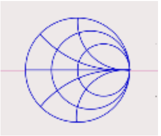
RF Simulation Basics

KEYSIGHT
TECHNOLOGIES

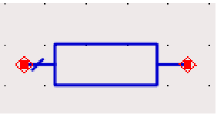
Agenda

- Introduction

- Applications



- S-Parameter Simulations – a closer look



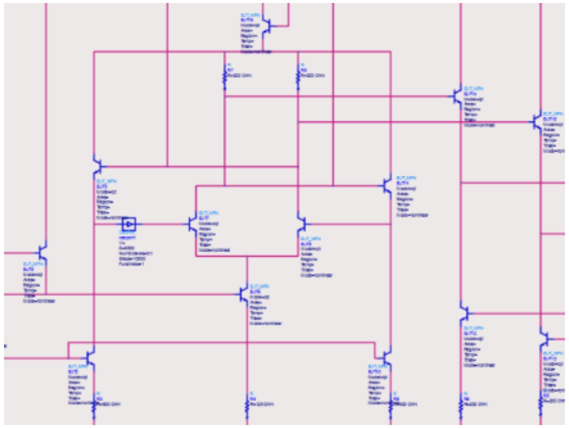
- Models: The building blocks for effective simulations

- Simulation Engines

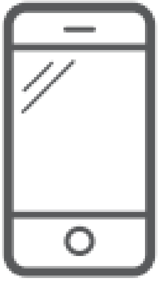
Introduction

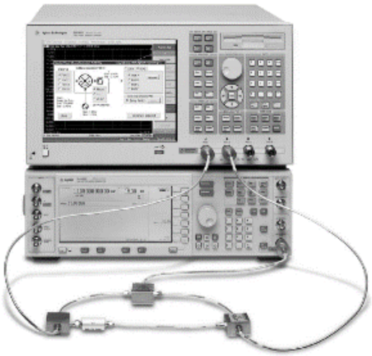
Electronic Design Automation (EDA)

IDEA



CONCEPT | DESIGN





PRODUCT

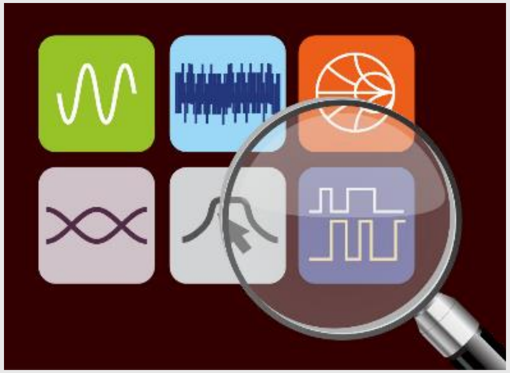
Do you need to perform RF simulations?

If you encounter any of these phrases, you probably do.

- Maxwell's Equations
- Antenna
- Distributed Circuit
- Physical Layer design
- High Frequency
- Radio Frequency (RF)
- Microwave (uW)
- Power Amplifier
- LoadPull
- SourcePull
- X Band
- Ku Band
- Wearables
- IoT
- Matching Networks
- Impedance Matching
- Smith Chart
- S-Parameters
- S21/S11
- ACPR/ACLR
- Noise Figure
- Radiation
- EMI/EMC
- Gain
- Return Loss
- TOI
- IP3
- P1dBc
- EVM

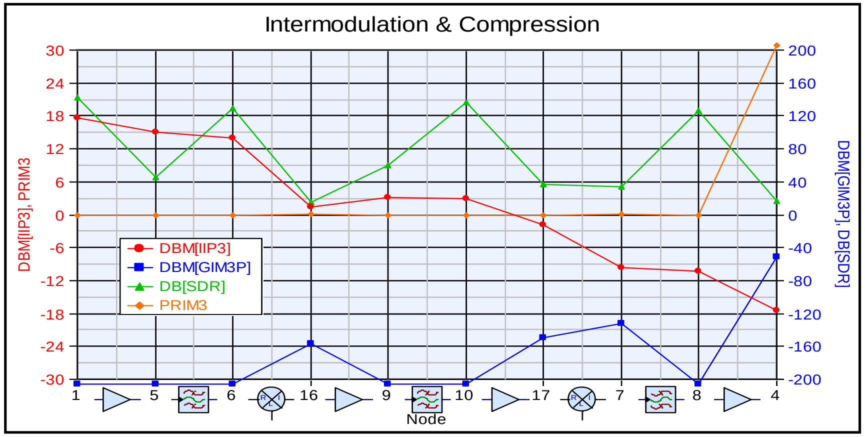
Applications

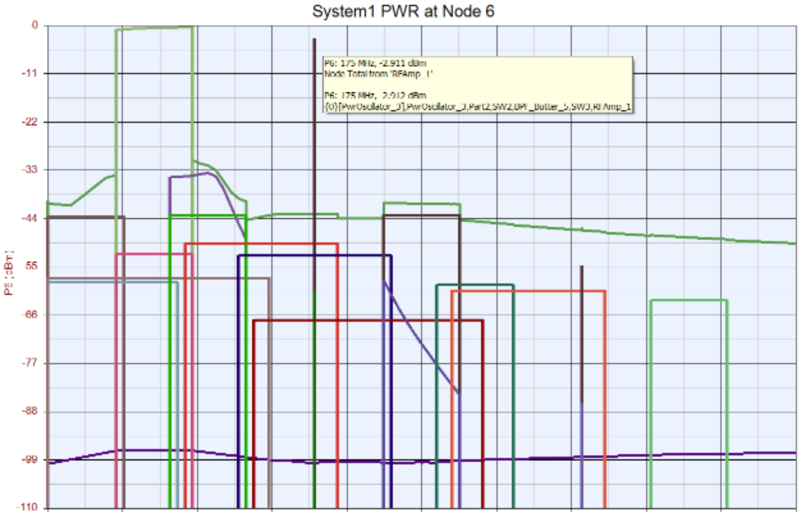
What could you achieve if you could do RF simulations?

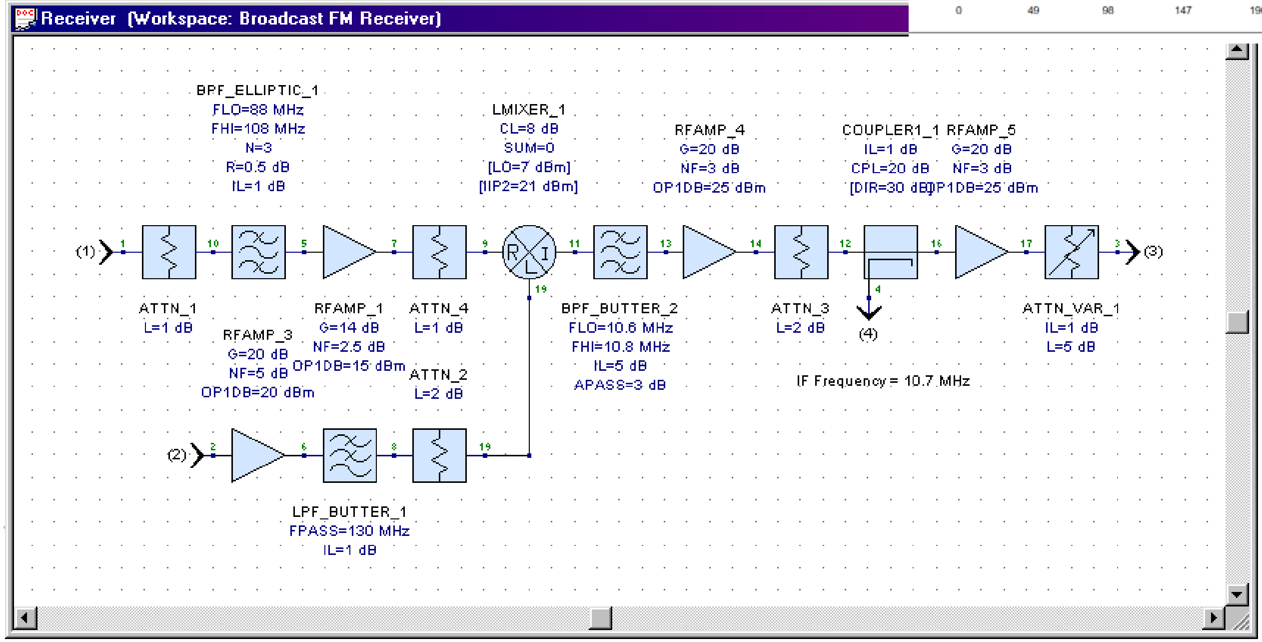


RF System performance

Simulating your car's FM radio

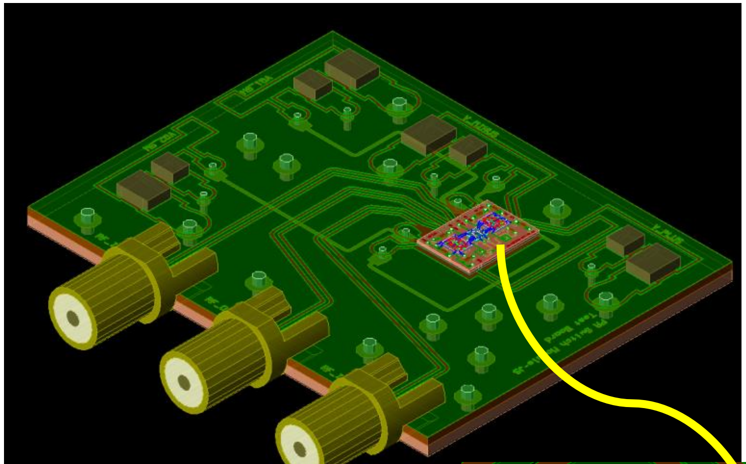


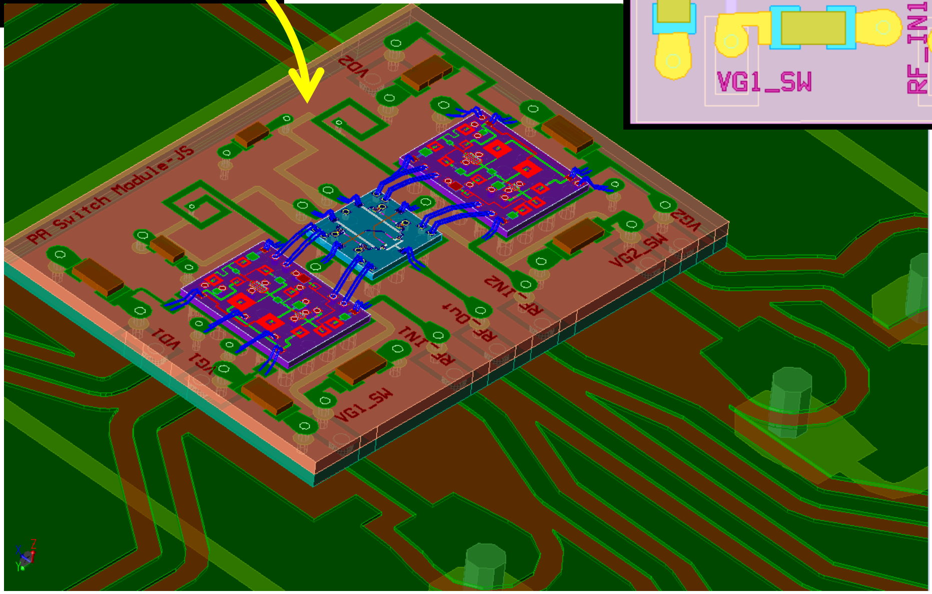




Multi Chip RF Front End Modules

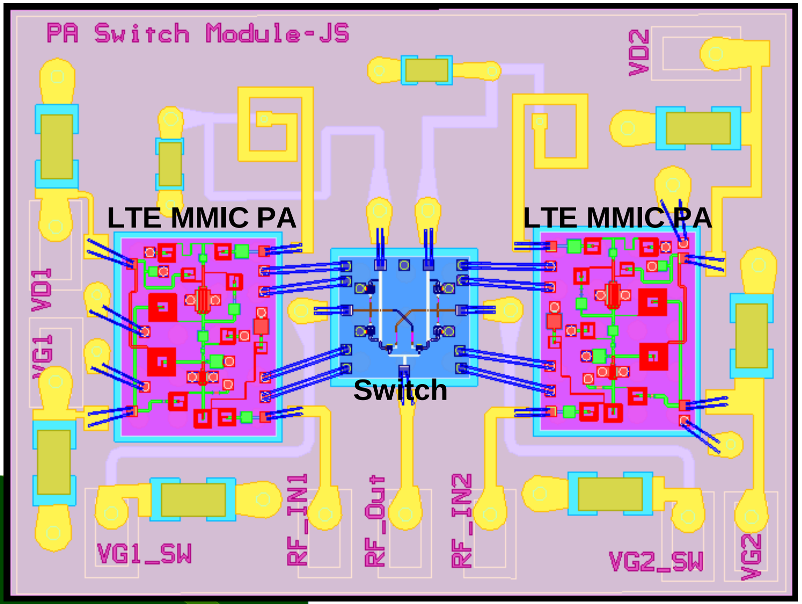
Powering smart phones/tablets





The Complete PA / Switch Multi-Chip Module

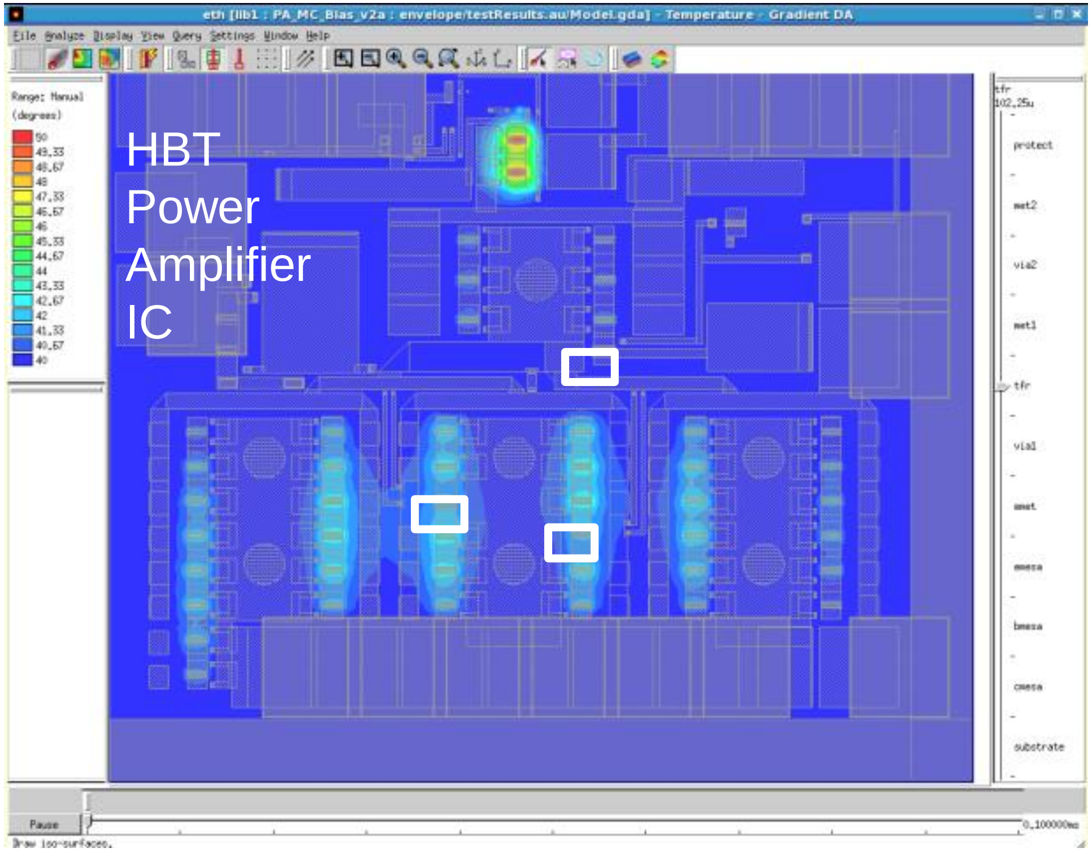
- PA / Switch IC's
- Bond wires
- Laminate board
- Solder bumps
- PCB test board
- Connectors

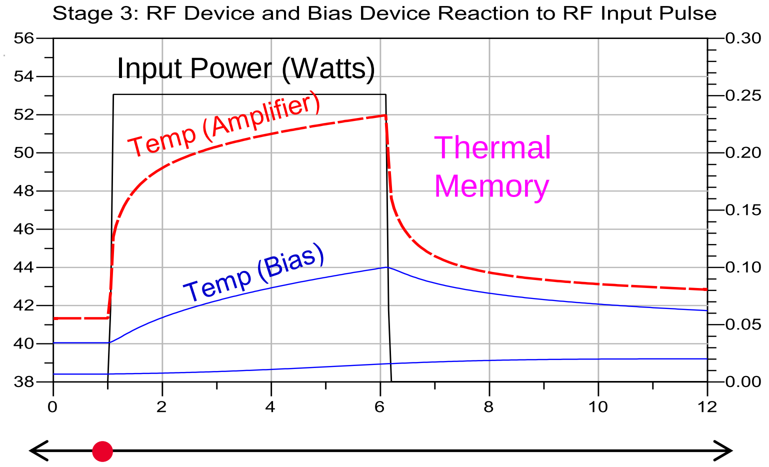


Laminate Board with PA / Switch IC's

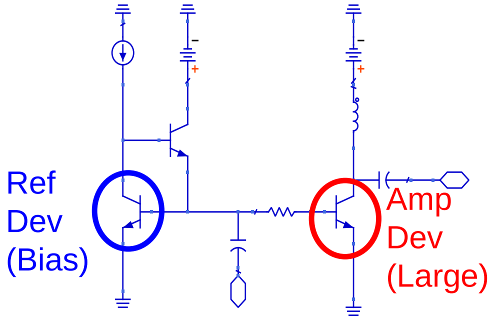
Electro-Thermal Simulation

Dynamic thermal behavior





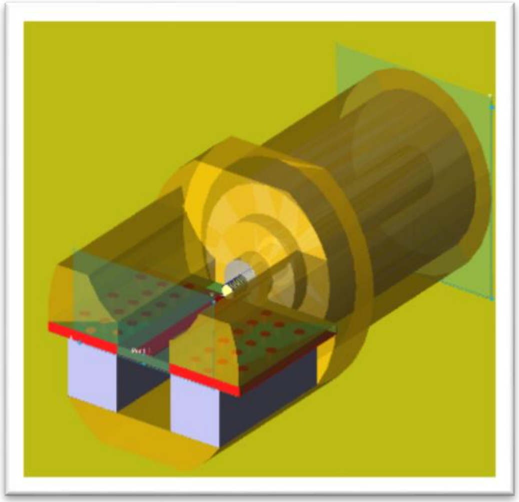
Time scale

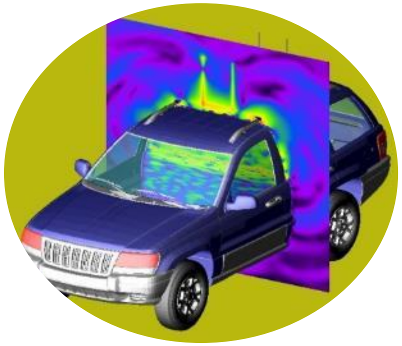


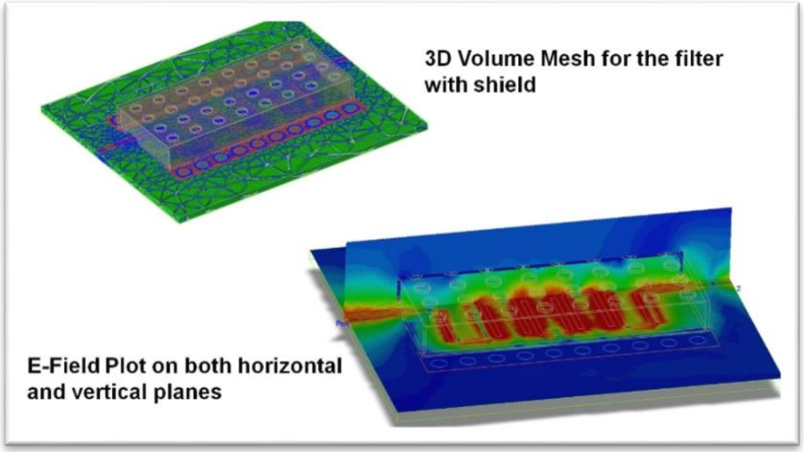
“The Impact of Electro-Thermal Coupling on HBT Power Amplifiers”, Matt Ozalas, Keysight, CSIC 2014

Electromagnetic Analysis

Signal Propagation in arbitrary structures

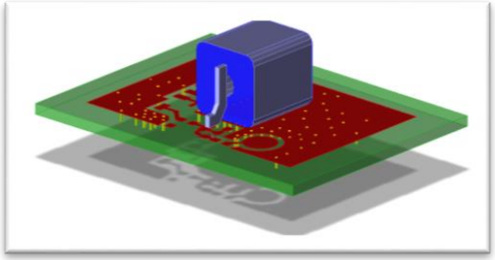


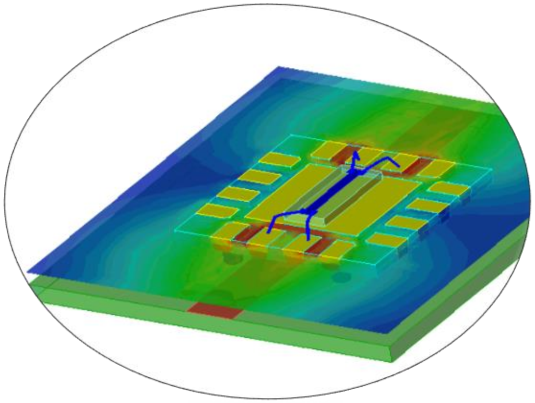


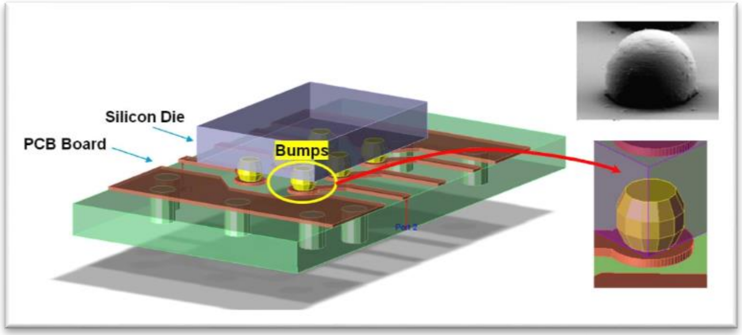


3D Volume Mesh for the filter with shield

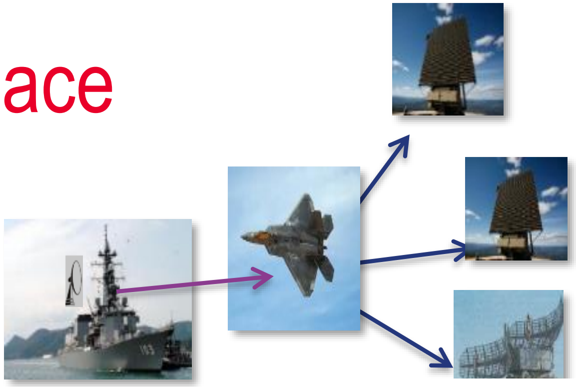
E-Field Plot on both horizontal and vertical planes





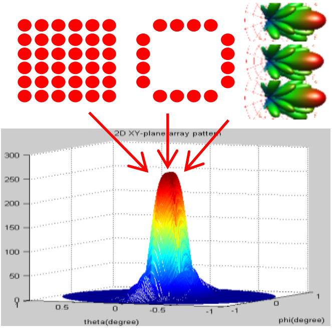


Electronic Warfare / Aerospace



3D Scenario Modeling

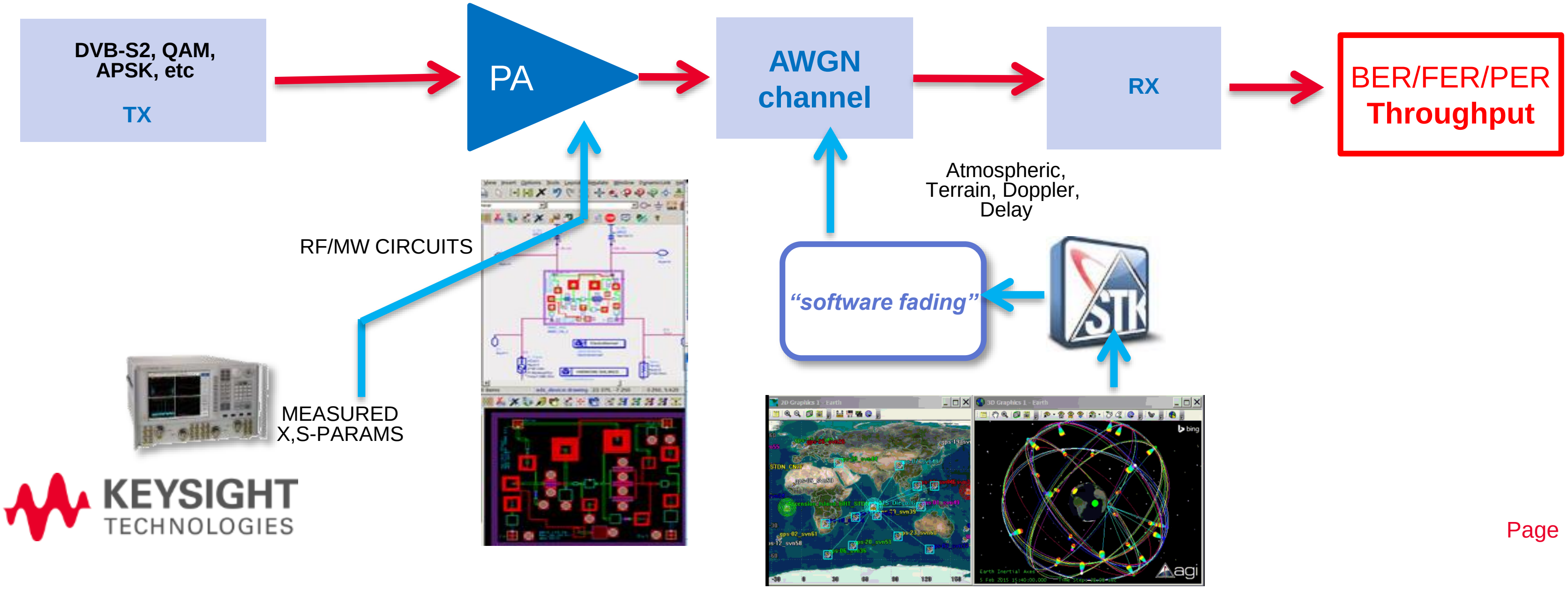
- Model multiple moving TX and RX platforms including clutter and environment



Phased Array Degradations

- Model beamforming & jamming performance at the system level

Satcom Dynamic Channel Modeling



DVB-S2, QAM, APSK, etc

TX

PA

AWGN channel

RX

BER/FER/PER
Throughput

RF/MW CIRCUITS

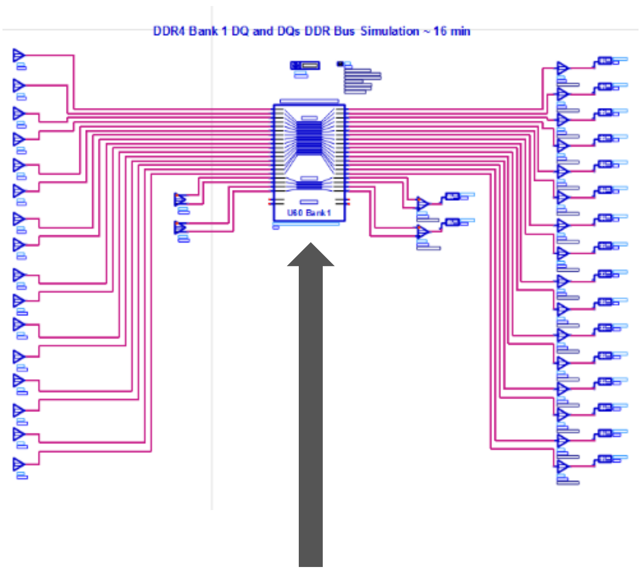
MEASURED X,S-PARAMS

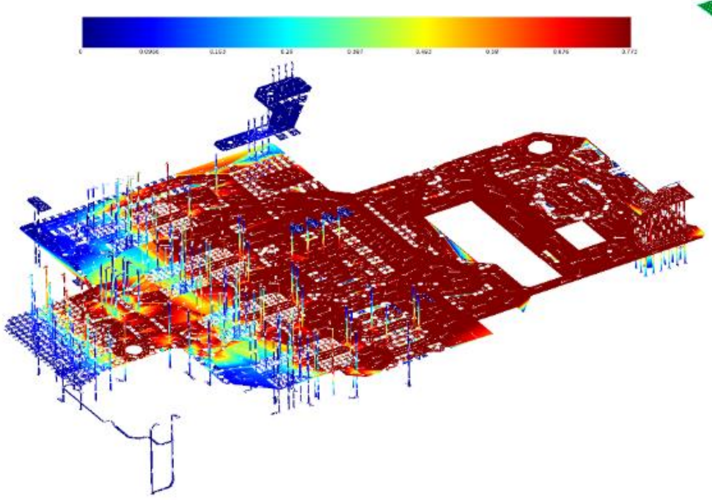
Atmospheric, Terrain, Doppler, Delay

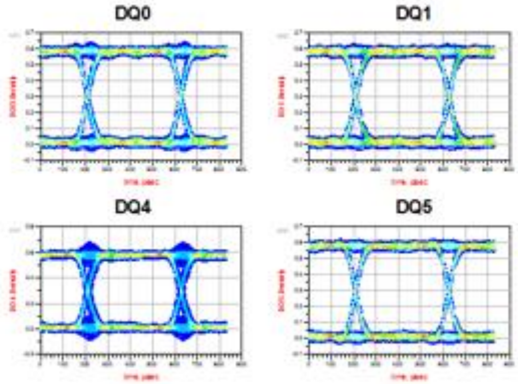
"software fading"

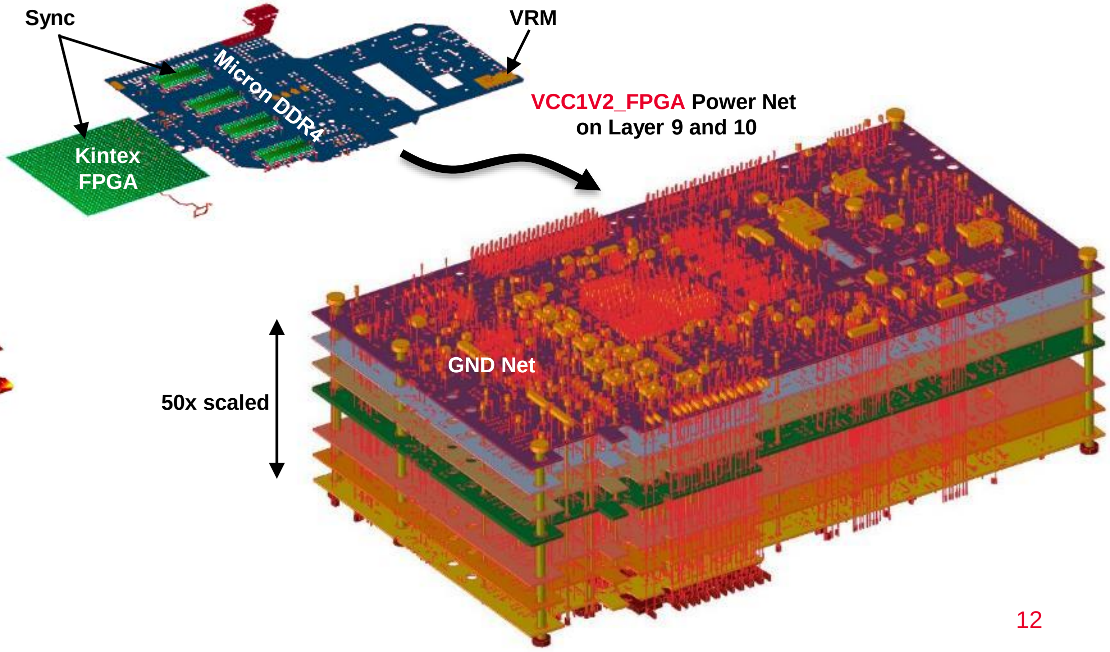
DDR4 Memory

Signal Integrity and Power Integrity





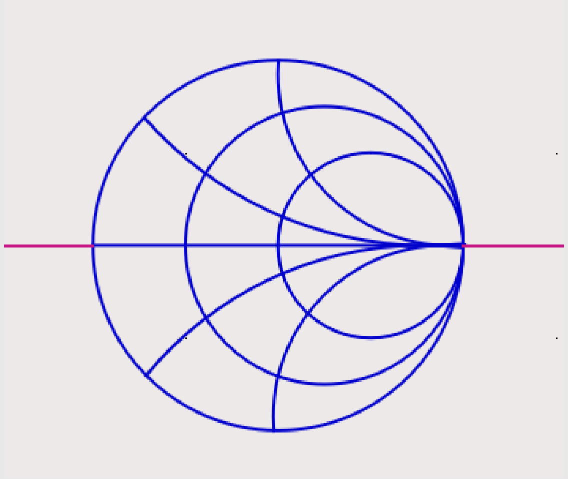




VCC1V2_FPGA Power Net on Layer 9 and 10

S-Parameter Simulations

A closer look



S Parameter Simulations

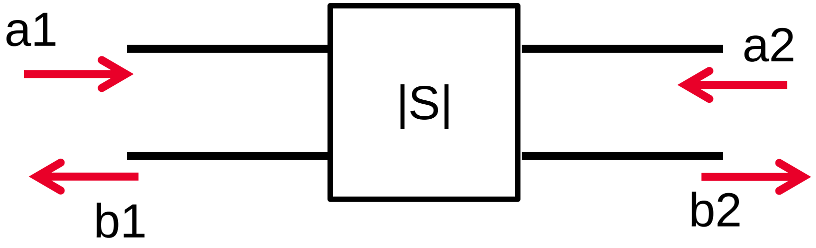
You already learned about S Parameters. But how does one simulate S- Parameters in an EDA tool?

$$S_{11} = \frac{\text{Reflected}}{\text{Incident}} = \frac{b_1}{a_1}\bigg|_{a_2=0}$$

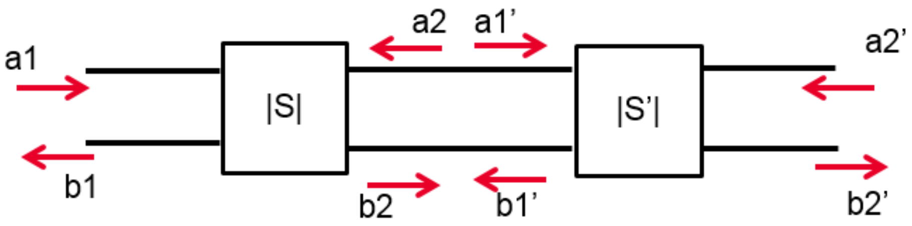
$$S_{21} = \frac{\text{Transmitted}}{\text{Incident}} = \frac{b_2}{a_1}\bigg|_{a_2=0}$$

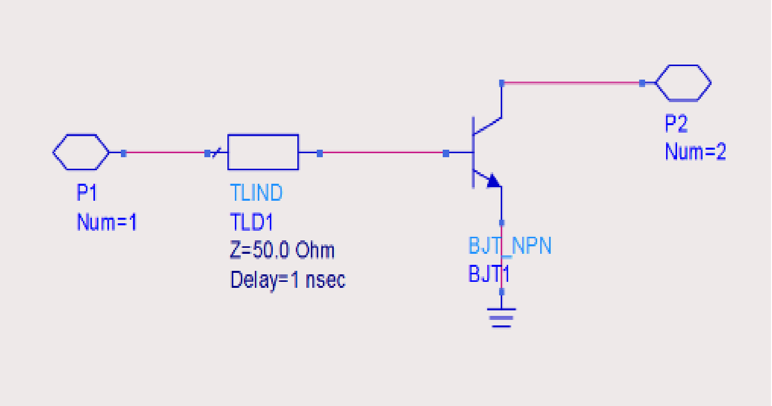
$$S_{22} = \frac{\text{Reflected}}{\text{Incident}} = \frac{b_2}{a_2}\bigg|_{a_1=0}$$

$$S_{12} = \frac{\text{Transmitted}}{\text{Incident}} = \frac{b_1}{a_2}\bigg|_{a_1=0}$$



Should we employ matrix math to cascade S-Parameters?





For Cascaded S Matrix a1'=b2 and a2=b1'

b1=S11*a1+S12*a2=S11a1+S12*b1' where b1'=S11'*a1'+S12'*a2'

substituting yields, b1=S11*a1+S12*S11'*a1'+S12*S12'*a2' eq 1

a1'=b2=S21*a1+s22*a2 where a2=b1'substituting and rearranging yields,

a1'=(S21**a1+S22*S12'*a2')/1-S22*S11 eq 2 then eq 2 into eq 1,

Repeating for b2' results in cascaded S-Parameter

$$\begin{matrix} b1 \\ b2' \end{matrix} = \begin{vmatrix} S11 + \frac{S12*S11'*S21}{1-S22*S11'} & \frac{S12*S12'}{1-S22*S11'} \\ \frac{S21*S21'}{1-S22*S11'} & S22 + \frac{S22*S12'*S21\prime}{1-S22*S11'} \end{vmatrix} * \begin{matrix} a1 \\ a2' \end{matrix}$$

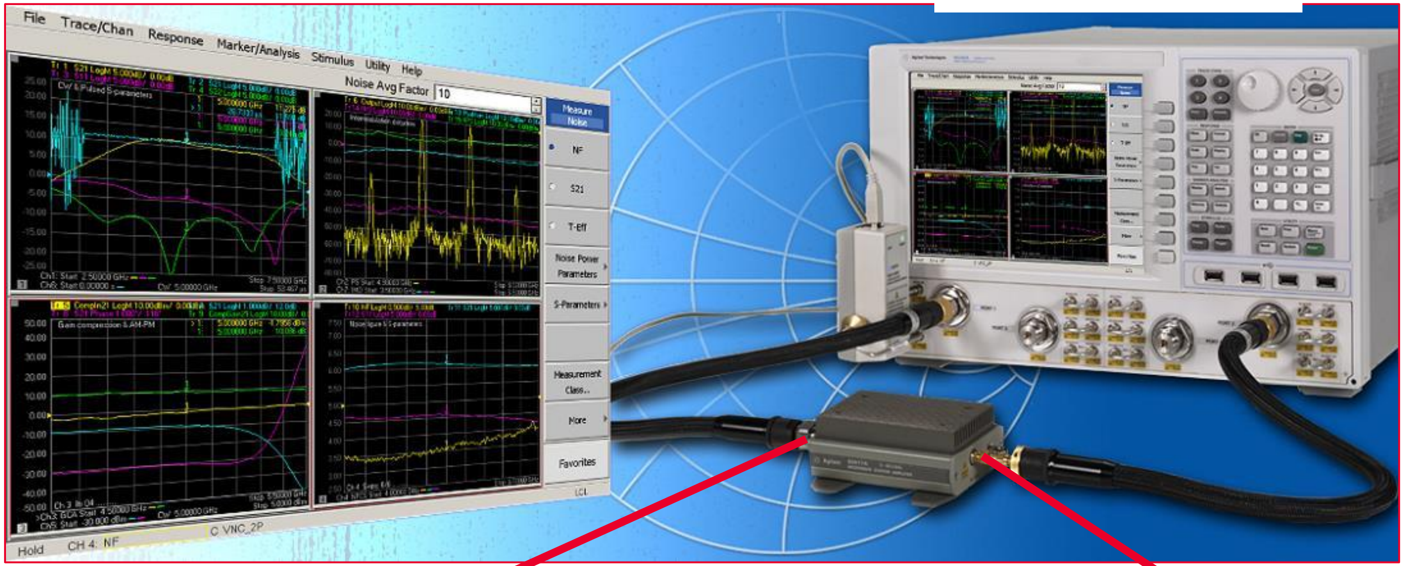
S-Parameter Simulation

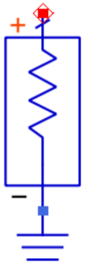
- Matrix math runs out of steam if you have bigger complicated designs.
- Modern Simulators actually behave similar to Network analyzers. Excite one “end” of the circuit (at certain frequencies) and measure incident and reflected waves at the same “end” and also at other “ends”.
- Then compute ratios and get S-Parameters.
- For this to work, the EDA tool needs to know how each device (transmission line, capacitor, transistor, etc..) reacts to RF excitation.
- EDA tools contain built-in models to represent the most common devices. (More on device models later)
- And you can supplement the built-in models with measurement based models too.

S-Parameter Simulation

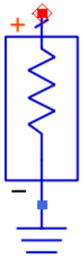
S-PARAMETERS

S_Param
SP1
Start=1.0 GHz
Stop=10.0 GHz
Step=0.1 GHz



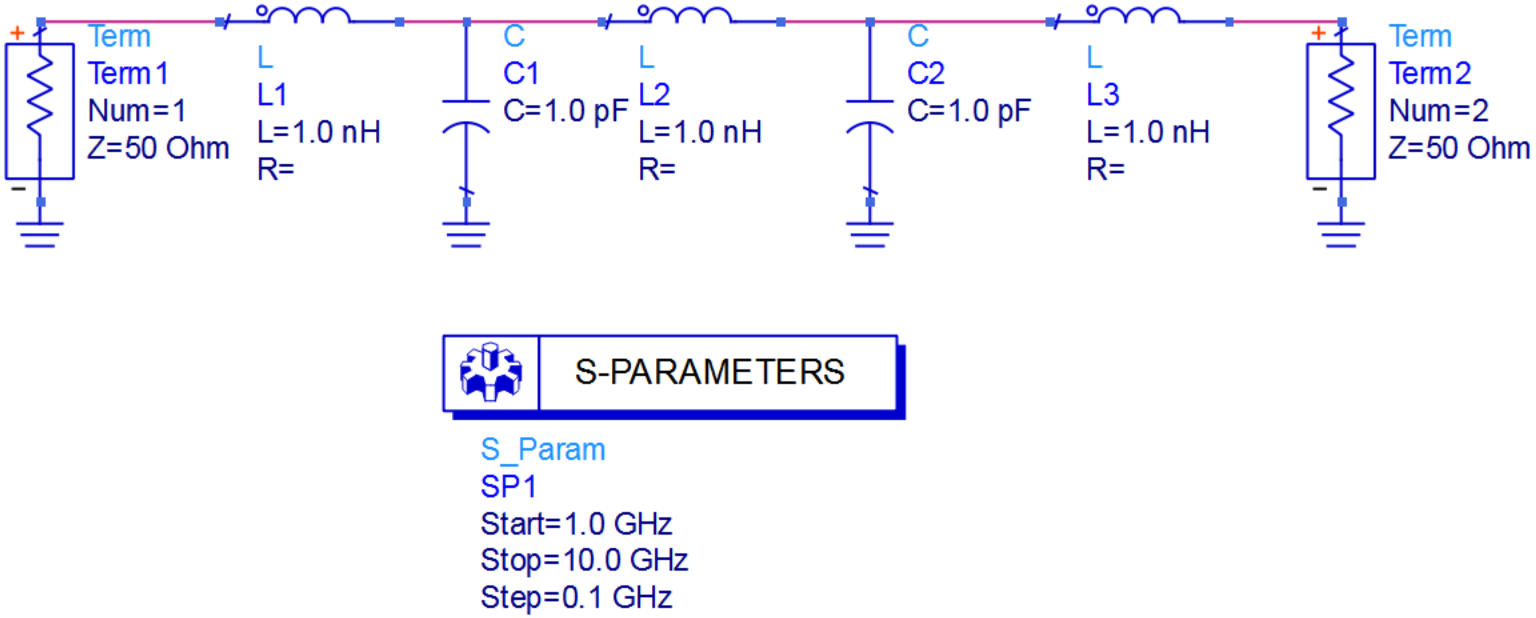


Term
Term1
Num=1
Z=50 Ohm



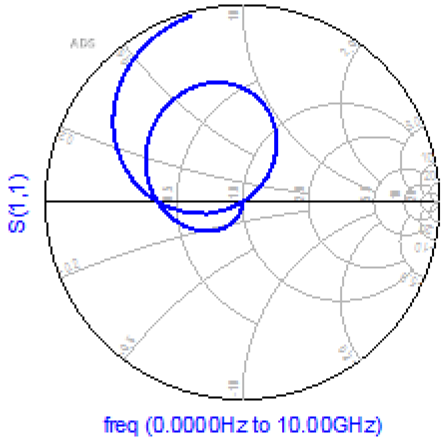
Term
Term2
Num=2
Z=50 Ohm

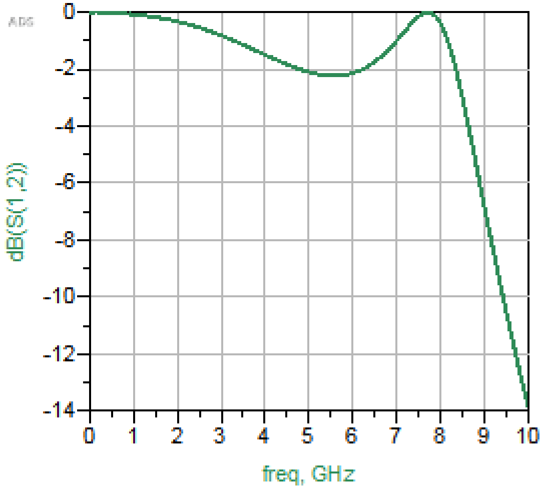
S-Parameter Simulation

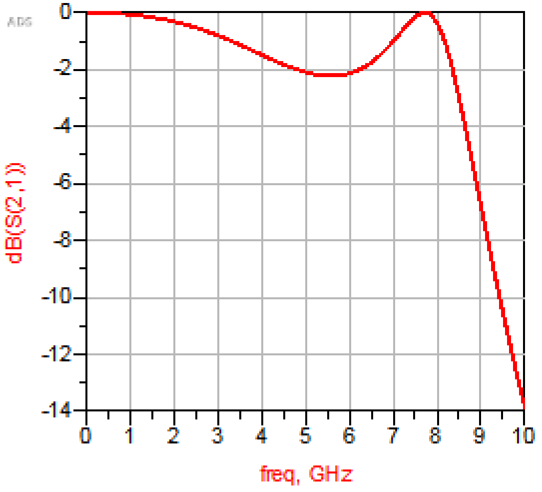


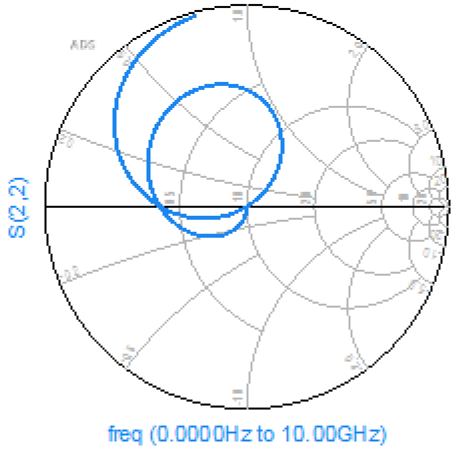
Port Count is not limited
No Calibration needed
Impedance can be any value

Simulation Results

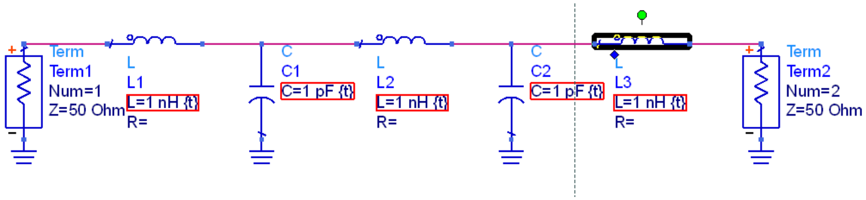

Input Reflection Coefficient

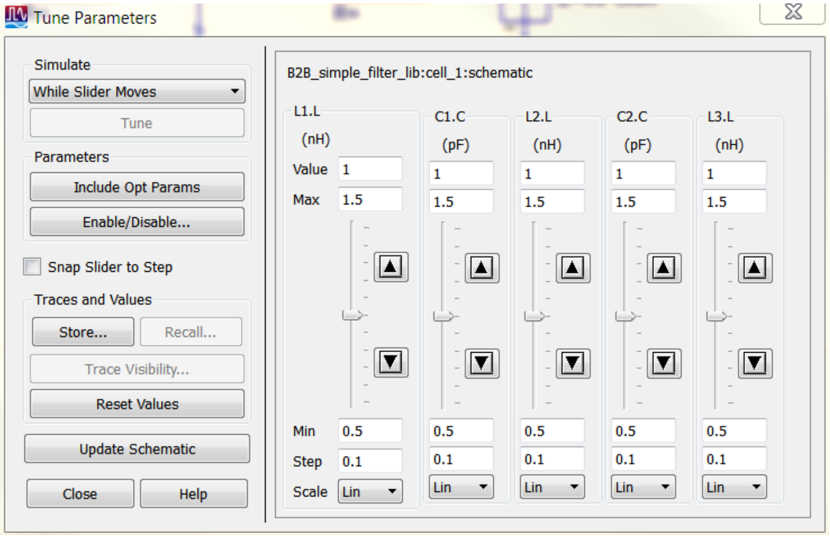

Reverse Transmission, dB


Forward Transmission, dB


Output Reflection Coefficient

Tune & Optimize– What if scenarios



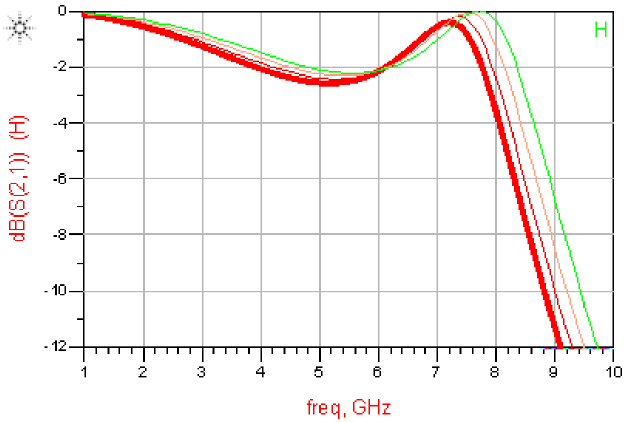


Simulate: While Slider Moves

☐ Snap Slider to Step

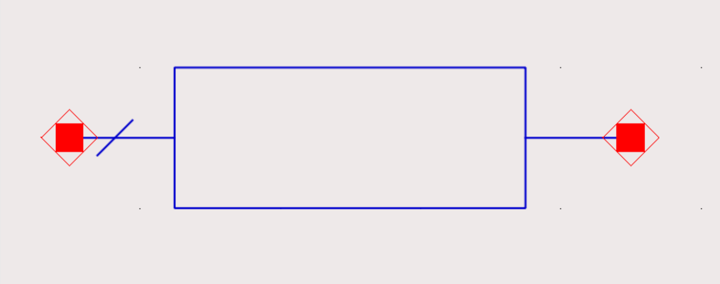
B2B_simple_filter_lib:cell_1:schematic

	L1.L (nH)	C1.C (pF)	L2.L (nH)	C2.C (pF)	L3.L (nH)
Value	1	1	1	1	1
Max	1.5	1.5	1.5	1.5	1.5
Min	0.5	0.5	0.5	0.5	0.5
Step	0.1	0.1	0.1	0.1	0.1
Scale	Lin	Lin	Lin	Lin	Lin

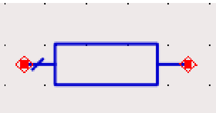


Models

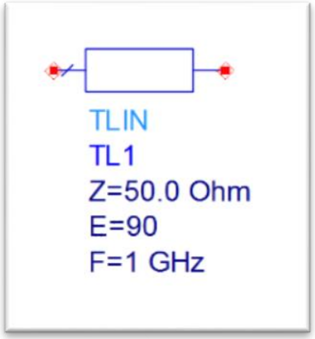
The building blocks for effective simulations



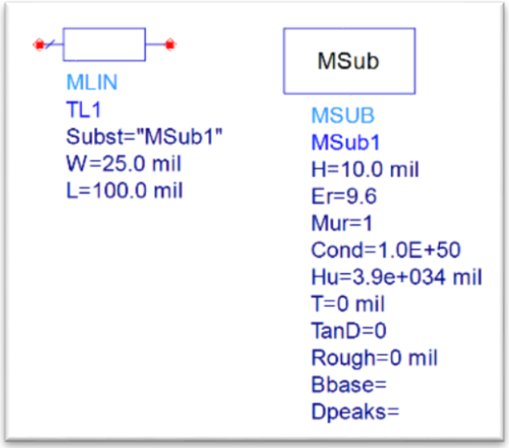
Models



- Previously we saw that “models” are required to represent transmission lines, transistors, capacitors etc.
- Devices that are linear in nature (resistors, transmission lines) have linear models.
- Devices that are non linear in nature (diodes, transistors) have both linear and non-linear models.
- Models can be ideal or more realistic



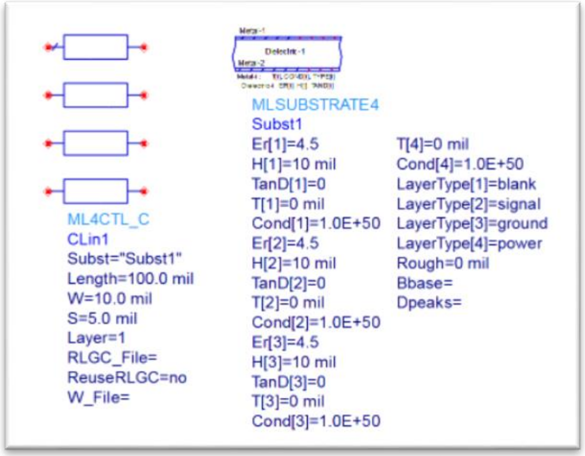
TLIN
TL1
Z=50.0 Ohm
E=90
F=1 GHz



MLIN
TL1
Subst="MSub1"
W=25.0 mil
L=100.0 mil

MSub

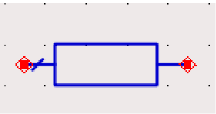
MSUB
MSub1
H=10.0 mil
Er=9.6
Mur=1
Cond=1.0E+50
Hu=3.9e+034 mil
T=0 mil
TanD=0
Rough=0 mil
Bbase=
Dpeaks=



ML4CTL_C
CLin1
Subst="Subst1"
Length=100.0 mil
W=10.0 mil
S=5.0 mil
Layer=1
RLGC_File=
ReuseRLGC=no
W_File=

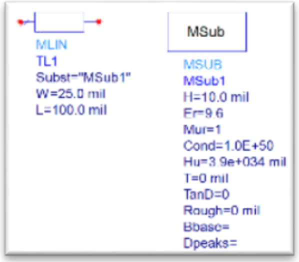
MLSUBSTRATE4
Subst1
Er[1]=4.5
H[1]=10 mil
TanD[1]=0
T[1]=0 mil
Cond[1]=1.0E+50
Er[2]=4.5
H[2]=10 mil
TanD[2]=0
T[2]=0 mil
Cond[2]=1.0E+50
Er[3]=4.5
H[3]=10 mil
TanD[3]=0
T[3]=0 mil
Cond[3]=1.0E+50
T[4]=0 mil
Cond[4]=1.0E+50
LayerType[1]=blank
LayerType[2]=signal
LayerType[3]=ground
LayerType[4]=power
Rough=0 mil
Bbase=
Dpeaks=

Models



– Models are typically based on important works of research. For e.g. the MLIN model:

  - W. J. Getsinger, "Measurement and Modeling of the Apparent Characteristic Impedance of Microstrip," *MTT-31,* August 1983.
  - E. Hammerstad and O. Jensen, "Accurate Models for Microstrip Computer-aided Design," *MTT Symposium Digest* , 1980.



MLIN
TL1
Subst="MSub1"
W=25.0 mil
L=100.0 mil

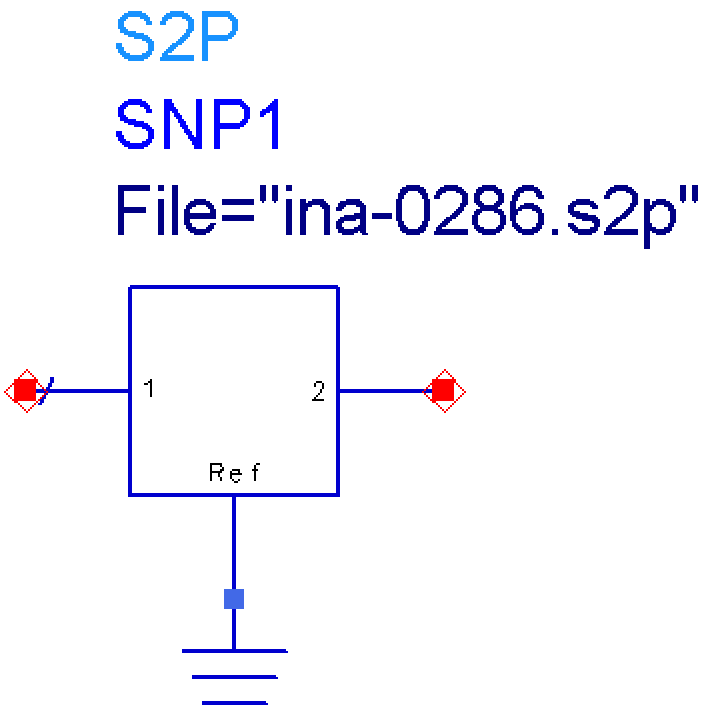
MSUB
MSub1
H=10.0 mil
Er=9.6
Mur=1
Cond=1.0E+50
Hu=3.9e+034 mil
T=0 mil
TanD=0
Rough=0 mil
Bbase=
Dpeaks=

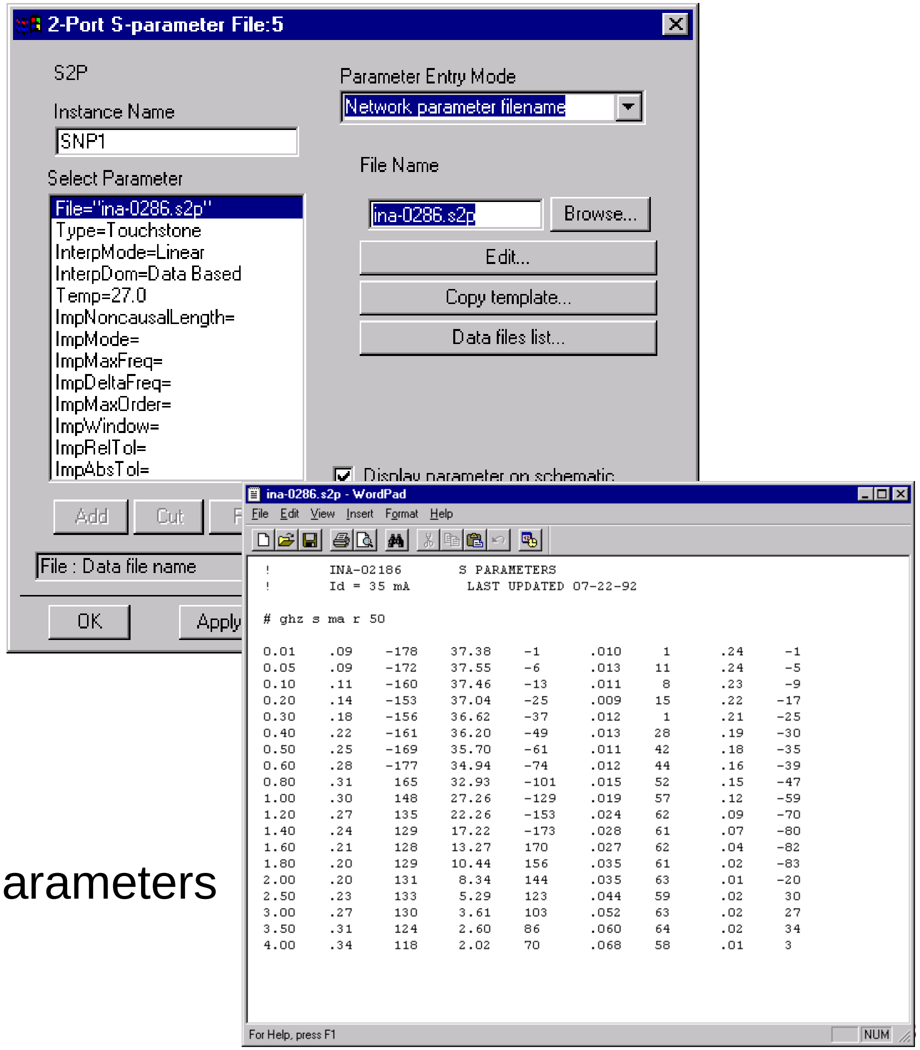
– The research is translated into equations and then implemented in the EDA tool.

– Models have a working “range”. For e.g. MLIN model is not expected to work at 1 THz.

Models

Measured or Simulated S-Parameters





S2P

Instance Name: SNP1

Parameter Entry Mode: Network parameter filename

File Name: ina-0286.s2p

Select Parameter:
- File="ina-0286.s2p"
- Type=Touchstone
- InterpMode=Linear
- InterpDom=Data Based
- Temp=27.0
- ImpNoncausalLength=
- ImpMode=
- ImpMaxFreq=
- ImpDeltaFreq=
- ImpMaxOrder=
- ImpWindow=
- ImpRelTol=
- ImpAbsTol=

☑ Display parameter on schematic

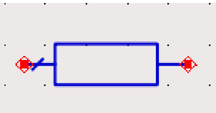
File : Data file name

```
!       INA-02186         S PARAMETERS
!       Id = 35 mA         LAST UPDATED 07-22-92

# ghz s ma r 50

0.01    .09    -178    37.38    -1      .010    1     .24    -1
0.05    .09    -172    37.55    -6      .013    11    .24    -5
0.10    .11    -160    37.46    -13     .011    8     .23    -9
0.20    .14    -153    37.04    -25     .009    15    .22    -17
0.30    .18    -156    36.62    -37     .012    1     .21    -25
0.40    .22    -161    36.20    -49     .013    28    .19    -30
0.50    .25    -169    35.70    -61     .011    42    .18    -35
0.60    .28    -177    34.94    -74     .012    44    .16    -39
0.80    .31     165    32.93    -101    .015    52    .15    -47
1.00    .30     148    27.26    -129    .019    57    .12    -59
1.20    .27     135    22.26    -153    .024    62    .09    -70
1.40    .24     129    17.22    -173    .028    61    .07    -80
1.60    .21     128    13.27    170     .027    62    .04    -82
1.80    .20     129    10.44    156     .035    61    .02    -83
2.00    .20     131     8.34    144     .035    63    .01    -20
2.50    .23     133     5.29    123     .044    59    .02     30
3.00    .27     130     3.61    103     .052    63    .02     27
3.50    .31     124     2.60    86      .060    64    .02     34
4.00    .34     118     2.02    70      .068    58    .01     3
```

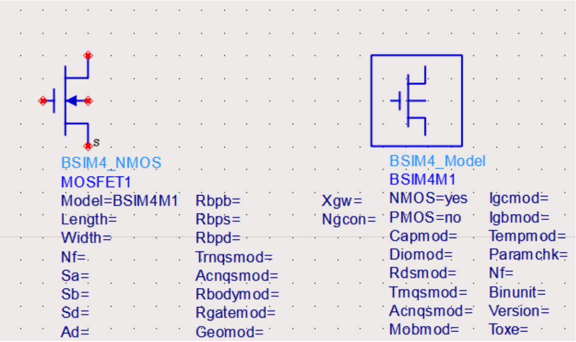
Modeling Linear Behavior Using S-parameters



Models

Nonlinear models for transistors

- Non linear models are based on complex differential equations. Research groups (e.g. BSIM group at University of California, Berkeley) develop these models and share with the industry.
- By feeding the right parameter values in the model “card” you can match the software model to a real world device.
- The parameter values are typically obtained by measurements and “fitting” algorithms.
- Typically takes several PhDs to do this right.

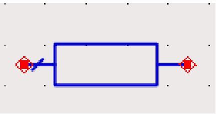


BSIM4_NMOS
MOSFET1
Model=BSIM4M1
Length=
Width=
Nf=
Sa=
Sb=
Sd=
Ad=
Rbpb=
Rbps=
Rbpd=
Trnqsmod=
Acnqsmod=
Rbodymod=
Rgatemod=
Geomod=
Xgw=
Ngcon=

BSIM4_Model
BSIM4M1
NMOS=yes
PMOS=no
Capmod=
Diomod=
Rdsmod=
Trnqsmod=
Acnqsmod=
Mobmod=
Igcmod=
Igbmod=
Tempmod=
Paramchk=
Nf=
Binunit=
Version=
Toxe=

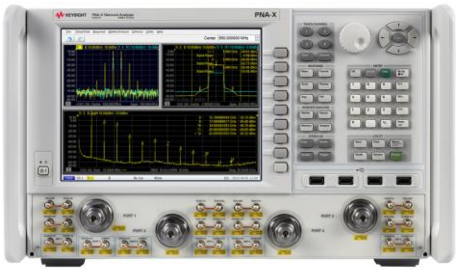
https://en.wikipedia.org/wiki/BSIM

What are X-Parameters?

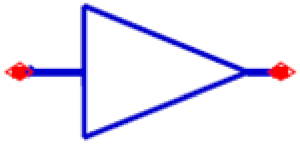


- X-parameters are the mathematically correct superset of S-parameters, applicable to both large-signal and small-signal conditions, for linear and nonlinear components. *The math exists!*
- We can measure, model, & simulate with X-parameters
- Each part of the puzzle has been created
- The pieces now fit together seamlessly

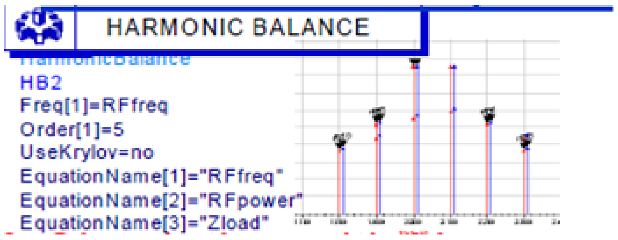
NVNA: Measure X-parameters



PHD: X-parameter block



ADS: Simulate X-parameters



HARMONIC BALANCE

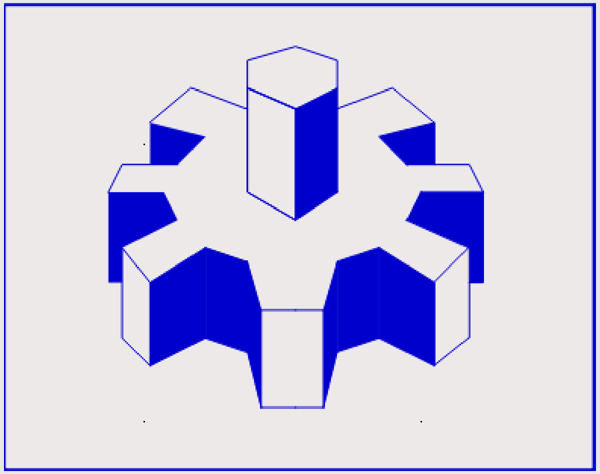
HarmonicBalance
HB2
Freq[1]=RFfreq
Order[1]=5
UseKrylov=no
EquationName[1]="RFfreq"
EquationName[2]="RFpower"
EquationName[3]="Zload"

Interoperable Nonlinear Measurement, Modeling & Simulation with X-parameters

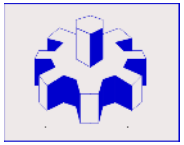
"X-parameters have the potential to do for characterization, modeling, and design of nonlinear components and systems what linear S-parameters do for linear components & systems"

Simulation Engines

Analyze your RF design



Simulation Types

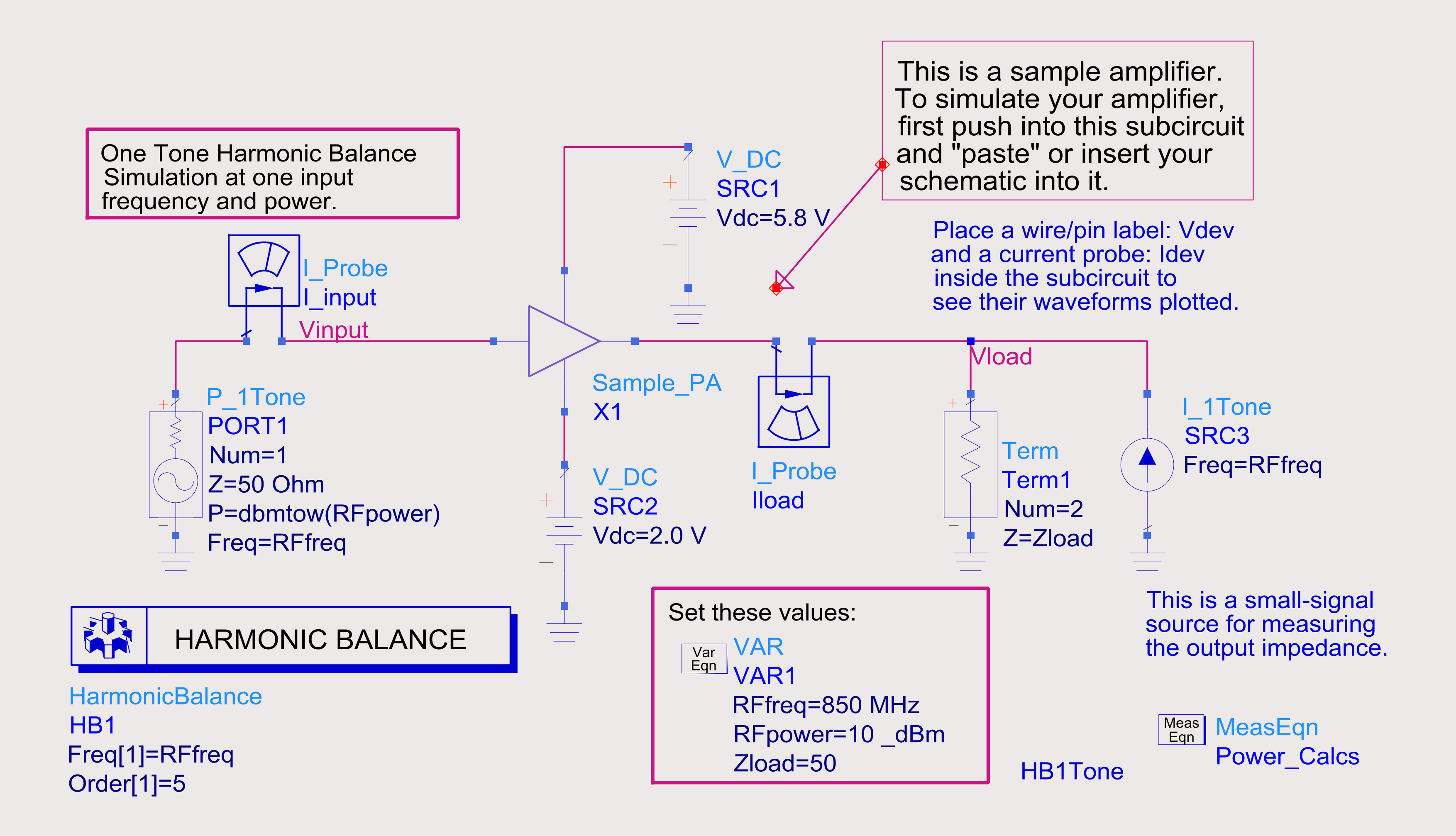


- Frequency vs Time
- Linear vs Non-Linear
- Circuit vs System
- Circuit vs EM
- Multi-Physics (Electrical Circuit + Thermal)

Simulation Engines

- DC
- AC
- S-Parameter
- Harmonic Balance
- Transient (High Frequency Spice)
  - Channel Sim
- Circuit Envelope
- EM Simulation
  - MoM
  - FEM
  - FDTD
- Spectral
- Data Flow
- ElectroThermal

Harmonic Balance Setup



One Tone Harmonic Balance
Simulation at one input
frequency and power.

This is a sample amplifier.
To simulate your amplifier,
first push into this subcircuit
and "paste" or insert your
schematic into it.

Place a wire/pin label: Vdev
and a current probe: Idev
inside the subcircuit to
see their waveforms plotted.

I_Probe
I_input

V_DC
SRC1
Vdc=5.8 V

P_1Tone
PORT1
Num=1
Z=50 Ohm
P=dbmtow(RFpower)
Freq=RFfreq

Sample_PA
X1

V_DC
SRC2
Vdc=2.0 V

I_Probe
Iload

Term
Term1
Num=2
Z=Zload

I_1Tone
SRC3
Freq=RFfreq

HarmonicBalance
HB1
Freq[1]=RFfreq
Order[1]=5

Set these values:

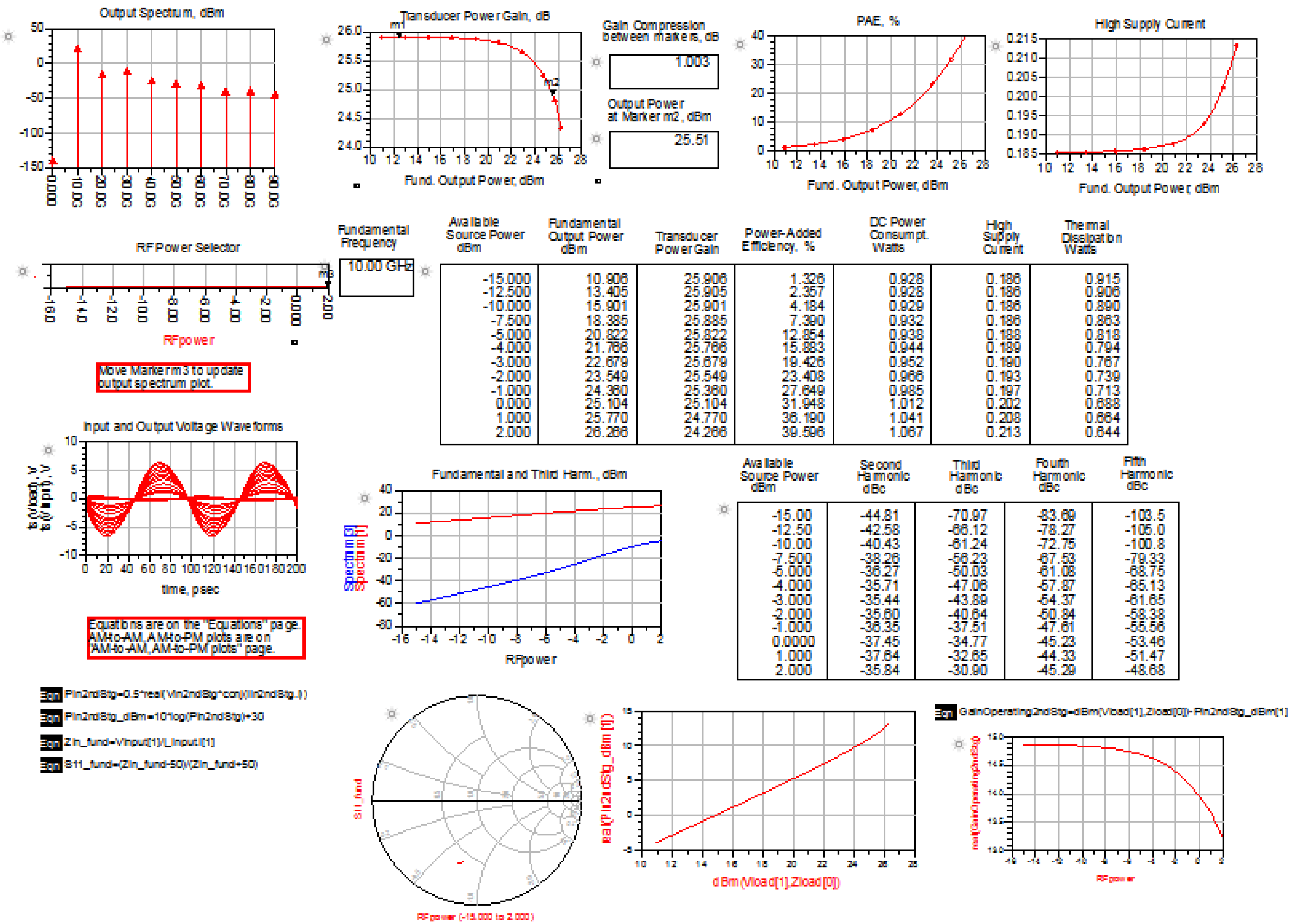
VAR
VAR1
RFfreq=850 MHz
RFpower=10 _dBm
Zload=50

HB1Tone

This is a small-signal
source for measuring
the output impedance.

MeasEqn
Power_Calcs

Harmonic Balance Results



Move Marker m3 to update output spectrum plot.

Available Source Power dBm	Fundamental Output Power dBm	Transducer Power Gain	Power-Added Efficiency, %	DC Power Consumpt. Watts	High Supply Current	Thermal Dissipation Watts
-15.000	10.906	25.906	1.326	0.928	0.186	0.915
-12.500	13.405	25.905	2.357	0.928	0.186	0.906
-10.000	15.901	25.901	4.184	0.929	0.186	0.890
-7.500	18.385	25.885	7.390	0.932	0.186	0.863
-5.000	20.822	25.822	12.854	0.938	0.188	0.818
-4.000	21.766	25.766	15.883	0.944	0.189	0.794
-3.000	22.679	25.679	19.426	0.952	0.190	0.767
-2.000	23.549	25.549	23.408	0.966	0.193	0.739
-1.000	24.360	25.360	27.649	0.985	0.197	0.713
0.000	25.104	25.104	31.948	1.012	0.202	0.688
1.000	25.770	24.770	36.190	1.041	0.208	0.664
2.000	26.266	24.266	39.596	1.067	0.213	0.644

Available Source Power dBm	Second Harmonic dBc	Third Harmonic dBc	Fourth Harmonic dBc	Fifth Harmonic dBc
-15.00	-44.81	-70.97	-83.69	-103.5
-12.50	-42.58	-66.12	-78.27	-105.0
-10.00	-40.43	-61.24	-72.75	-100.8
-7.500	-38.26	-56.23	-67.53	-79.33
-5.000	-36.27	-50.03	-61.08	-68.75
-4.000	-35.71	-47.06	-57.87	-65.13
-3.000	-35.44	-43.89	-54.37	-61.65
-2.000	-35.60	-40.64	-50.84	-58.38
-1.000	-36.35	-37.51	-47.61	-55.56
0.0000	-37.45	-34.77	-45.23	-53.46
1.000	-37.64	-32.65	-44.33	-51.47
2.000	-35.84	-30.90	-45.29	-48.68

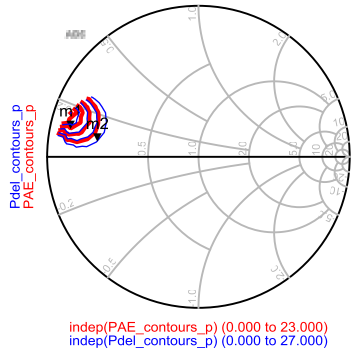
Equations are on the "Equations" page. AM-to-AM, AM-to-PM plots are on "AM-to-AM, AM-to-PM plots" page.

```
Eqn Pin2ndStg=0.5*real(Vin2ndStg*conj(Iin2ndStg.i))
Eqn Pin2ndStg_dBm=10*log(Pin2ndStg)+30
Eqn Zin_fund=Vinput[1]/I_Input.i[1]
Eqn S11_fund=(Zin_fund-50)/(Zin_fund+50)
Eqn GainOperating2ndStg=dBm(Vload[1],Zload[0])-Pin2ndStg_dBm[1]
```

Harmonic Balance Load Pull Typical Results

System Reference Impedance: 50.000

PAE (thick) and Delivered Power (thin) Contours



m1
indep(m1)=7
PAE_contours_p=0.865 / 167.515
level=36.510, number=1
impedance = Z0 * (0.073 + j0.109)

m2
indep(m2)=17
Pdel_contours_p=0.676 / 171.170
level=29.929, number=1
impedance = Z0 * (0.194 + j0.074)

Set Delivered Power contour step size (dB) and PAE contour step size (%), and number of contour lines

Eqn Pdel_step=0.5

Eqn PAE_step=4

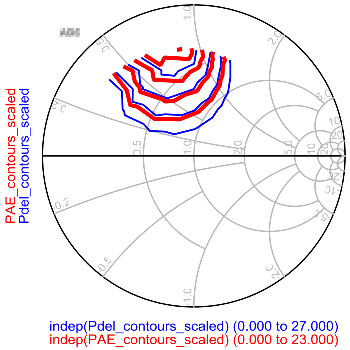
Eqn NumPAE_lines=5

Eqn NumPdel_lines=5

Maximum Power-Added Efficiency, %: 44.61

Maximum Power Delivered, dBm: 31.94

Re-Normalized PAE (thick) and Delivered Power (thin) Contours

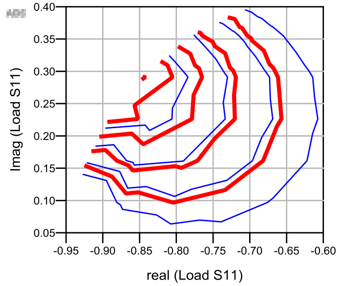


Set new reference impedance:

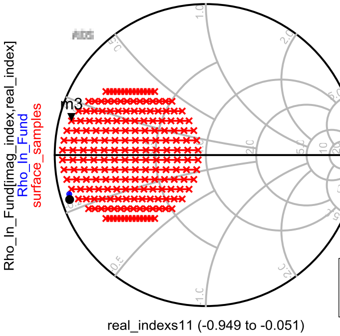
Eqn Z0new=10

Equations are on the "Equations" page.

PAE (thick) and Delivered Power (thin) Contours



Simulated Source Impedances and Input Reflection Coefficients



m3
real_indexs11=0.889
surface_samples=0.917 / 165.728
imag_indexs11=0.226
impedance = Z0 * (0.044 + j0.125)

Move Marker m3 to select load impedance value. Corresponding PAE, delivered power, input reflection coefficient and impedance values will be updated.

Impedance at marker m3: 2.189 + j6.248

PAE, %: 41.28

Power Delivered (dBm): 31.68

Input Reflection Coefficient: 0.95 / -1.62E2

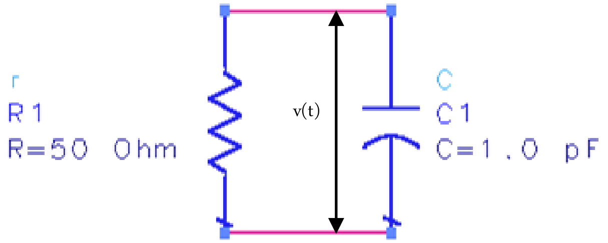
Input Impedance: 1.35 - j7.96

KEYSIGHT TECHNOLOGIES

Transient Analysis

Just like SPICE, only better

- Kirchoff's current equations are derived at each node in differential form



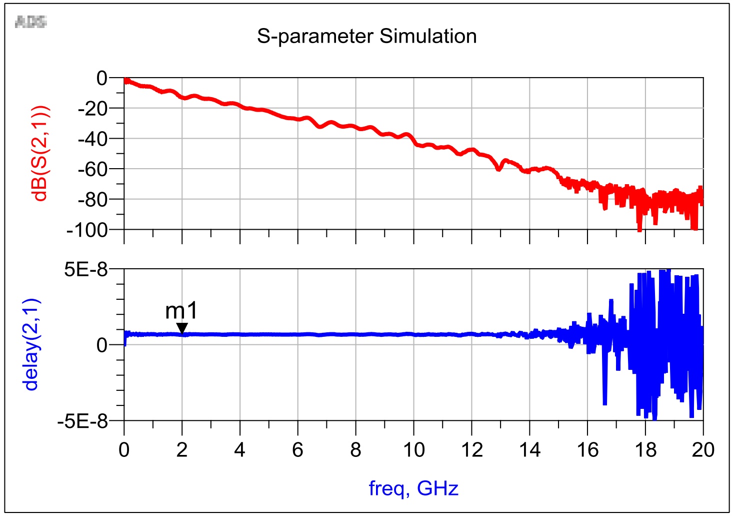
$$\frac{v(t)}{R} + C\frac{dv(t)}{dt} = 0 \quad (1)$$

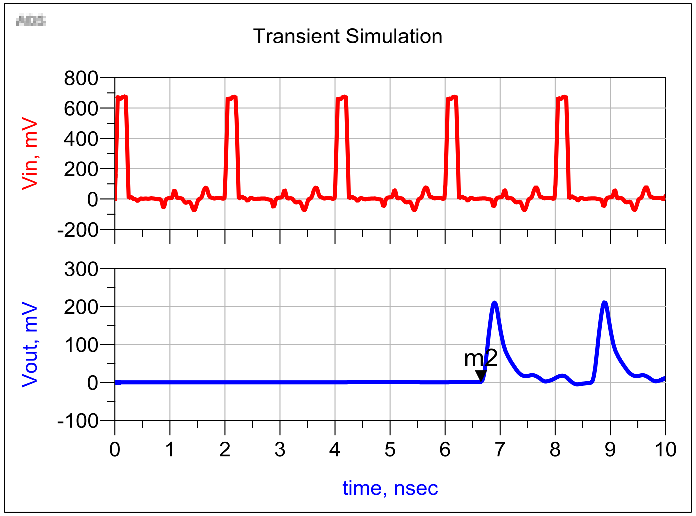
- The time derivatives are replaced with discrete-time approximations (integration)
- The solution, in the case of a complex circuit, will consist of a system of nonlinear equations which is solved using the Newton-Raphson method

Transient Simulation

m1
freq=2.000GHz
delay(2,1)=6.685E-9

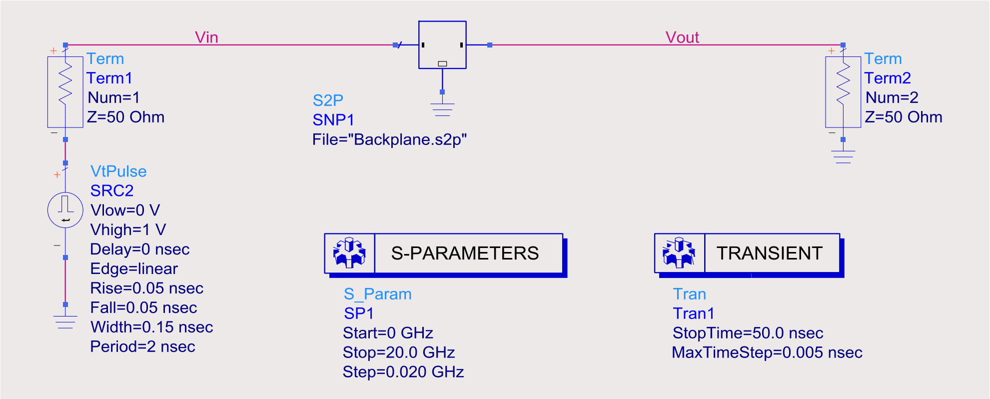
m2
time=6.651nsec
Vout=0.001





lay calculated from measured S-parameters (as group delay) corresponds very well with delay observed in Transient simulati

ote the clearly causal response and good behavior even when using somewhat non-ideal measured data.



Term
Term1
Num=1
Z=50 Ohm

VtPulse
SRC2
Vlow=0 V
Vhigh=1 V
Delay=0 nsec
Edge=linear
Rise=0.05 nsec
Fall=0.05 nsec
Width=0.15 nsec
Period=2 nsec

S2P
SNP1
File="Backplane.s2p"

S_Param
SP1
Start=0 GHz
Stop=20.0 GHz
Step=0.020 GHz

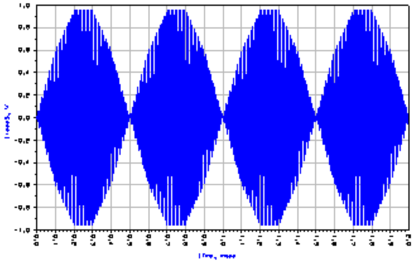
Term
Term2
Num=2
Z=50 Ohm

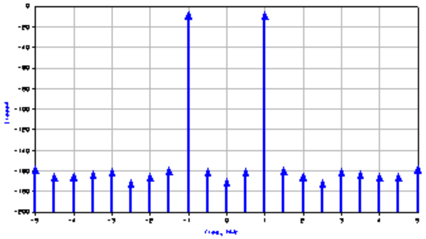
Tran
Tran1
StopTime=50.0 nsec
MaxTimeStep=0.005 nsec

Circuit Envelope

Beyond CW and onto Modulated signals.

- Time samples the modulation envelope (not carrier)
- Compute the spectrum at each time sample
- Output a time-varying spectrum
- Use equations on the data
- Faster than HB or Spice in many cases
- Integrates with System Simulations & Keysight’s Ptolemy





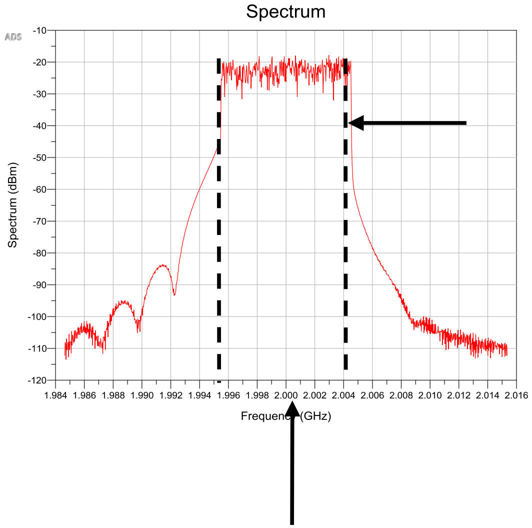
Circuit Envelope

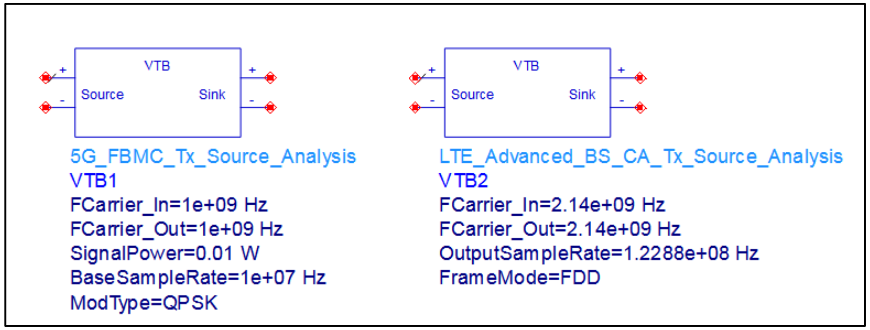
Test Circuits with Realistic Signals

LTE, LTE-A, 802.11ac, BTLE, 5G

Example CE results:

LTE DL





5G_FBMC_Tx_Source_Analysis
VTB1
FCarrier_In=1e+09 Hz
FCarrier_Out=1e+09 Hz
SignalPower=0.01 W
BaseSampleRate=1e+07 Hz
ModType=QPSK

LTE_Advanced_BS_CA_Tx_Source_Analysis
VTB2
FCarrier_In=2.14e+09 Hz
FCarrier_Out=2.14e+09 Hz
OutputSampleRate=1.2288e+08 Hz
FrameMode=FDD

2 GHz carrier

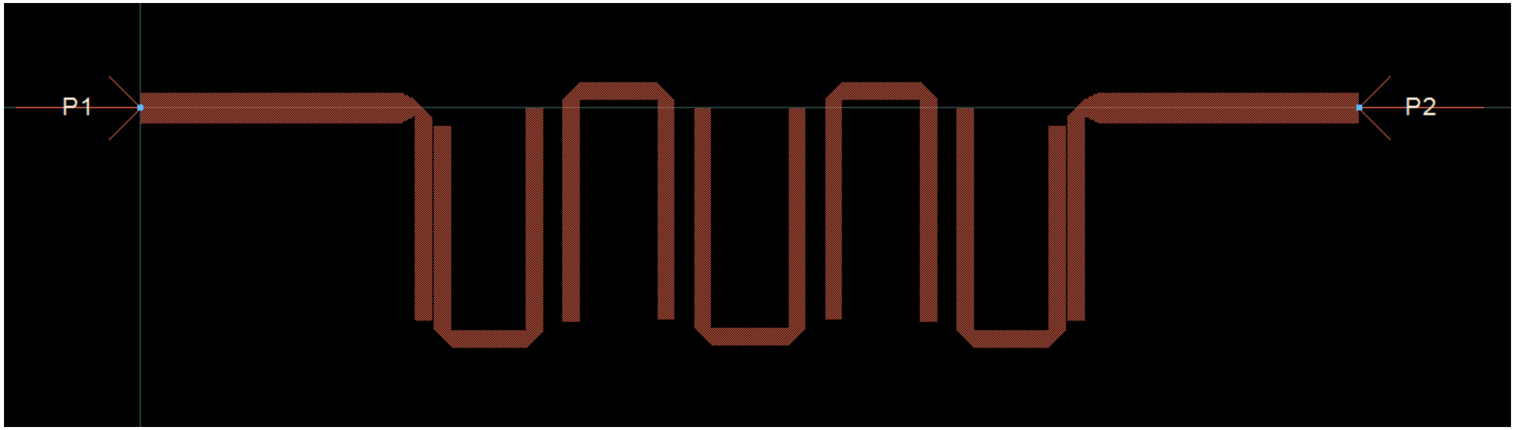
Simulations can include:

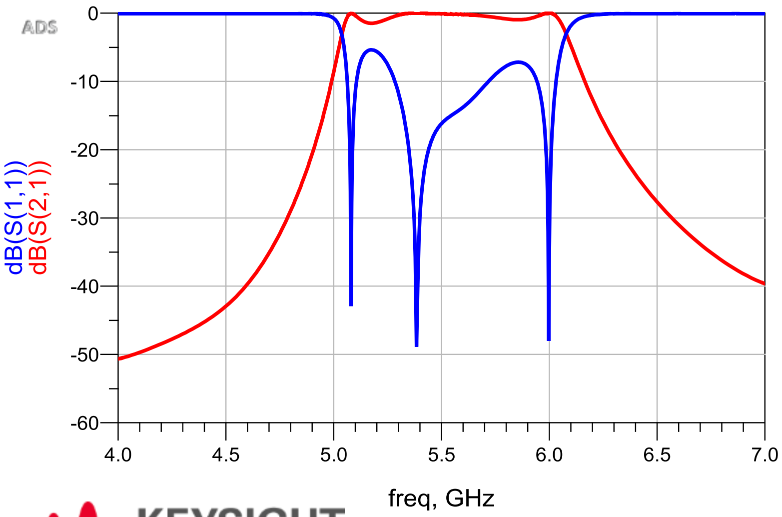
- Adjacent Channel Power Ratio
- Noise Power Ratio
- Error Vector Magnitude
- Power Added Efficiency
- Bit Error Rate

2-tone tests and linearized models do not predict this behavior as easily!

Electromagnetic

Method of Moments solver

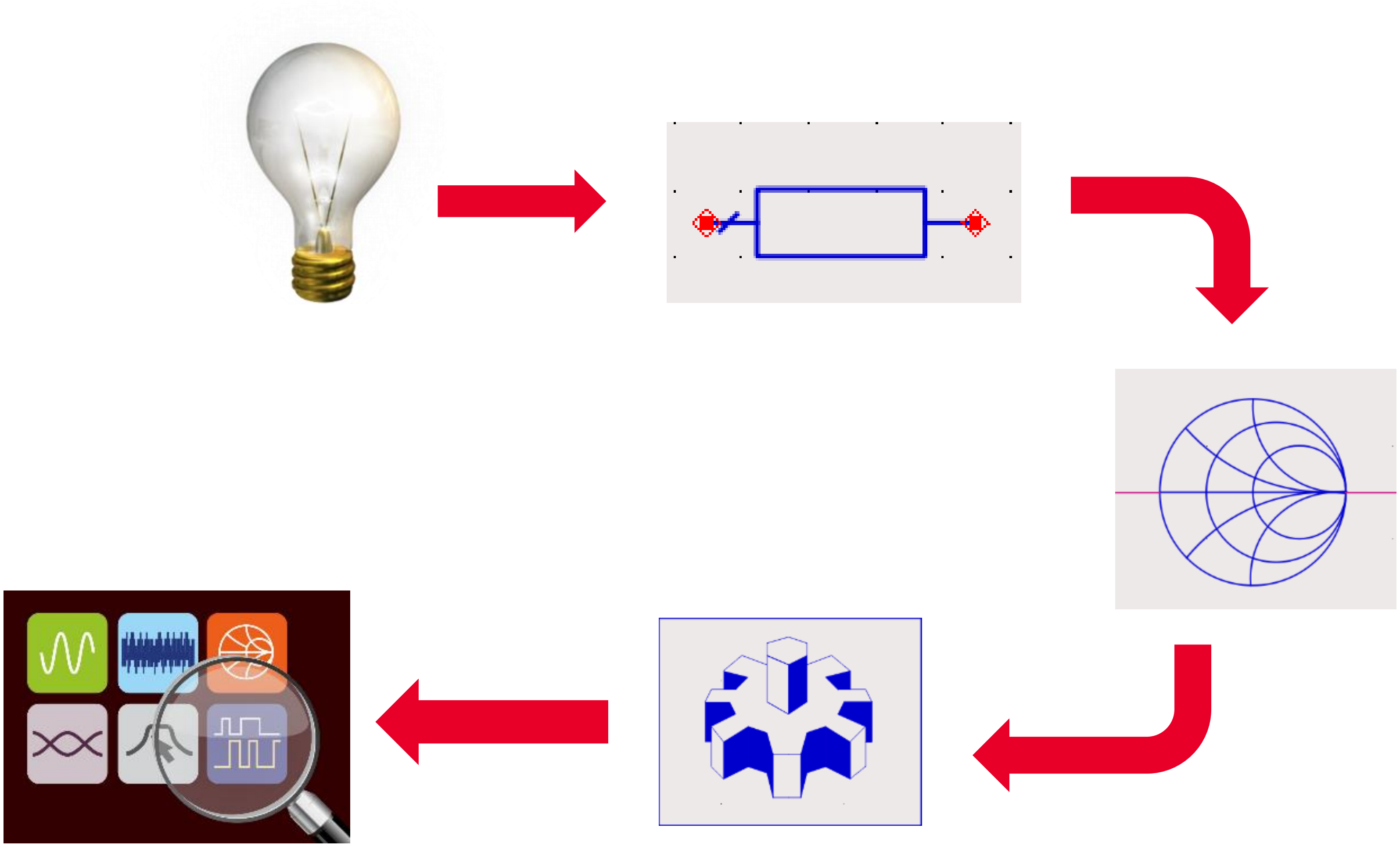




- No good Circuit model exists
- Physical dimensions and properties are known.
- The entire geometry is “meshed”
- Results are S Parameters
- Design can be optimized

Summary

Start with your great idea, choose your EDA environment, use appropriate models to construct the designs. Run simulations to verify performance and build great RF applications.



Learn more about RF Simulations

– How to Design an RF Power Amplifier and other How-to videos:

https://www.youtube.com/playlist?list=PLtq84kH8xZ9HIYgBYDsP7TbqBpftidzI8

– For More Information www.keysight.com/find/eesof-ads-info

– ADS on YouTube www.keysight.com/find/eesof-ads-videos

–

– Genesys on YouTube

https://www.youtube.com/playlist?list=PLtq84kH8xZ9E8S_y5dmCXtJFPo14NsCtt