Spectral Domain Techniques for System Design

MTT Society: Long Island Chapter

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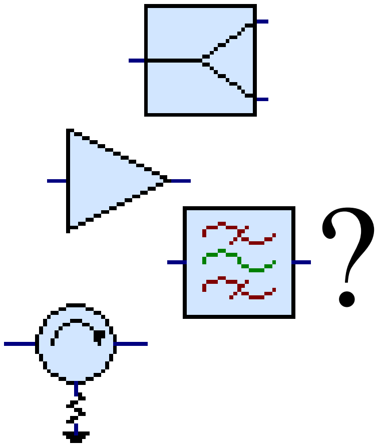
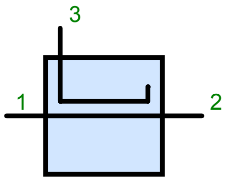
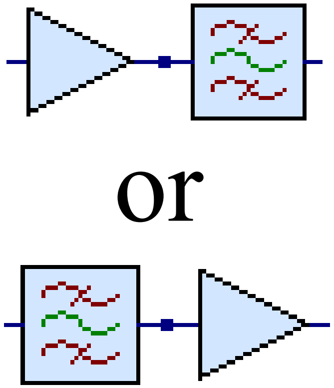
RF Architecture Design

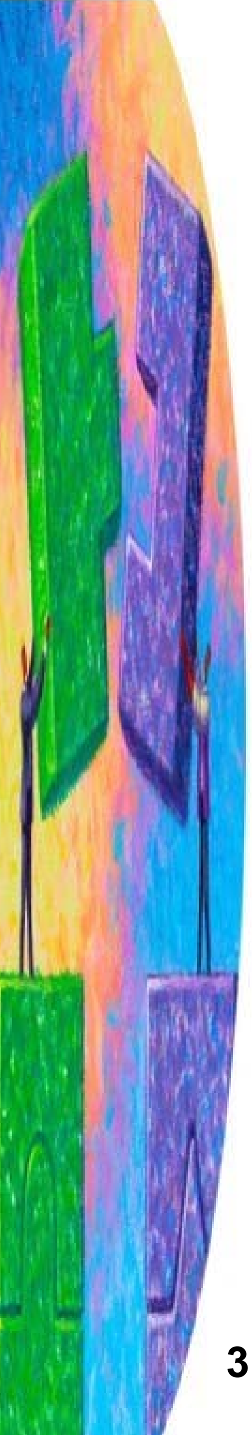
- During RF architecture design engineers determine how many, what type, parameters, and the order of stages required to meet system specifications





Coupler
IL=2 dB
CPL=20 dB
DIR=30 dB
Z0=50 ohm

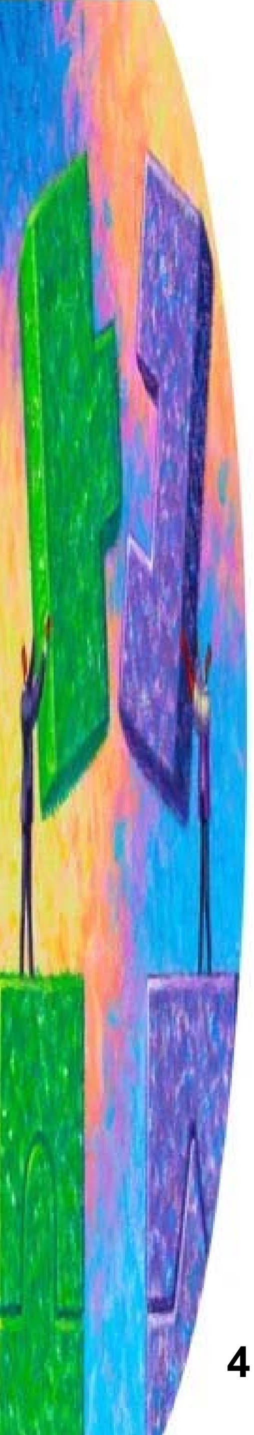




The Architecture is Critical

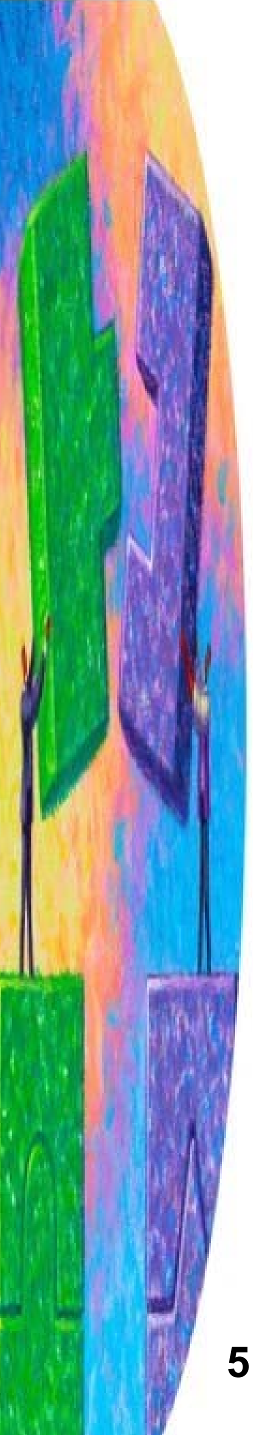
Architecture is the system foundation

- Poor architecture causes poor performance
- Poor architecture causes more design turns
- Poor architecture causes increased cost
- Poor architecture causes increased time to market



Traditional RF Architecture Analysis Methods

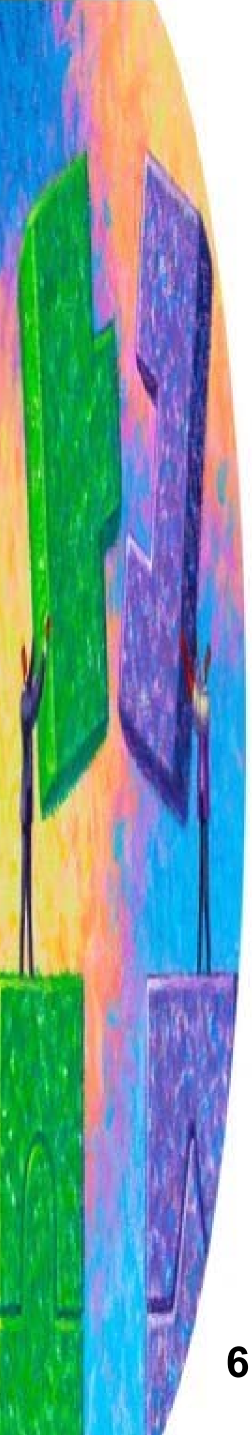
- SPICE
- Linear Analysis
- Harmonic Balance
- Time Domain System Simulation
- Spreadsheets / Cascade Tools



SPICE

Spice simulation time steps a non-linear nodal circuit from initial conditions with a converging iterative solution.

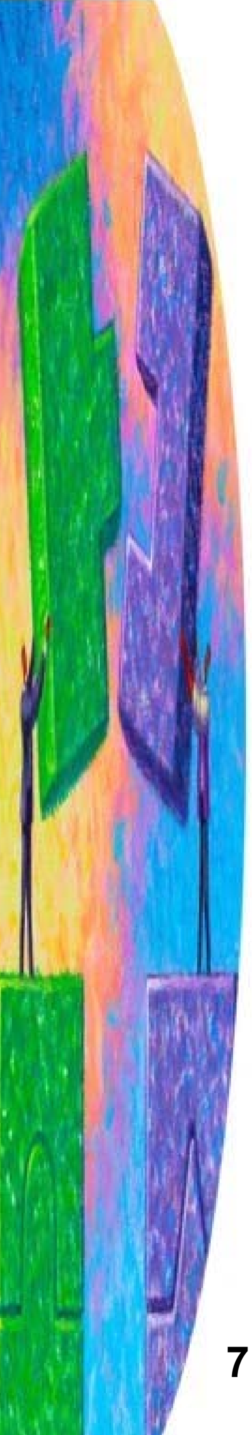
Advantages	Disadvantages
Transient analysis	Can be very slow. Long simulation time to integrate over thousands of RF cycles
Oscillator startup	Intermod analysis with wide frequency differences is difficult
Non-repetitive waveforms	Static component models
	Convergence issues



Linear Analysis

Steady state solution of multi-node matrix. Technique is closed form and not iterative.

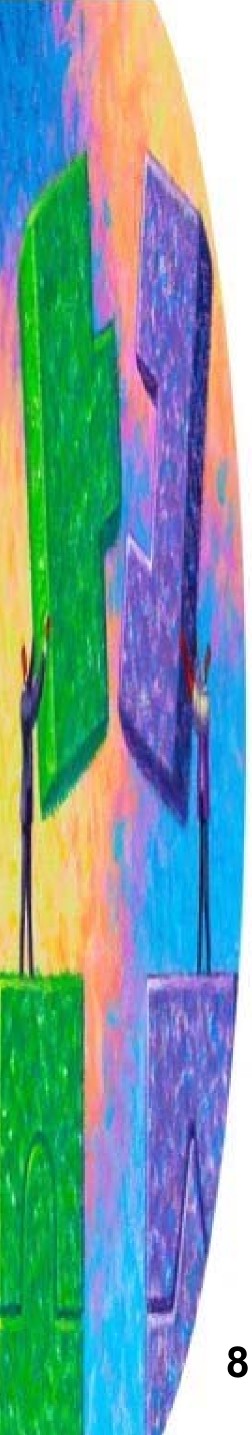
Advantages	Disadvantages
Very fast, real-time tuning.	No non-linear effects
Effective optimization because of simulation speed	Designed for circuits, not systems
Effective statistical analysis	No transient analysis
Frequency dependent (dispersive) model support	Active devices characterized at fixed bias conditions
Accuracy limited only by models	Single swept tone analysis



Harmonic Balance

Steady state solution of currents at every node balanced at all signal frequencies and specified harmonics. Uses iteration.

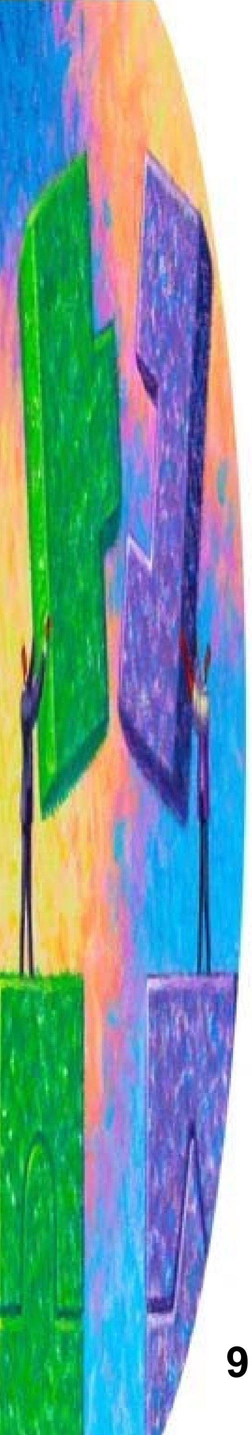
Advantages	**Disadvantages**
Supports dispersive transmission lines	Limited number of independent tones
Typically faster than SPICE	No bandwidth features
Analysis time independent of component values	Only small circuits truly interactive
Intermod analysis with wide frequency spacing	No concept of a channel



Time Domain System Simulation

Time step simulation of unilateral models described by parameters. Works best for baseband & modulation analysis.

Advantages	Disadvantages
Ideal for complex modulation analysis	Models are unilateral and mismatch is not simulated
Faster than SPICE since sampling is at baseband	Multi-path is supported, but only forward
Visualization of effects on baseband due to circuitry	Quantifies system degradation but does not identify root cause
Rich model & library availability	Poorly suited for RF architecture analysis
Supports BER/EVM analysis	



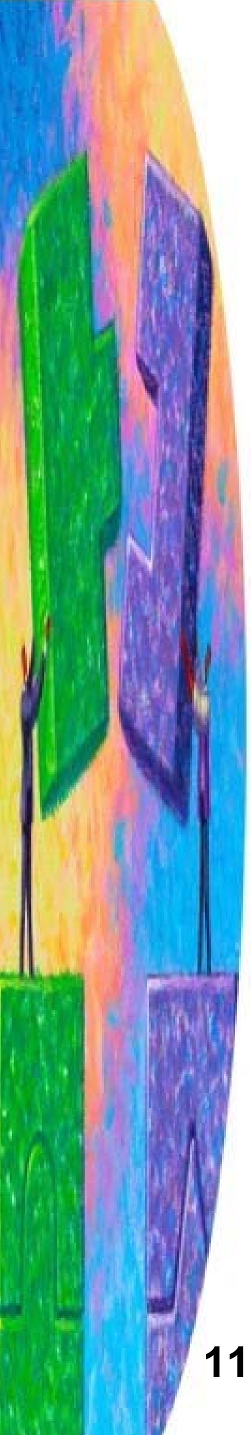
Spreadsheets/Cascade Tools

Analytical equations are programmed for each path of interest. Typically scalar, unilateral and unfiltered.

Advantages	Disadvantages
Readily available	Poor integration with other tools
Simple data entry	Typically scaler calculations
Cheap	All paths must be anticipated and programmed
	Typically assumes unfiltered and flat frequency response
	No VSWR effects
	Difficult to hand off & maintain

Traditional Method Limitations

- SPICE, linear, and harmonic balance simulators are designed for components, not system realization
- Programming spreadsheets is extremely difficult when image noise, intermod filtering, mismatch effects and multiple paths are considered
- Summary: traditional tools are ill suited for analyzing RF architectures



What is Required for RF Architecture Analysis?

- Spur identification and resolution
- Noise analysis that considers the channel bandwidth
- In-channel and out of band intermod analysis
- Consideration of real issues (mismatch, phase, images, measured vs. ideal models, etc.)
- Identifying root causes is critical in systems with hundreds of leakage, harmonic and intermod tones.
- Integration with other software tools and measurement instruments

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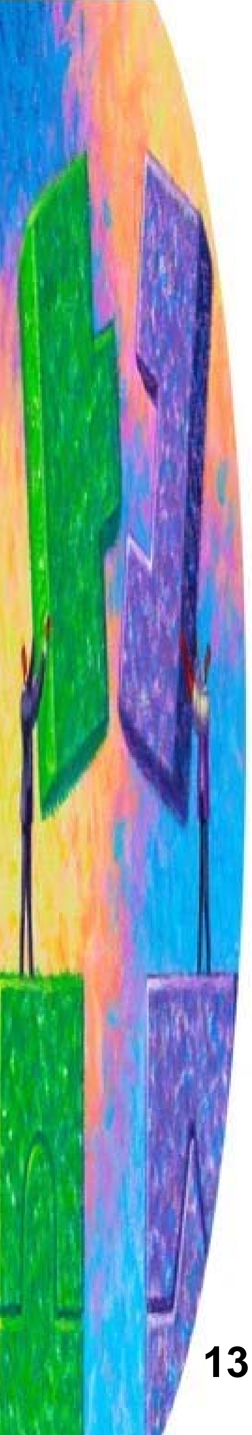
SPARCA

These needs led to the development of the **SPARCA** method, an acronym for **S**ignal **P**ropagation and **R**oot **C**ause **A**nalysis.

- New method developed in 2002
- Based in the frequency domain
- Bilateral signal flow of all paths
- Magnitude and phase modeling (Vector)
- Channel concepts integrated into the method
- The software implementation I will demonstrate is SPECTRASYS



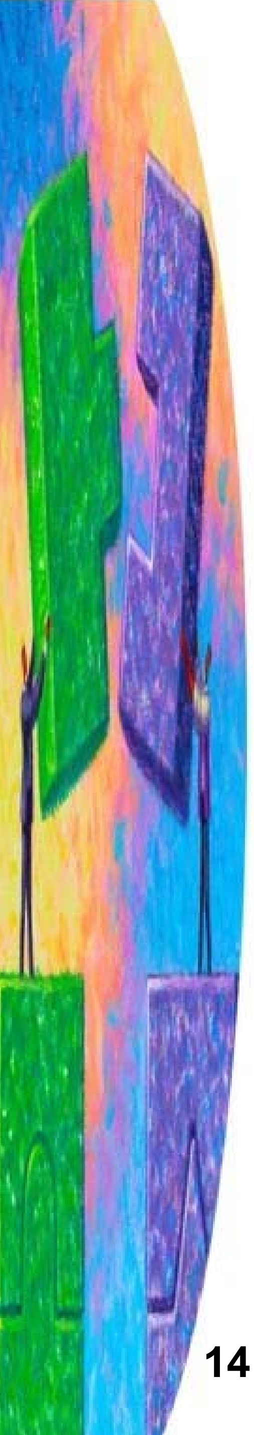
System Description

To begin

- A schematic is drawn to describe the system
- CW, modulated and LO input signals are specified
- Initial parameters for each block are entered

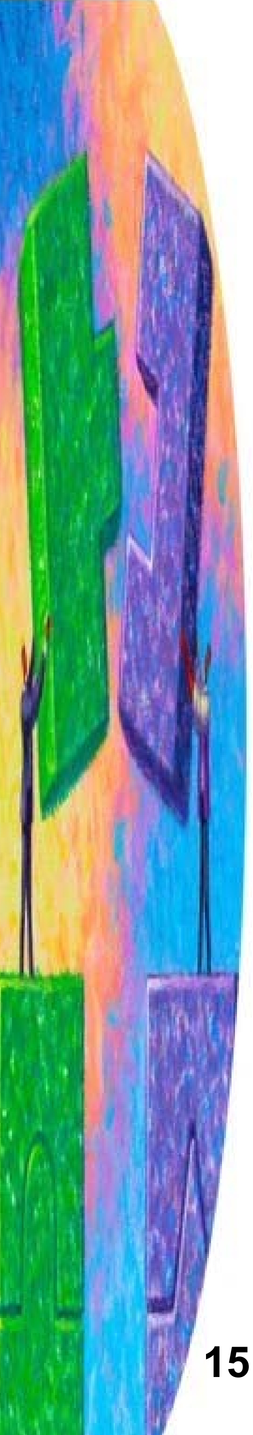
This approach has the advantages that it:

- Considers all paths while spreadsheet analysis only considers anticipated paths
- Integrates the schematic, block parameters and signal descriptions with other simulators and even synthesis tools



How SPARCA Works

- All signal sources are propagated through all paths to all nodes in the system
- All harmonic and intermod products generated in all non-linear models propagate to all nodes
- All noise sources in the system propagate through all paths to all nodes
- Noise is integrated in the channel bandwidth and adjacent channel measurements are supported
- Devices are bilateral
- The true filtered and non-flat transfer function including phase is used for each path
- Reflections are considered

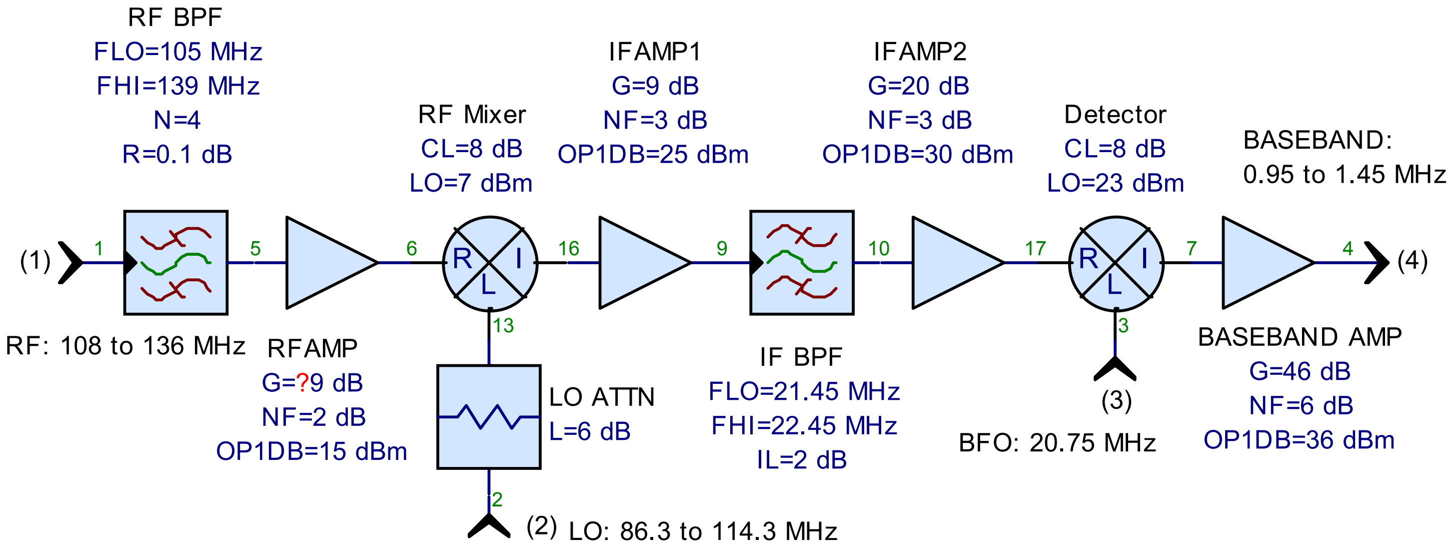


SPARCA Method

SPARCA does not replace other analysis methods (except perhaps spreadsheets), it complements them. It is optimized for RF architecture design.

Advantages	Disadvantages
Identifies root causes	Sole source software vendor
Handles multiple paths	No transient simulation
More accurate than ideal model and scalar methods	Not a modulation analyzer
Handles more signals & tones than other methods	Doesn’t “know” bits
Handles channel concepts	
Integrates well with other software and lab tools	

Example:
Aviation Band Downconverter



RF BPF
FLO=105 MHz
FHI=139 MHz
N=4
R=0.1 dB

RF Mixer
CL=8 dB
LO=7 dBm

IFAMP1
G=9 dB
NF=3 dB
OP1DB=25 dBm

IFAMP2
G=20 dB
NF=3 dB
OP1DB=30 dBm

Detector
CL=8 dB
LO=23 dBm

BASEBAND:
0.95 to 1.45 MHz

RF: 108 to 136 MHz

RFAMP
G=?9 dB
NF=2 dB
OP1DB=15 dBm

LO ATTN
L=6 dB

IF BPF
FLO=21.45 MHz
FHI=22.45 MHz
IL=2 dB

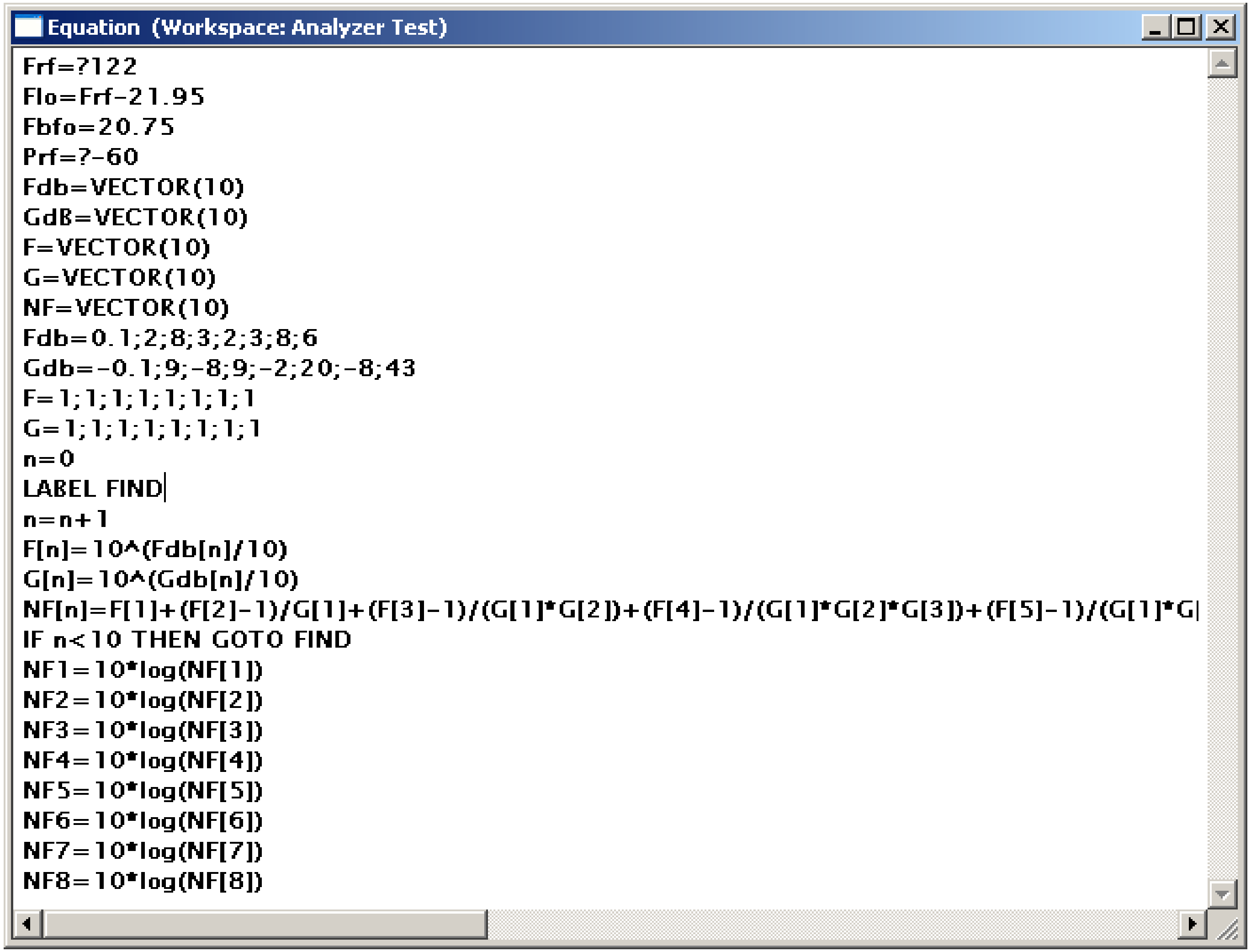
BFO: 20.75 MHz

BASEBAND AMP
G=46 dB
NF=6 dB
OP1DB=36 dBm

(2) LO: 86.3 to 114.3 MHz

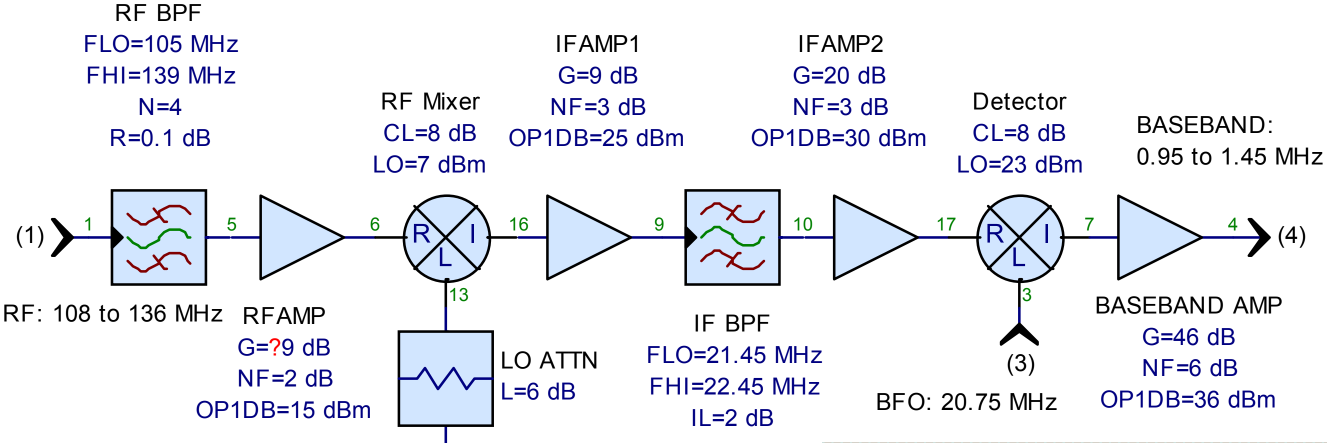
The analyzer uses a tunable 1st LO to convert 500 KHz segments of the aviation band to 0.95 to 1.45 MHz for baseband processing.

Simple Cascade Noise Figure



```
Frf=?122
Flo=Frf-21.95
Fbfo=20.75
Prf=?-60
Fdb=VECTOR(10)
GdB=VECTOR(10)
F=VECTOR(10)
G=VECTOR(10)
NF=VECTOR(10)
Fdb=0.1;2;8;3;2;3;8;6
Gdb=-0.1;9;-8;9;-2;20;-8;43
F=1;1;1;1;1;1;1;1
G=1;1;1;1;1;1;1;1
n=0
LABEL FIND
n=n+1
F[n]=10^(Fdb[n]/10)
G[n]=10^(Gdb[n]/10)
NF[n]=F[1]+(F[2]-1)/G[1]+(F[3]-1)/(G[1]*G[2])+(F[4]-1)/(G[1]*G[2]*G[3])+(F[5]-1)/(G[1]*G
IF n<10 THEN GOTO FIND
NF1=10*log(NF[1])
NF2=10*log(NF[2])
NF3=10*log(NF[3])
NF4=10*log(NF[4])
NF5=10*log(NF[5])
NF6=10*log(NF[6])
NF7=10*log(NF[7])
NF8=10*log(NF[8])
```

Results of the Cascade Calculation



RF BPF
FLO=105 MHz
FHI=139 MHz
N=4
R=0.1 dB

RF Mixer
CL=8 dB
LO=7 dBm

IFAMP1
G=9 dB
NF=3 dB
OP1DB=25 dBm

IFAMP2
G=20 dB
NF=3 dB
OP1DB=30 dBm

Detector
CL=8 dB
LO=23 dBm

BASEBAND:
0.95 to 1.45 MHz

RF: 108 to 136 MHz

RFAMP
G=?9 dB
NF=2 dB
OP1DB=15 dBm

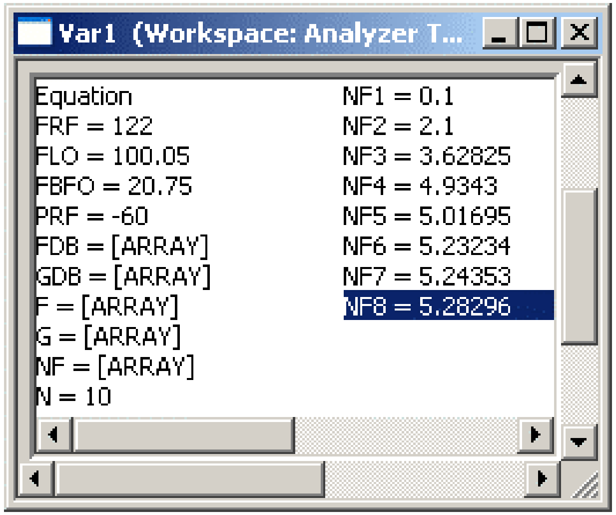
LO ATTN
L=6 dB

IF BPF
FLO=21.45 MHz
FHI=22.45 MHz
IL=2 dB

BFO: 20.75 MHz

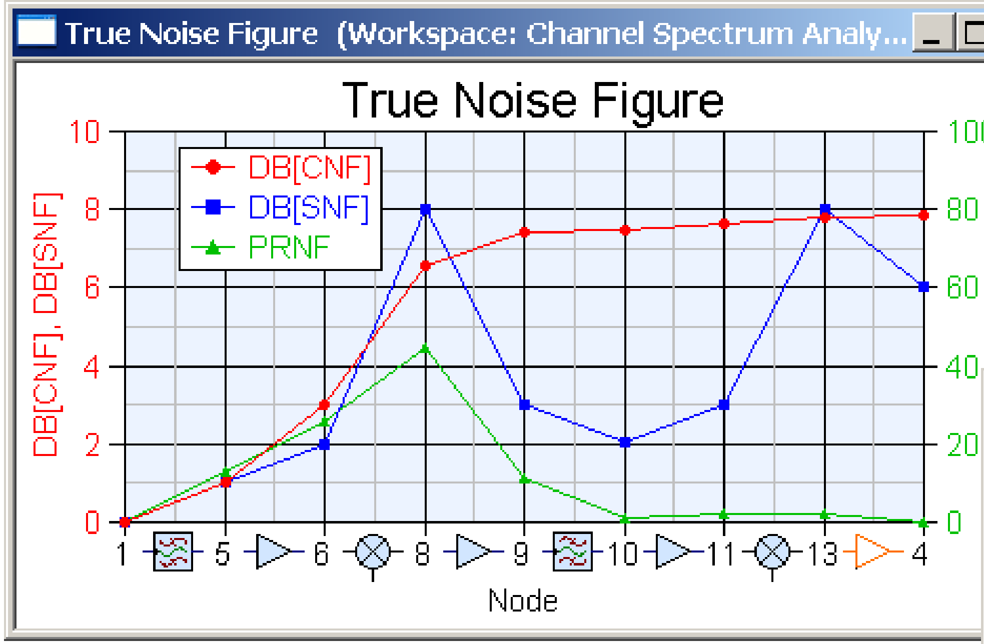
BASEBAND AMP
G=46 dB
NF=6 dB
OP1DB=36 dBm

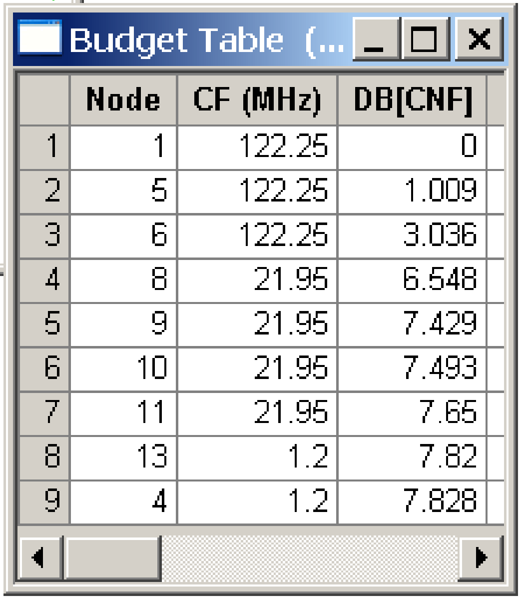
LO: 86.3 to 114.3 MHz



```
Equation                NF1 = 0.1
FRF = 122               NF2 = 2.1
FLO = 100.05            NF3 = 3.62825
FBFO = 20.75            NF4 = 4.9343
PRF = -60               NF5 = 5.01695
FDB = [ARRAY]           NF6 = 5.23234
GDB = [ARRAY]           NF7 = 5.24353
F = [ARRAY]             NF8 = 5.28296
G = [ARRAY]
NF = [ARRAY]
N = 10
```

Results by Spectral Propagation

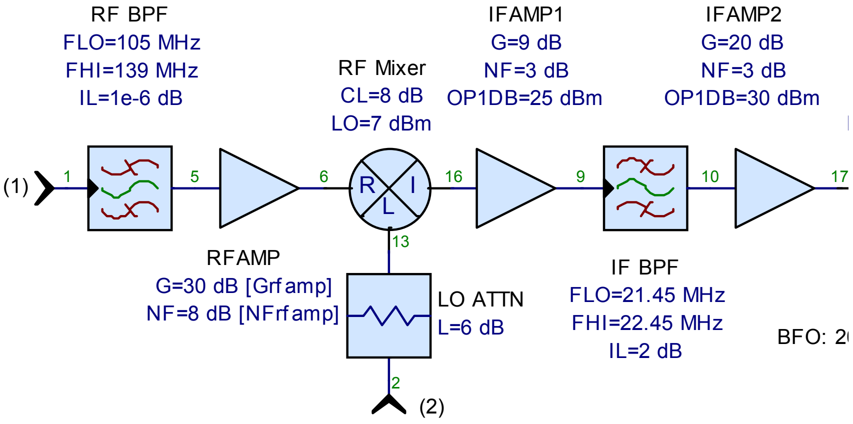


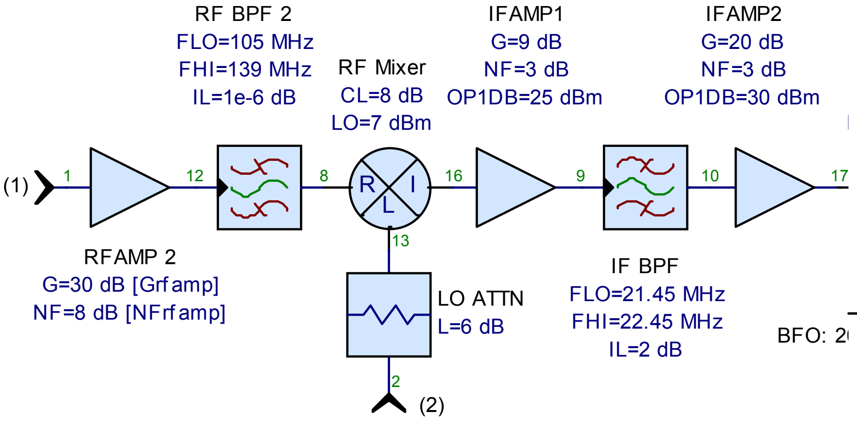


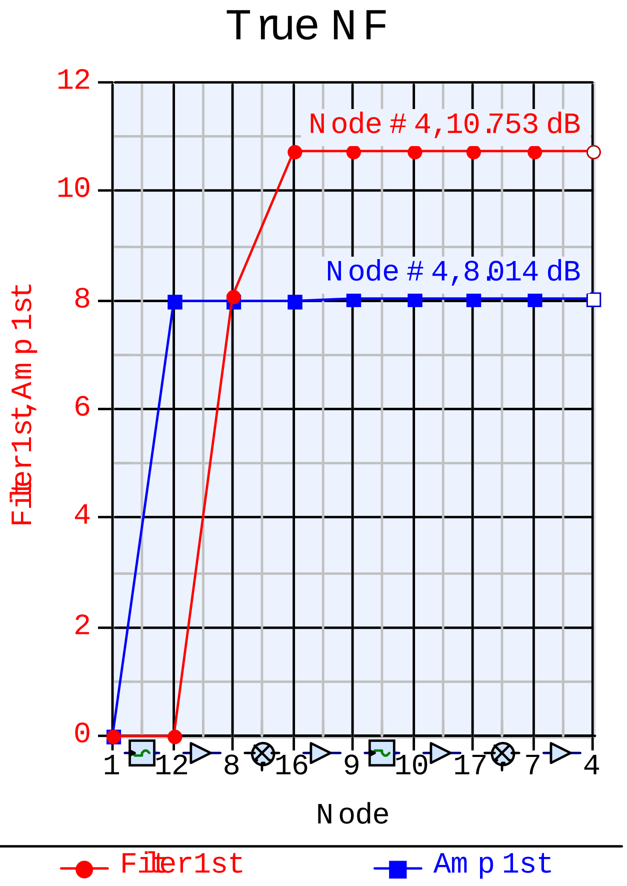
	Node	CF (MHz)	DB[CNF]
1	1	122.25	0
2	5	122.25	1.009
3	6	122.25	3.036
4	8	21.95	6.548
5	9	21.95	7.429
6	10	21.95	7.493
7	11	21.95	7.65
8	13	1.2	7.82
9	4	1.2	7.828

By cascade analysis: 5.28 dB

Image Noise: Filters Can’t be Ignored

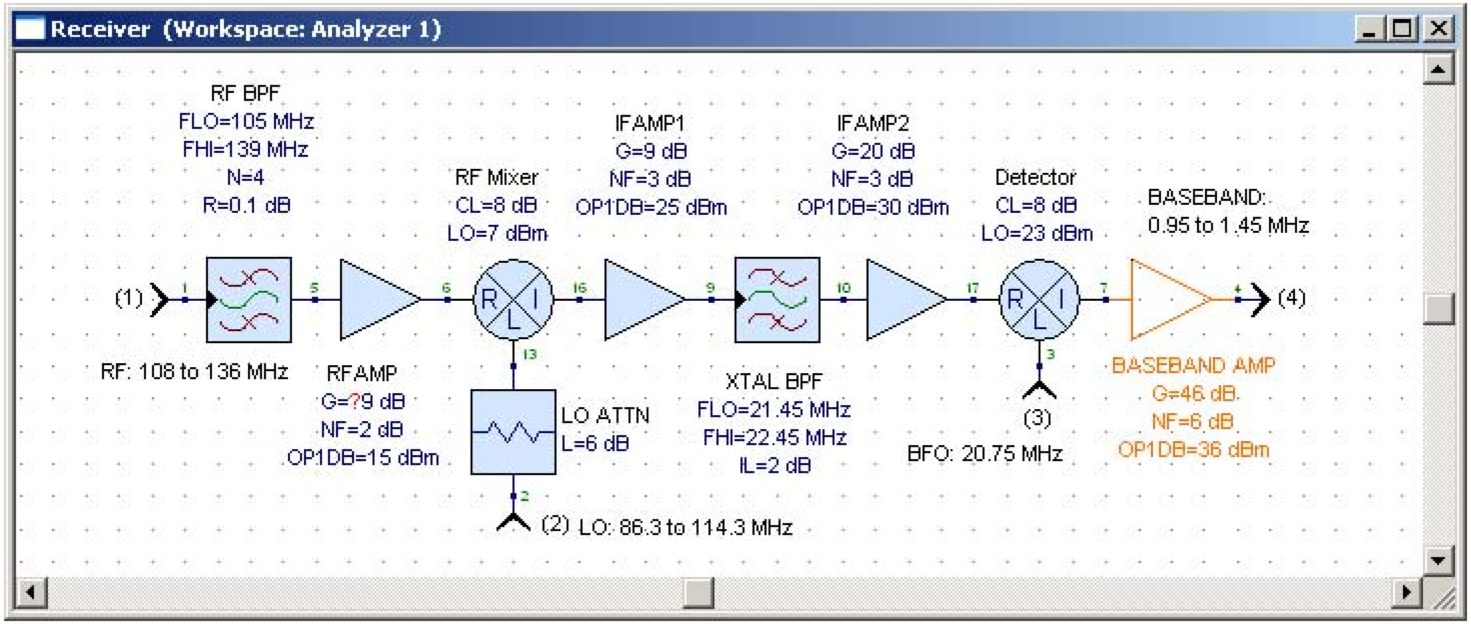






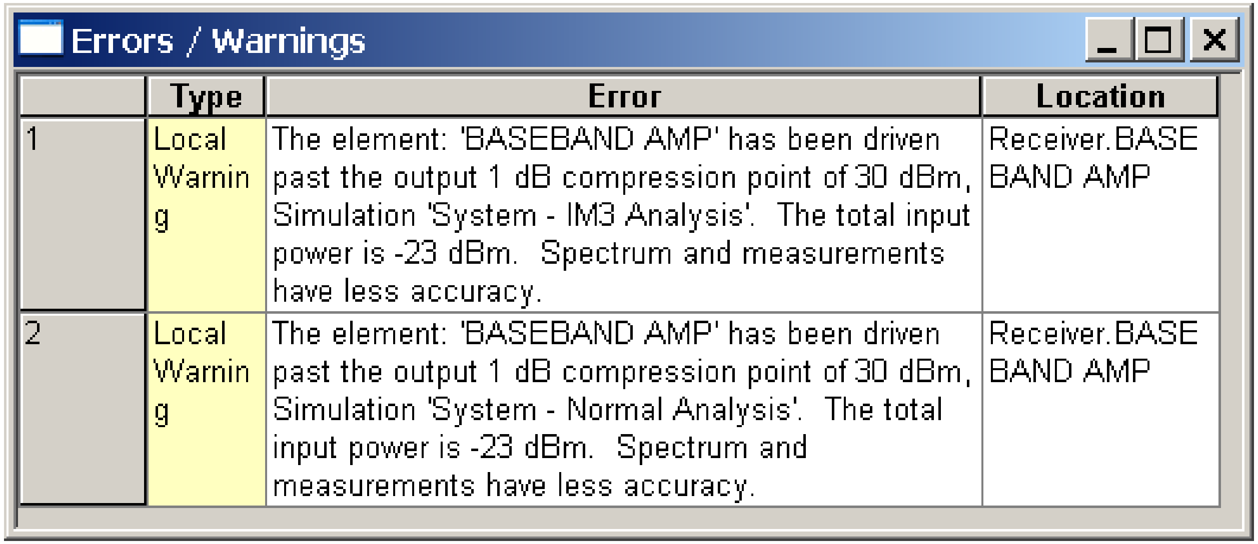
Error Flagging

Let’s return to the original configuration. Notice that the Baseband Amplifier is yellow rather than blue. Using SPARCA, SPECTRASYS has identified a problem with this block.



Error Messaging

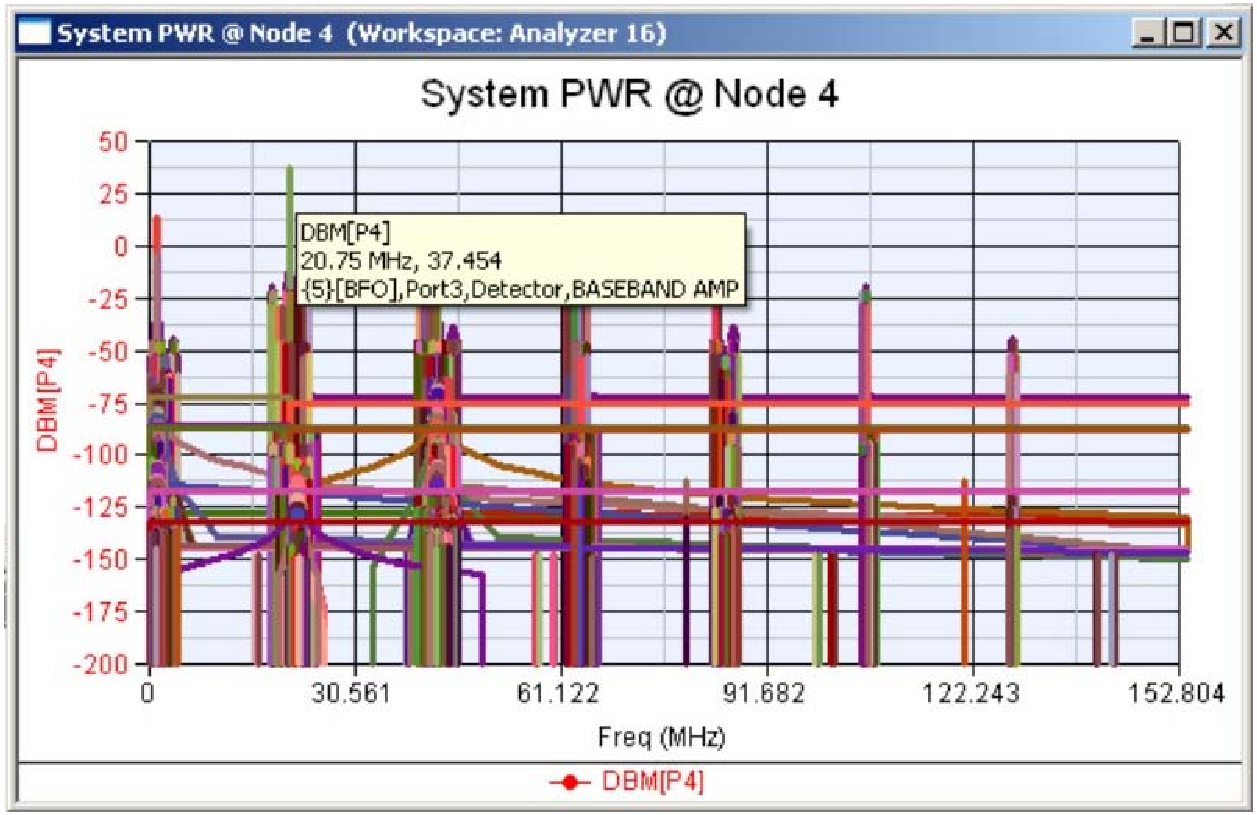
Right clicking on this amplifier provides access to local error messages associated with that block. Because SPARCA propagates all signals to every node, it is possible to identify overdrive conditions.



	Type	Error	Location
1	Local Warning	The element: 'BASEBAND AMP' has been driven past the output 1 dB compression point of 30 dBm, Simulation 'System - IM3 Analysis'. The total input power is -23 dBm. Spectrum and measurements have less accuracy.	Receiver.BASEBAND AMP
2	Local Warning	The element: 'BASEBAND AMP' has been driven past the output 1 dB compression point of 30 dBm, Simulation 'System - Normal Analysis'. The total input power is -23 dBm. Spectrum and measurements have less accuracy.	Receiver.BASEBAND AMP

Root Cause Analysis

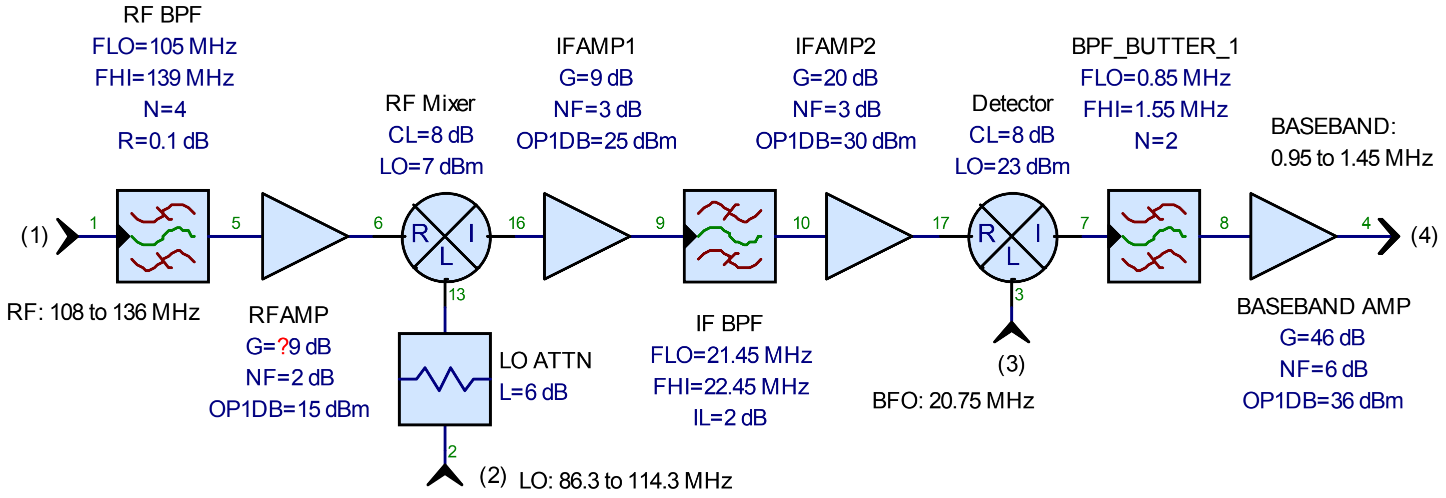
Is the Baseband Amplifier overdriven by the signal? Any node may be probed by right clicking the node and adding a plot. Because all propagation paths are recorded, the offending signal is identified as BFO leakage through the mixer.



System PWR @ Node 4 (Workspace: Analyzer 16)

DBM[P4]
20.75 MHz, 37.454
{5}[BFO],Port3,Detector,BASEBAND AMP

Repairing the Overdrive

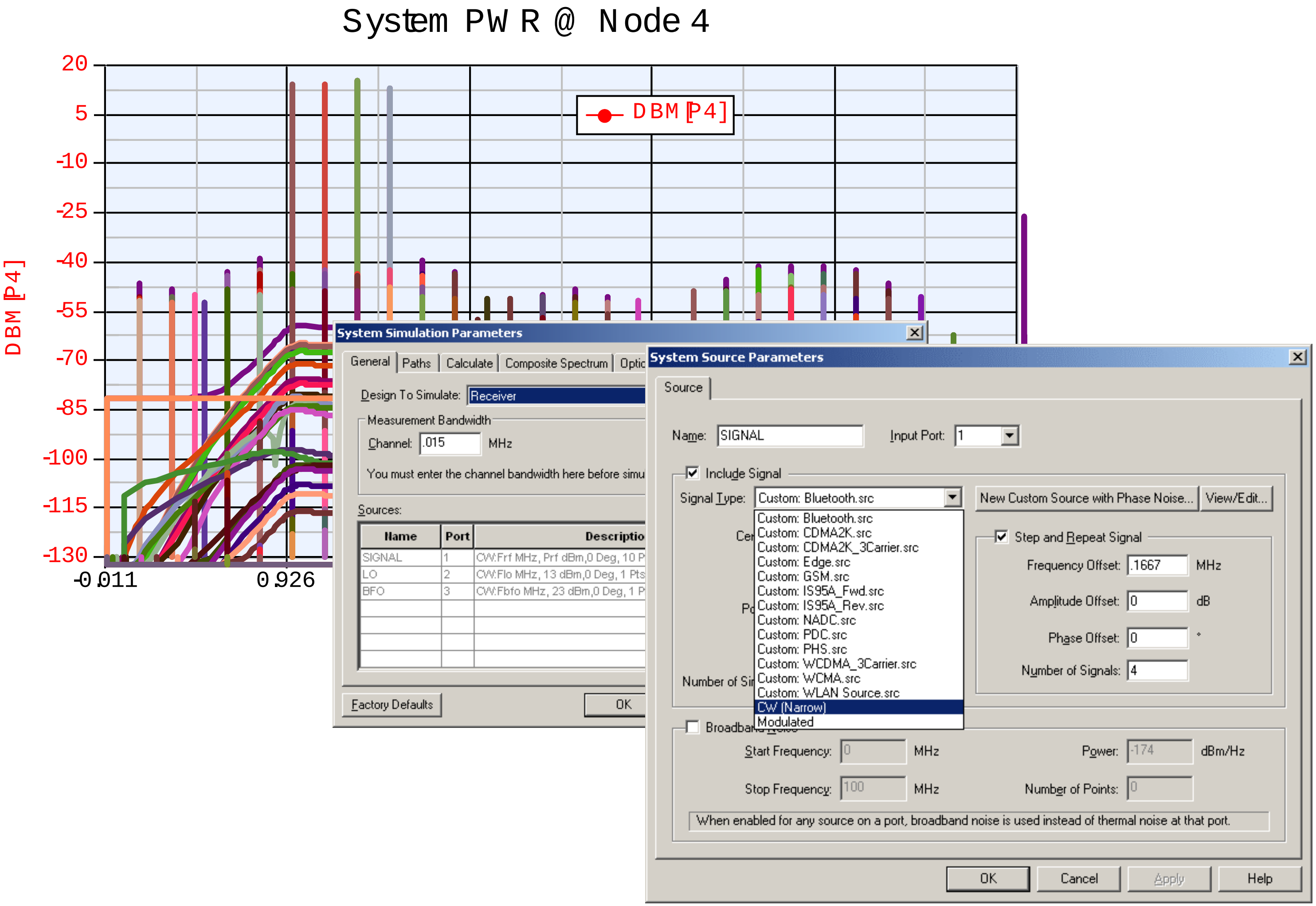


Once identified, this particular problem is easily repaired because the desired baseband frequencies and the BFO are well separated. A baseband filter is added prior to the baseband amplifier to attenuate the BFO leakage.

A low order (2nd) filter is used.

The error message is extinguished.

The Output Spectrum



System Simulation Parameters

Design To Simulate: Receiver

Measurement Bandwidth

Channel: .015 MHz

You must enter the channel bandwidth here before simu

Sources:

Name	Port	Descriptio
SIGNAL	1	CW:Frf MHz, Prf dBm,0 Deg, 10 P
LO	2	CW:Flo MHz, 13 dBm,0 Deg, 1 Pts
BFO	3	CW:Fbfo MHz, 23 dBm,0 Deg, 1 P

System Source Parameters

Name: SIGNAL

Input Port: 1

☑ Include Signal

Signal Type: Custom: Bluetooth.src

☑ Step and Repeat Signal

Frequency Offset: .1667 MHz

Amplitude Offset: 0 dB

Phase Offset: 0 °

Number of Signals: 4

☐ Broadband Noise

Start Frequency: 0 MHz

Stop Frequency: 100 MHz

Power: -174 dBm/Hz

Number of Points: 0

When enabled for any source on a port, broadband noise is used instead of thermal noise at that port.

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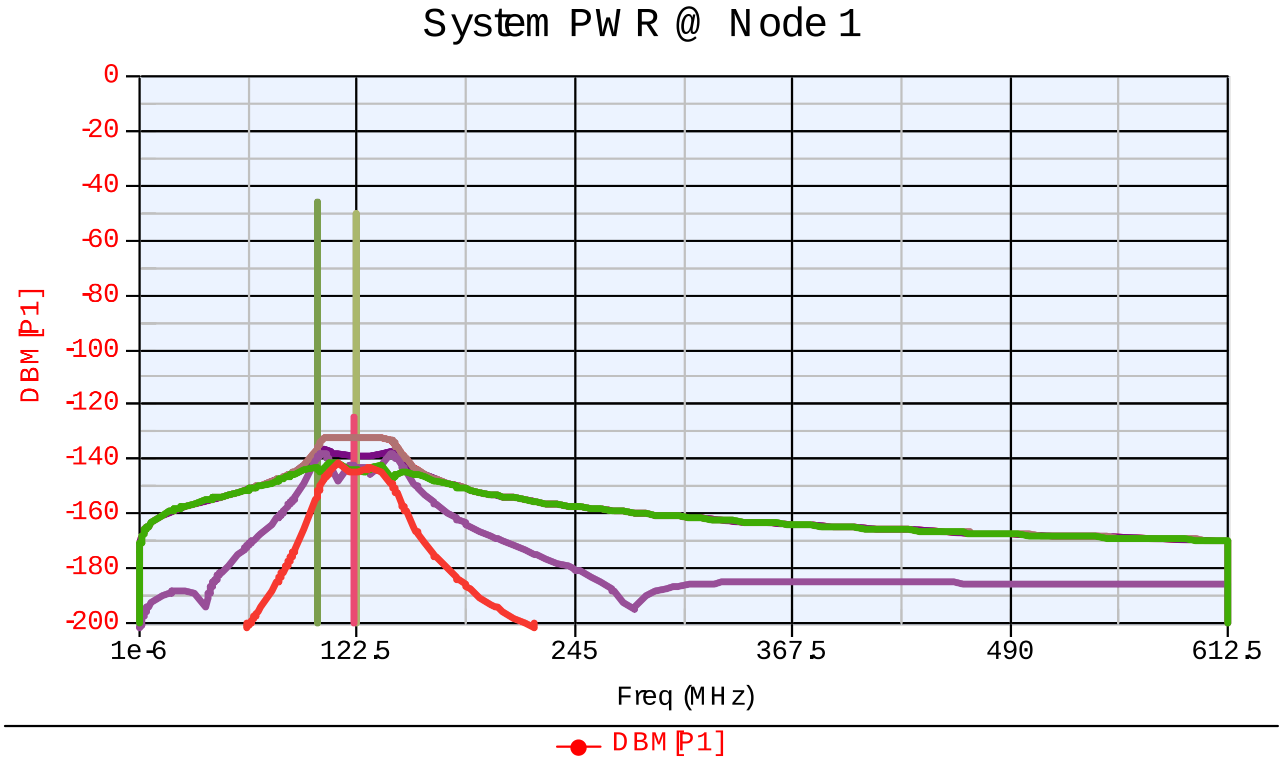
All Paths, All Nodes

Unlike spreadsheet analysis, schematic based SPARCA inherently offers data for all nodes and all paths. For example, examining LO radiation requires only adding a graph. Can you identify the source of all of these signals?



Measurements

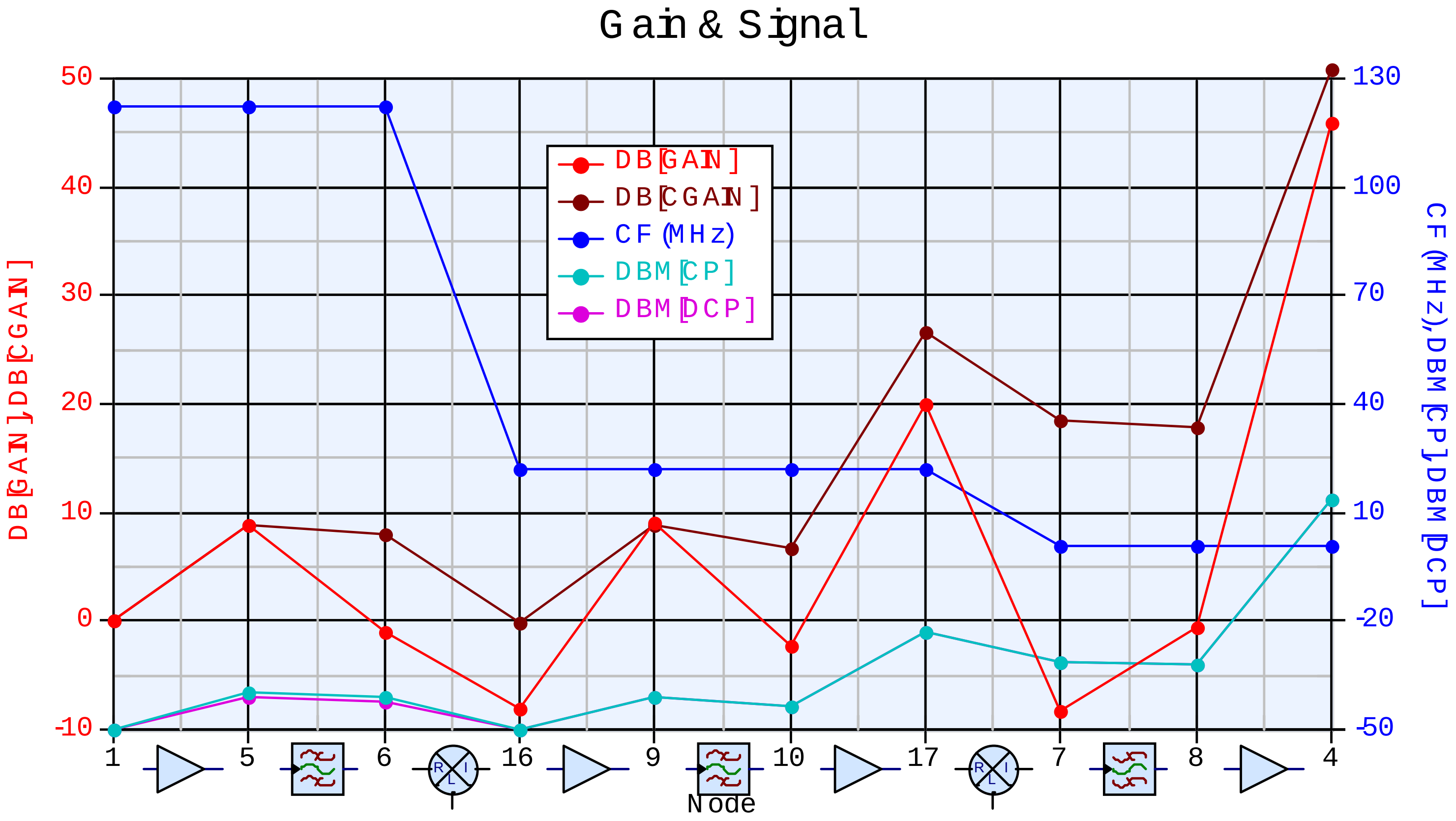
Different applications require different forms of output data. In the next 13 slides, brief definitions and examples of SPECTRASYS output data are provided.

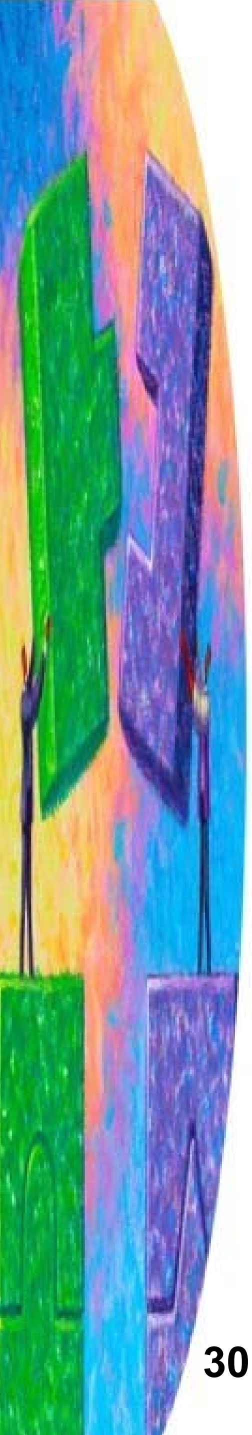
The system noise figure, the input intercept point, and adjacent channel power are example measurements.

Measurements:
Gain & Signals in the Channel

- Cascaded Gain
- Cascaded Gain (All Signals)
- Channel Frequency
- Channel Power
- Channel Power (Desired)
- Gain
- Gain (All Signals)
- Total Node Power

Example:
Gain & Signal Level Diagram

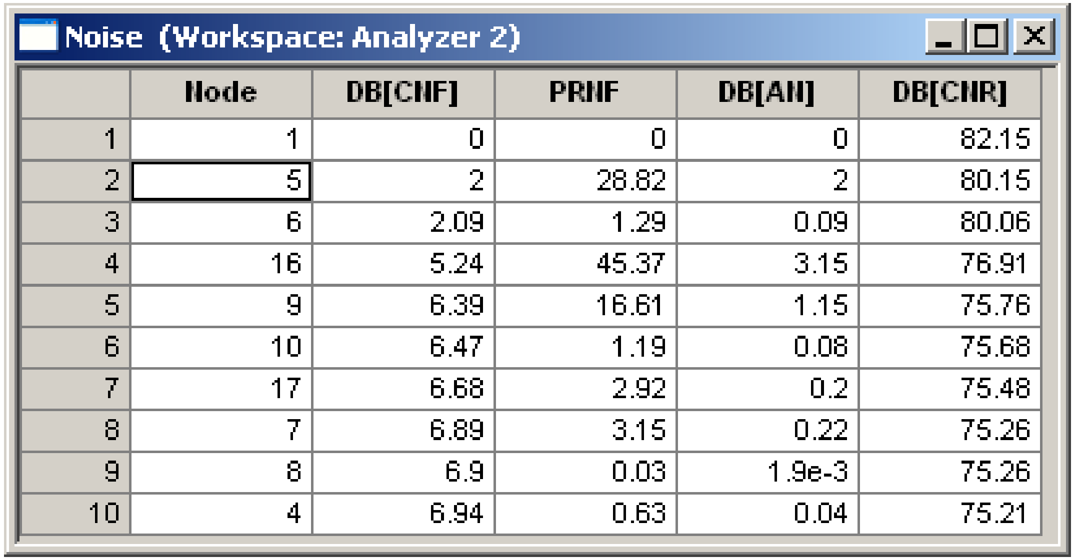




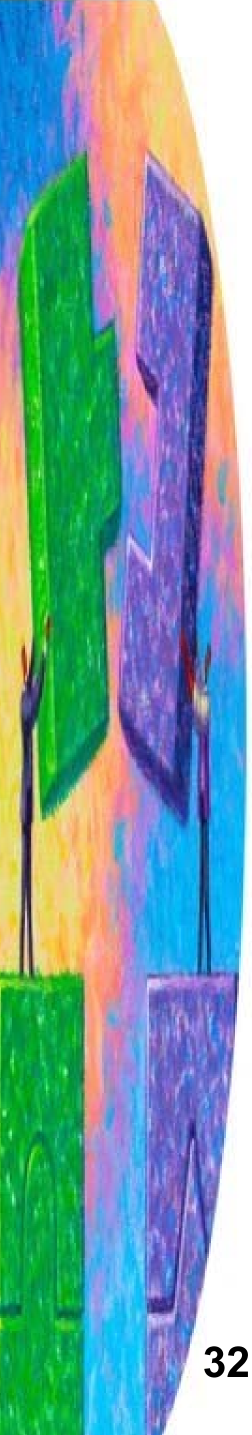
Measurements: Noise

- Added Noise
- Carrier to Noise Ratio
- Cascaded NF
- Channel Noise Power
- Image Channel Noise Power
- Image Noise Rejection Ratio
- Minimum Detectable Signal
- Percent Noise Figure
- Stage NF

Example: Noise



	Node	DB[CNF]	PRNF	DB[AN]	DB[CNR]
1	1	0	0	0	82.15
2	5	2	28.82	2	80.15
3	6	2.09	1.29	0.09	80.06
4	16	5.24	45.37	3.15	76.91
5	9	6.39	16.61	1.15	75.76
6	10	6.47	1.19	0.08	75.68
7	17	6.68	2.92	0.2	75.48
8	7	6.89	3.15	0.22	75.26
9	8	6.9	0.03	1.9e-3	75.26
10	4	6.94	0.63	0.04	75.21

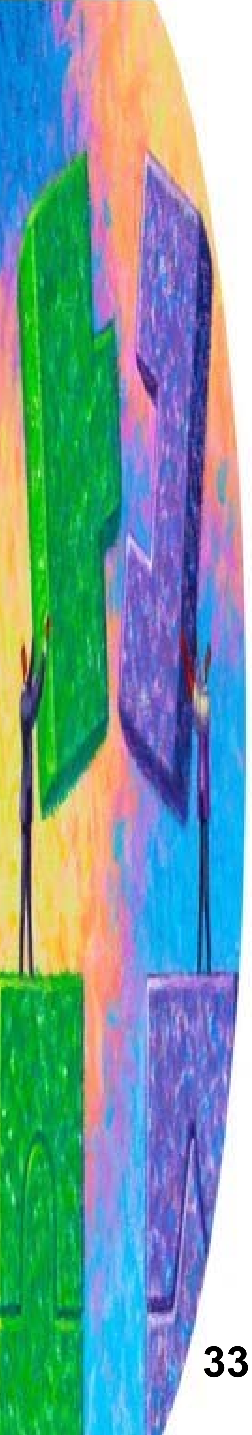


Intermodulation

Cascaded intermod equations are NOT used by SPECTRASYS. Just as with noise, cascade intermod equations are flawed because they:

1. Assume interfering signals are not filtered and maintain the same gain as the desired signal through all cascaded stages
2. Assume all stages are perfectly matched
3. Assume two equal tones
4. Assume infinite reverse isolation

Signal propagation generates intermods signals as they appear in real systems. Signals are not limited to two tones. All intermods are propagated through the system using the system transfer function. Consequently, intermod measurements are accurate for filtered and non-ideal systems.



Measurements: Intermodulation & Compression

- Cascaded Gain (3rd IM)
- Channel Frequency (Tone)
- Channel Power (Desired 3rd IM)
- Channel Power (Tone)
- Gain (3rd IM)
- Gain (All Signals)
- Percent 3rd IM
- Stage Output 1 dB Compression
- Stage Output 2nd IM
- Stage Output 3rd IM
- Stage Output Saturation Power
- 3rd Order Intercept (Input)
- 3rd Order Intercept (Output)
- 3rd IM Power (Propagated)
- 3rd IM Power (Generated)
- 3rd IM Power (Total)

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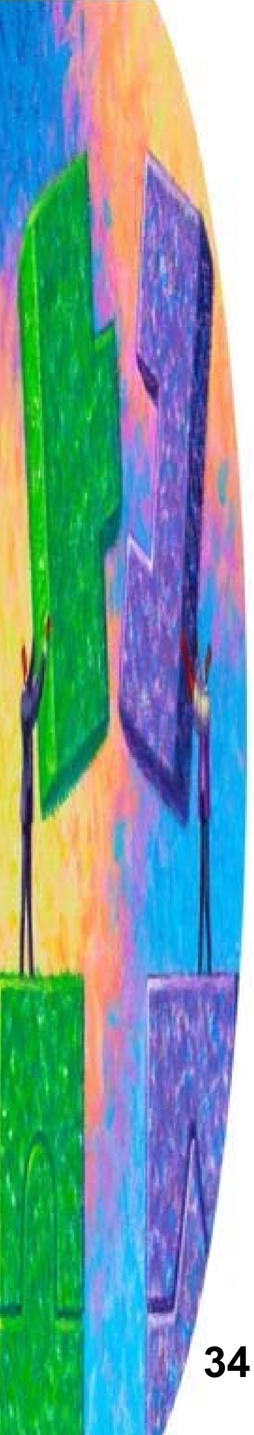
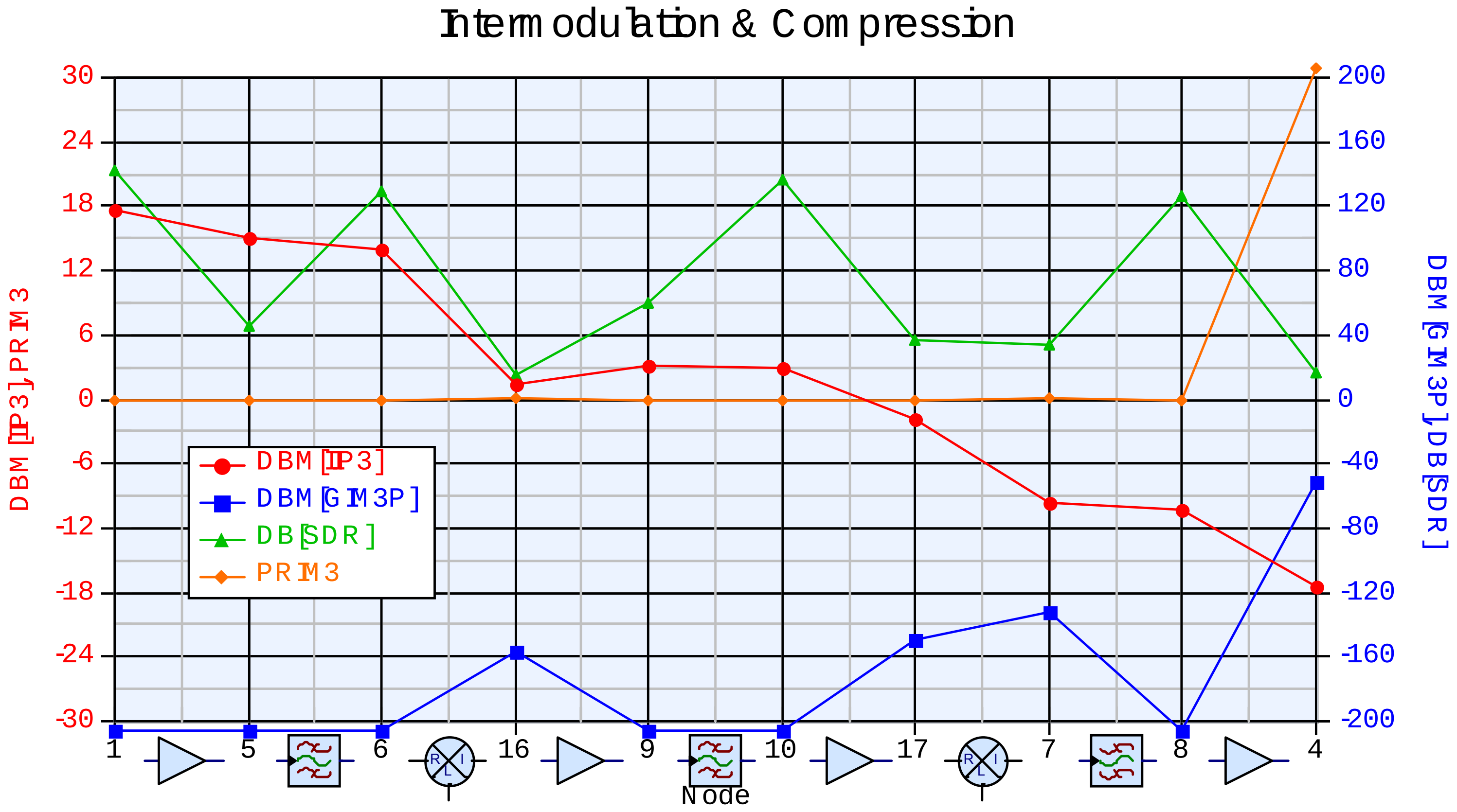


Example: Intermodulation & Compression



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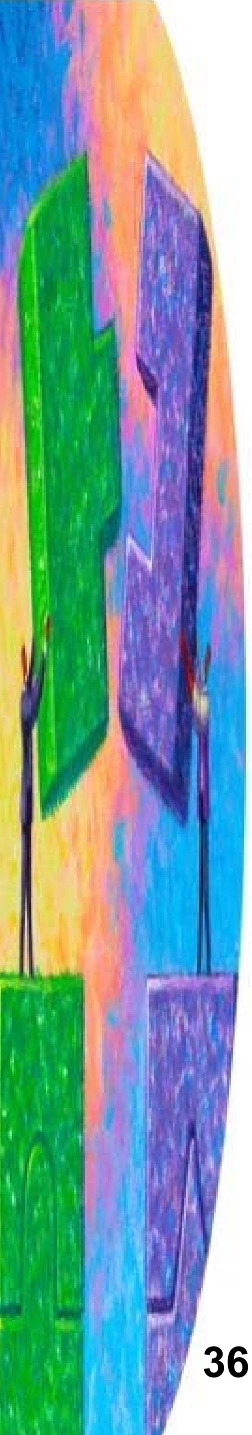
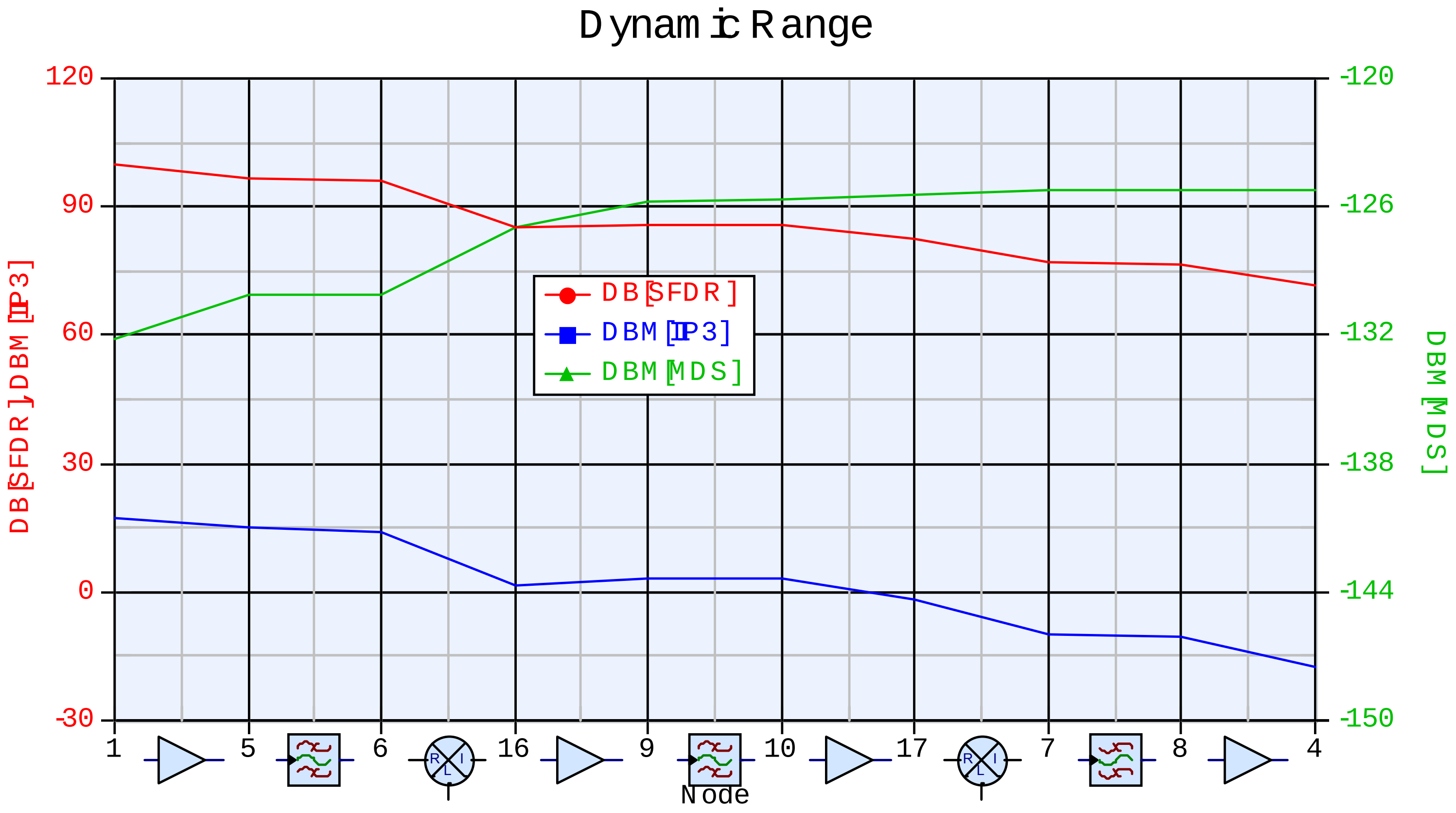
Measurements: Dynamic Range

- Spurious Free Dynamic Range
- Stage Dynamic Range



Example: Dynamic Range



$$SFDR = {}^{2}\!/_{3}\, IIP3 - MDS$$

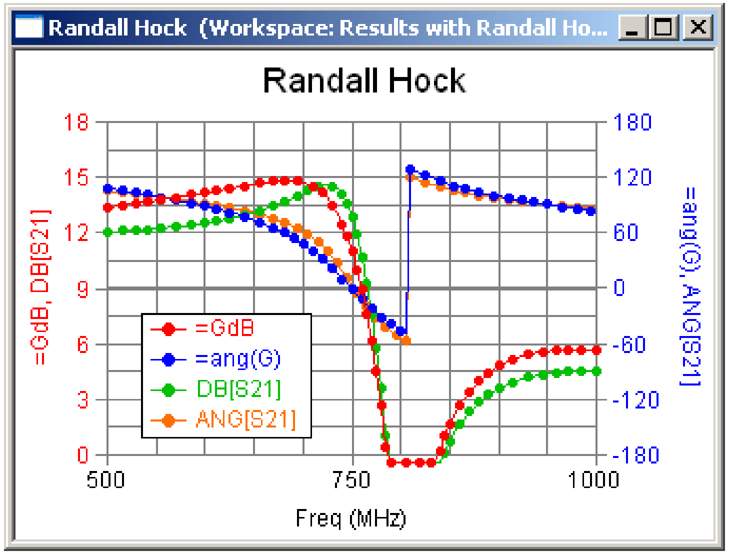
Measurements: Out of Channel

- Adjacent Channel Power
- Adjacent Channel Frequency
- Channel Frequency (Offset)
- Channel Power (Offset)
- Image Frequency
- Image Channel Noise Power
- Image Noise Rejection Ratio
- Mixer Image Channel Power
- Mixer Image Rejection Ratio

User Measurements: Post Processing

```
Using Fswp.Open Loop

G=(.rect[S21]-.rect[S12])/(1-.rect[S11]*.rect[S22]+.rect[S12]*.rect[S21]-2*.rect[S12])
GdB=20*log(mag(G))
```



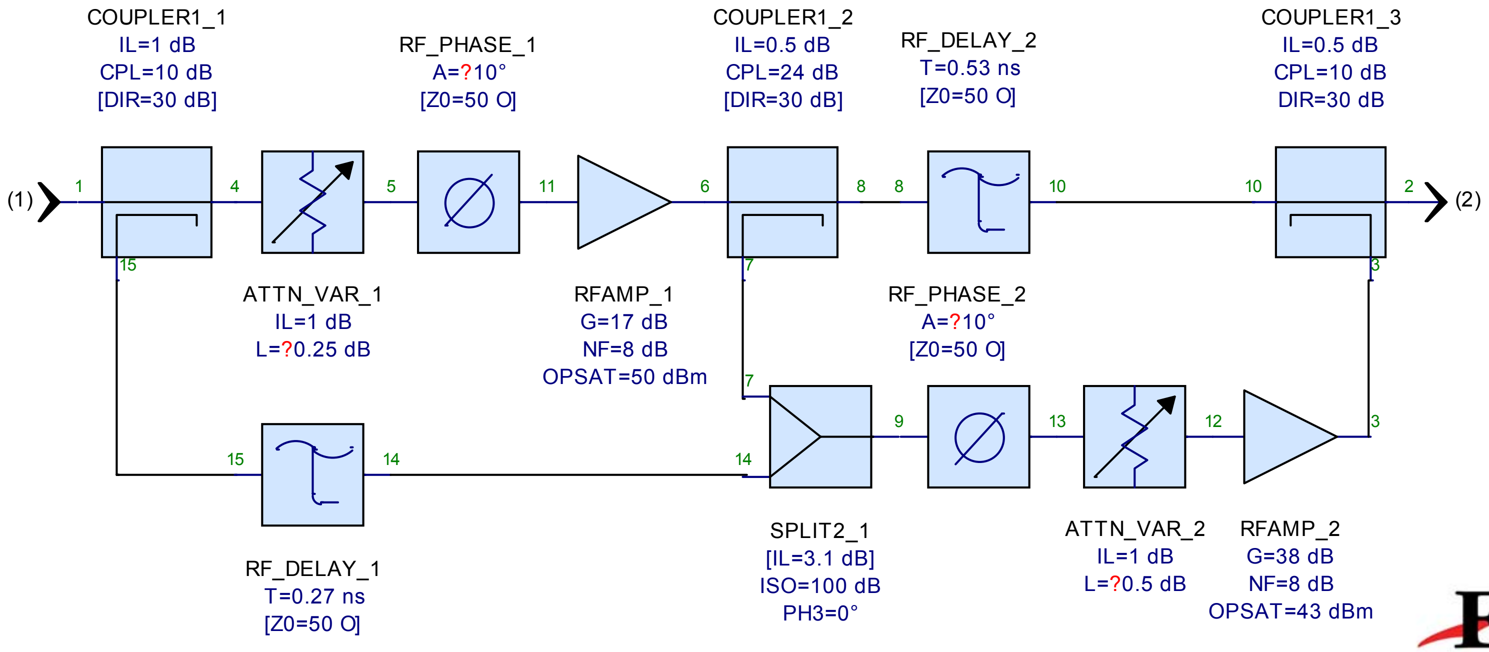
This is an open-loop analysis of an oscillator using the GENESYS linear simulator. Oscillator open-loop analysis accuracy is degraded by loop mismatch. The post-processing formula above computes the true open loop gain from the normal open-loop S-parameters[1].

[1] M. Randall and T. Hock, General Oscillator Characterization Using Linear Open-Loop S-Parameters, *Trans. MTT*, vol. 49, Jun 2001, pp. 1094-1100.

Phase & Complex Models

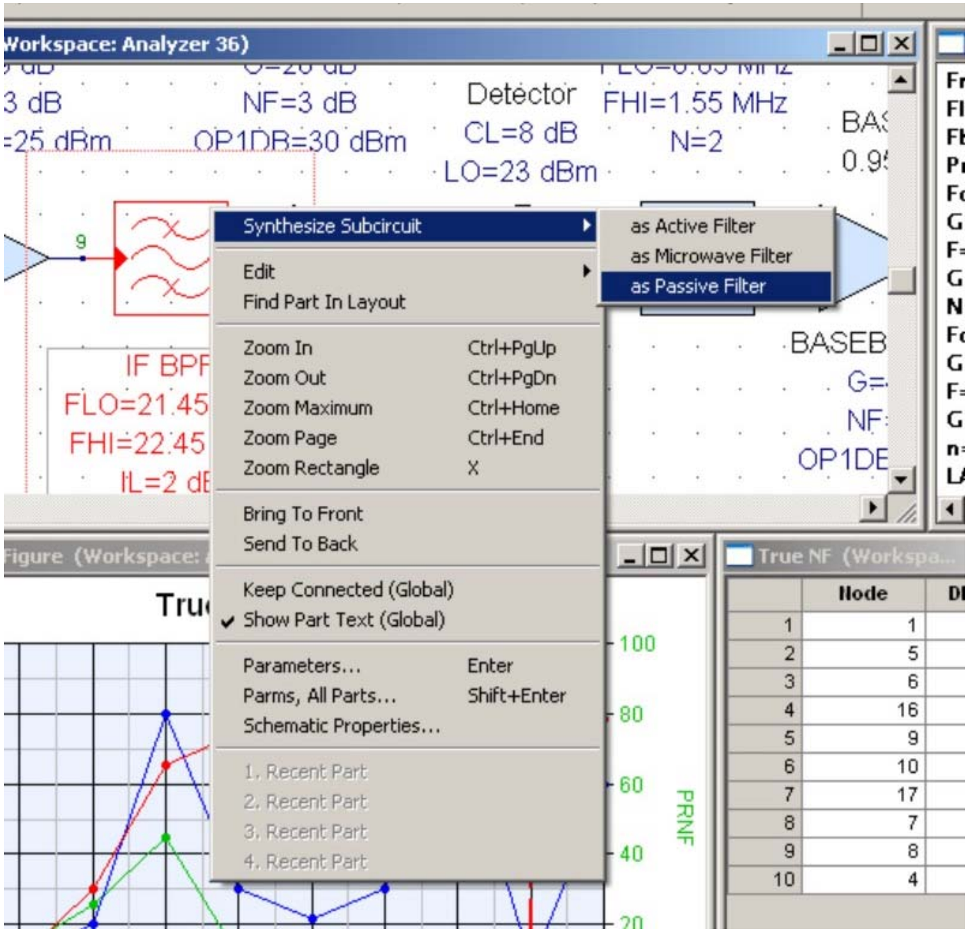
The Spectrasys SPARCA simulator propagates signals using complex multi-port transfer functions for the system.

- Phase data is retained and utilized
- Circuit models and schematics may be mixed with system models in the schematic
- The affects of mismatch are simulated
- Bilateral signal flow is simulated



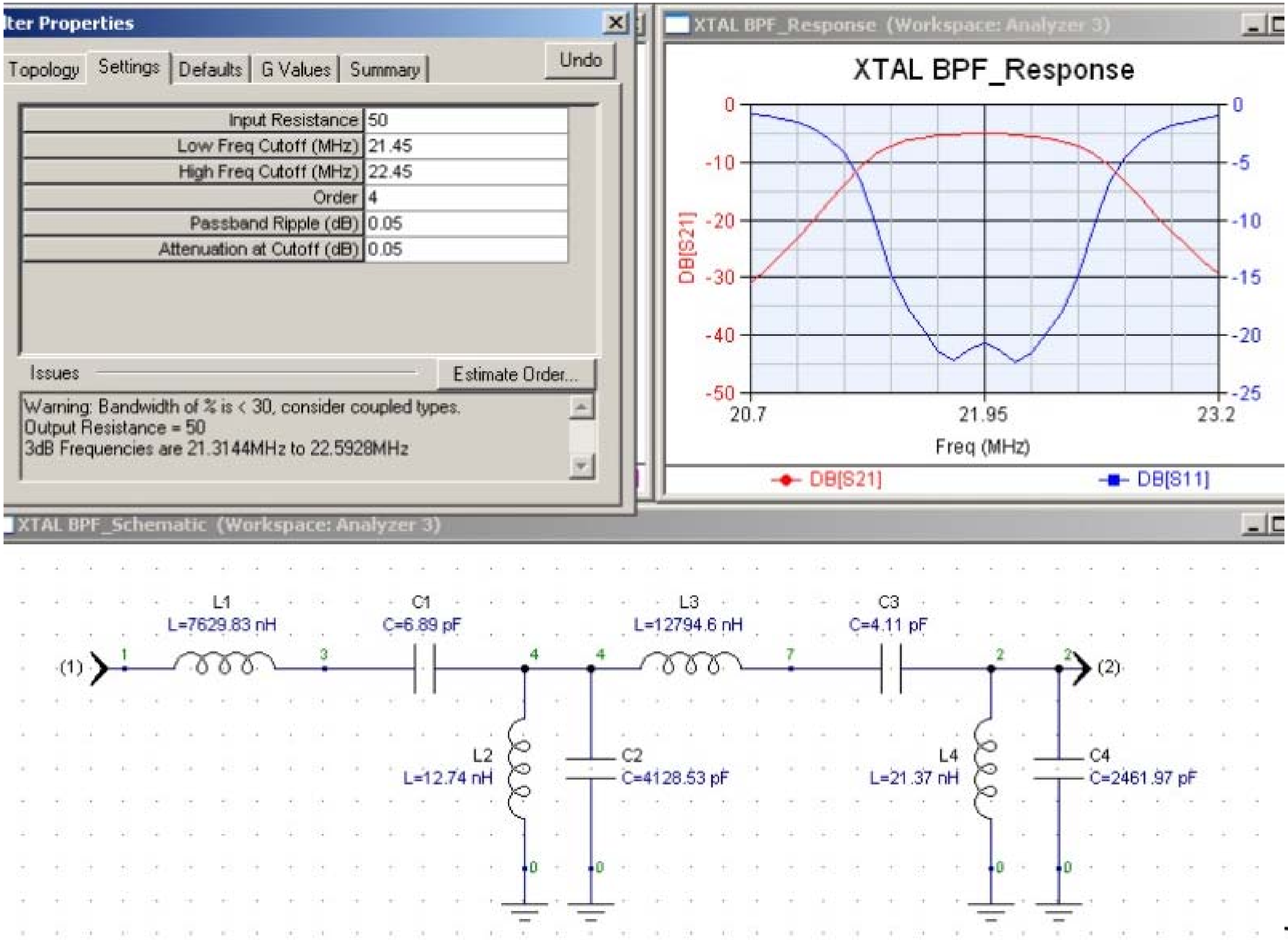
Circuit Level Integration

In the next 5 slides, I'll demonstrate how the design (synthesis) of individual system blocks is integrated into the environment.



	Node	DI
1	1	
2	5	
3	6	
4	16	
5	9	
6	10	
7	17	
8	7	
9	8	
10	4	

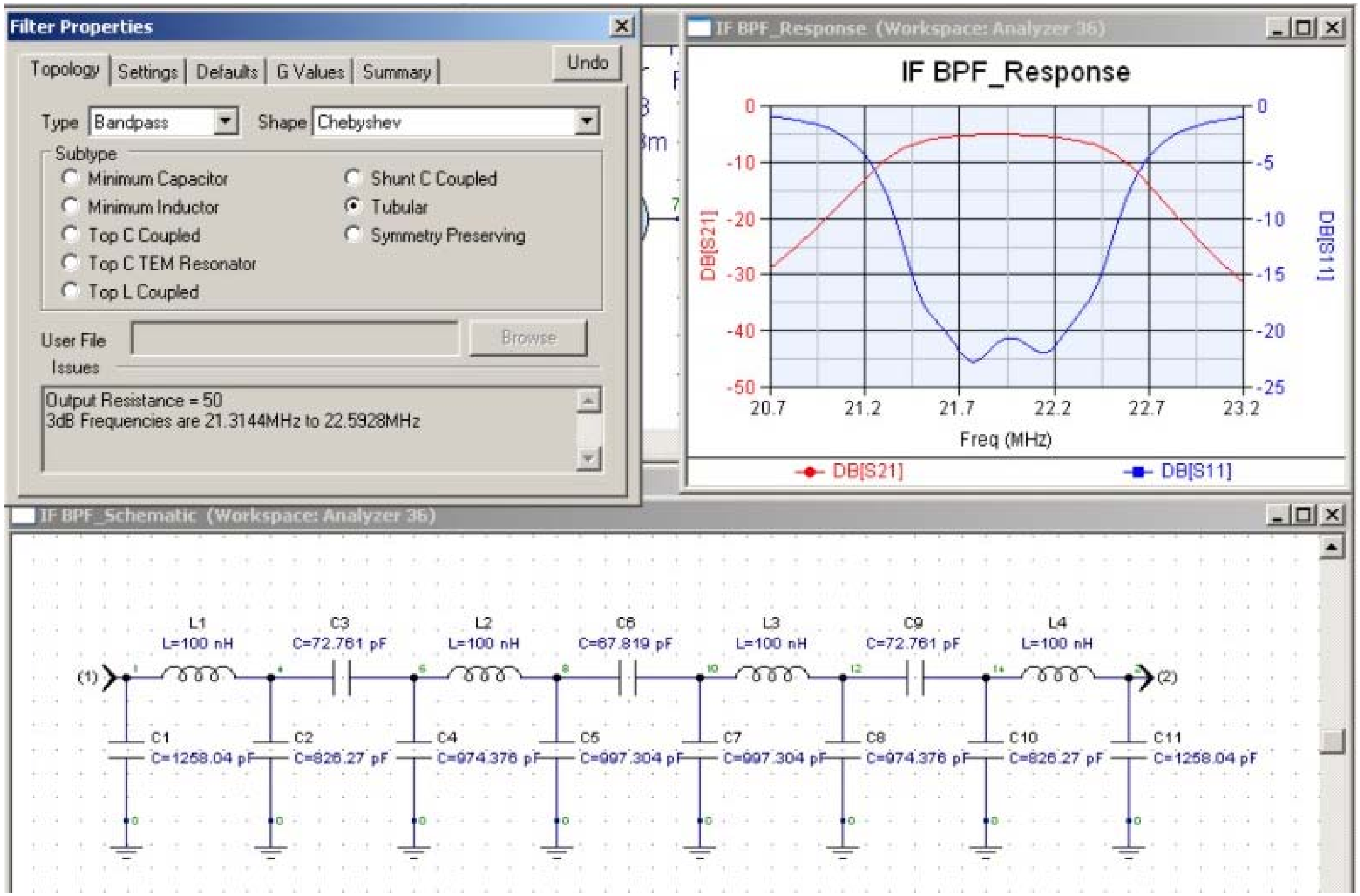
Synthesizing a Standard Filter



Input Resistance	50
Low Freq Cutoff (MHz)	21.45
High Freq Cutoff (MHz)	22.45
Order	4
Passband Ripple (dB)	0.05
Attenuation at Cutoff (dB)	0.05

Warning: Bandwidth of % is < 30, consider coupled types.
Output Resistance = 50
3dB Frequencies are 21.3144MHz to 22.5928MHz

A More Practical Filter



Filter Properties

Type: Bandpass

Shape: Chebyshev

Subtype

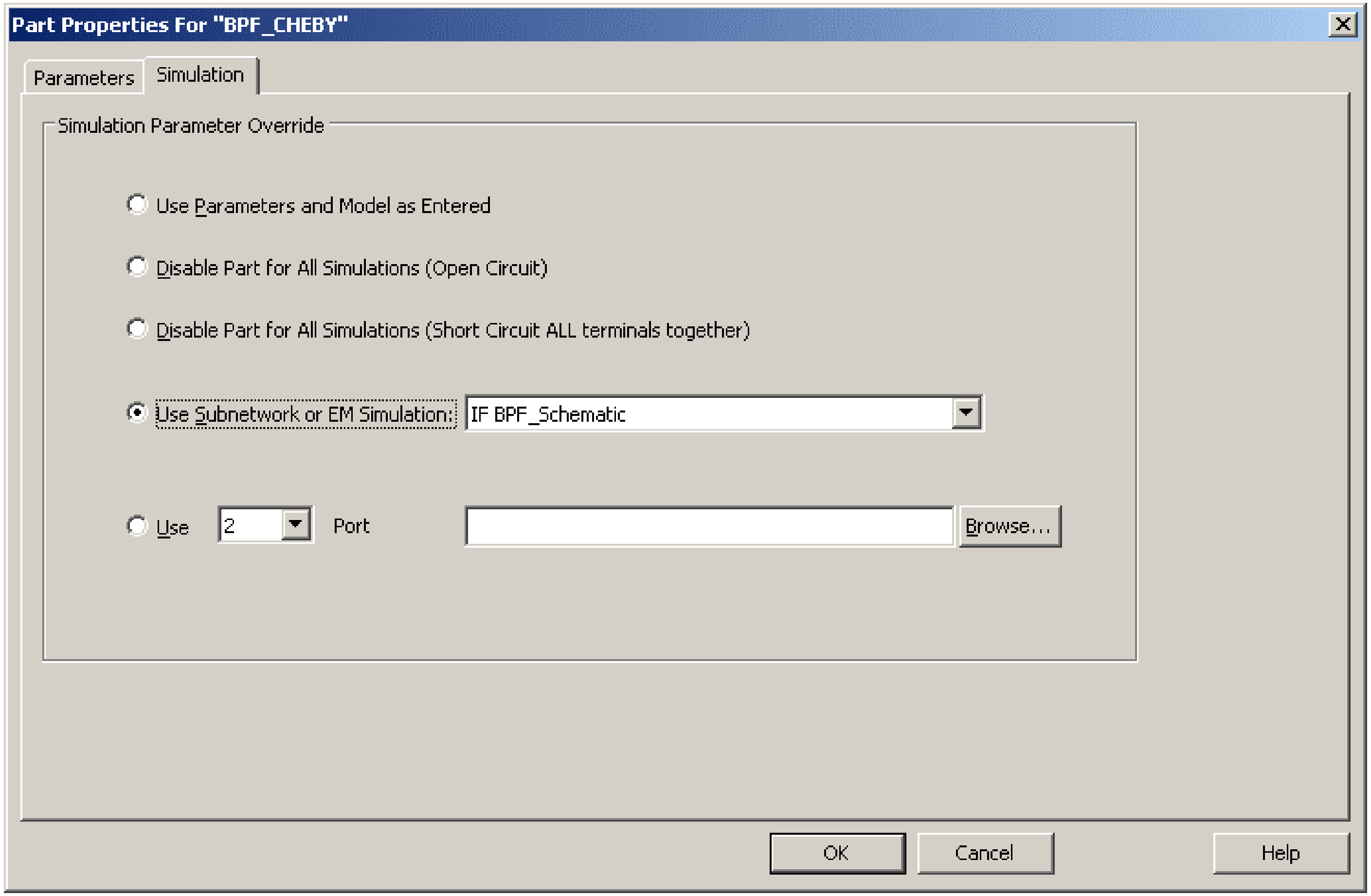
- ○ Minimum Capacitor
- ○ Minimum Inductor
- ○ Top C Coupled
- ○ Top C TEM Resonator
- ○ Top L Coupled
- ○ Shunt C Coupled
- ● Tubular
- ○ Symmetry Preserving

User File:

Issues

Output Resistance = 50
3dB Frequencies are 21.3144MHz to 22.5928MHz

Substituting the Subnetwork or Measured Data



Part Properties For "BPF_CHEBY"

Simulation Parameter Override

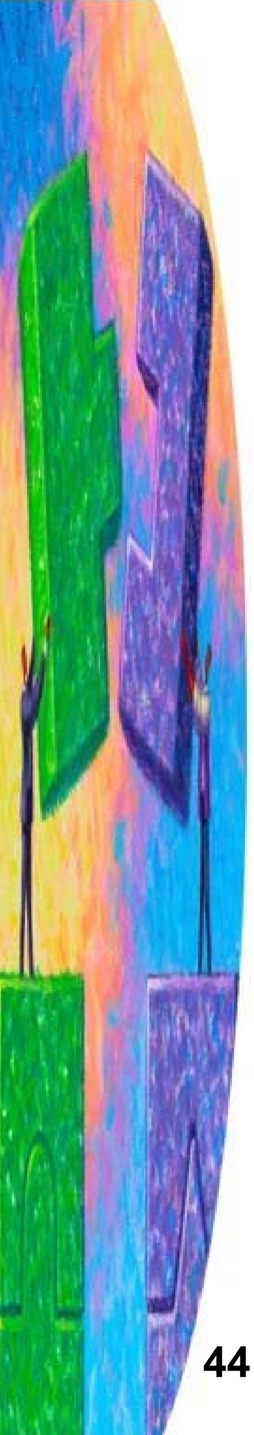
○ Use Parameters and Model as Entered

○ Disable Part for All Simulations (Open Circuit)

○ Disable Part for All Simulations (Short Circuit ALL terminals together)

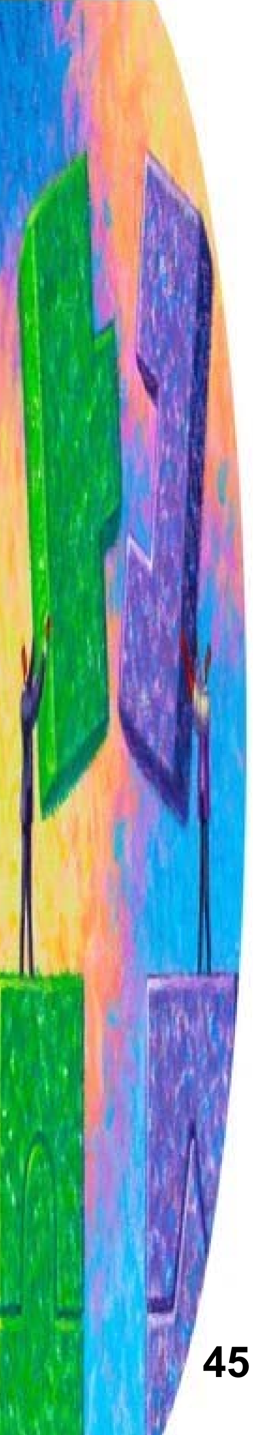
● Use Subnetwork or EM Simulation: IF BPF_Schematic

○ Use 2 Port



Current Integrated Synthesis Routines

- PASSIVE FILTER – Multiple LC filter topologies
- MICROWAVE FILTER – Multiple distributed filter topologies
- OSCILLATOR – LC, distributed, SAW and XTAL oscillators
- ACTIVE FILTER – RC operational amplifier filter
- SIGNAL CONTROL – Multiple coupler and splitter topologies
- MATCH – LC and distributed matching networks
- S/FILTER – Filter synthesis by specified transmission zeros
- EQUALIZER – Synthesis of group delay equalization networks



Current Integrated Simulation Engines & Interfaces

SIMULATION ENGINES

- LINEAR SIMULATOR - SuperStar
- ELECTROMAGNETIC SIMULATOR – EMPOWER, planar 3D
- HARMONIC BALANCE SIMULATOR – HARBEC
- PLL – Synthesis, noise and transient analysis
- TIME DOMAIN SYSTEM SIMULATOR – System View - 2005

INTERFACES

- Verlog-A model compiler
- Modelithics substrate dependent libraries
- Agilent IFF file export
- Touchstone export
- Sonnet *em* (integrated to co-simulation level)
- Testlink measurement instrument control
- Files: Windows documentation, Gerger, GDS II, S-parameters

Summary

A new system simulation technique referred to as Spectral Propagation and Root Cause Analysis (SPARCA) offers a new set of tools for the optimization of system architectures:

- Improved accuracy over conventional cascade analysis
- Rapid root cause discovery using spectral component display at any node
- Wide set of built-in as well as user specified measurements
- Complex, bilateral and mismatch analysis
- Integration of other spectral domain simulation and synthesis tools

SPARCA is optimized for system architecture development and saves multiple architecture and component design turns.

A demonstration of SPARCA was provided using the SPECTRASYS program for Windows.