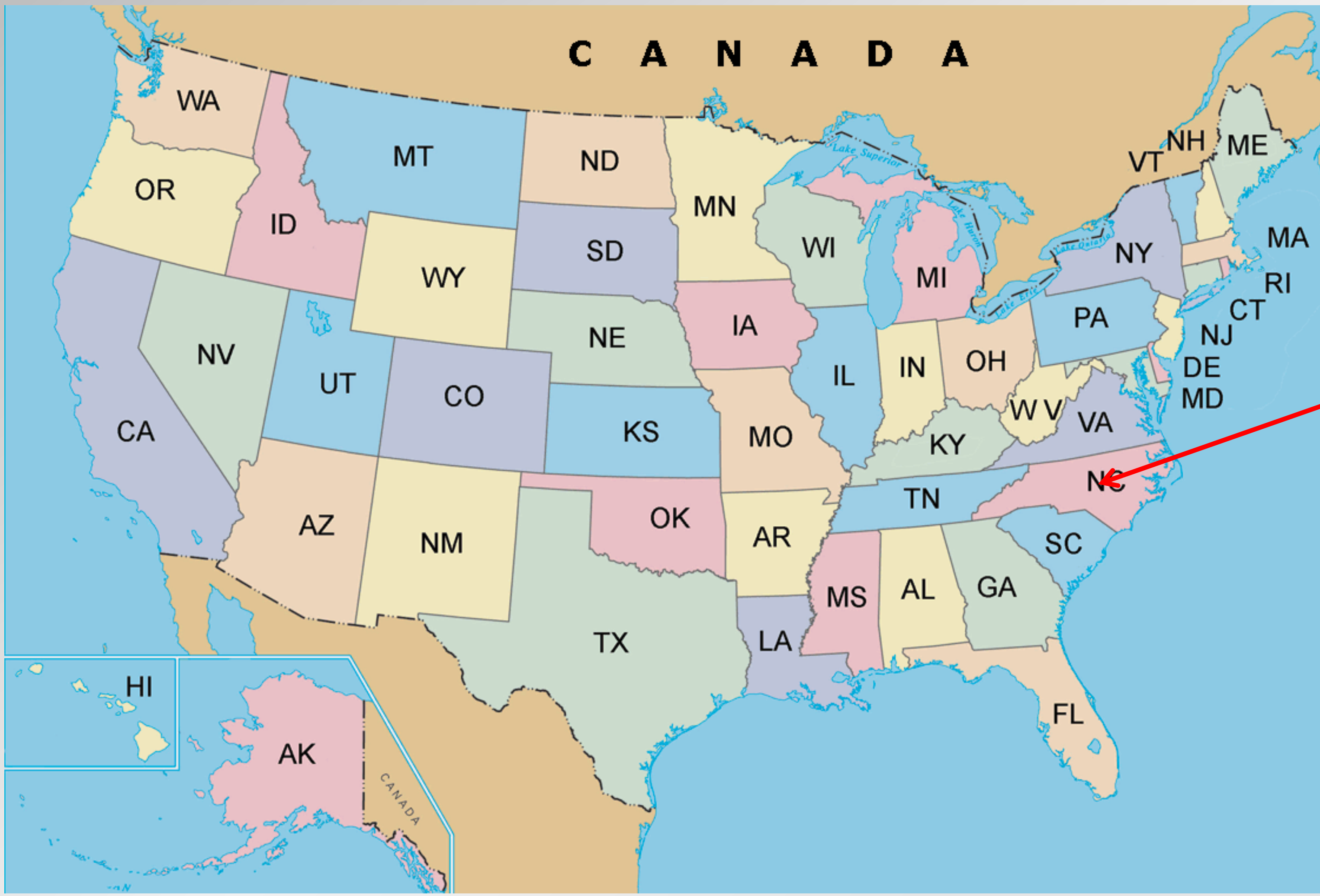
Behavioral Modeling of Nonlinear Amplifiers with Memory

Michael Steer
with
Jie Hu
and Aaron Walker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RALEIGH

Bloomberg Businessweek

September 20, 2011

http://www.businessweek.com/lifestyle/which-is-americas-best-city-09202011.html

Which Is America's Best City?

Based on metrics like school performance, green space, and cultural amenities, Raleigh, N.C., ranks No. 1 in Businessweek.com's first Best Cities ranking

By Venessa Wong

RALEIGH NO. 1

To most residents of Raleigh, it may not come as a surprise that their city earned the title of America's Best City. Raleigh shows the cultural graces that go along with anchoring the so-called Research Triangle, home to North Carolina State University, Duke University, and the University of North Carolina at Chapel Hill. Among its many attributes the city sports 867 restaurants, 110 bars, and 51 museums, according to Onboard Informatics, as well as a thriving social scene, good schools, and 12,512 park acres, equal to several times the green space per capita in cities like New York and Los Angeles, according to the Trust for Public Land. It also offers a great deal on nights and weekends—from concerts and opera, to the NHL's Carolina Hurricanes and college sports, to the 30,000-square-foot State Farmers Market.

BETTER, NOT BIGGER

With help from Bloomberg Rankings, Businessweek.com evaluated 100 of the country's largest cities based on 16 criteria including: the number of restaurants, bars, and museums per capita; the number of colleges, libraries, and professional sports teams; the income, poverty, unemployment, crime, and foreclosure rates; percentage of population with bachelor's degrees or higher; public school performance; park acres per 1,000 residents; and air quality. Greater weighting was placed on recreational amenities such as parks, bars, restaurants, and museums per capita, educational attainment, school performance, poverty, and air quality. As living in great cities can be expensive, affordability was not taken into account.

And … (for the US) Current rankings

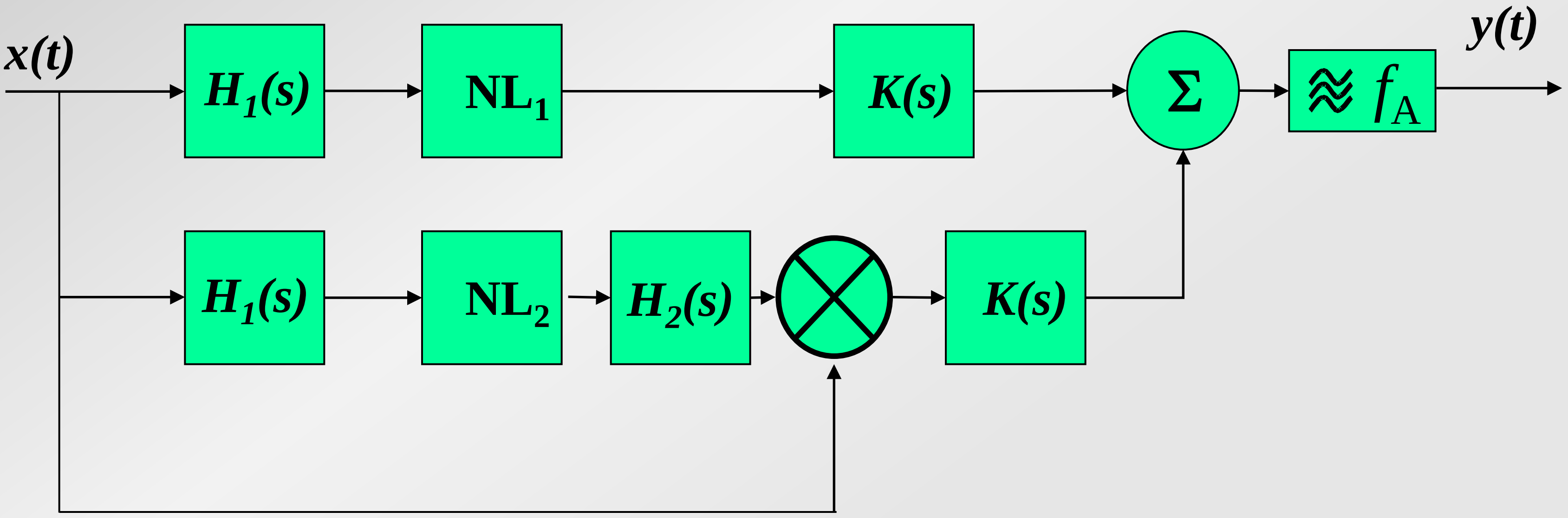
- No. 1 Region to Find Knowledge Workers, Forbes
- No. 1 Best City for Business, Forbes
- No. 1 Area for Tech Business, Silicon Valley Leadership Group
- No. 1 City with the Happiest Workers, Hudson Employment Index
- No. 2 Most Educated City, American Community Survey
- No. 3 Best City for Entrepreneurs, Entrepreneur.com
- No. 3 Top Metro Overall, Expansion Management Mayor’s Challenge
- No. 3 High Value Labor Market Quotient, Expansion Management
- No. 3 Top States for Work Force Training, Expansion Management

Outline

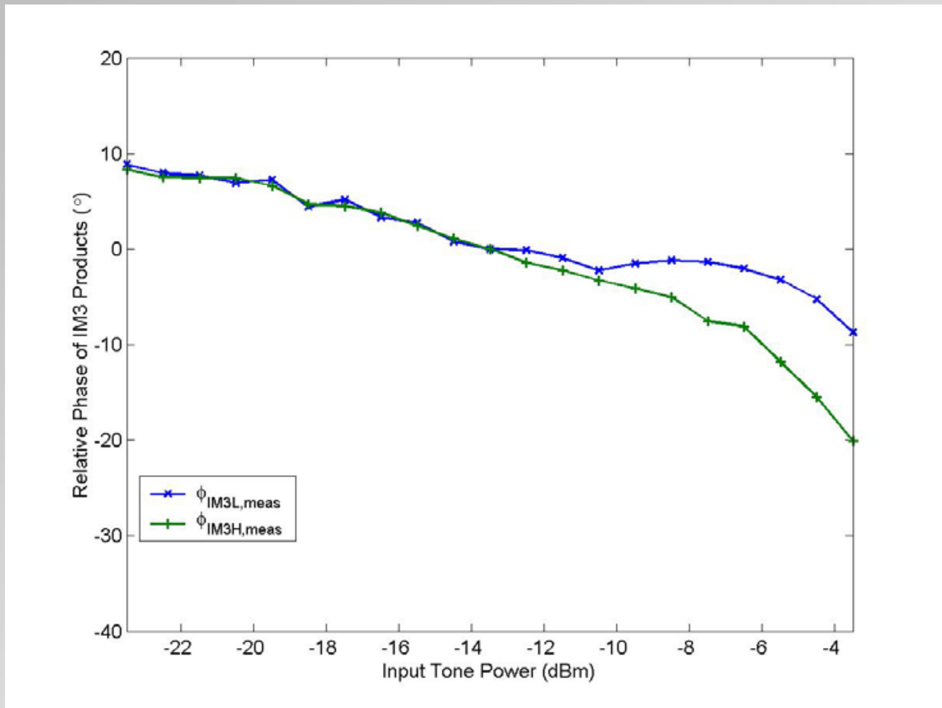
- Background
- Nonlinear Metrology
  - Novel 1-channel VSA-based NVNA
  - Novel Hybrid NVNA
- Behavioral Modeling
  - Grey-Box Model ID Methodology
  - ID Algorithm & Hybrid GA Optimizer
  - Modeling Cosite Interference

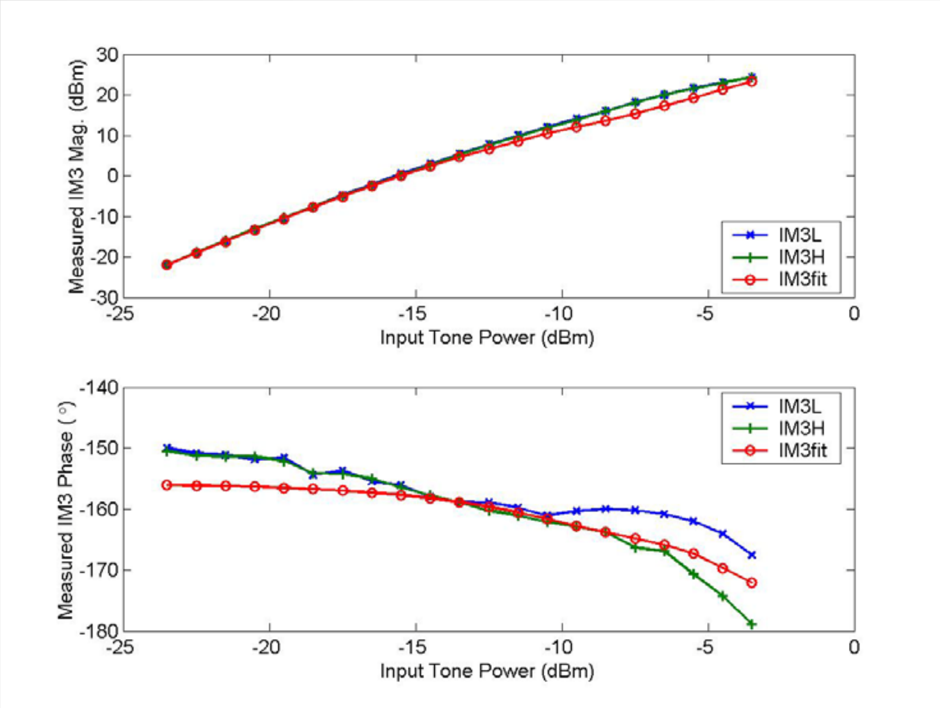
Multi Slice Behavioral Model

- Wired Characterization Utilizing IMD Phase Information
  - High power amplifier at 450 MHz, suitable for CDMA450 standard



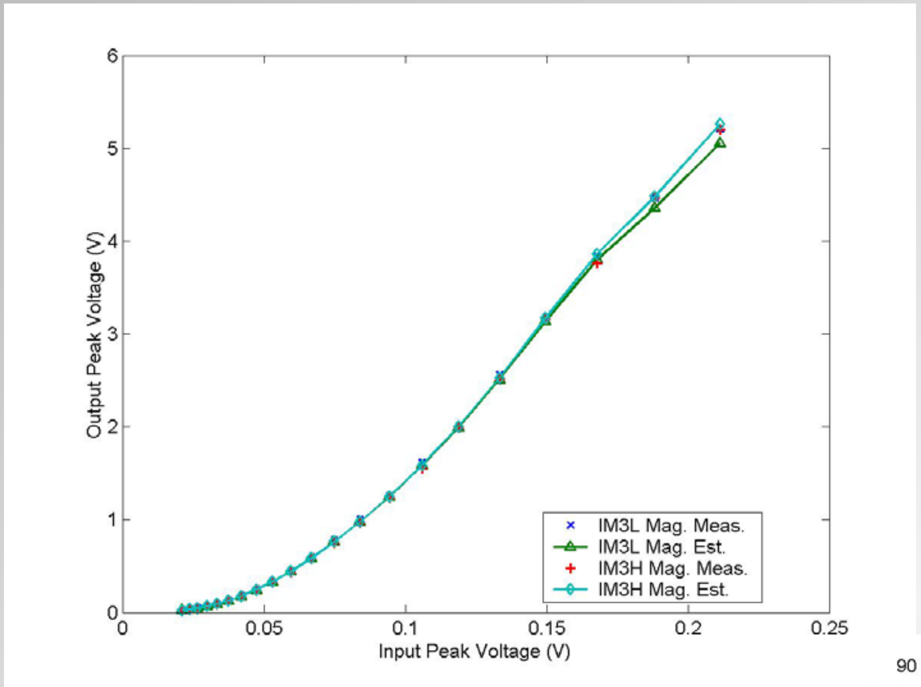
Model Fit

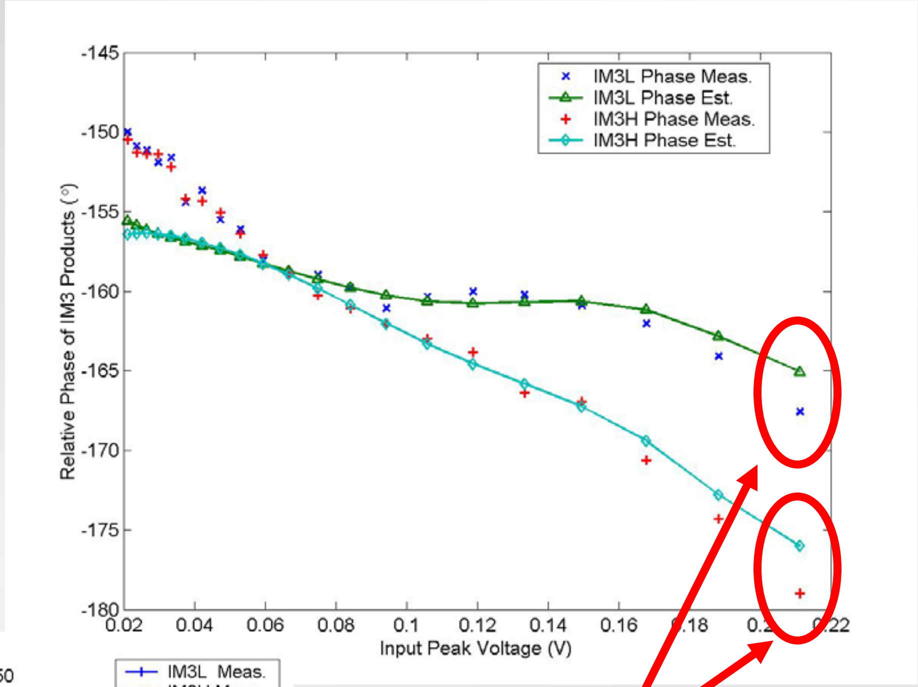


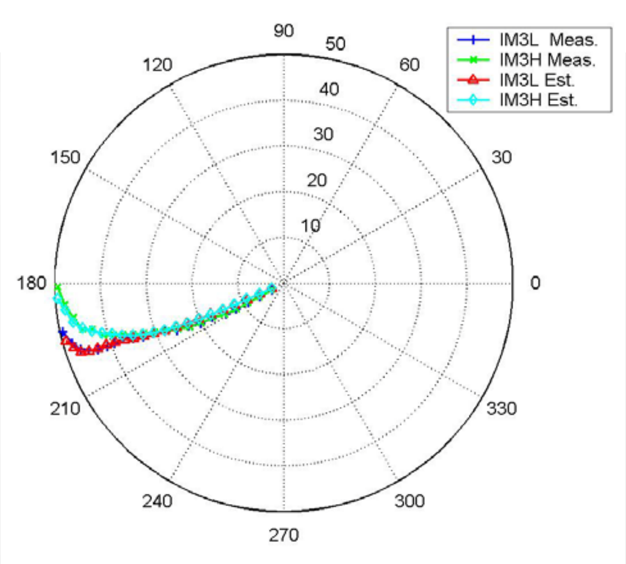


- Single slice fit underestimates IM3 magnitude, splits difference in phase asymmetry

Model Fit


Output Peak Voltage (V)
Input Peak Voltage (V)
0
1
2
3
4
5
6
0
0.05
0.1
0.15
0.2
0.25
IM3L Mag. Meas.
IM3L Mag. Est.
IM3H Mag. Meas.
IM3H Mag. Est.


Relative Phase of IM3 Products (°)
Input Peak Voltage (V)
-145
-150
-155
-160
-165
-170
-175
-180
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
IM3L Phase Meas.
IM3L Phase Est.
IM3H Phase Meas.
IM3H Phase Est.


90
120
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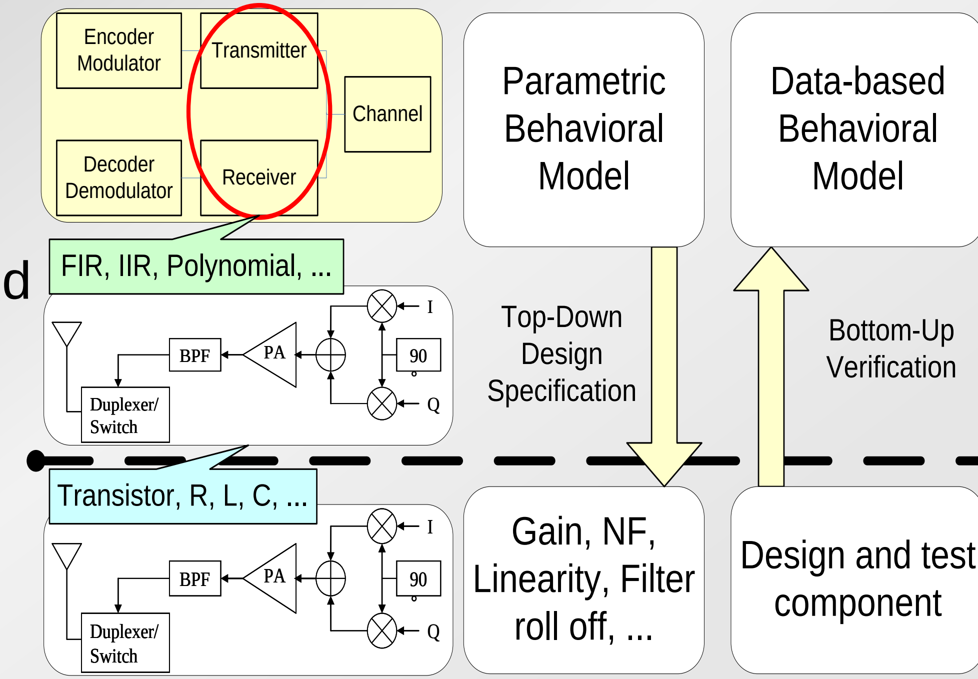
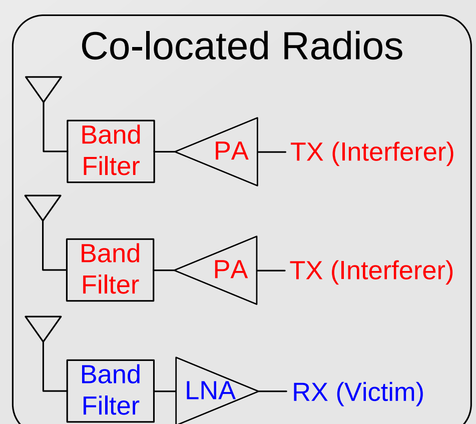
240
300
270
10
20
30
40
50
IM3L Meas.
IM3H Meas.
IM3L Est.
IM3H Est.

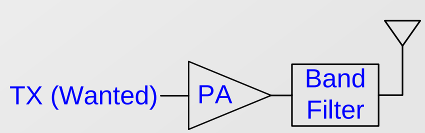
~3º

Model is an Application Specific Abstraction

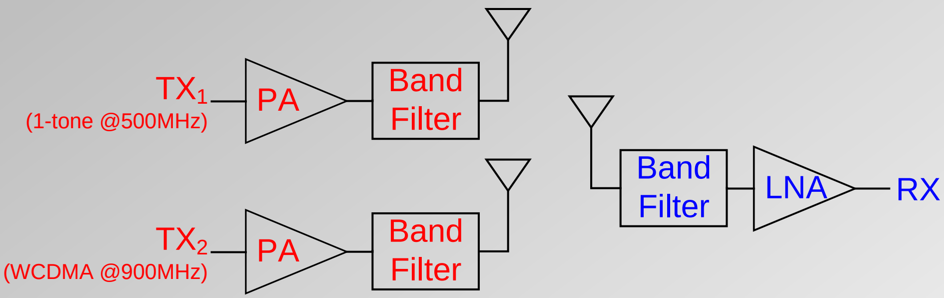
- Applications of nonlinear behavioral models
  - Compact RF transistor models
  - PA linearization
    - Model long-term memory
  - Wireless transceiver RF frontend
    - Top-down design
      - Design space exploration
    - Bottom-up verification
      - Design verification
      - Cosite simulation
        - Co-located radios
        - Same frequency band
        - Similar to Near-Far problem

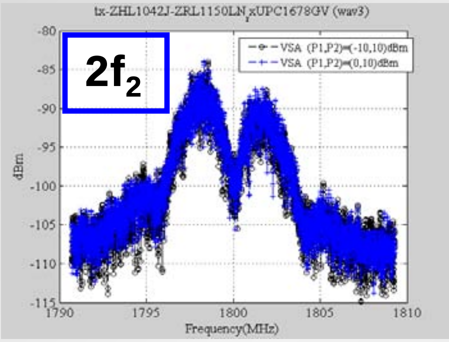


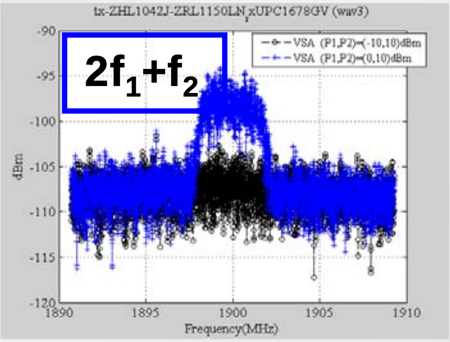


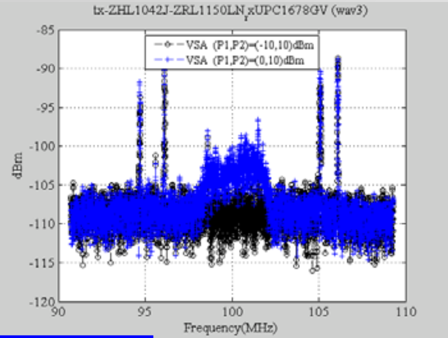


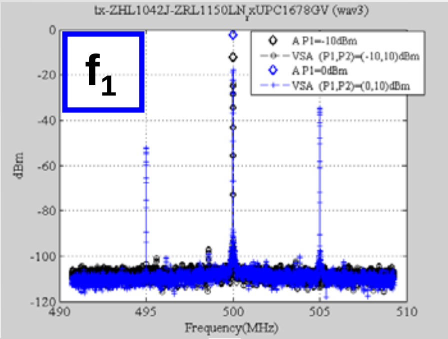
Modeling Broadband Response (EMI)

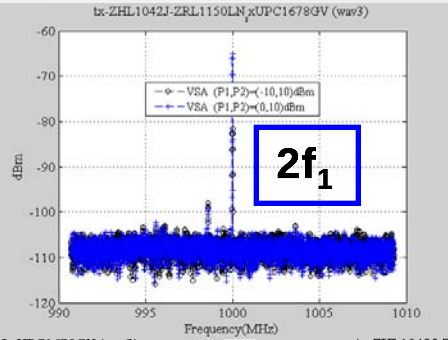


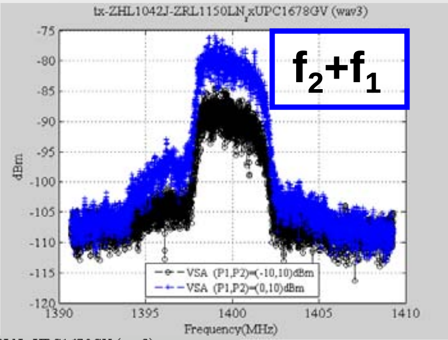


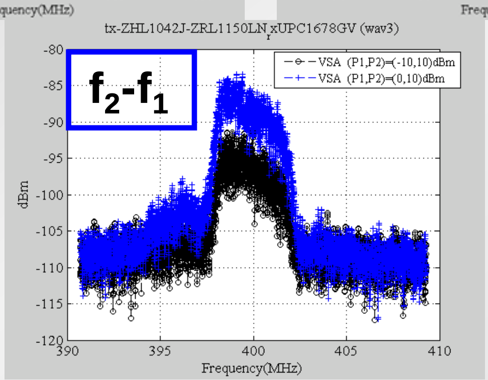


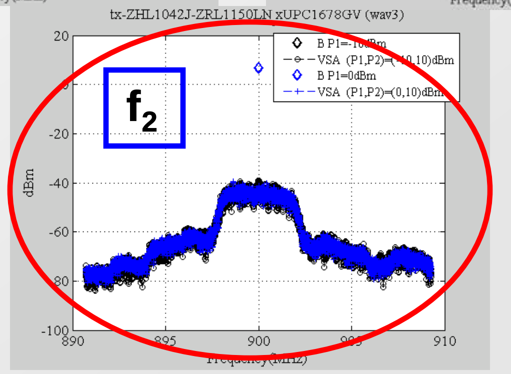


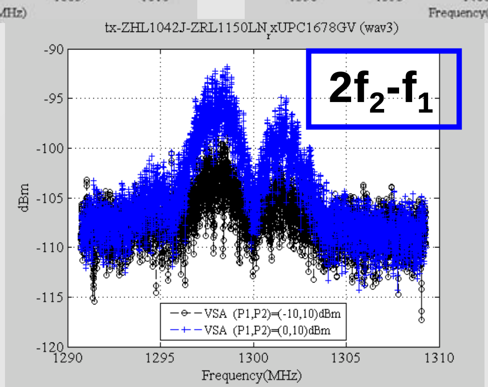












Types of RF Nonlinear Behavioral Models

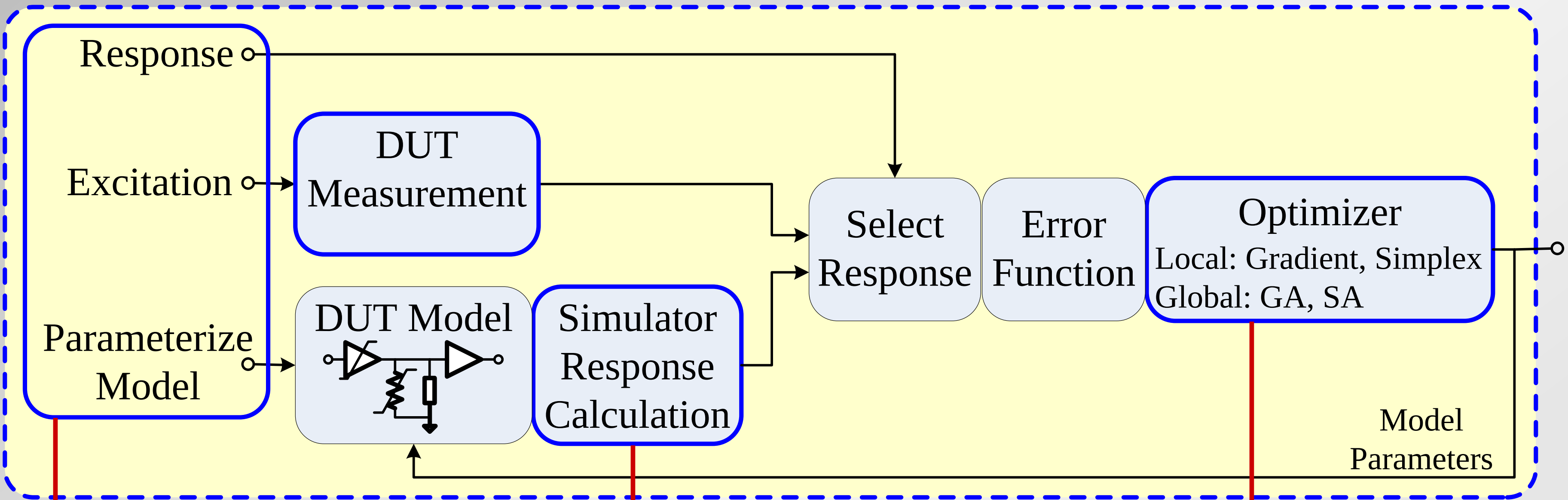
- Model attributes
  - Fidelity (frequency range & accuracy of the modeled response)
  - Development complexity (model parameter estimation)
  - Simulation compatibility & speed
  - IP protection

Model examples	Formula-based: Computationally efficient, Low fidelity (for top-down design)	Circuit simulator-based: Computationally complex, High fidelity (for verification)
Black-box	Parametric models (IP3, NF, ...) Power series Memory Polynomial	X-parameter (Harmonic balance, memory modeled in fundamental band) Volterra series (modify simulator, complex parameter estimation)
Grey-box (structure based on physical insight)	Weiner-Hammerstein family Multi-slice Weiner-Hammerstein w/lin-feedback	**General RF frontend model** (general circuit simulator, complex parameter estimation)

- Grey-box model
  - High fidelity for verification & cosite simulation
  - Supported in general circuit simulators

Grey-box Model ID, Prior Work vs. Here

Model ID Algorithm: a typical Parameter Estimation Step



Case-by-case
ad-hoc ID algorithm

Simple models with
easily derived expression

Deterministic optimizer
(depend on initial solution supplied, prong to trapping in local optimums)

General ID algorithm
minimize user intervention

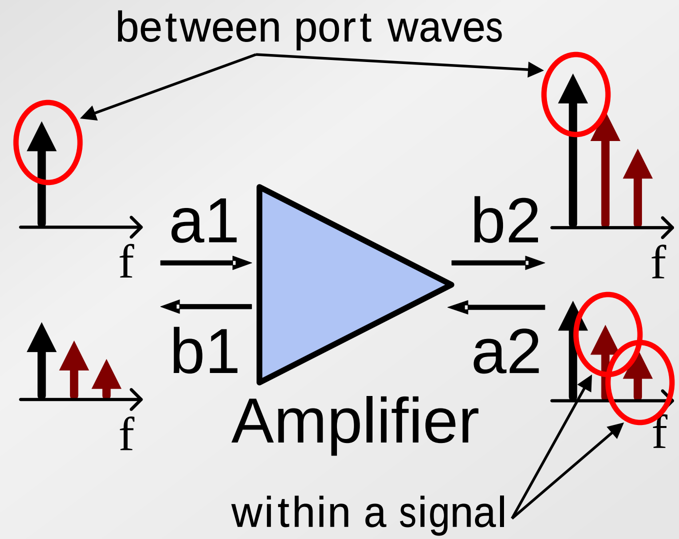
General models
require circuit simulation

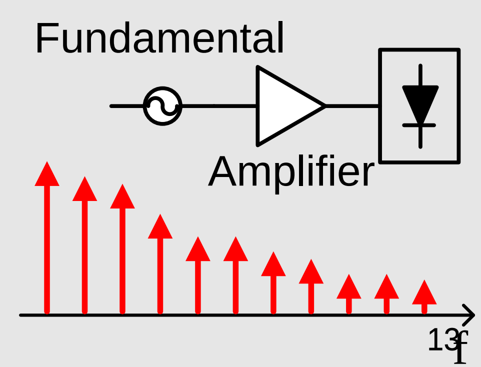
Hybrid-Genetic optimizer
find multiple optimums for user selection
(typical stochastic optimizer find only 1 global solution)

Experiment design
ensure no under-determined optimization problem

Nonlinear Metrology: Background

- What is measured
  - VNA: Ratios (between excitation and response)
  - NVNA: Signals (power, phase)
- Calibration (receiver & test-set frequency response)
  - VNA: Relative (between port waves)
  - NVNA: Relative + Absolute (within a signal)
- 'Absolute' phase calibration
  - Phase measured is relative to sampling time
  - Need receiver w/linear-phase
    - Different spectral components in a signal
    - Delay by same amount
  - Correct phase dispersion error
    - Multi-harmonic generator (maintain relative phase)
    - Characterize using linear-phase RX
      - Nose-to-nose oscilloscope, electro-optical sampling.
    - Using the phase transfer standard
      - 1) determine phase dispersion error
      - 2) serve as phase transfer mechanism



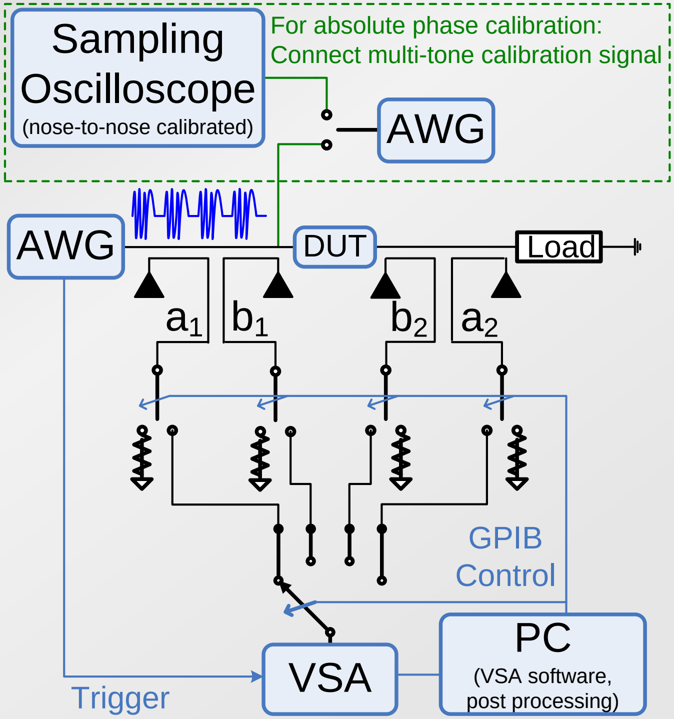


NL Metrology, Prior Work vs. This Work

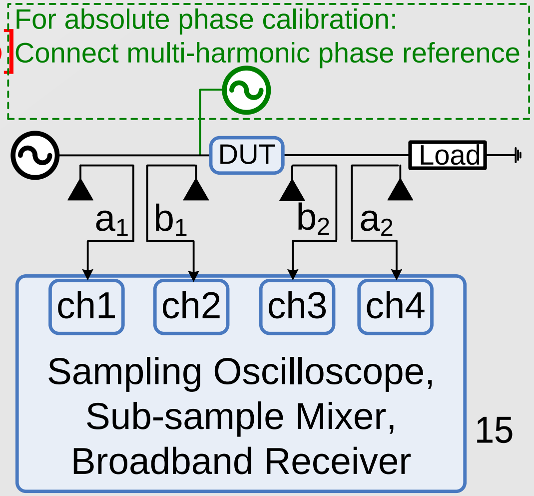
- Broaden NVNA application
  - Phase essential to IM cancellation in multi-stages circuits
  - Use available instruments (1-channel receiver, no multi-harmonic generator)
  - Improvements (dynamic range, tone spacing)
- NVNA using broadband receivers
  - 4-ch sub-sampling receiver & multi-harmonic generator
    - 60dB dynamic range
  - 1-ch VSA & switches & AWG & sampling oscilloscope
    - 75dB dynamic range
    - Power/area efficient for on-chip self-characterization
- NVNA using narrowband receivers
  - 4-port VNA & multi-harmonic generator
    - Tone spacing 1.242MHz (80dB dynamic range) (10MHz in commercial version)
  - 4-port VNA & phase-lock CW source & sampling oscilloscope
    - Tone spacing 200Hz (40dB dynamic range, increasing to 80dB at 200kHz)

1-ch VSA-based NVNA

- 1-ch VSA-based NVNA
  - AWG & sampling oscilloscope
    Repeatability verified [Remley06]
  - 1-ch VSA & switches
    75dB dynamic range
    36MHz bandwidth
      In-band characterization only
    Mimic multiple synchronous channels
  - Apply to on-chip self-characterization
    Ubiquitous integrated receivers
    Power/area efficient



- Sub-sampling Mixer-based NVNA [Verspecht95]
  - Multi-harmonic generator
    Determine receiver phase dispersion error
  - 4-ch sub-sampling receiver
    60dB dynamic range
    20GHz bandwidth



Nonlinear Metrology: 1-ch VSA-based NVNA (Chapter 3.2)

- Mimic multiple synchronous channels
  - Repeat multi-tone excitation
  - Hot-switch port waves
  - Continuous sampling during switching interval
  - Align sequential meas. using sampler timebase

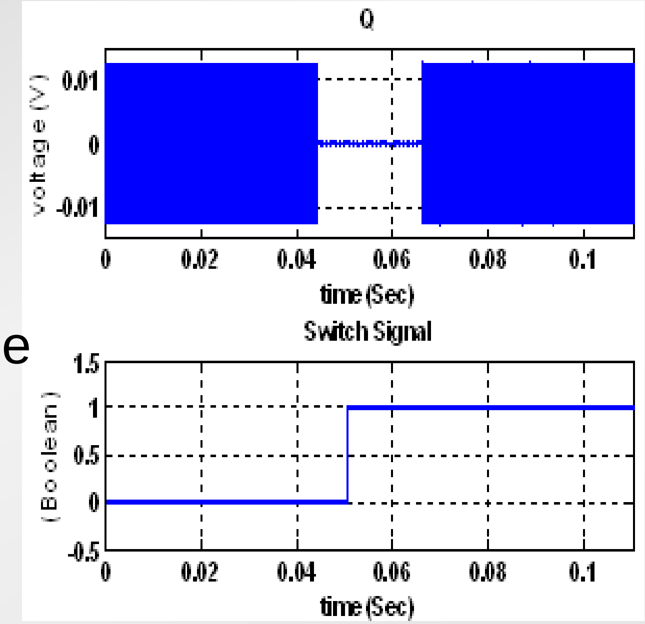
    Excitation/distortion on f-grid

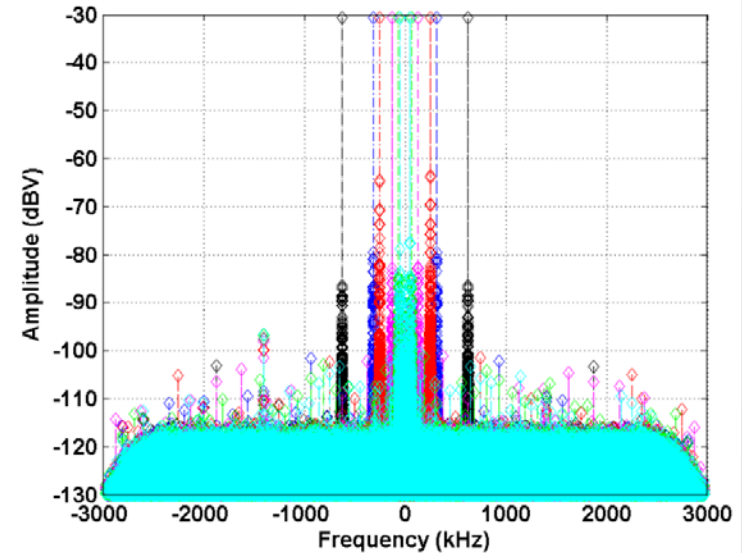
    Design minimum tone spacing

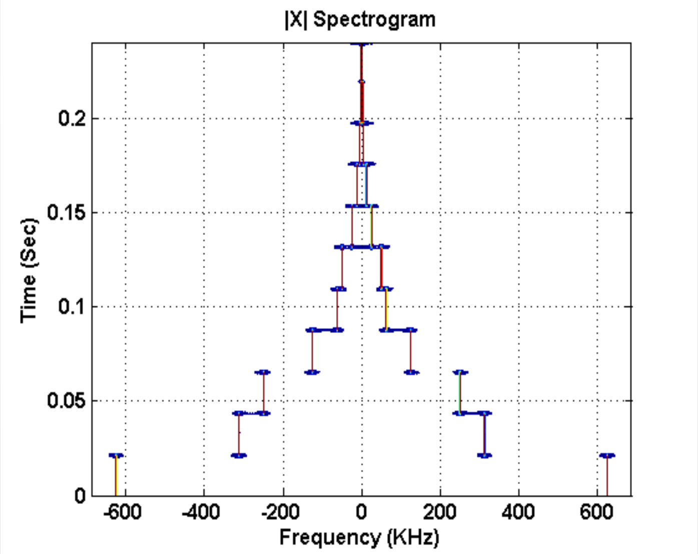
$$T_{\mathrm{Sig}} = n \times T_{s,\mathrm{AWG}}$$
$$T_{\mathrm{Sig}} = m \times T_{s,\mathrm{VSA}}$$

Concatenate wave segments o

(uniform time duration, equal DFT bins for noise to distribute)





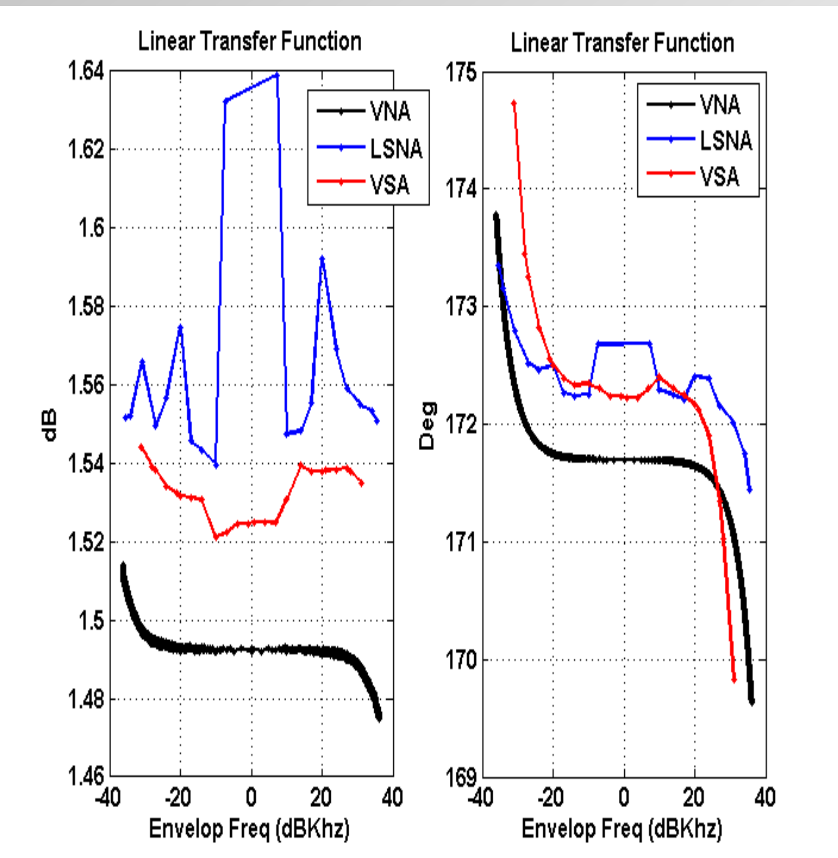


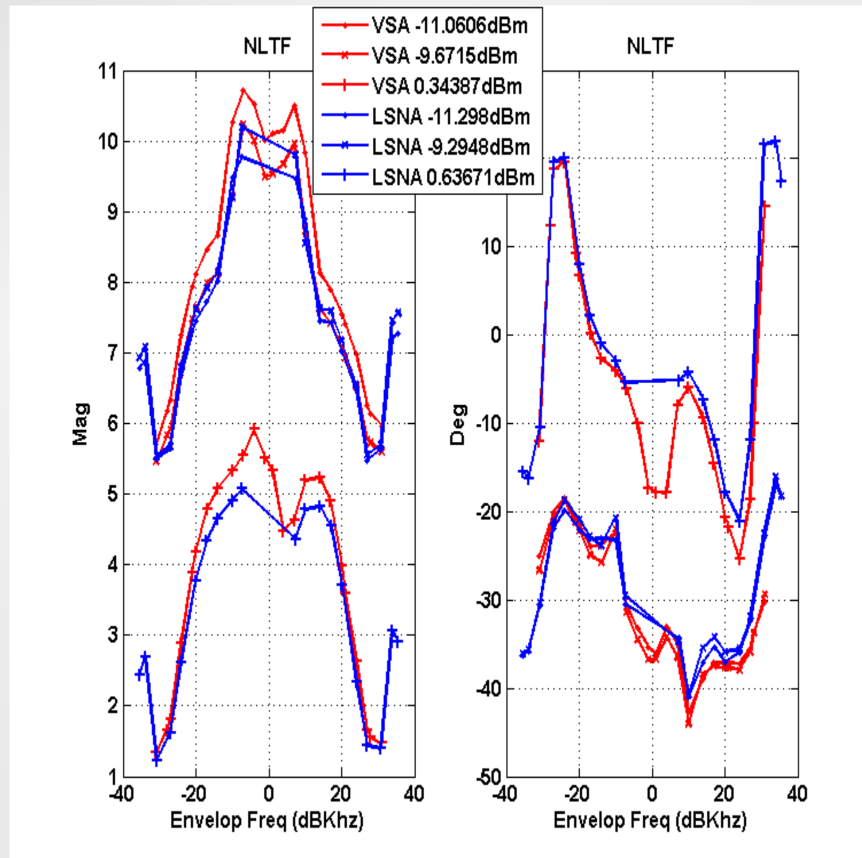
1-ch VSA-based NVNA

- Verify with sub-sampling mixer-based NVNA

  Linear TF: Mag < 0.2dB, Phase < 2deg

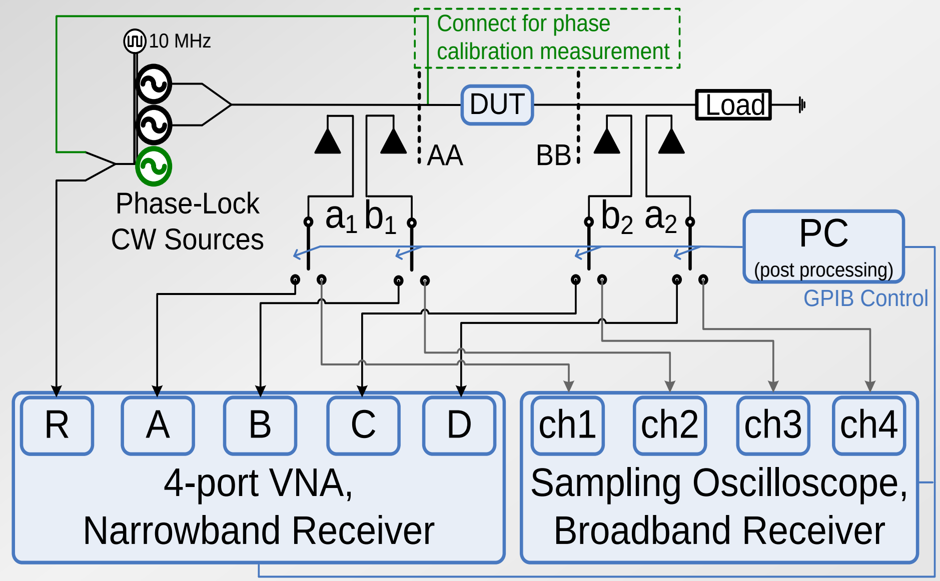
  NLTF: Mag < 10%, Phase < 5deg



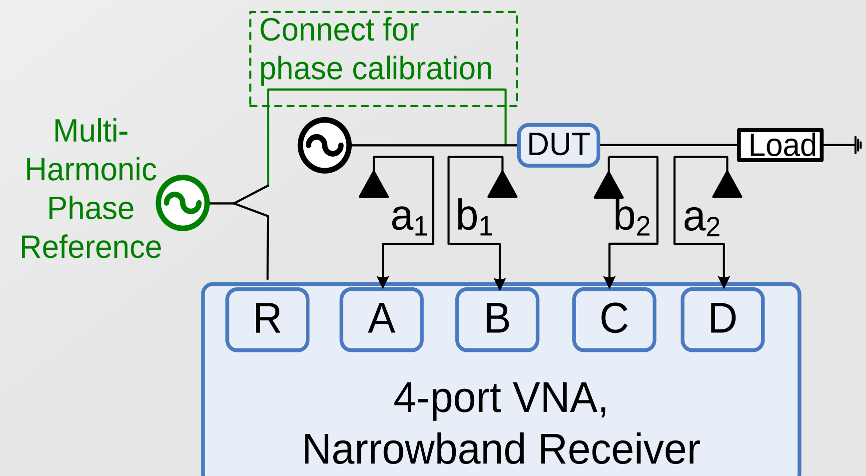


4-port VNA-based Hybrid NVNA

- Hybrid NVNA
  - Phase-lock CW source
    Relate phase of during power sweep
  - Sampling oscilloscope
    Relate phase of diff. spectral components
  - Tone spacing
    40dB dynamic range @200Hz
    Increasing to 80dB @200kHz
    Limited by oscilloscope memory depth & spectral leakage (FFT window)



- 4-port VNA-based NVNA [Blockley05]
  - 4-port VNA
    80dB dynamic range
    250kHz instantaneous bandwidth
  - Multi-harmonic generator
    Relate phase of diff. spectral components
    20GHz bandwidth achieved in NVNA
  - Tone spacing
    1.242MHz (10MHz in commercial version)

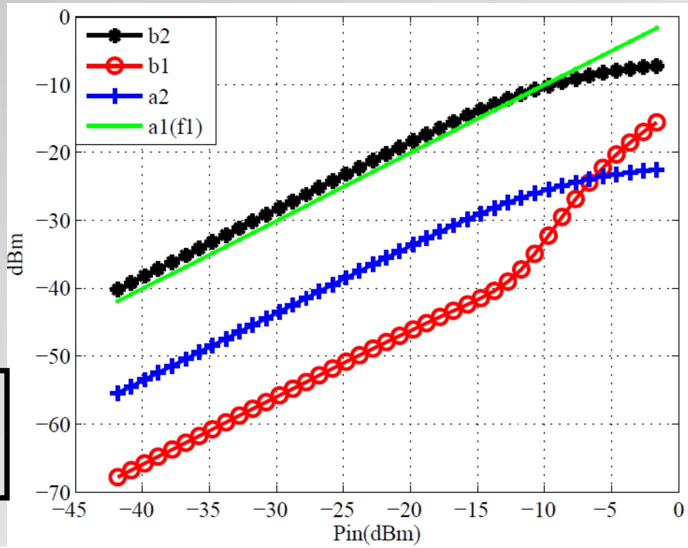


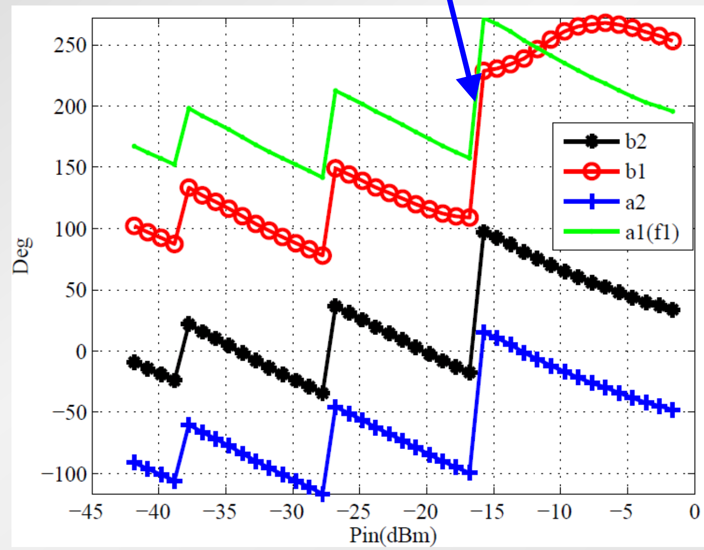
4-port VNA-based Hybrid NVNA

- DUT measurement
  - 2-tone excitation (200kHz tone-spacing @2GHz)

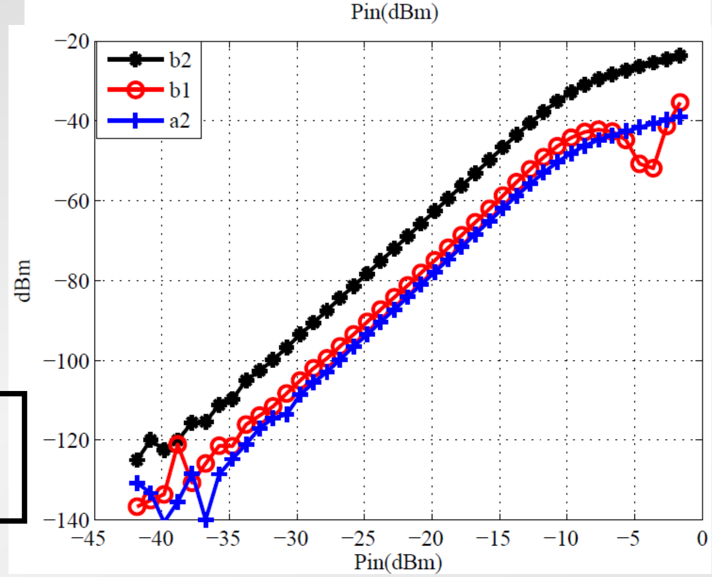
Phase jumps due to switching attenuators in excitation source

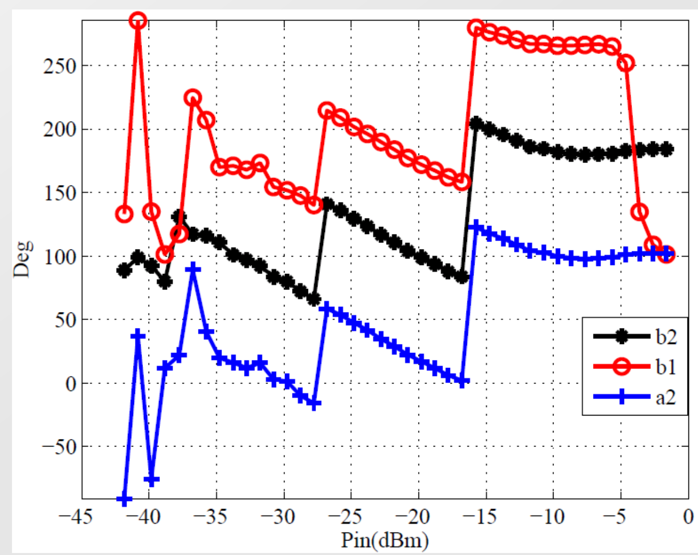
Lower Fundamental





Lower IM3





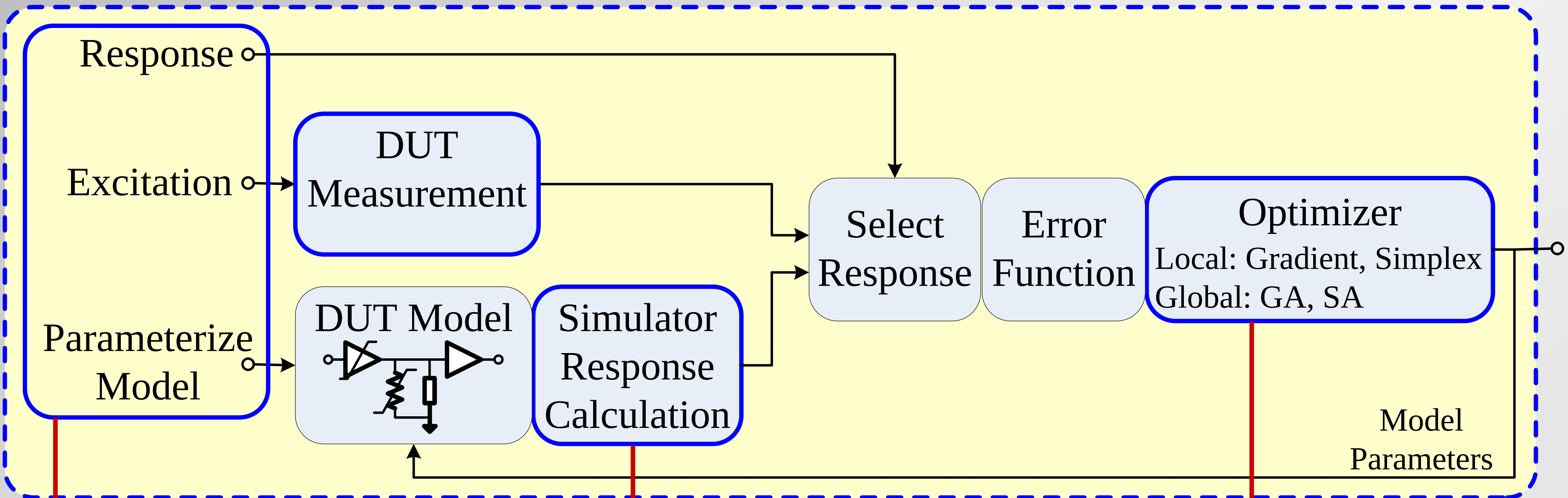
Time-Invariant Phase

- 'Absolute' phase measurement
  - DUT port waves characterized as signals
  - Phase jumps in excitation is part of signal
- Time-Invariant phase $\phi'_{2w_1-w_2,out} = \phi_{2w_1-w_2,out} - \phi_{w_2} + 2\phi_{w_1}$
  - Previously considered only for alignment [Blockley06]
    Phase is relative to sampling time
  - Cancel phase variation in excitation
  - Phase contribution only from DUT: DUT characterization

$$
\begin{aligned}
Y(f_{\mathrm{IM}}) &= \sum_n \sum_{\vec{m}_{n,\mathrm{IM}}} \frac{(n:\vec{m})}{2^n} |A_2|^{m_{-2}} |A_1|^{m_{-1}} |A_1|^{m_1} |A_2|^{m_2} |H_n(\vec{m})| \\
&\times e^{j(\theta_{A_1}(m_1-m_{-1})+\theta_{A_2}(m_2-m_{-2})+\theta_{H_n(\vec{m})})} \\
&= e^{j(\theta_{A_1}(m_1-m_{-1})+\theta_{A_2}(m_2-m_{-2}))} \\
&\times \left[\sum_n \sum_{\vec{m}_{n,\mathrm{IM}}} \frac{(n:\vec{m})}{2^n} |A_2|^{m_{-2}} |A_1|^{m_{-1}} |A_1|^{m_1} |A_2|^{m_2} |H_n(\vec{m})|\ e^{j(\theta_{H_n(\vec{m})})}\right] \\
&= e^{j(\theta_{A_1}(m_1-m_{-1})+\theta_{A_2}(m_2-m_{-2}))} \left[|Y(f_{\mathrm{IM}})|\ e^{j(\theta_{\mathrm{DUT}}(|A_1|,|A_2|,H))}\right] \\
\phi'_{f_{\mathrm{IM}}} &= \phi_{f_{\mathrm{IM}}} - (\theta_{A_1}(m_1 - m_{-1}) + \theta_{A_2}(m_2 - m_{-2})) \\
&= \theta_{\mathrm{DUT}}(|A_1|, |A_2|, H)
\end{aligned}
$$

Grey-box Model ID Methodology

Model ID Algorithm: a typical Parameter Estimation Step



Case-by-case
ad-hoc ID algorithm

Simple models with
easily derived expression

Deterministic optimizer
(depend on initial solution supplied, prong to trapping in local optimums)

General ID algorithm
minimize user intervention

General models
require circuit simulation

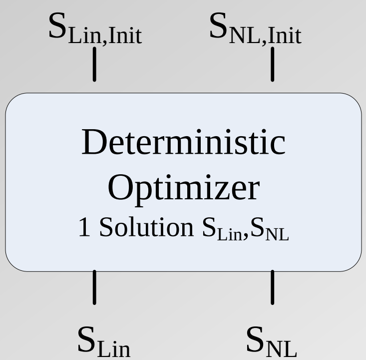
Hybrid-Genetic optimizer
find multiple optimums for user selection
(typical stochastic optimizer find only 1 global solution)

Experiment design
ensure no under-determined optimization problem

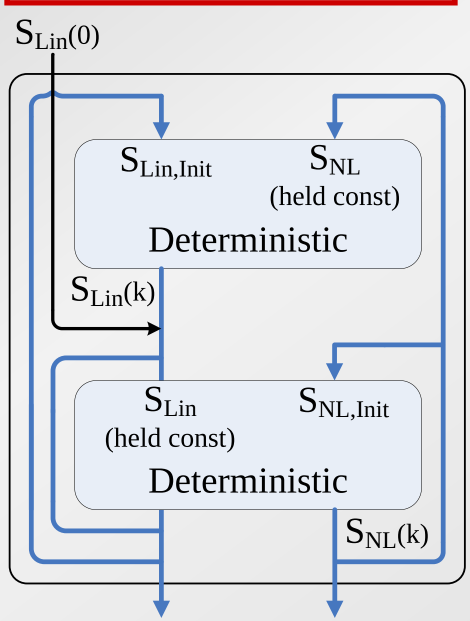
Identification Algorithm

- **Case-by-case**
  - Deterministic optimizer
    - Depend on initial solution
    - Trap in local optimum

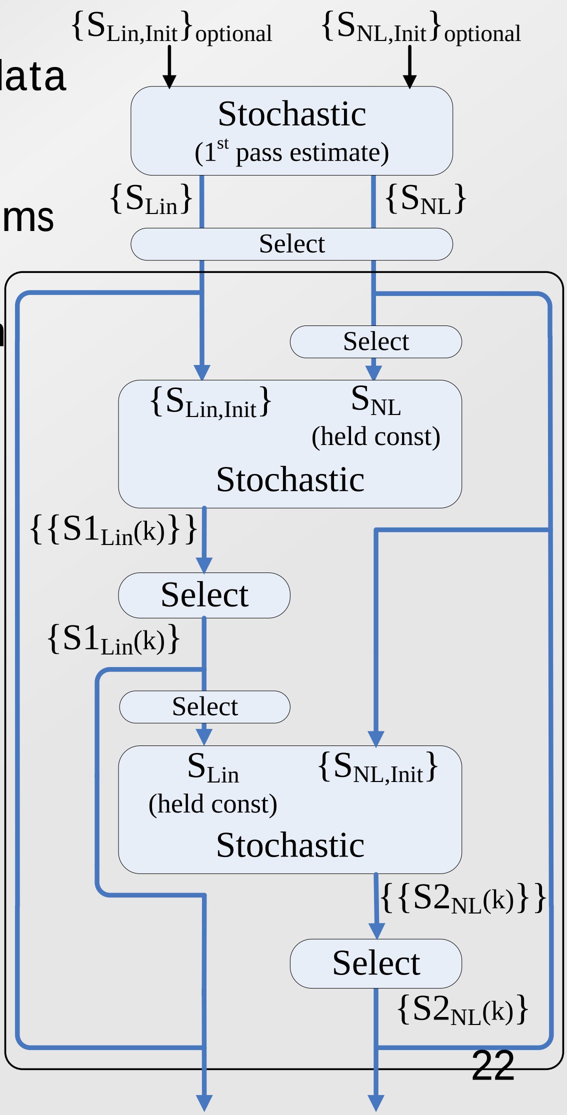
L-N-L [Boutayeb95]
N-L-N [Zhu95]



L-N-L [Crama05]
L-N [Vandersteen99]

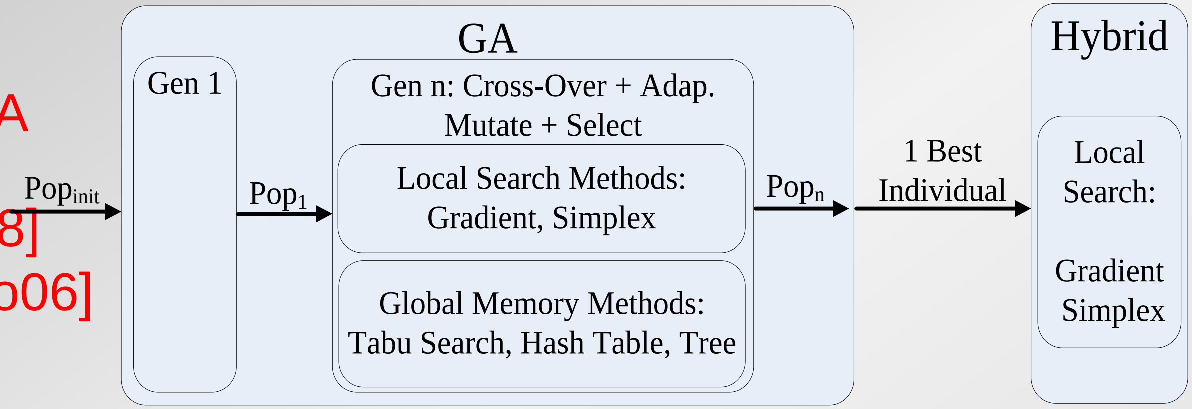


- **General RF frontend model**
  - Multiple solution
    - Due to incomplete/noisy data
  - Stochastic optimizer
    - Find multiple local optimums & global optimum
    - Minimize user intervention

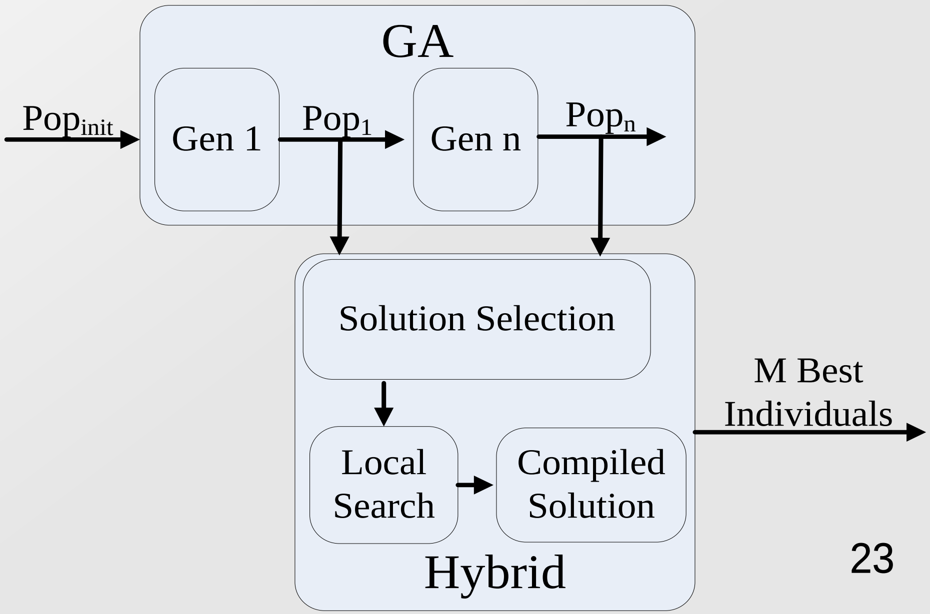


Model Optimizer

- Stochastic optimizer
  - Conventional hybrid-GA
    1 global optimum
  - Parallel-GA [Quintero08] & Niching-GA [Dilettoso06]
    Multiple sub-populations
    Around local optimums
  - Tree Anneal [Bilbro90] & No-Revisit-GA [Yuen08]
    Record past searches to guide future searches



- Hybrid-GA optimizer
  Record past searches
  Exist population around local optimums
  Use as initial solution in local search

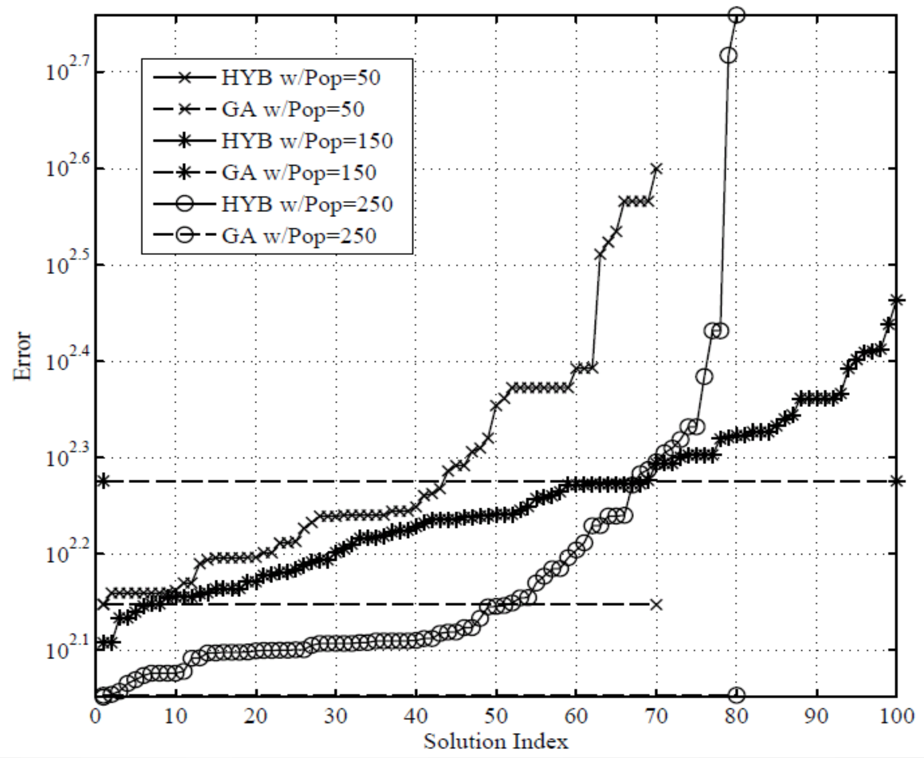


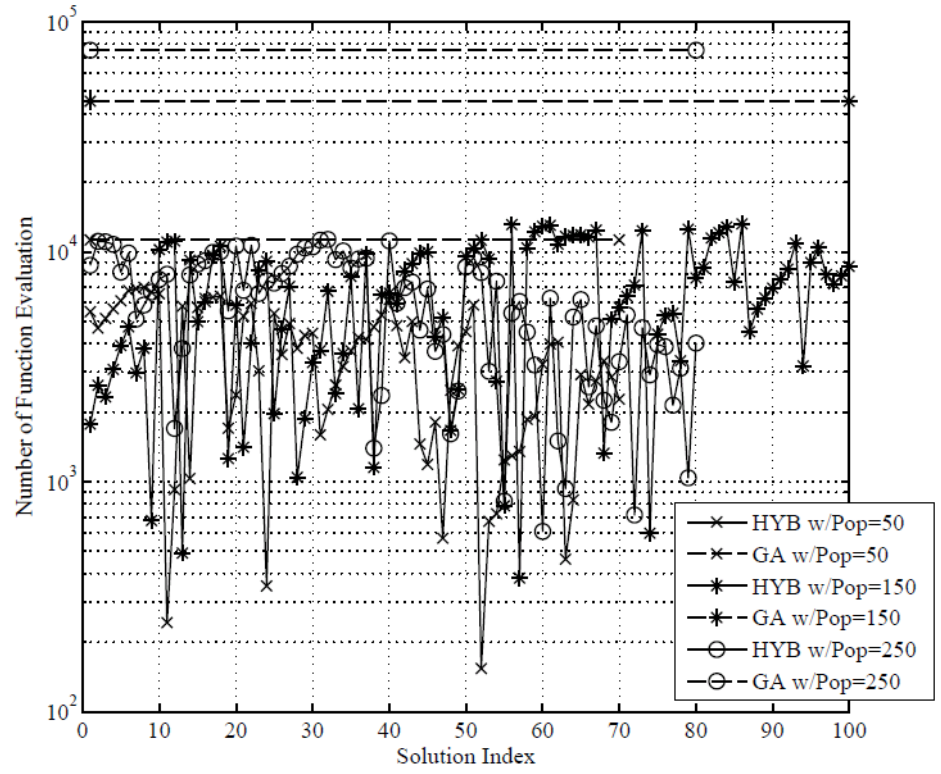
Model Optimizer

- Hybrid-GA performance
  - Find global & multiple local optimums

    User select based on error and physical intuition
  - Number of function evaluations

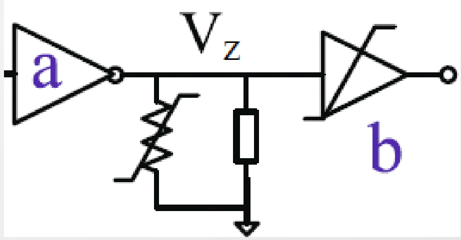
    same to 1/7th of conventional hybrid-GA

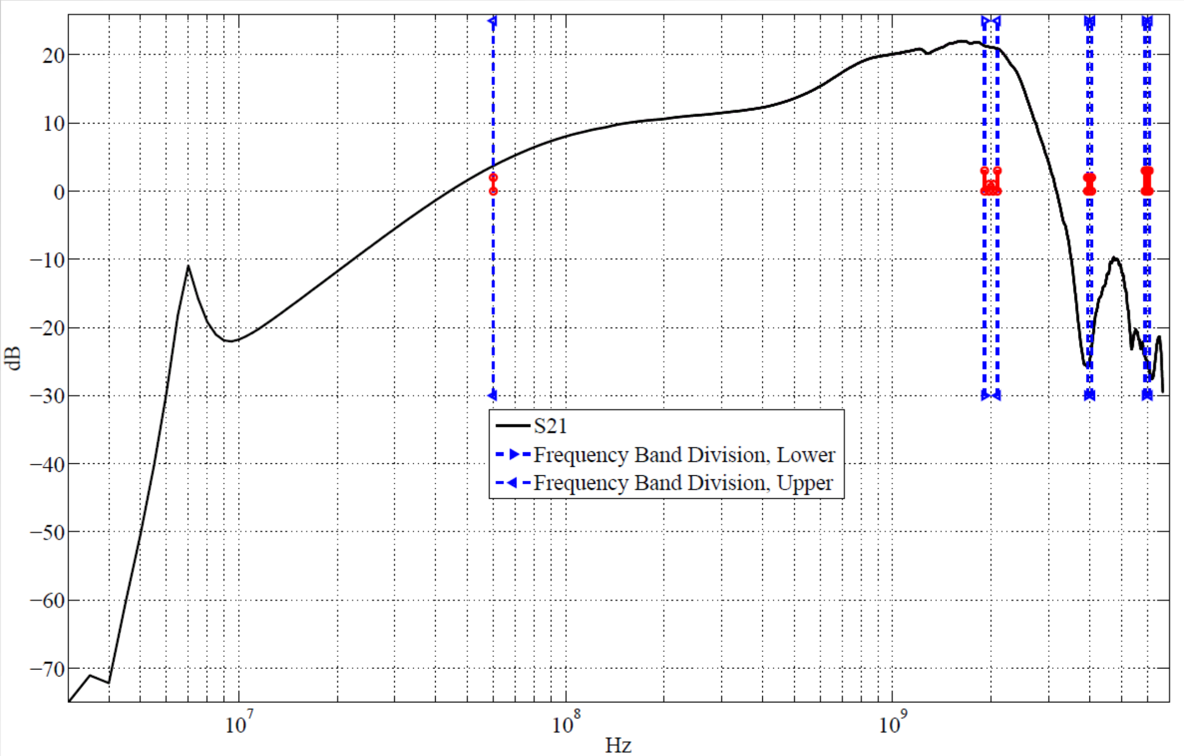


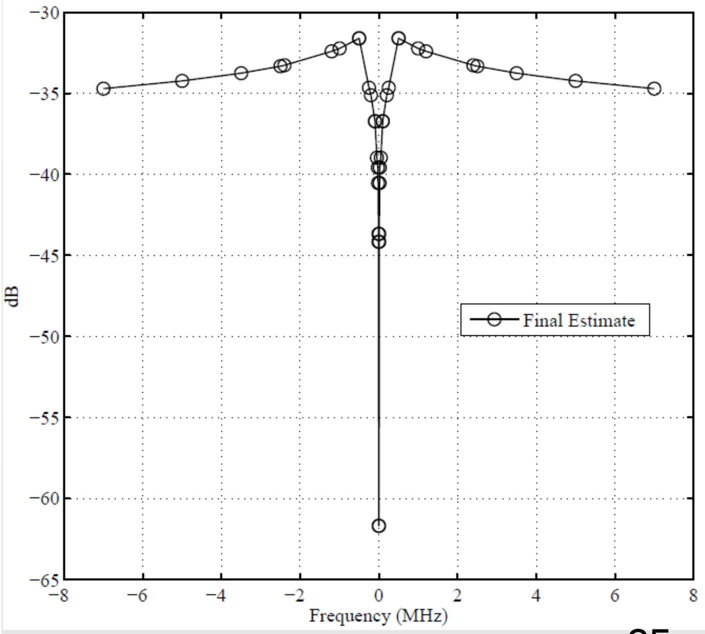


Power Amplifier w/Long-term Memory

- Model fundamental and IM3 transmission response
  - Asymmetric phase of IM3
    - Due to baseband impedance (parameterize as freq. varying)
    - Parameterize impedance in other bands as constant
  - Identified baseband impedance
    - Reflect inductive nature of bias network
    - Correlates with S21 measurement



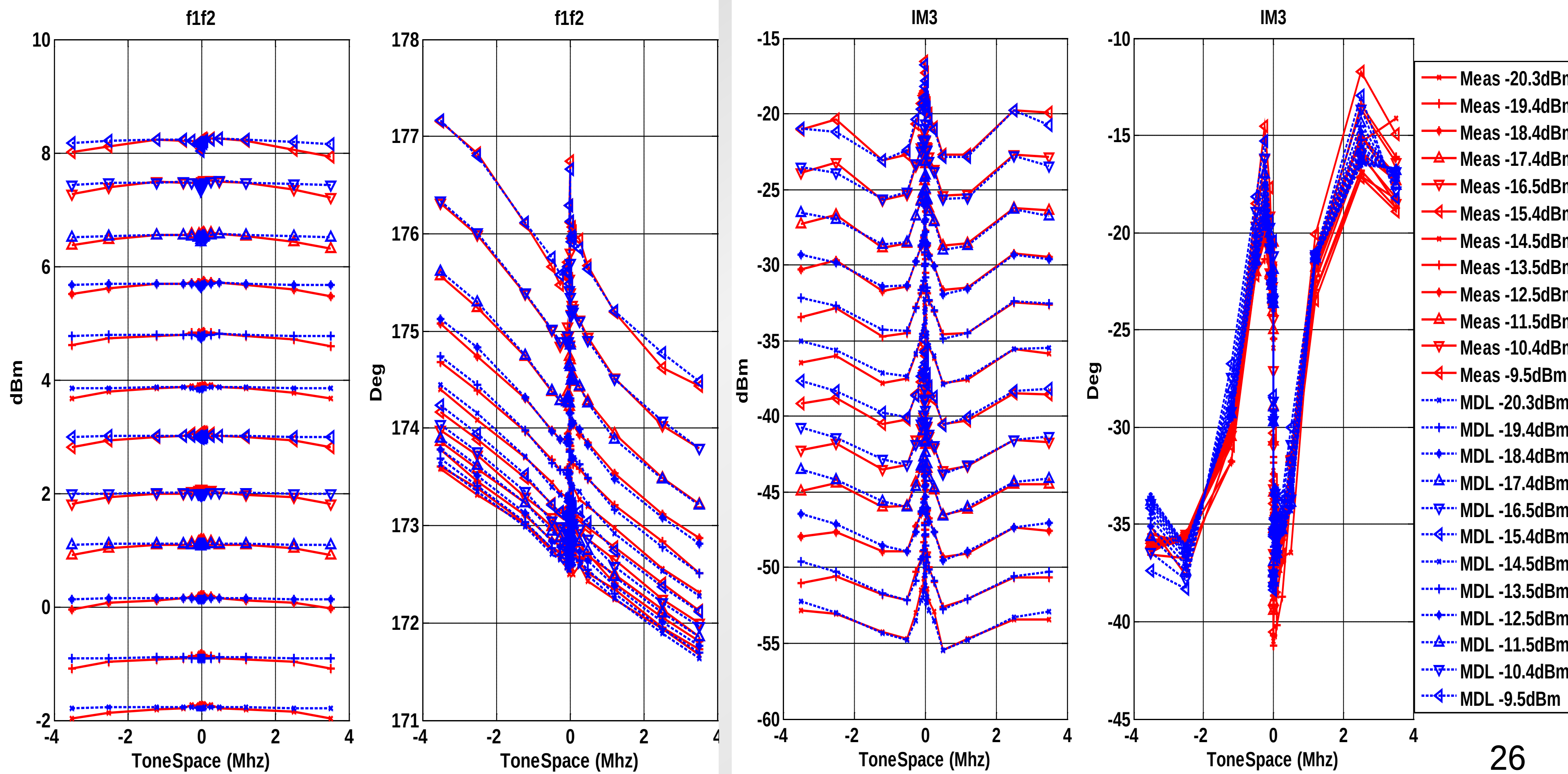




Power Amplifier w/Long-term Memory

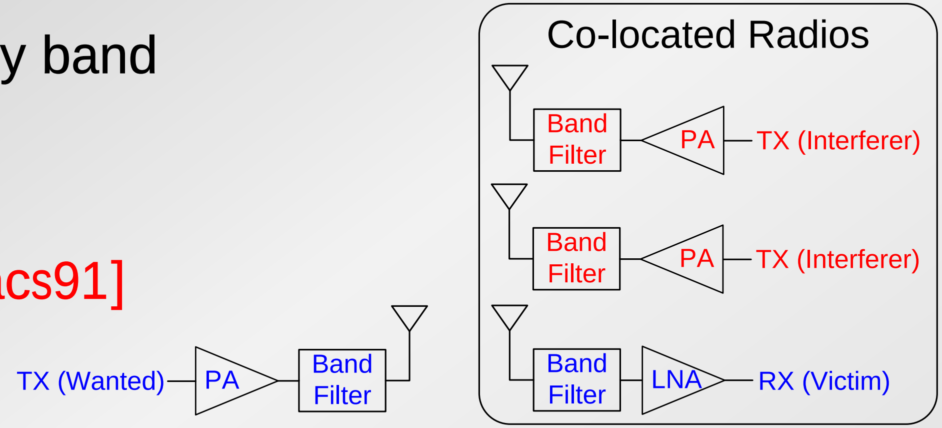
➢ Modeled transmission response

Up to 2-tone P_{-1dB}; -20dBc IM3 (state-of-art Black-box model P_{-4dB})

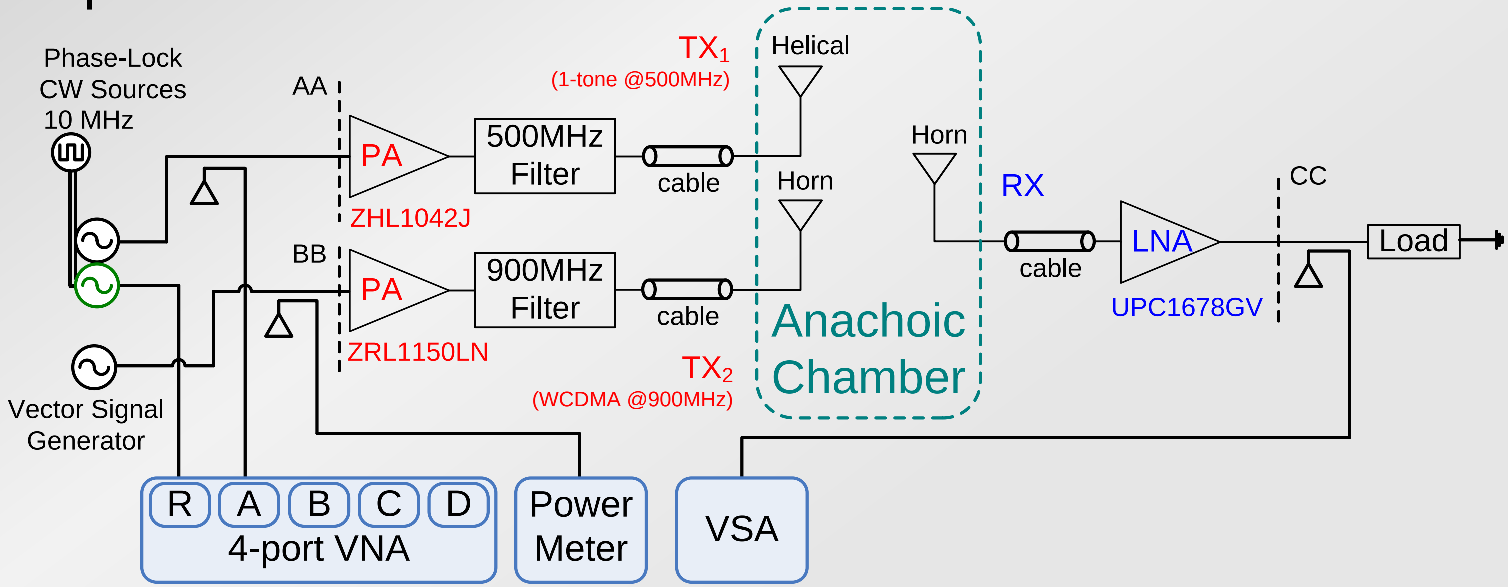


Cosite Interference

- Cosite interference
  - Co-located radios in same frequency band
  - Similar to Near-Far problem
- Cosite simulation
  - Formula-based BER evaluation [Isaacs91]
  - Using parametric models (IP3, NF),

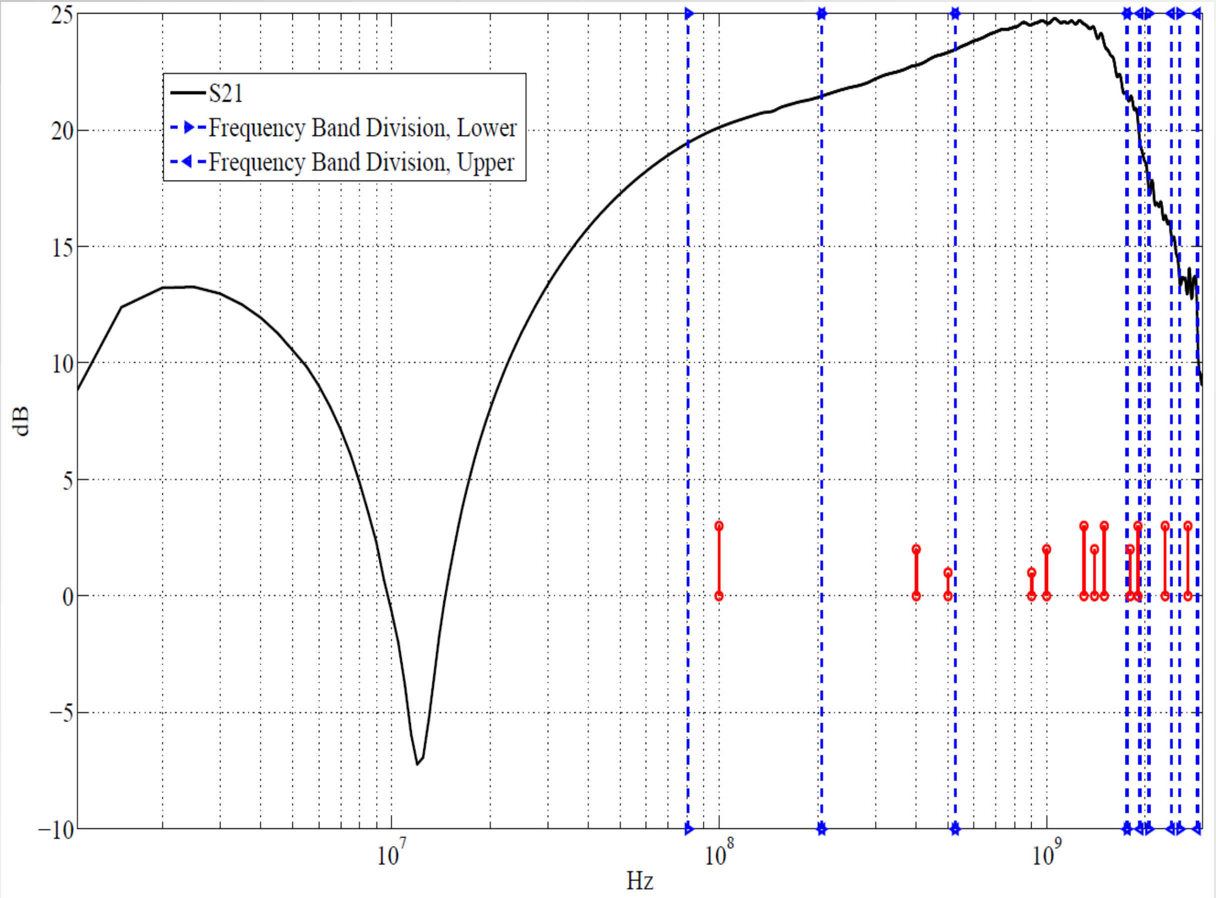


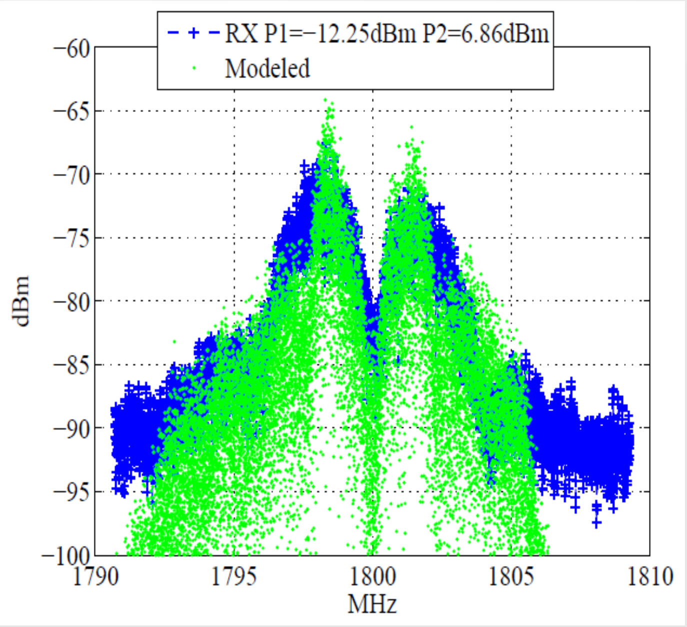
- Measurement
  - Modulated signal, >2 port: phase can't be measured
  - Amplitude measurement to be modeled



Cosite Interference

- Model broadband EMI transmission response
  - Notch centered at IM frequencies $2f_2$ & $2f_2 - f_1$
    - Due to baseband impedance (parameterize as freq. varying)
    - Correlates with S21 measurements





Summary

- Nonlinear Characterization (for multi-tone excitation)
  - 1-ch VSA-based NVNA
    - 1-channel receiver (power/area efficient for on-chip self-characterization)
    - 75dB dynamic Range
  - 4-port VNA-based hybrid NVNA
    - Phase-locked CW source as effective phase transfer mechanism when using narrowband receivers
    - Tone spacing 200Hz (40dB dynamic range, increasing to 80dB at 200kHz)
- Grey-box Model ID for RF Frontend
  - General ID algorithm for minimum user intervention
  - Hybrid-GA optimizer to find multiple optimums
  - Direct calculation algorithm for Volterra circuit analysis
  - Model PA w/long-term memory
    - Fidelity up to P-1dB (comparable to state of the art)
  - Model cosite interference
    - Fidelity in broadband EMI response

References

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