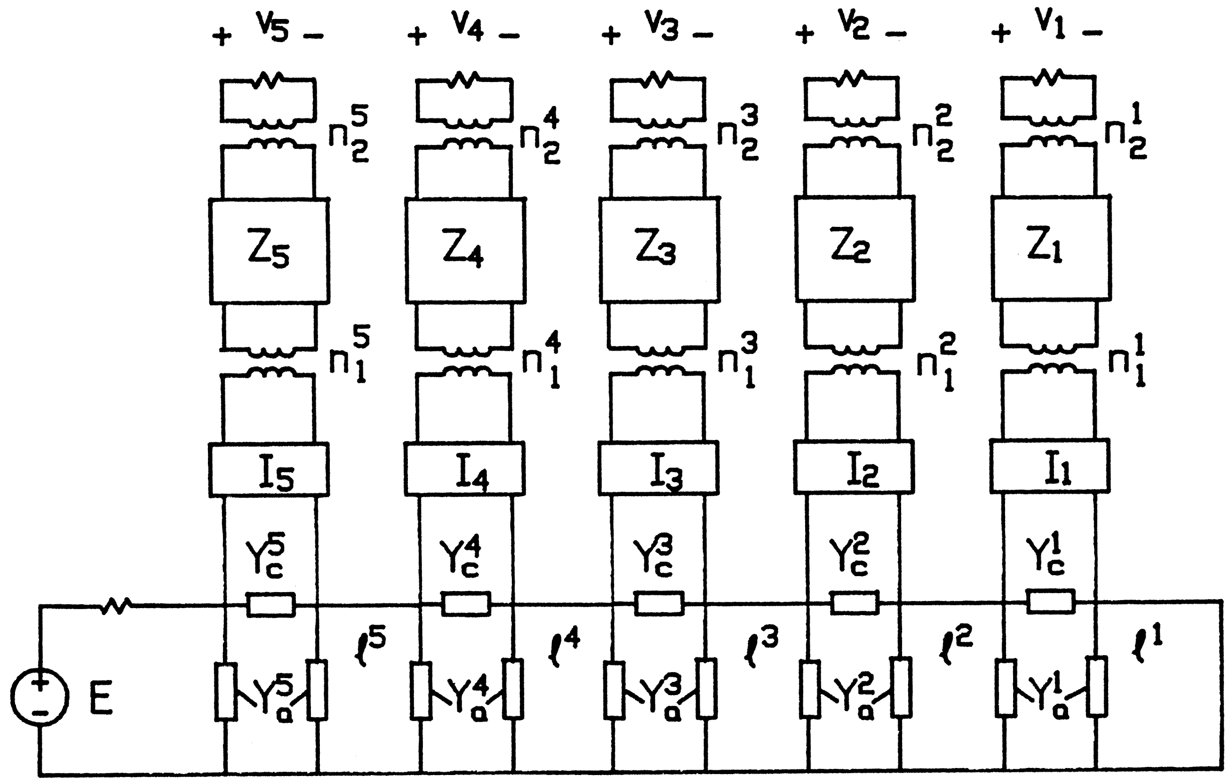
Yield Optimization of a 5-Channel Multiplexer (cont'd)

specifications for statistical design

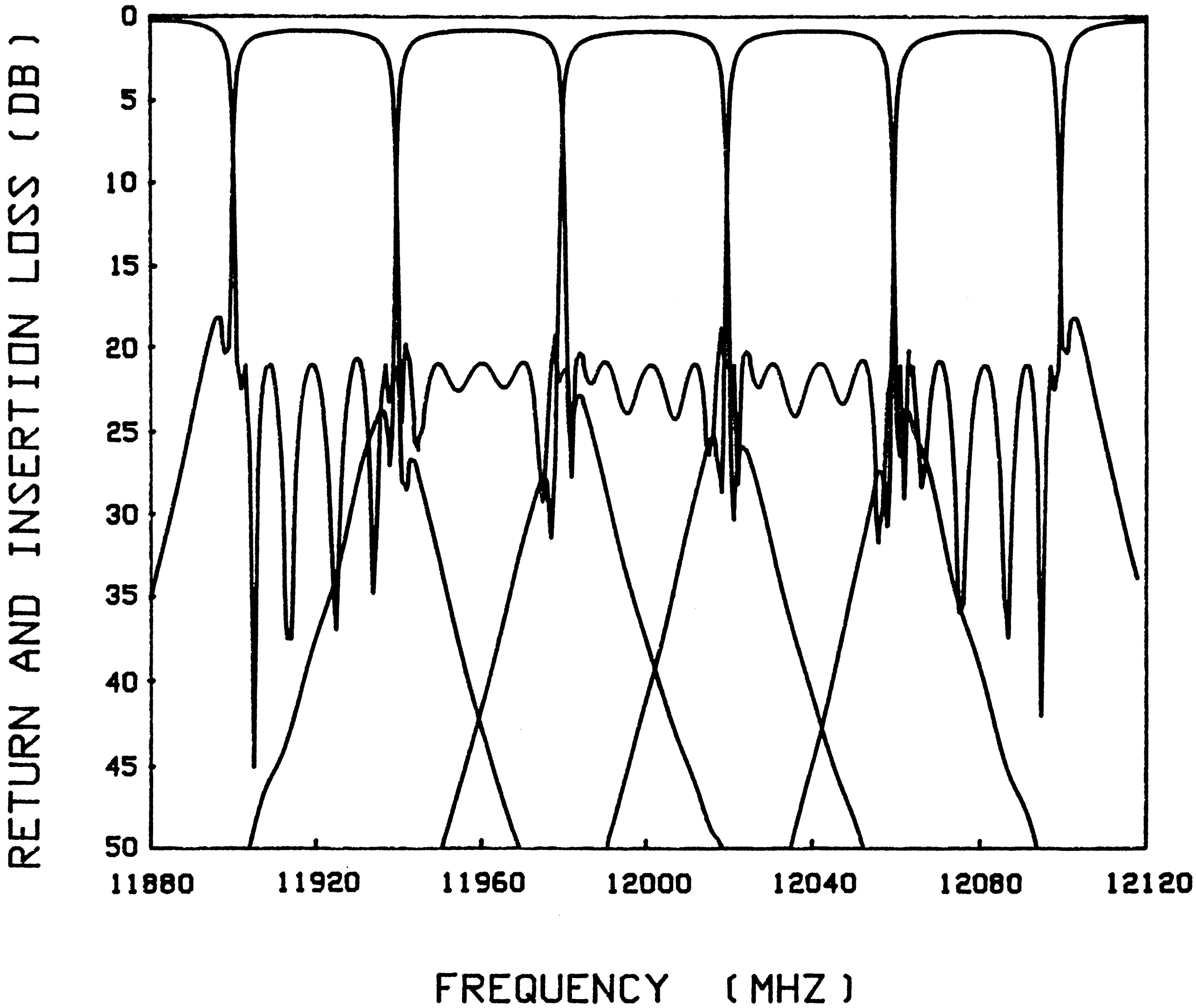
10dB for the return and stopband insertion losses

results

yield increased from 75% to 90%
CPU time on CRAY X-MP/22 was 69.5 seconds



5-channel multiplexer

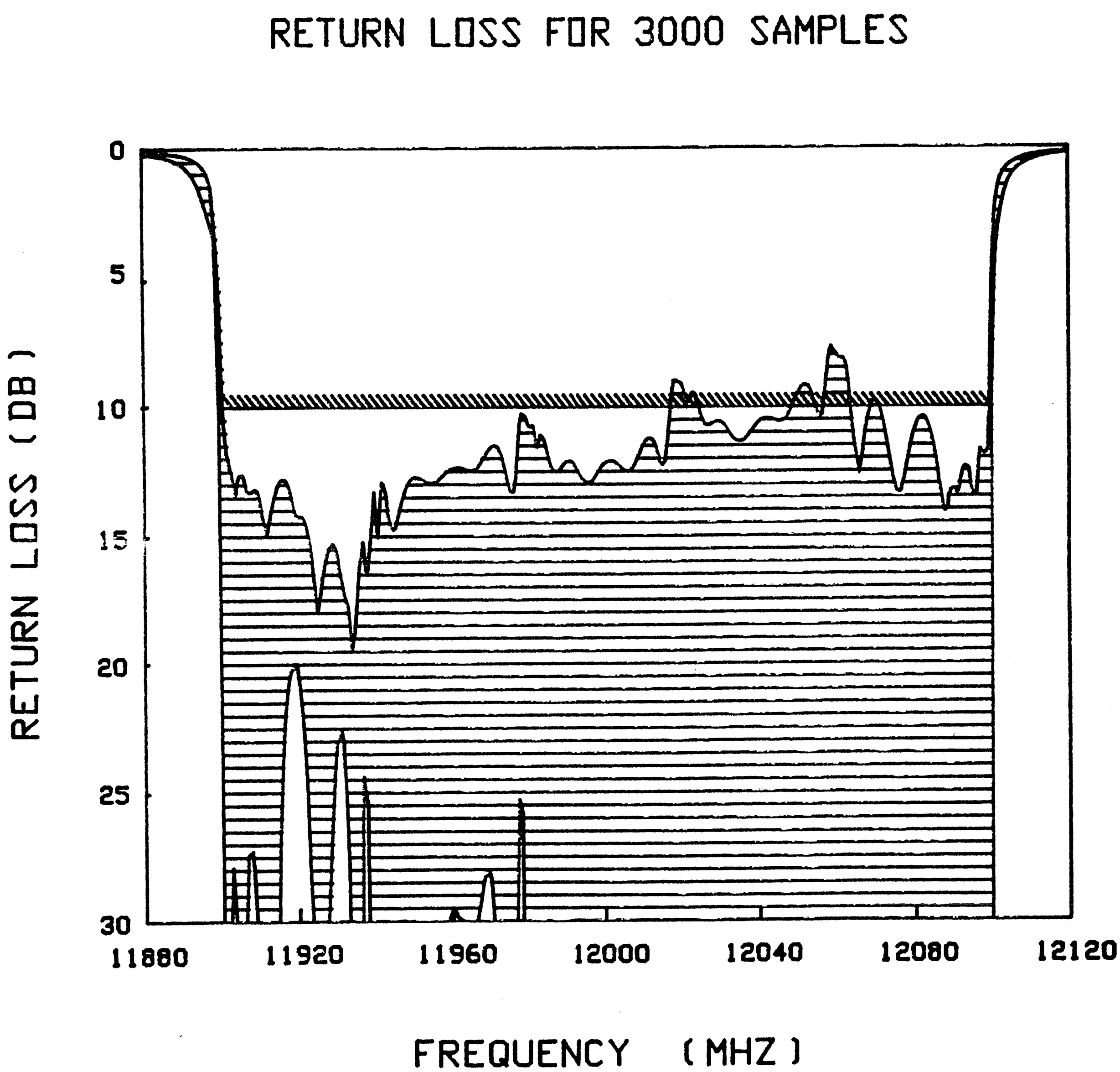


Optimized return and insertion loss for
5-channel multiplexer

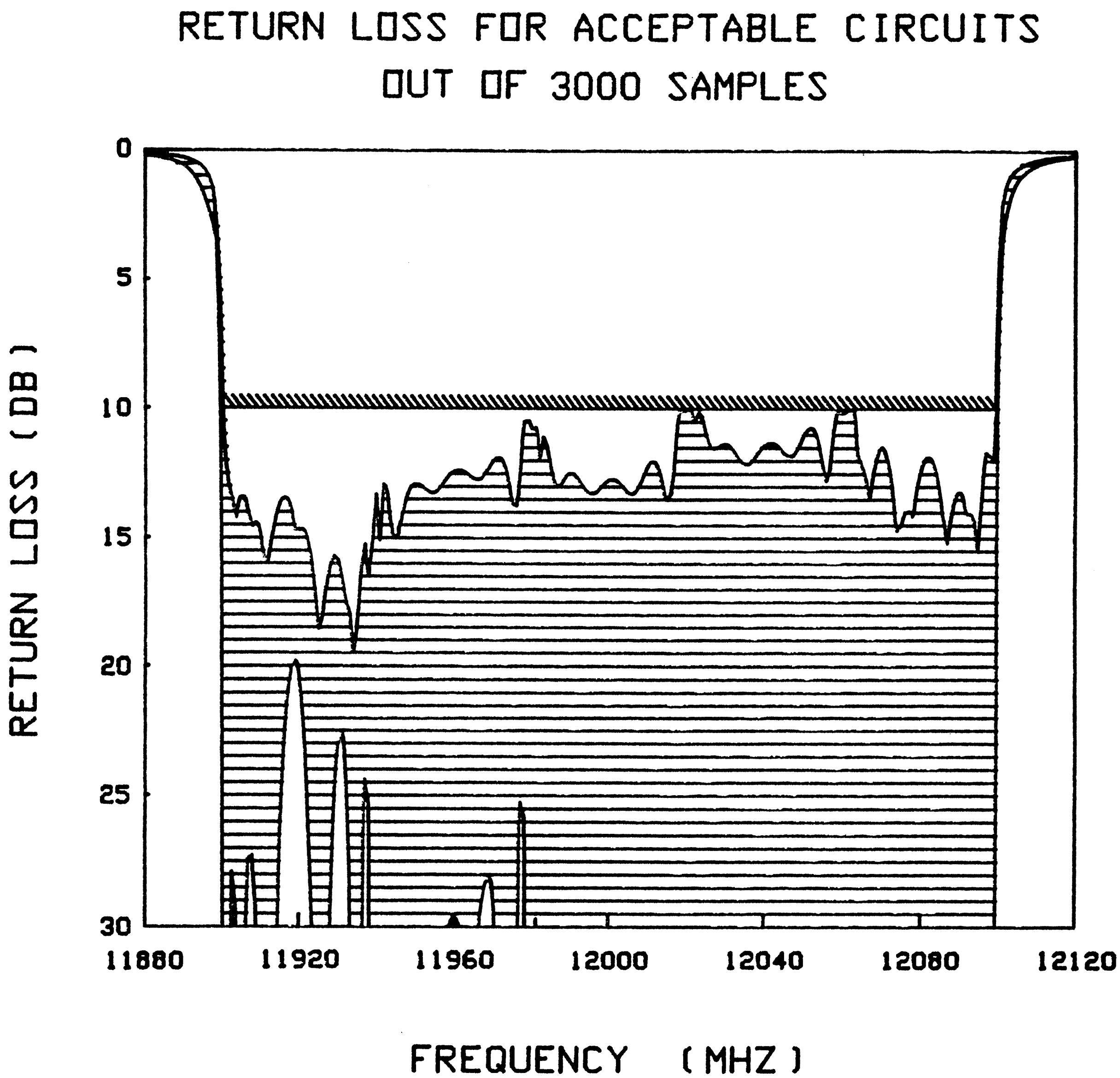
STATISTICAL DESIGN OF A 5-CHANNEL MULTIPLEXER USING QUADRATIC APPROXIMATION

	Phase 1	Phase 2	Phase 3	Phase 4
Starting Point of the Phase	Nominal Design	Solution of Phase 1	Solution of Phase 2	Solution of Phase 3
Initial Yield Estimated from Exact Simulation	75.0%	81.0%	84.3%	90.0%
Initial Yield Estimated from Approximation	56.3%	69.0%	69.3%	92.0%
Number of Outcomes Used for Optimization	50	100	150	200
Number of Iterations	4	6	6	4
Final Yield Estimated by Simulation	81.0%	84.3%	90.0%	90.3%
Final Yield Estimated by Approximation	77.3%	77.3%	91.3%	94.0%
CPU Time (CRAY X-MP/22)	16.5s	17.6s	17.8s	17.6s

CPU times do not include yield estimation based on actual simulation.
All yields are estimated using 300 samples.



Envelope diagram for all outcomes of centered 5-channel multiplexer



Envelope diagram for acceptable outcomes of centered 5-channel multiplexer

Impact of Yield Optimization on Tunable Circuit Design

drive up the probability of obtaining circuits that exhibit good initial responses for the tuning process

increase the possibility of the circuit outcomes satisfying specifications after tuning easy-to-tune elements

Statistical Outcomes

the *k*th tunable outcome $\mathbf{x}^k$ may be described by

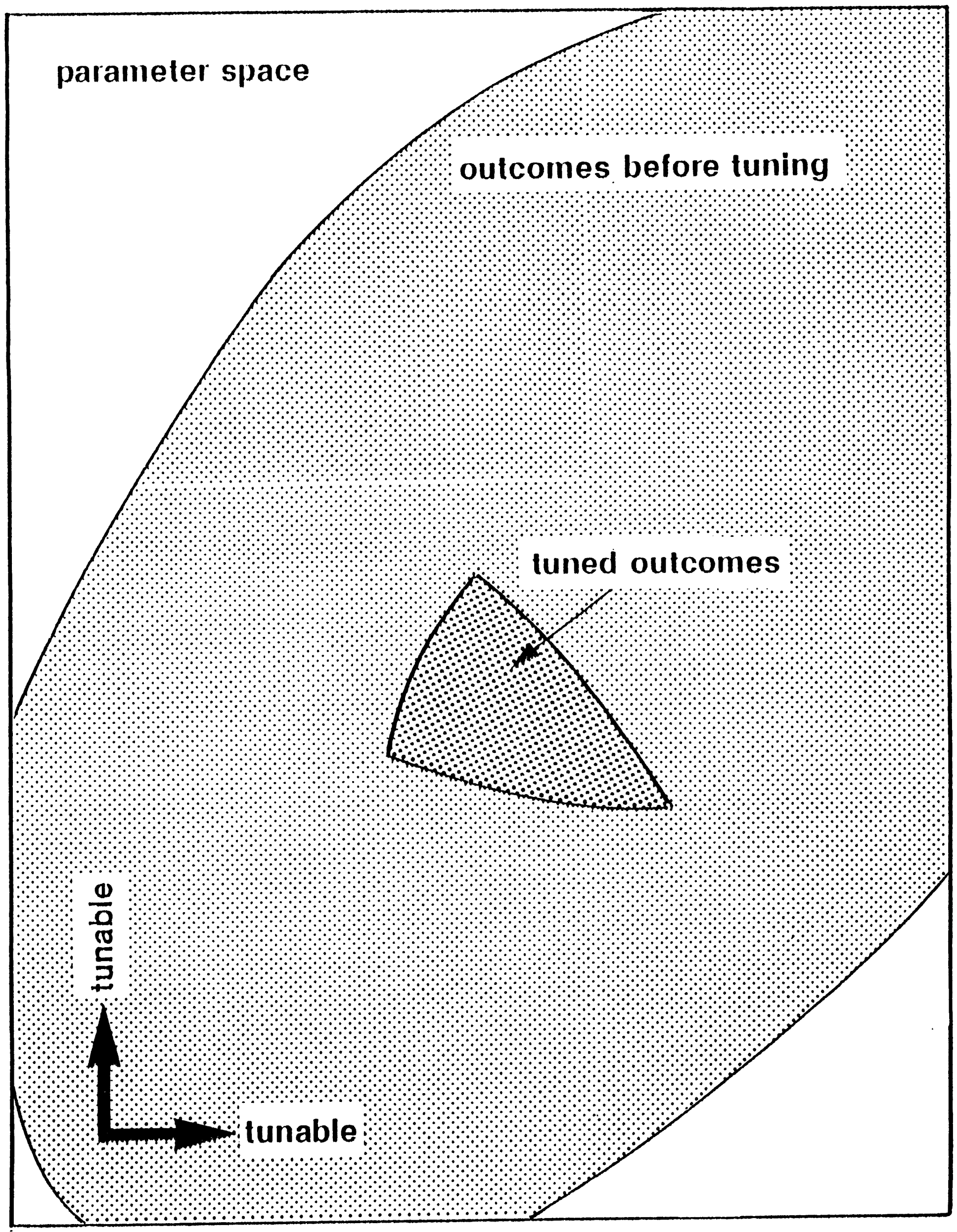
$$\mathbf{x}^k = \mathbf{x}^0 + \mathbf{r}^k, \quad \mathbf{r}^k = \mathbf{s}^k + \mathbf{t}^k + \mathbf{s}_t^{\,k}, \quad k = 1, 2, \ldots, N_t$$

where

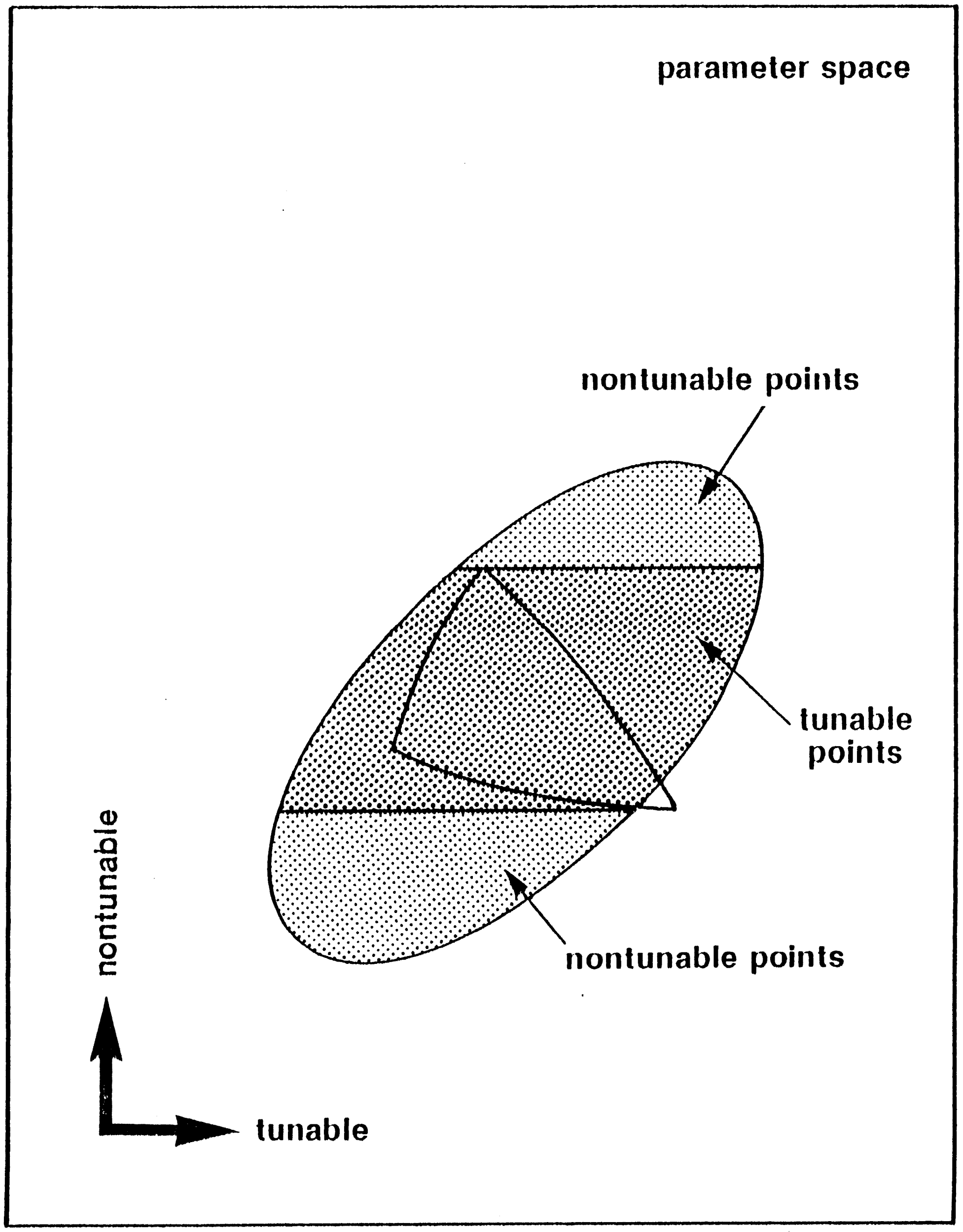
$\mathbf{s}^k$ represents model uncertainties and manufacturing tolerances

$\mathbf{t}^k$ represents postproduction tuning adjustments

$\mathbf{s}_t^{\,k}$ represents tuning imprecisions



Effect of tuning



Impact of tunable and nontunable parameters

EAST

a theoretical breakthrough in harmonic balance

50 times faster than perturbation in our tests

expensive to implement in general purpose programs

FAST Analysis of a FET Mixer

the mixer circuit

LO frequency	f_{LO} = 11 GHz
RF frequency	f_{RF} = 12 GHz
IF frequency	f_{IF} = 1 GHz
DC bias voltages	V_{GS} = -0.9, V_{DS} = 3.0
LO power	P_{LO} = 8 dBm
RF power	P_{RF} = -15 dBm
conversion gain	6.9 dB

computed sensitivities of the conversion gain w.r.t. all 26 variables

- all parameters in the linear part
- all parameters in the nonlinear part
- DC bias, LO power, RF power
- IF, LO and RF terminations

Results of FAST Analysis of a FET Mixer

excellent agreement between sensitivities computed using FAST, PAST and EAST

CPU times on VAX 8600

circuit simulation	22 seconds
FAST sensitivity analysis	10.7 seconds
EAST sensitivity analysis	3.7 seconds
PAST sensitivity analysis	240 seconds

NUMERICAL VERIFICATION OF FAST FOR THE MIXER EXAMPLE

Variable	Sensitivity from FAST	Sensitivity from EAST	Sensitivity from PAST	Difference between FAST and EAST (%)	Difference between FAST and PAST (%)
linear subnetwork					
C_{ds}	-24.28082	-24.28081	-24.03669	0.00	1.01
C_{gd}	-32.16238	-32.16237	-32.33670	0.00	-0.54
C_{de}	-8.8×10^{-13}	1.7×10^{-13}	0	120.21	100.00
R_g	10.00754	10.00756	9.89609	-0.00	1.11
R_d	11.71325	11.71327	11.71338	-0.00	-0.00
R_s	-4.98829	-4.98827	-4.98861	0.00	-0.01
R_{de}	-0.07171	-0.07171	-0.07115	0.00	0.79
L_g	-0.30238	-0.30238	-0.30054	0.00	0.61
L_d	-0.87824	-0.87824	-0.87247	0.00	0.66
L_s	-0.33527	-0.33527	-0.33191	0.00	1.00
nonlinear subnetwork					
C_{gs0}	-5.43110	-5.43110	-5.38265	0.00	0.89
τ	1.52983	1.52984	1.56057	-0.00	-2.01
V_ϕ	-20.84224	-20.84223	-20.84308	-0.00	-0.00
V_{p0}	-14.62206	-14.62206	-14.62469	0.00	-0.02
V_{dss}	0.30209	0.30209	0.30210	0.00	-0.00
I_{dsp}	9.39335	9.39335	9.39338	-0.00	-0.00
bias and driving sources					
V_{GS}	-4.94402	-4.94402	-4.94271	-0.00	0.03
V_{DS}	-0.67424	-0.67424	-0.67429	0.00	-0.01
P_{LO}	2.02886	2.02885	2.02882	0.00	0.00
P_{RF}	-0.09073	-0.09072	-0.09077	0.01	-0.05
terminations					
$R_g(f_{LO})$	8.83598	8.83596	8.76244	0.00	0.83
$X_g(f_{LO})$	2.20500	2.20496	2.16567	0.00	1.78
$R_g(f_{RF})$	0.71282	0.71281	0.70568	0.00	1.00
$X_g(f_{RF})$	0.46410	0.46409	0.45702	0.00	1.53
$R_d(f_{IF})$	0.65950	0.65950	0.65272	-0.00	1.03
$X_d(f_{IF})$	0.09024	0.09024	0.09207	-0.00	-2.02

Simple and Efficient Computation of Jacobian

exact Jacobian for HB simulation is available but very expensive to implement

the perturbation (or incremental) approach is typically used in practice but is slow

FAST concept extends to Jacobian calculation by

- computing time domain derivatives at the device level using perturbations
- converting these derivatives to the frequency domain by a Fourier transform
- assembling the resulting Fourier coefficients into the Jacobian matrix

Approximate Jacobian for a Frequency Doubler

the doubler circuit

input frequency	5 GHz
output frequency	10 GHz

four harmonics were considered

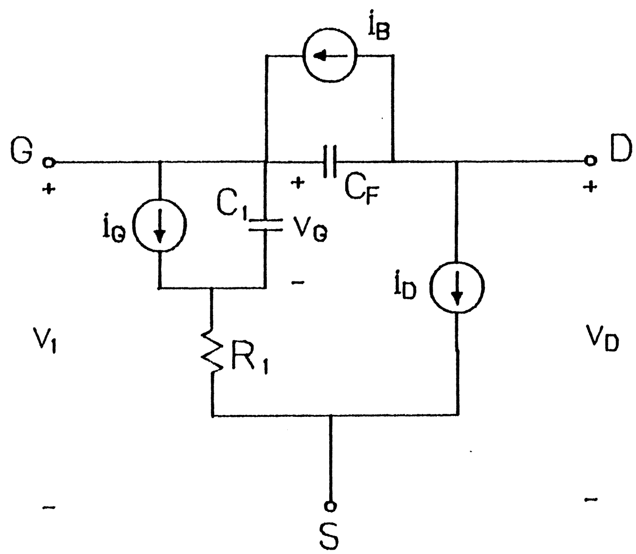
the Jacobians were computed using

- the FAST approach
- the conventional perturbation approach

numerical results agree very well

the corresponding CPU times on MicroVAX II

FAST	0.89 second
perturbations	5.3 seconds



Intrinsic part of modified Materka FET model

INPUT LEVELS USED WITH DIFFERENT FUNDAMENTAL FREQUENCIES AND DIFFERENT BIAS POINTS

(V_{GB}, V_{DB})	P_{in} (dBm)			
	f_1=0.5GHz	f_1=1.0GHz	f_1=1.5GHz	f_1=2.0GHz
(-0.3, 3)	0, 4	0, 4	0, 4	0, 4
(-0.3, 7)	0, 4	0, 4	0, 4	0, 4
(-1.0, 3)	0	0	0	0
(-1.0, 7)	0	0, 4	0, 4	0
(-0.5, 3)	--	8	8	--
(-0.5, 7)	8	8	8	8

f_1 denotes the fundamental frequency

Confidence Levels of Estimated Statistical Parameters

suppose x represents the true value of mean, or standard deviation or correlation coefficient of the device statistics

let X represent the estimation of x from statistical samples

the confidence level (e.g., 90%) is the probability of x falling into the confidence interval

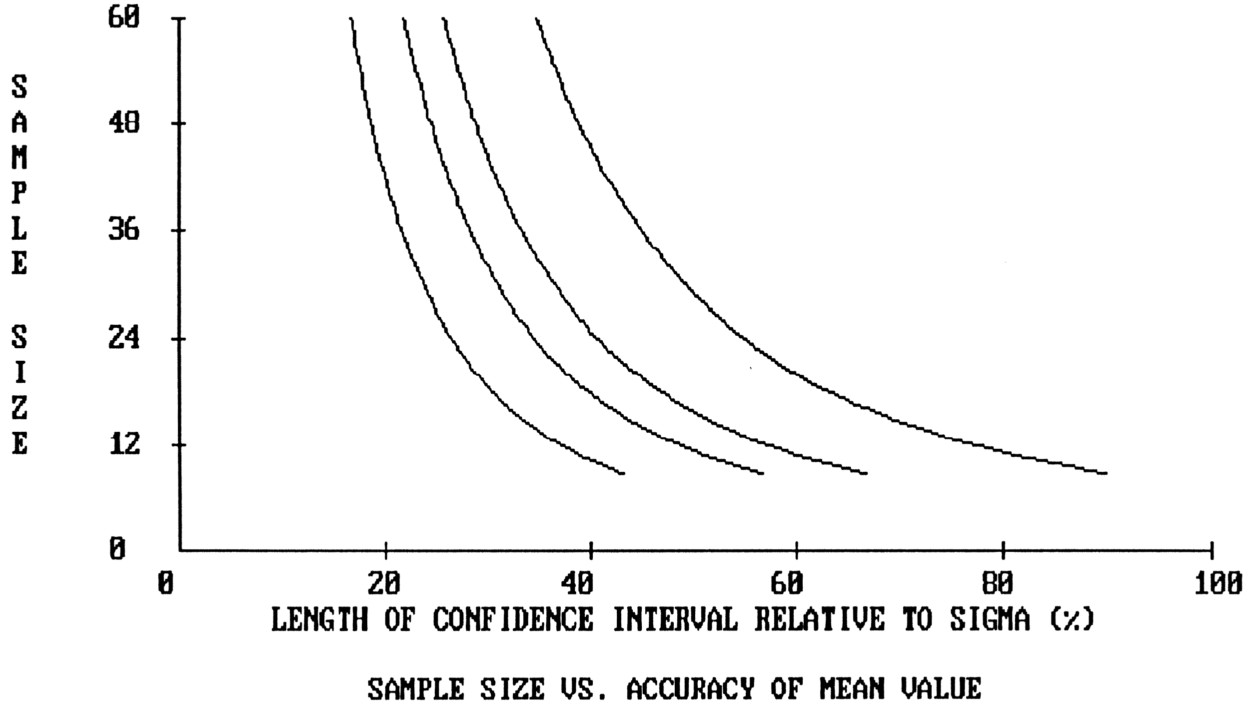
$$X - \Delta X_{lower} < x < X + \Delta X_{upper}$$

ΔX_{lower} and ΔX_{upper} define the size of confidence interval and are computed from

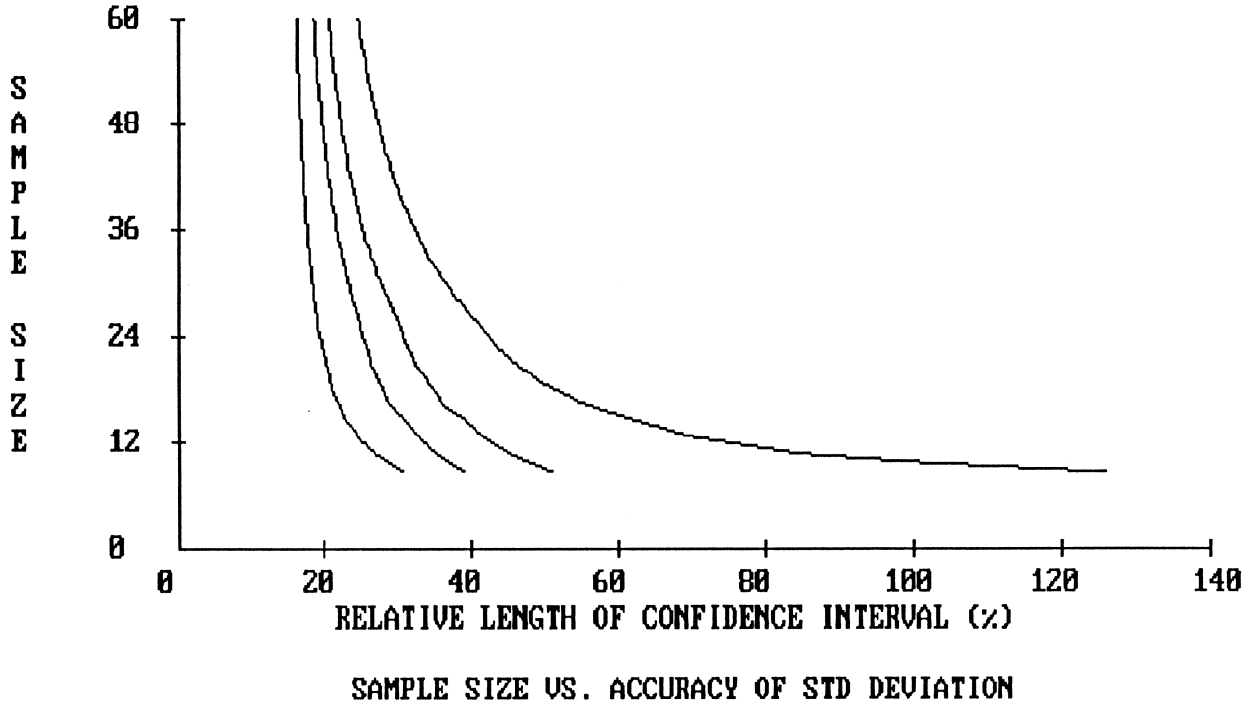
t distribution if x represents mean value

chi-square distribution if x represents std. deviation

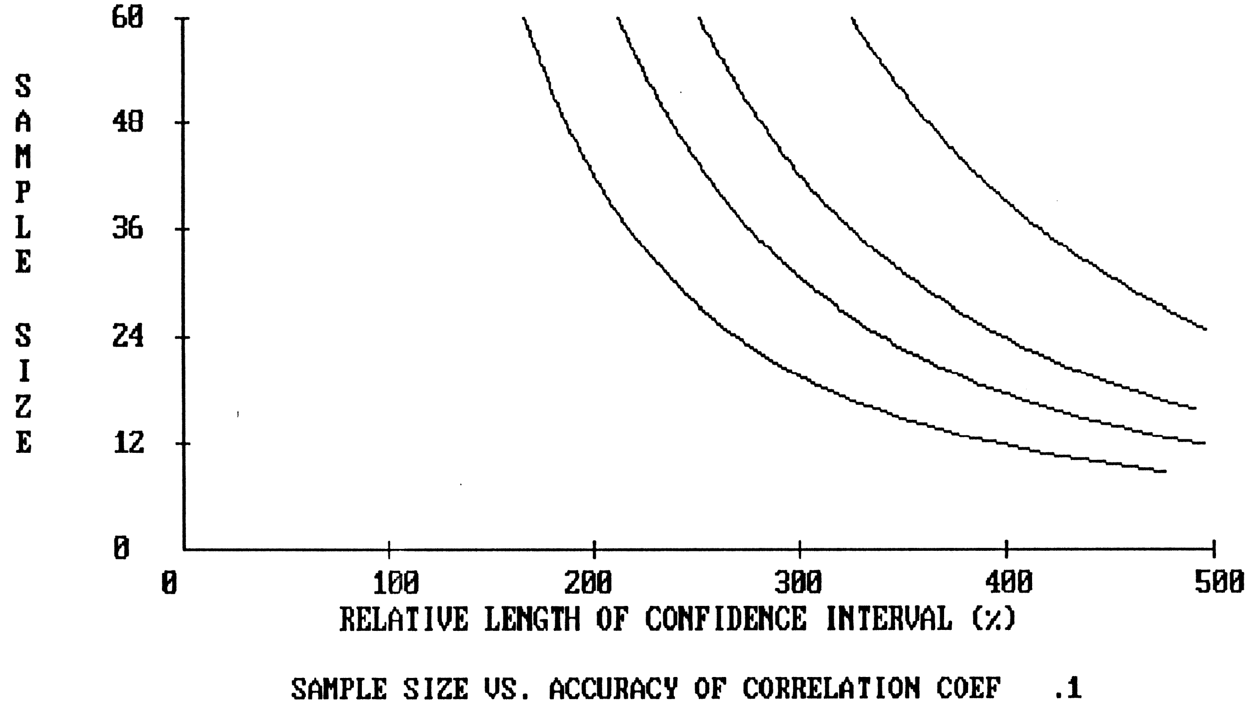
normal distribution if x represents correlation coef.



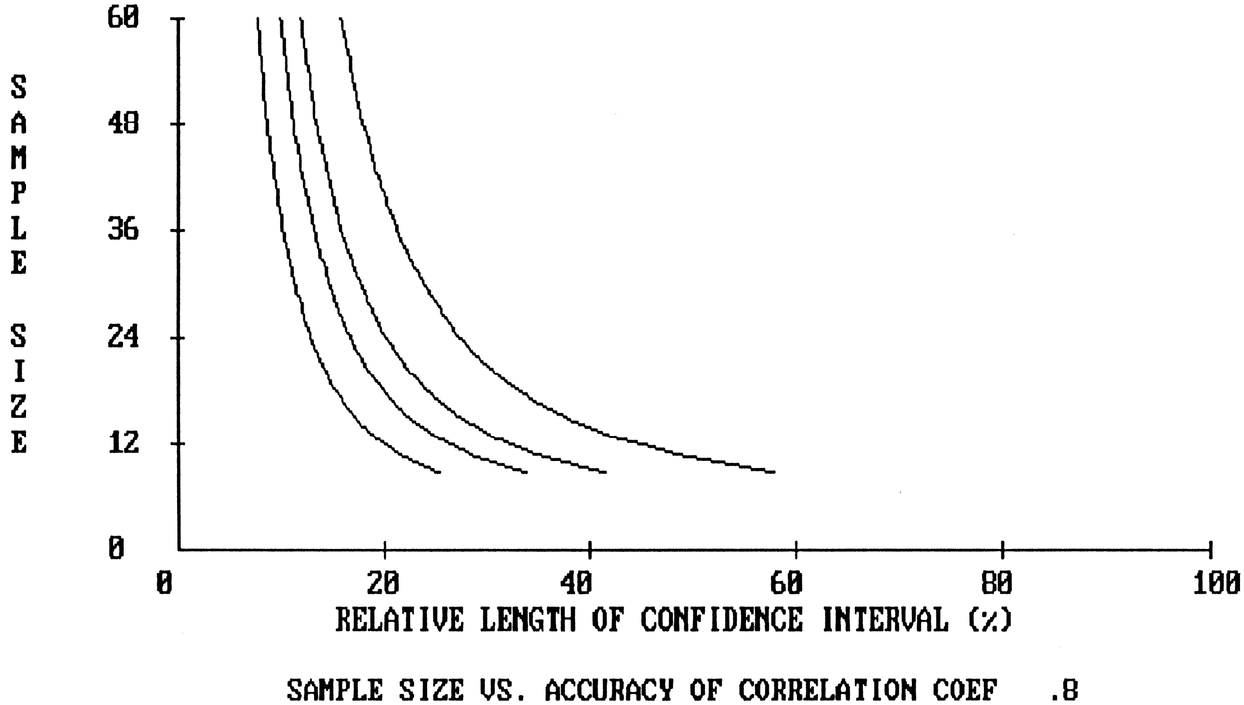
Sample size vs. confidence interval of the mean value



Sample size vs. confidence interval of the standard deviation



Sample size vs. confidence interval of a correlation coefficient



Sample size vs. confidence interval of a correlation coefficient

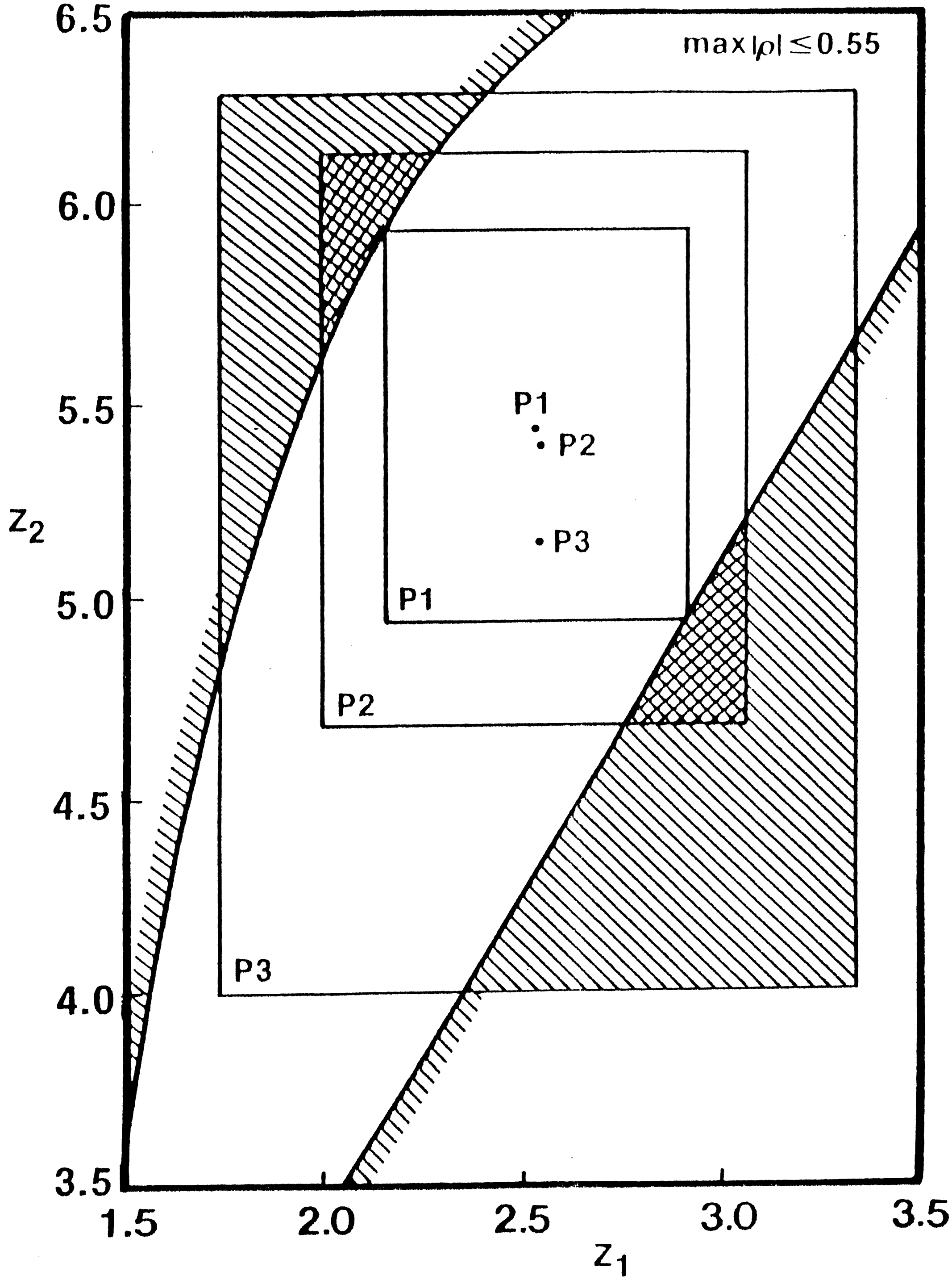
Worst-Case Design

goal: centered design with largest possible tolerances

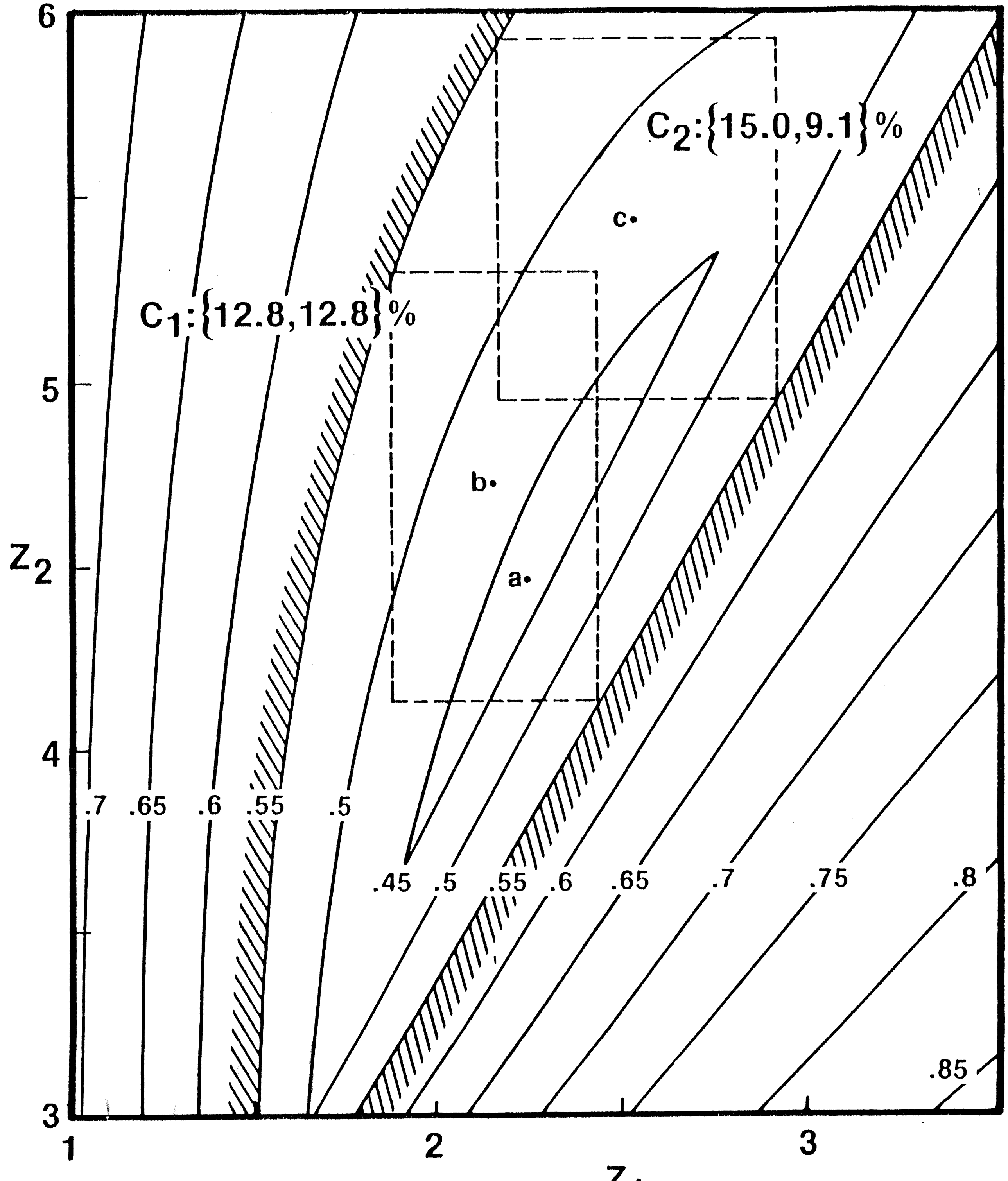
vertex selection

worst-case estimates by sensitivities
worst-case estimates by exact simulation
worst-case estimates by optimization
Monte-Carlo estimate of worst cases

optimization for 100% yield



max |ρ| ≤ 0.55
6.5
6.0
5.5
5.0
4.5
4.0
3.5
z_2
1.5
2.0
2.5
3.0
3.5
z_1
P1
P2
P3
P1
P2
P3



C1:{12.8,12.8}%
C2:{15.0,9.1}%
a
b
c
.7
.65
.6
.55
.5
.45
.5
.55
.6
.65
.7
.75
.8
.85
6
5
4
3
1
2
3
z2
z1

OSA's Microwave CAE Innovations

OSA has originated features never previously offered by commercial microwave software houses

key role in current releases of popular microwave CAE products

Super-Compact
Microwave Harmonica
Super-Compact PC
Microwave Harmonica PC
Touchstone

HarPE - OSA's device parameter extractor

contributor to the Raytheon/Texas Instruments/Compact Software MIMIC team

Our Role in Microwave CAE

comprehensive CAE software system

yield- and cost-driven design of microwave integrated circuits

optimal accommodation of tolerances and device statistics

features for the designer for enhancing wafer/chip yields

workstation environment

layout/geometrical and process/technological parameters

based on combined field/circuit theoretical approach

Future Plans

maintaining, upgrading and providing support to OSA's HarPE

specialized modules for device parameter extraction and modeling, including statistics

statistical modeling of linear devices for small-signal applications

statistical modeling of nonlinear devices for large-signal applications within a harmonic balance environment

high performance software engine for the next generation microwave CAE systems

goal: comprehensive system for general microwave circuit simulation, modeling and design, including statistics