EDI CON 2018
Electronic Design Innovation
Conference & Exhibition

October 17-19 2018
Santa Clara Convention Center
Santa Clara, CA

High speed/mm-wave measurement-based model development: uncertainties and model sensitivities

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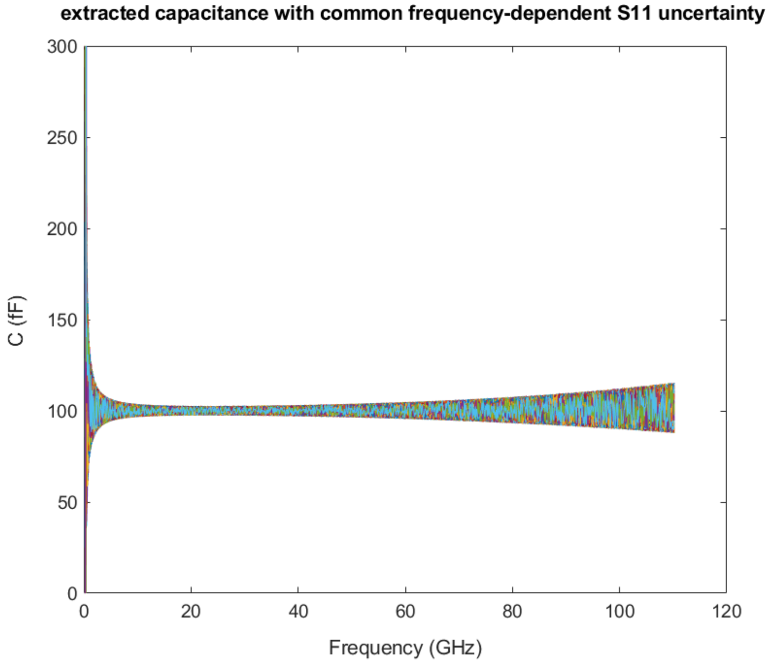
envision : ensure

Introduction/motivation

- Measurement-based model extraction does not get easier at mm-wave frequencies
  - Uncertainties in measurement increase
  - Extraction processes can have sensitive zones



- A better understanding of the parameter space (focus on network analyzer measurements) and behaviors of the extractions can perhaps improve results.

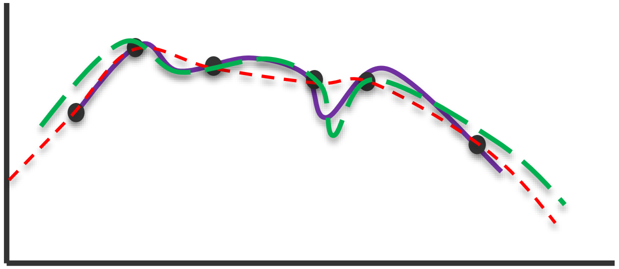
Outline

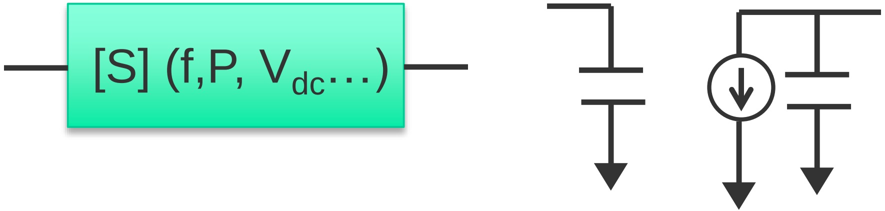
- Background
- Measurement uncertainties
  - Instrumentation-related terms
  - Calibration and de-embedding
  - Quasi-linear measurements: source purity, power accuracy
  - Correlation
- Extraction
  - Common conversions for compact models
  - Correlation implications
  - Behavioral extractions
- Uncertainty and extraction overlap
  - Mitigation possibilities
  - Asymptotic choices

Background 1

- While EM and multi-physics models can satisfy many needs, measurement-based models are still needed
  - *To evaluate/characterize new processes*
  - *Use for extended range applications*
  - *In more nonlinear realms*

- The models may be compact/circuit-based or may be behavioral. The extraction interacts with underlying data in different ways.



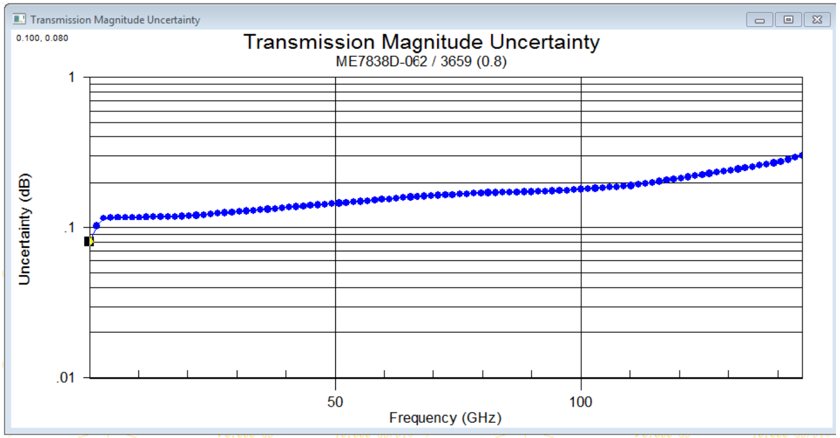


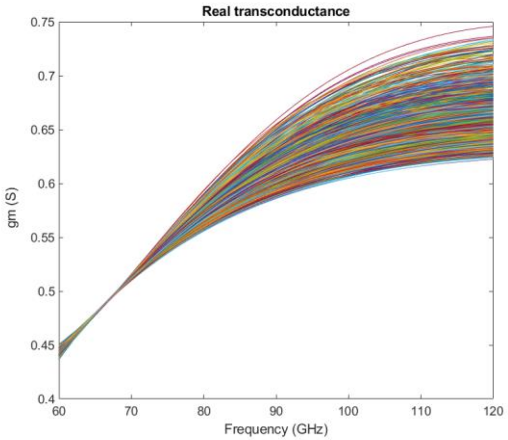
Mm-wave models may be changing more rapidly with many input parameters

Background 2

- At higher frequencies, measurement uncertainties generally increase.
  - Higher conversion loss and lower power → more noise issues.
  - Degrading repeatability
  - Shorter wavelength → more phase issues from minor physical problems

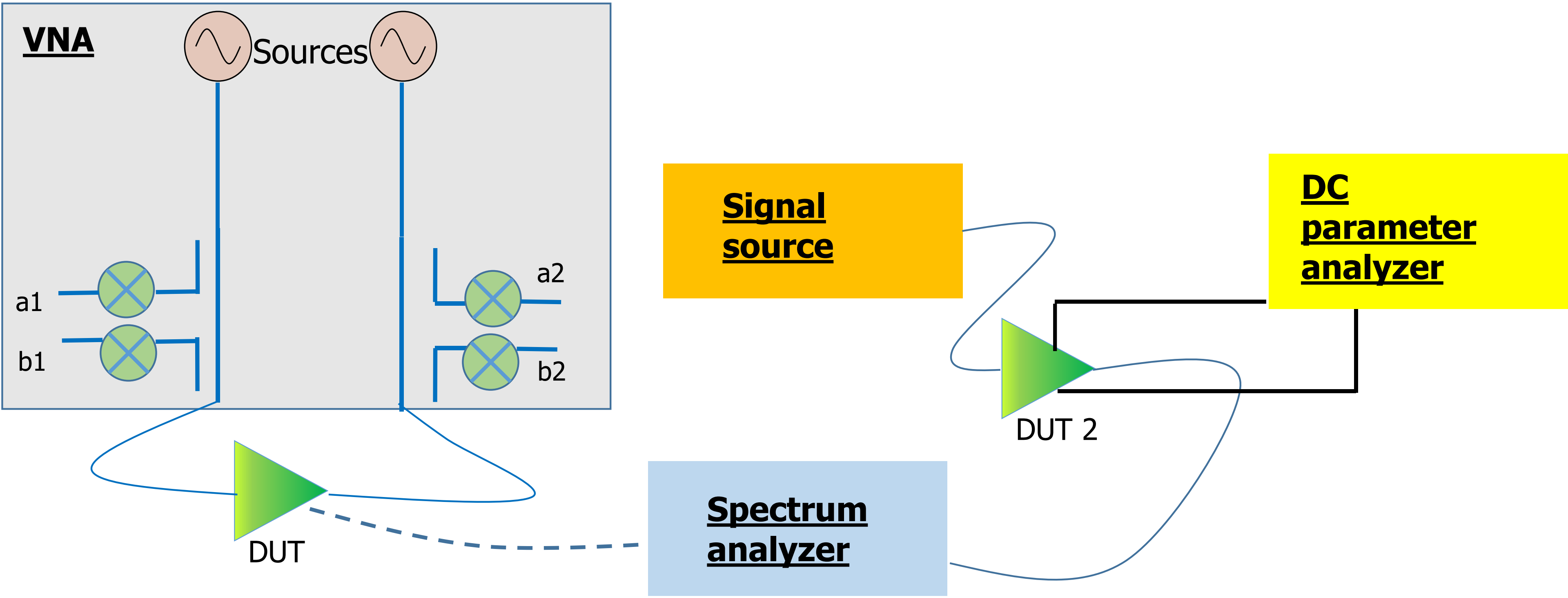
- Very large model uncertainties have been the outcome in some cases.





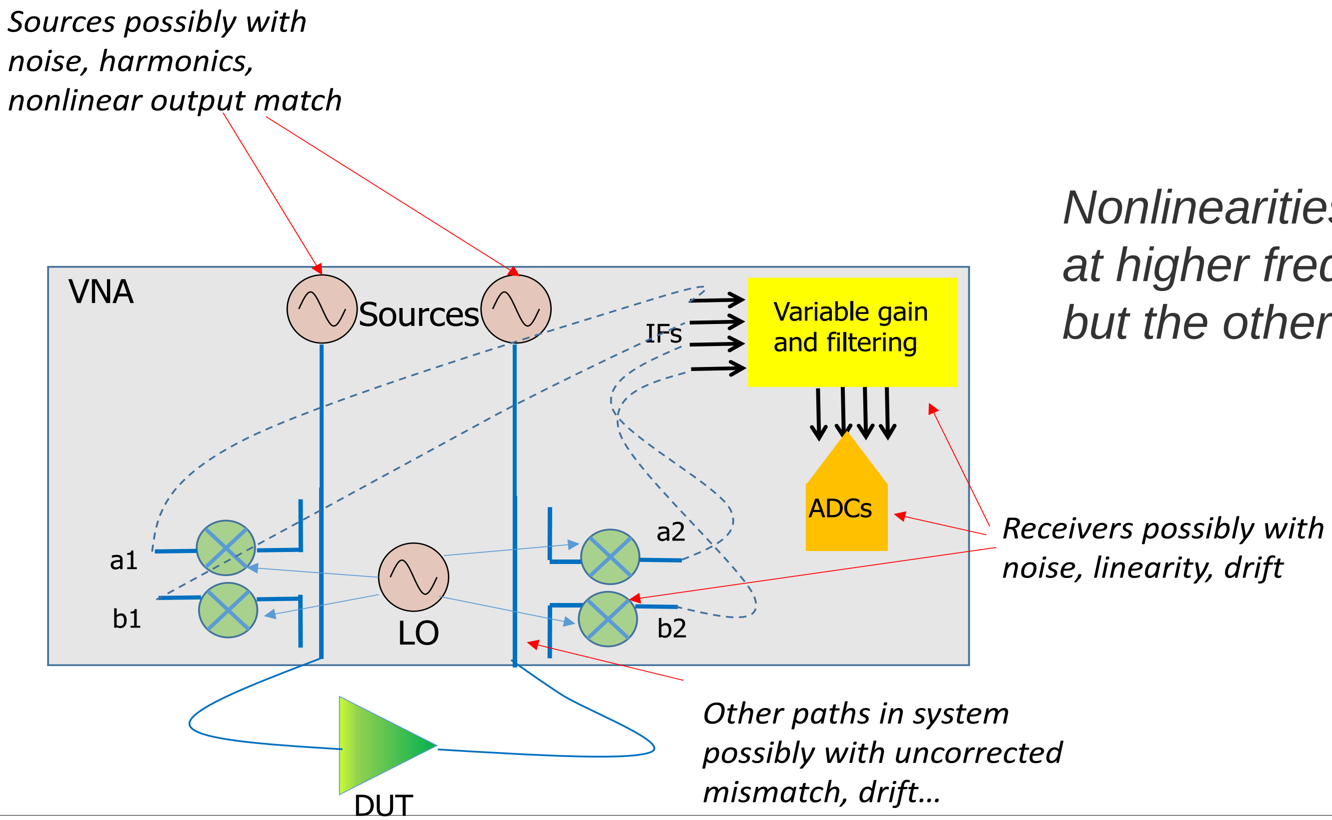
Measurement configurations

- Many tools may be employed but we will focus on the VNA effects. The uncertainty parameters for the other RF tools are often a subset.



Measurement configurations II

- VNA uncertainty elements: repeatability, nonlinearities, noise, drift, correction/de-embedding limitations…



Sources possibly with noise, harmonics, nonlinear output match

Receivers possibly with noise, linearity, drift

Other paths in system possibly with uncorrected mismatch, drift…

Nonlinearities usually do not get worse at higher frequencies (until near-THz), but the other elements all do.

Measurement configurations III

The physical DUT environment has a strong influence on net uncertainty:

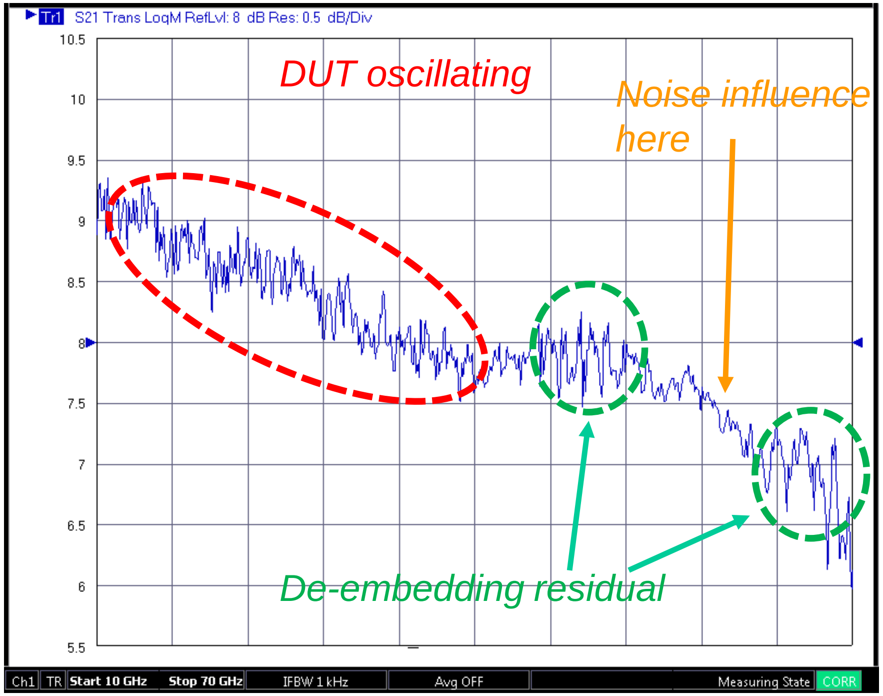
- Waveguide/coax: repeatability (and not direct for device modeling)

- Fixtured: repeatability, how good are the de-embedding structures?, crosstalk

- On-wafer: contact repeatability, de-embedding limits, crosstalk, multi-mode propagation

Mechanisms: Noise

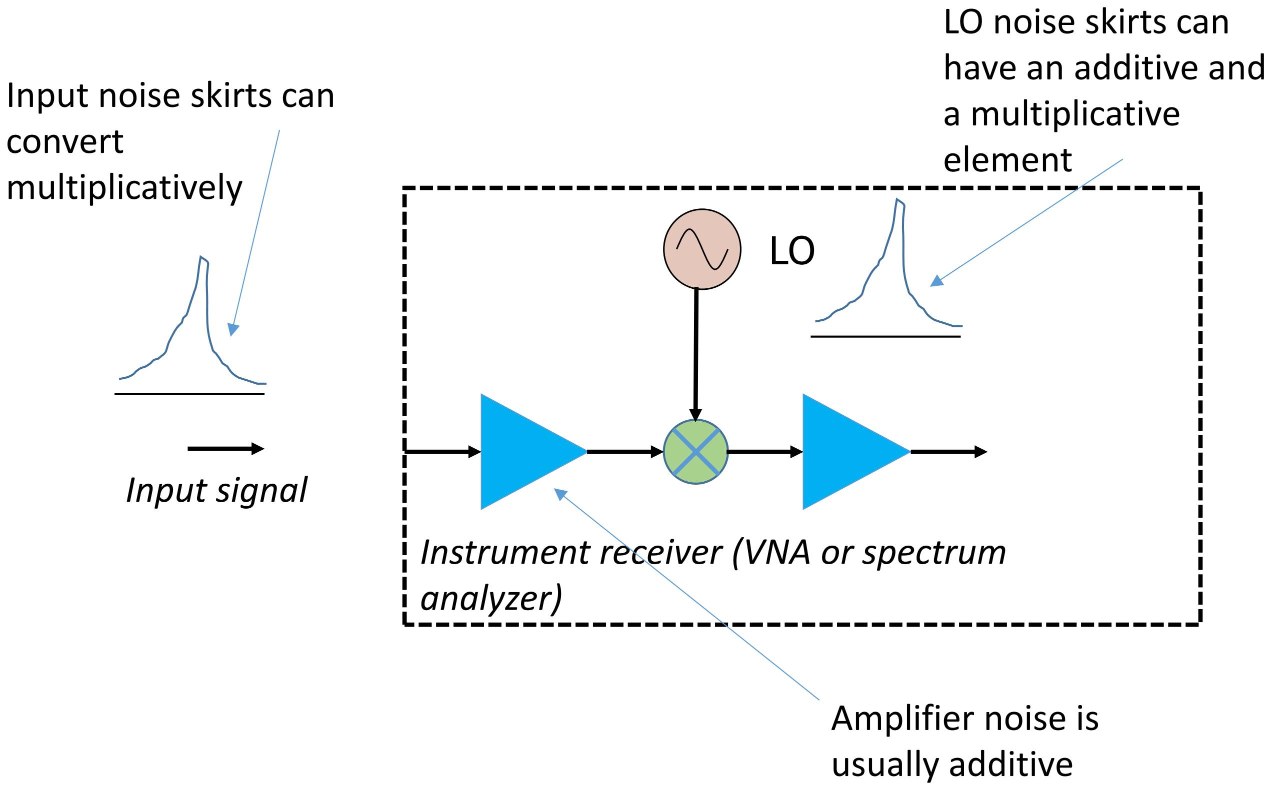
- Is it really noise?
  - If so, which mechanism?
  - This actually matters since the dependencies are not the same.



- In most measurements, there is an additive noise component (not dependent on input signal amplitude) and a multiplicative one.

Mechanisms: Noise (2)

- The signal and LO-based noise contributors can be complicated. Knowing the weights can enable an optimal signal plan…



Input noise skirts can convert multiplicatively

LO noise skirts can have an additive and a multiplicative element

Input signal

Instrument receiver (VNA or spectrum analyzer)

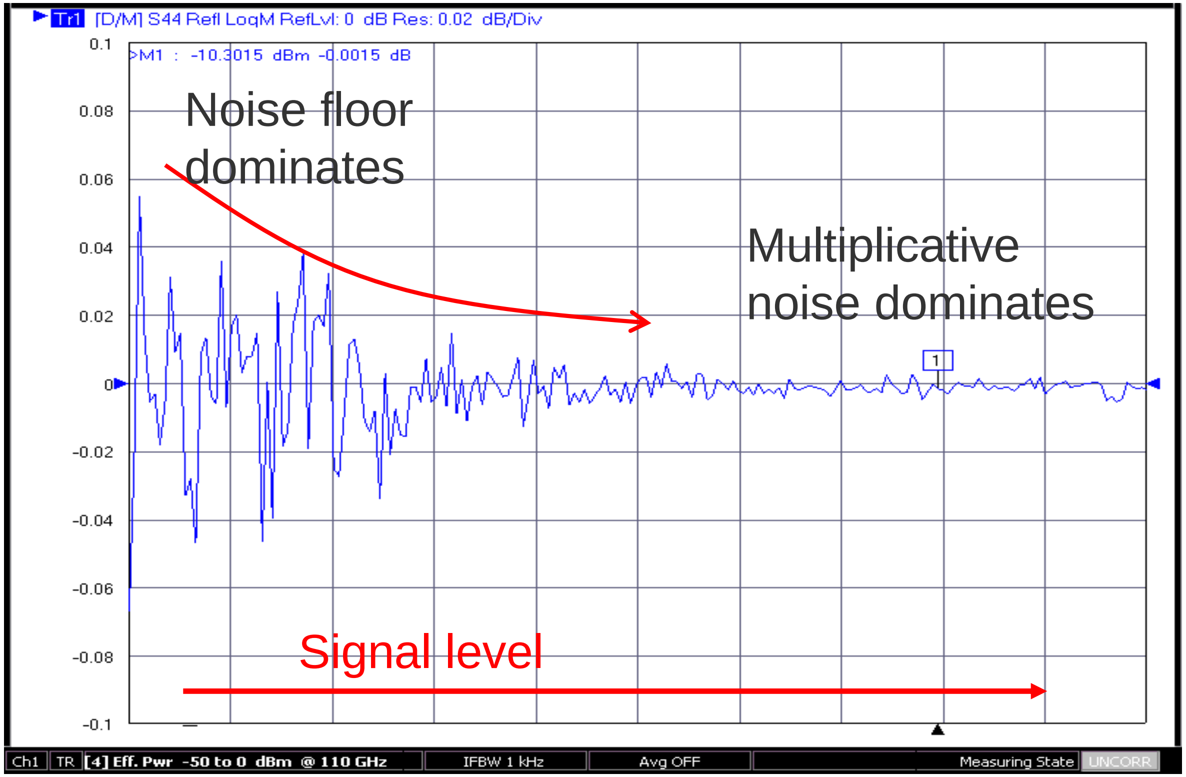
Amplifier noise is usually additive

Mechanisms: Noise (3)

- At low levels, additive noise dominates so increasing the desired signal level helps (in dB terms).

- At higher levels, the noise and signal increase at the same relative rate

- Some cancellation does occur in a ratioed measurement at high levels.



Mechanisms: Repeatability

- Environment matters
  - Coax: Repeatability levels ~ -50 to -60 dB through 145 GHz (well-maintained connectors). <<0.1 dB usually.
  - On-wafer: contact pad changes
    - Without fully automatic probing, placement repeatability also an issue (10 μm variances common: >2 deg @ 100 GHz)
  - Fixture: DUT placement vs. standards placement…>50 μm variances common

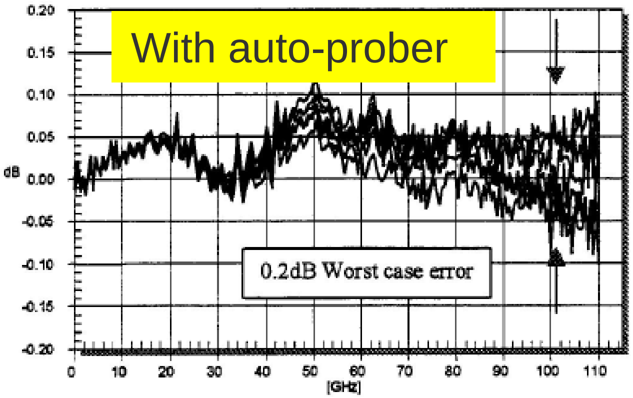
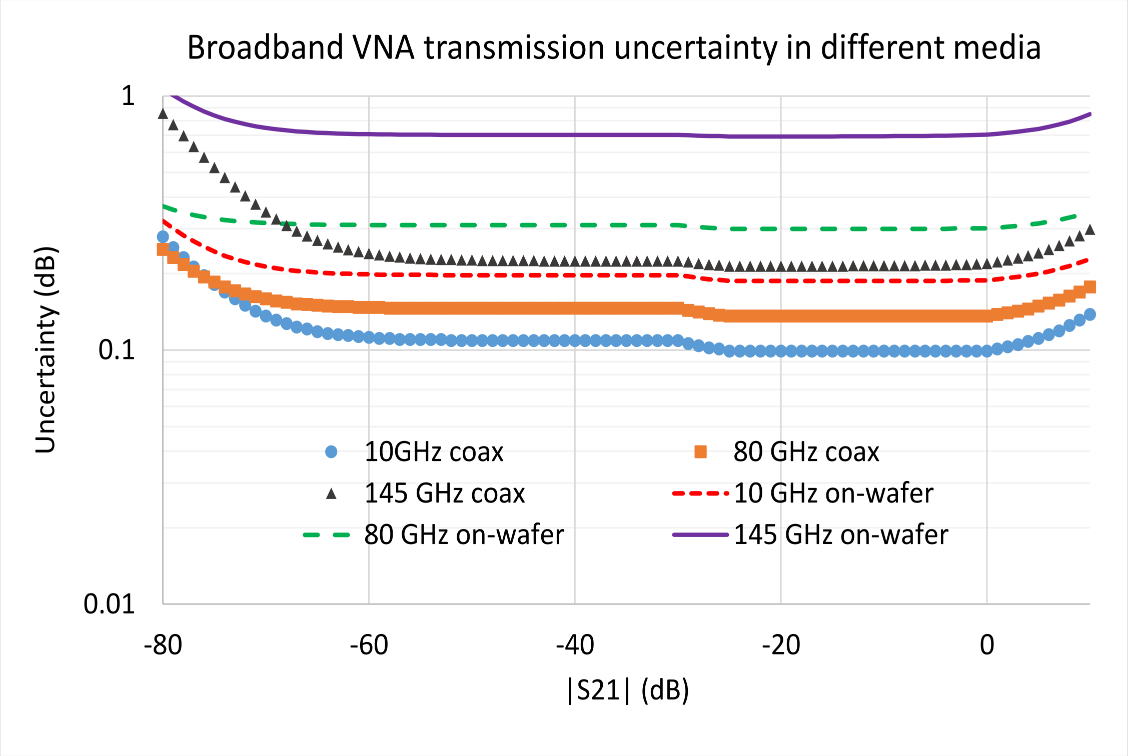


Fig. 14. Sii Open measurement of 8 LRRM calibration using different sets of calibration

From A. Lord, EuMW Conf. Dig., 1999

Mechanisms: Repeatability (2)

- Mid-range transmission uncertainty is often dominated by repeatability-like terms.

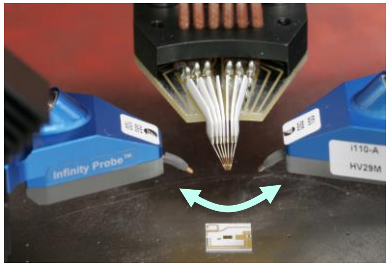

Broadband VNA transmission uncertainty in different media

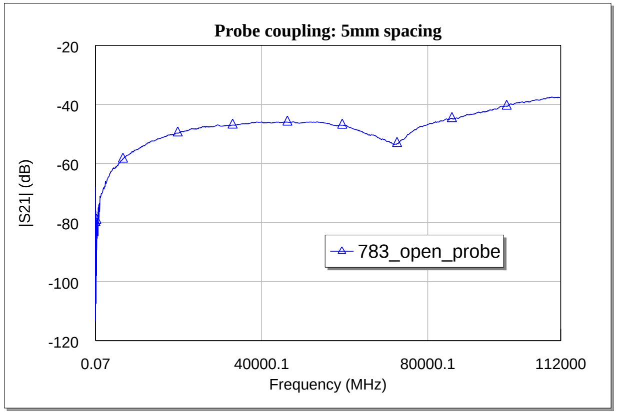
- These vary strongly with
  - Frequency,
  - Media, and
  - Condition of the components

Mechanisms: Repeatability → crosstalk

- Crosstalk internal to instruments generally negligible now.

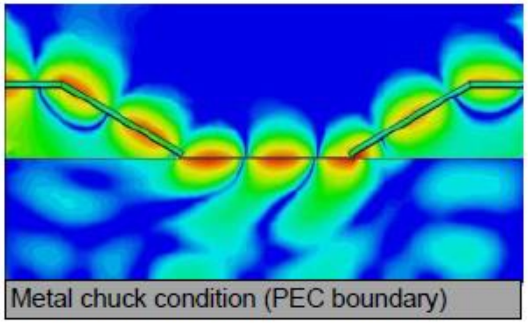
- Coupling in on-wafer and fixtured measurements is not:
  - Direct probe-to-probe





  - Substrate modes

(energy couples into substrate depending on thickness, chuck details and varies with cal standard/DUT)



From M. Spirito, et al, 91st ARFTG Conf. Dig., 2018

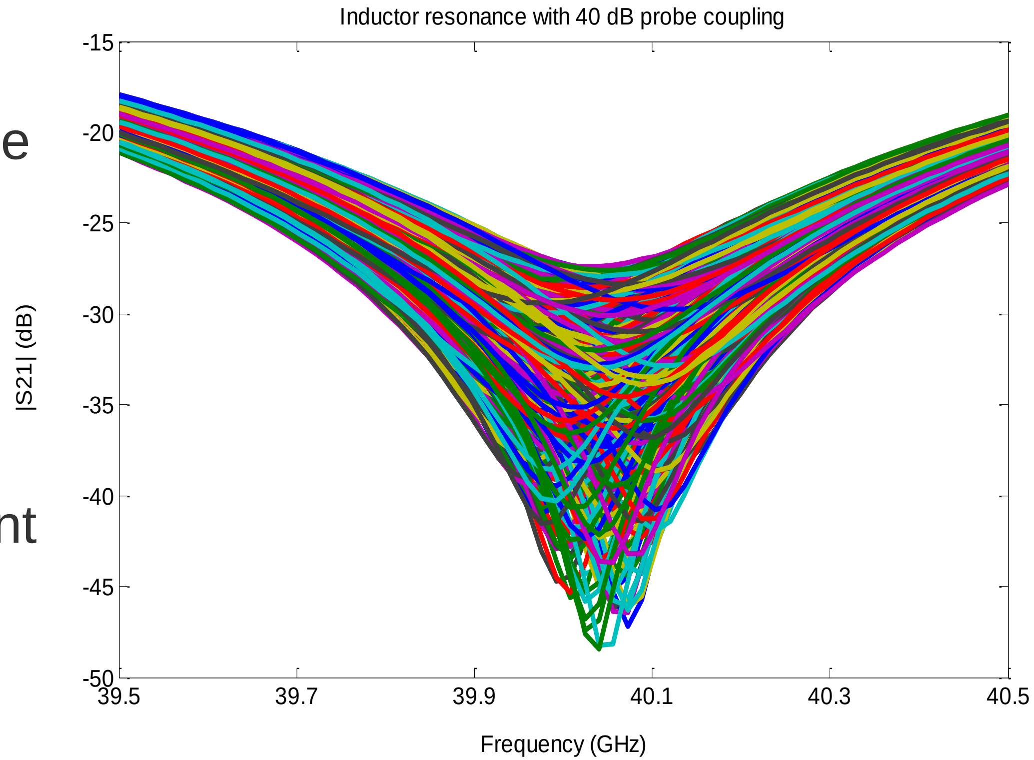
  - Surface waves

Crosstalk variation and what it can do

- Local resonant frequencies are often used in extraction (e.g., $\frac{1}{\sqrt{LC}}$).

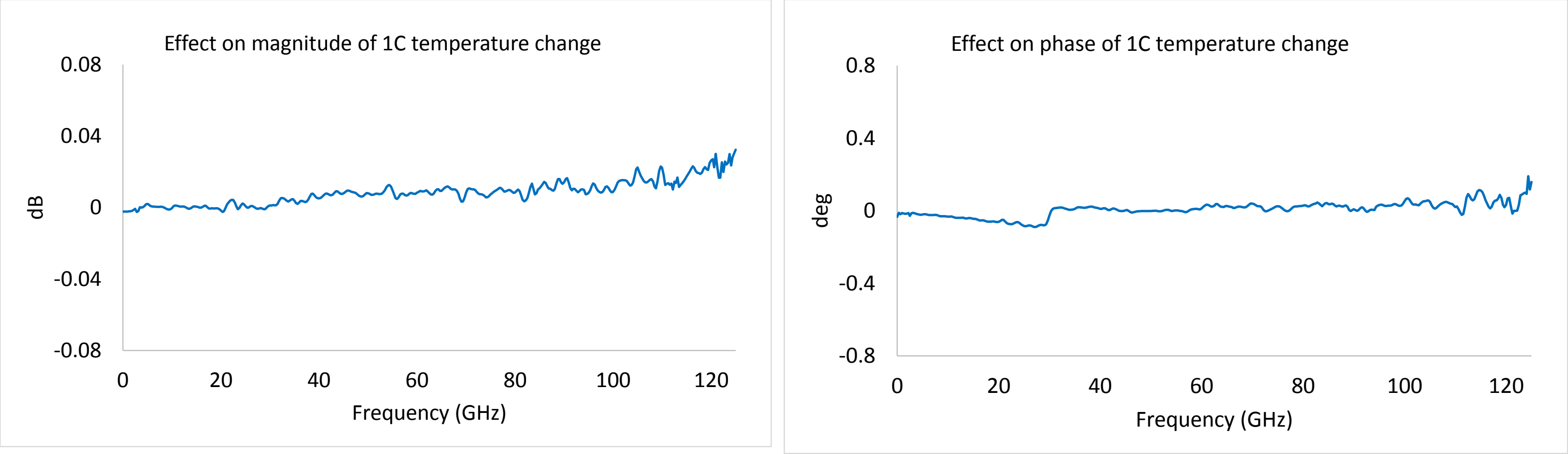
- Depending on the absolute level of the resonant dip, crosstalk variation can obscure the resonant frequency.

- Several % variation in resonant frequency which doubles in component extraction.



Mechanisms: Repeatability → drift

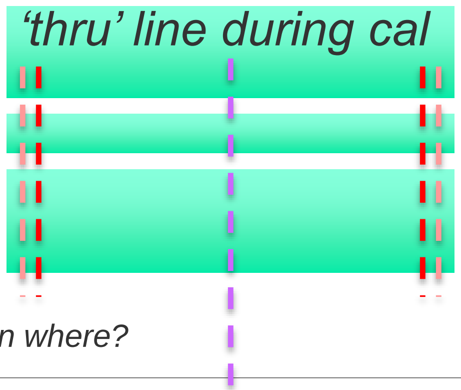
- Setup details (particularly cabling) are very important.
- Magnitude and phase tend to vary at significantly different rates
  - E.g., phase length of coax cables vs. temp
  - Dependent on receiver switching details in some systems



- Since some extractions are dependent on real and imaginary parts of Y- and Z-parameters, this magnitude/phase de-correlation can be important.

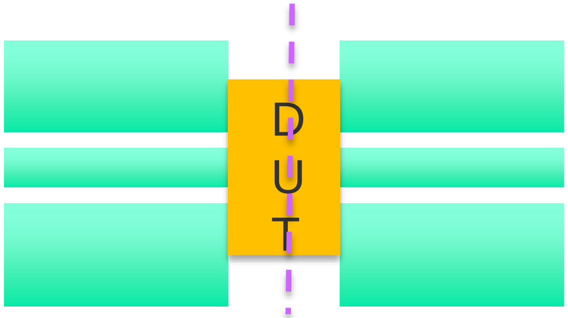
Mechanisms: Calibrations and de-embedding

- A very large topic area…but two recurring themes
  - What assumptions were made?
    - TRL family *strongly* assumes consistent touchdowns/contacts
      - Calibration standards on a different substrate?
    - Some methods require standards (shorts, opens…) to be well-known in advance.
  - Where are the reference planes (really)?

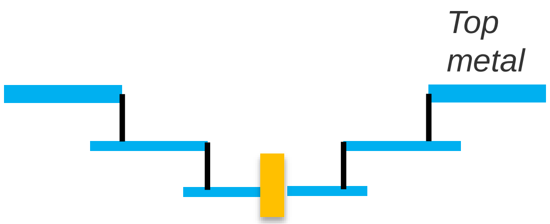


Touchdown where?

Ref plane left in the middle?



DUT electrical size?
Changes in probe coupling?

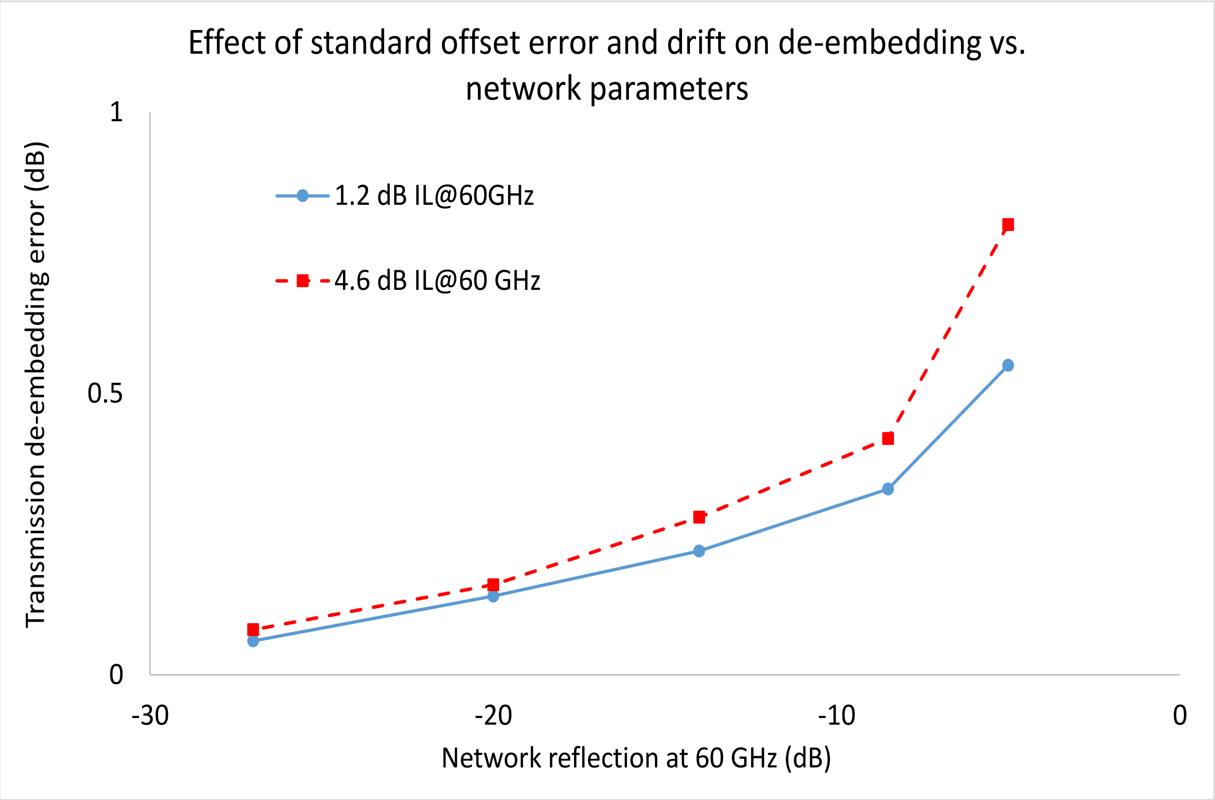


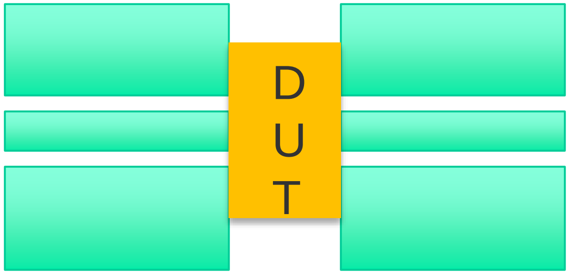
Side view: Many metal layers and via stacks can make the de-embedding more interesting

Calibrations and de-embedding

- Usually, de-embedding a mismatched/lossy network is more sensitive to standards problems and drift.

- The sensitivity gradient is often high for severe mismatches in the network.





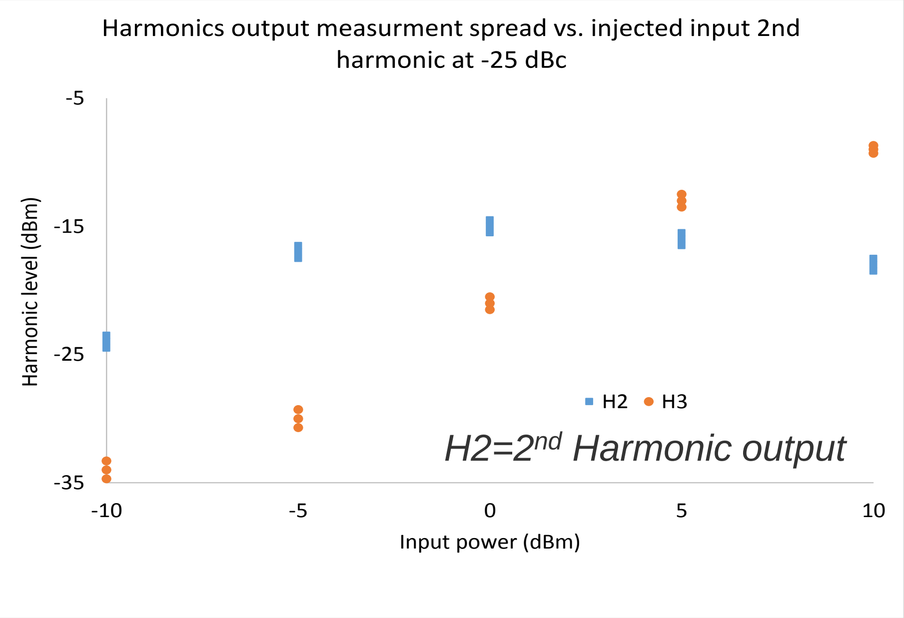
Mechanisms in quasi-linear measurements

- Gain compression, AM-PM conversion, intermodulation distortion, harmonic generation…. can all useful for model generation.

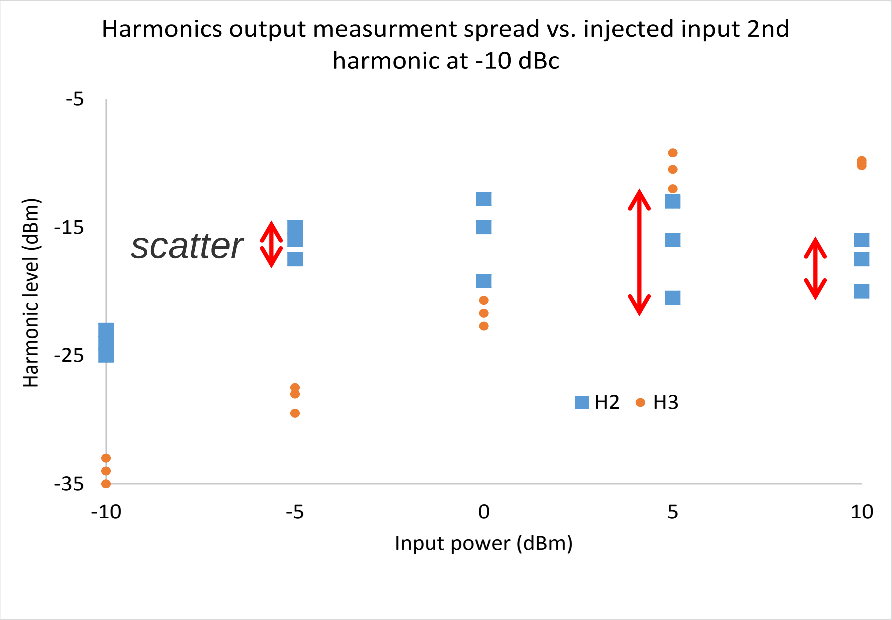
- Potential added measurement issues:
  - Receiver linearity
    - The receiver had better not be generating the nonlinear products. Shifting signal ranges can help.
  - Source contamination
    - Are extra stimulus signals altering the response?
  - Absolute power
    - How accurate are the drive levels?

Quasi-linear mechanisms: source harmonics

- An artificial 2nd harmonic was injected at the input with variable phase.
- At high injection levels, the interaction grew dramatically and with variable sensitivity to injection phase.


Harmonics output measurment spread vs. injected input 2nd harmonic at -25 dBc

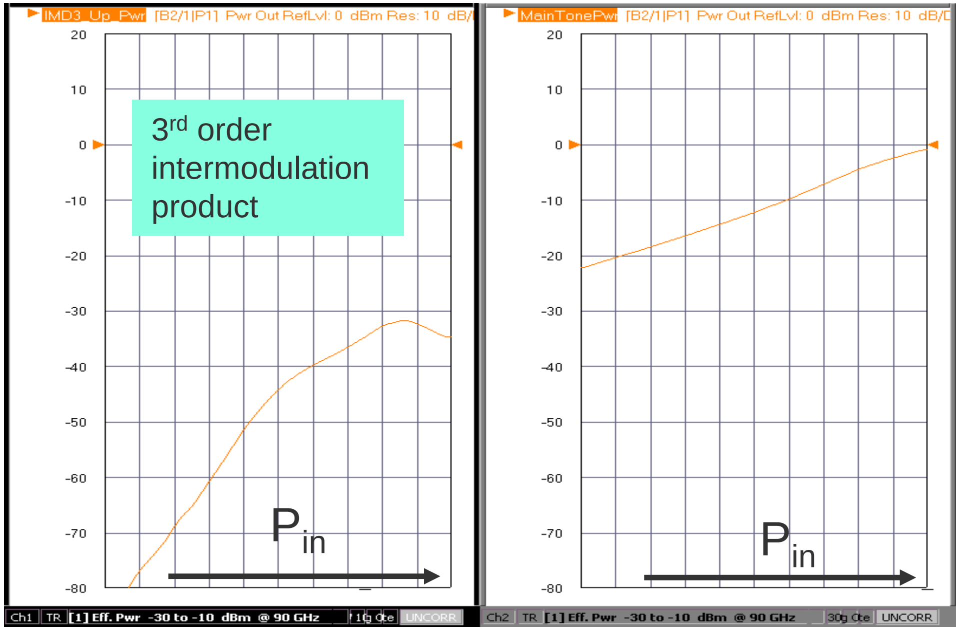
H2=2nd Harmonic output


Harmonics output measurment spread vs. injected input 2nd harmonic at -10 dBc

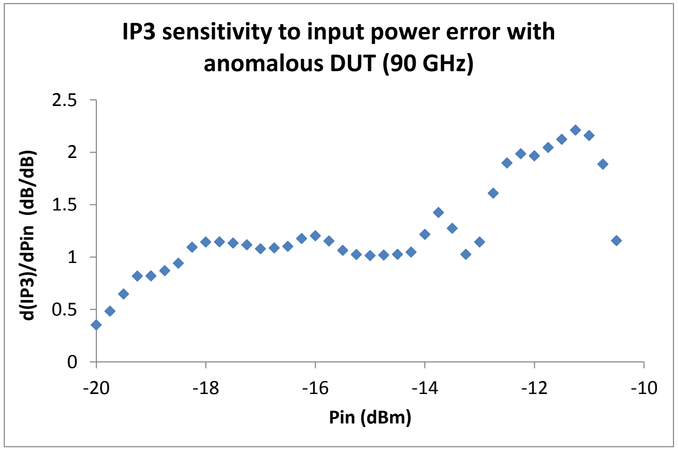
scatter

Quasi-linear mechanisms: absolute power

- If the drive level is not know accurately, the main hazard is that the DUT is in a different state than intended.
- The more nonlinear the state, the more it matters…



Some calculated values (e.g., intercept point) can increase sensitivities further!



Correlation of uncertainties

- Within an S-parameter
  - Real and imaginary parts could be uncorrelated (e.g., noise dominated)
  - Could be correlated since magnitude and phase have specific behaviors (e.g., drift, some calibration errors)
  - Could be correlated intrinsically (e.g., linearity)

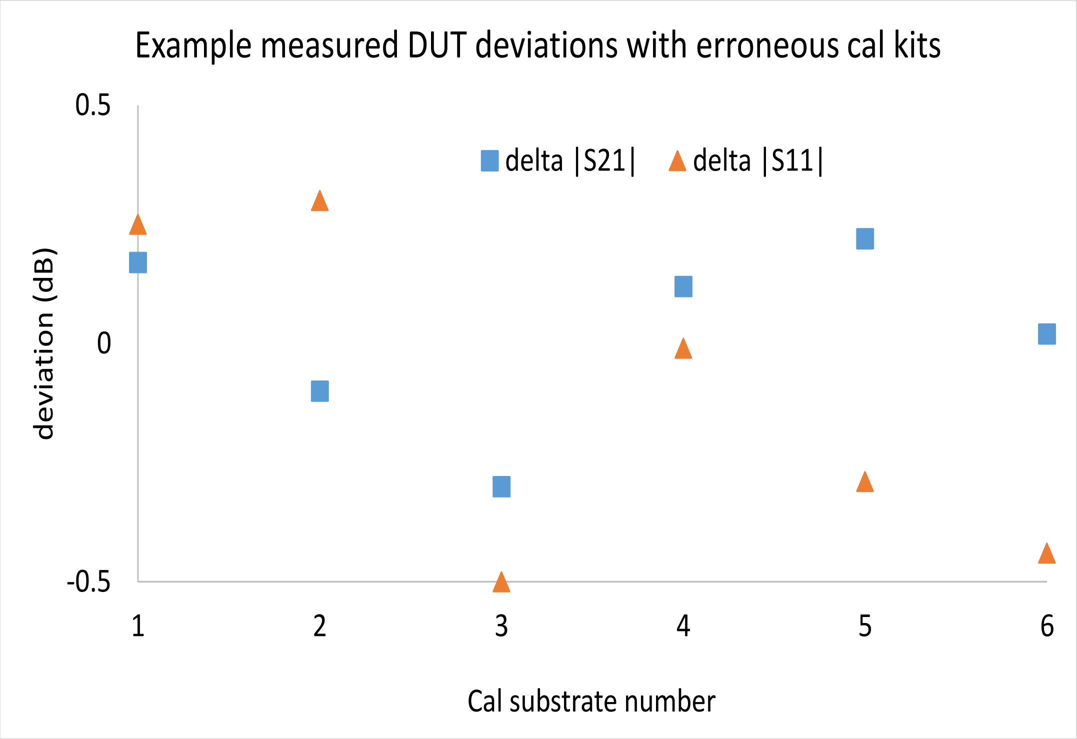
- Between multiple input parameters
  - The S-parameters interact through the calibration/de-embedding so their uncertainties may be correlated
  - Other receivers (e.g., spectrum analyzer) may have uncertainties correlated with the VNA data (e.g., similar linearity issues)

Correlation effects

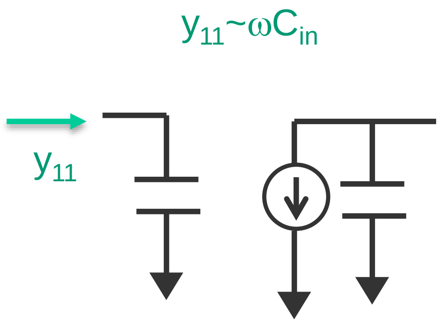
- The same DUT was measured after calibrating with a series of different (defective) calibration kits.

- Depending on the defect (offset lengths wrong, bad reference impedance…), S_{11} and S_{21} errors may move in the same of different directions.

- …and we didn't even show phase errors here.



Extraction: compact models



- Y- and Z-parameter conversions are useful since they can pull simple shunt/series circuit elements directly.
- But these transformations are nonlinear in the underlying S-parameters and sensitivities can explode in certain cases.

$$y_{11} = \frac{(1 - S_{11})(1 + S_{22}) + 2S_{21}S_{12}}{(1 + S_{11})(1 + S_{22}) - 2S_{21}S_{12}}$$

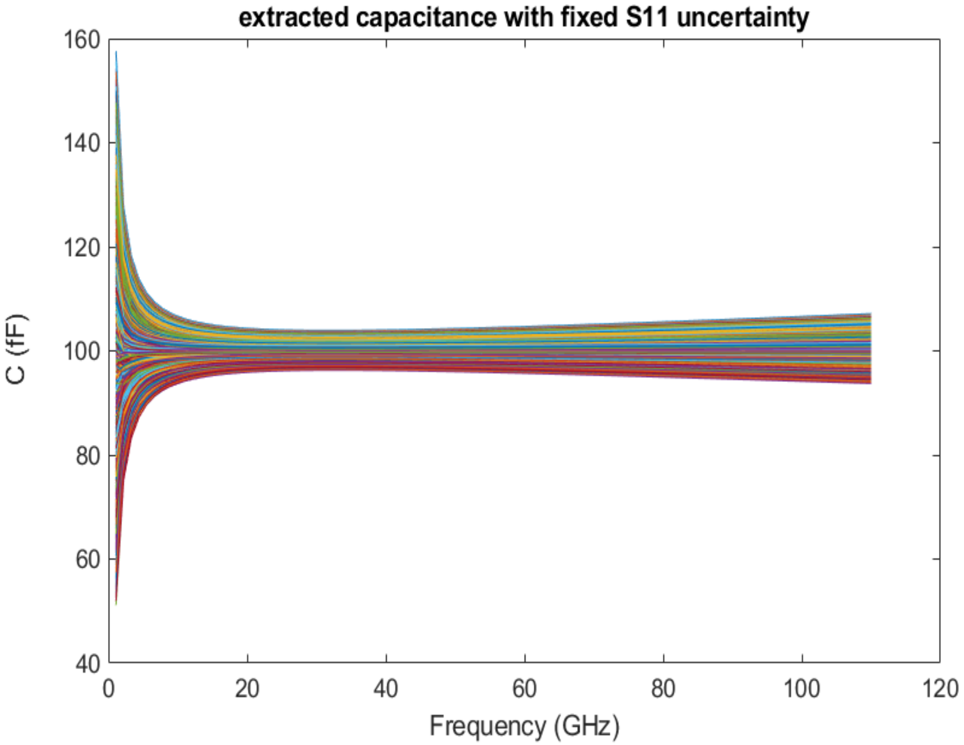
$$\frac{(\partial\, y_{11}/y_{11})}{(\partial\, S_{11}/S_{11})} = \frac{-2S_{11}}{1 - S_{11}^2}$$

Fractional sensitivity gets interesting as S_{11}-> open or short.

Extraction example: Monte Carlo uncertainties

- Even if the underlying S-parameter uncertainty was constant with frequency, the capacitance uncertainty has structure.

- In practice, reflection uncertainty is fairly constant at modest- to high-reflection levels so this approximation is ~realistic.

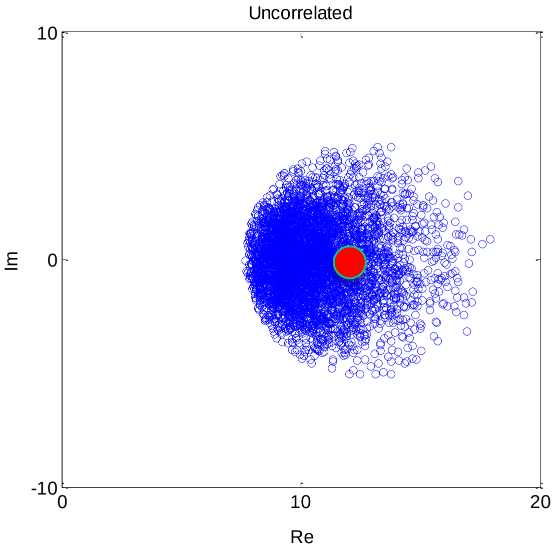


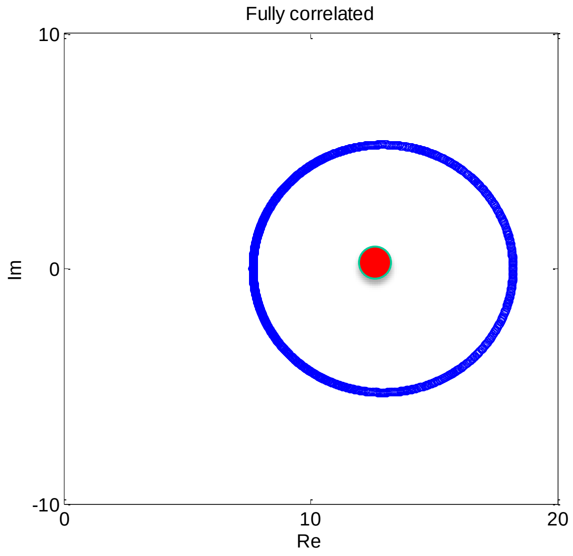
Extractions and correlation

$$z_{21} = \frac{2S_{21}}{(1 - S_{11})(1 - S_{22}) - 2S_{21}S_{12}}$$

- Even the simplest component extraction (e.g., a series inductor) might involve multiple S-parameters. How are those uncertainties correlated?

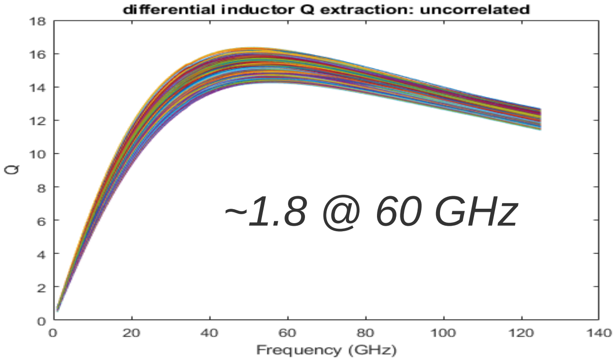
If drift/linearity dominates, the terms may be highly correlated and the distribution of uncertainty would be less favorable.



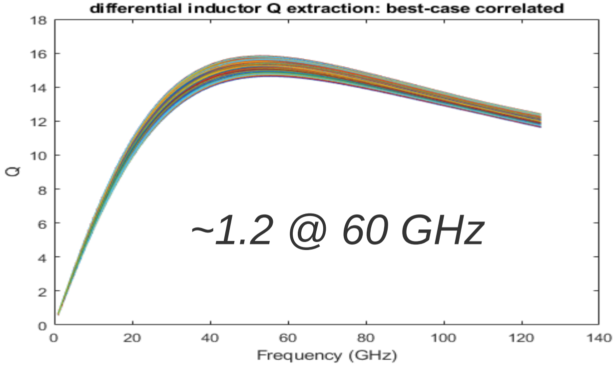


Extraction example: inductor Q

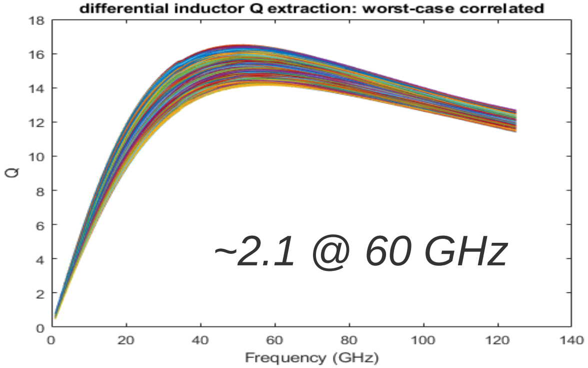
- Inductor Q ($\mathit{Im}(1/Y_{12})/\mathit{Re}(1/Y_{12})$) makes use of several S-parameters. How those uncertainties are correlated can significantly affect the Q uncertainty.



~1.8 @ 60 GHz



~1.2 @ 60 GHz



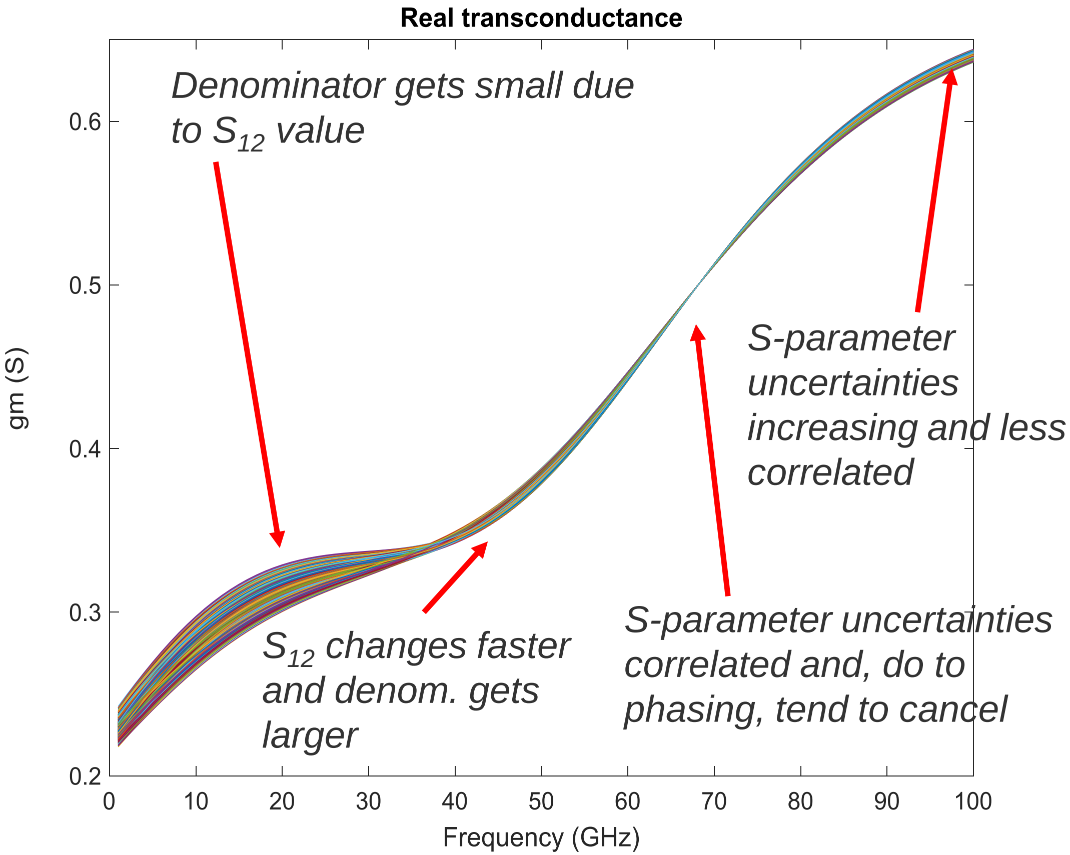
~2.1 @ 60 GHz

- Level of correlation affected by the measurement hardware choice, the parameter space, and the calibration/de-embedding choices.

Extraction example (3)

- Sometimes high frequency transconductance is extracted directly (rather than low freq. I-V data + high freq. parasitics).
- $\mathrm{Re}(Y_{21})$ can be used but S-parameter uncertainty are usually mag/phase local so interesting conversions happen.

$$y_{21} = \frac{-2S_{21}}{(1+S_{11})(1+S_{22}) - 2S_{21}S_{12}}$$



Denominator gets small due to S_{12} value

S_{12} changes faster and denom. gets larger

S-parameter uncertainties increasing and less correlated

S-parameter uncertainties correlated and, do to phasing, tend to cancel

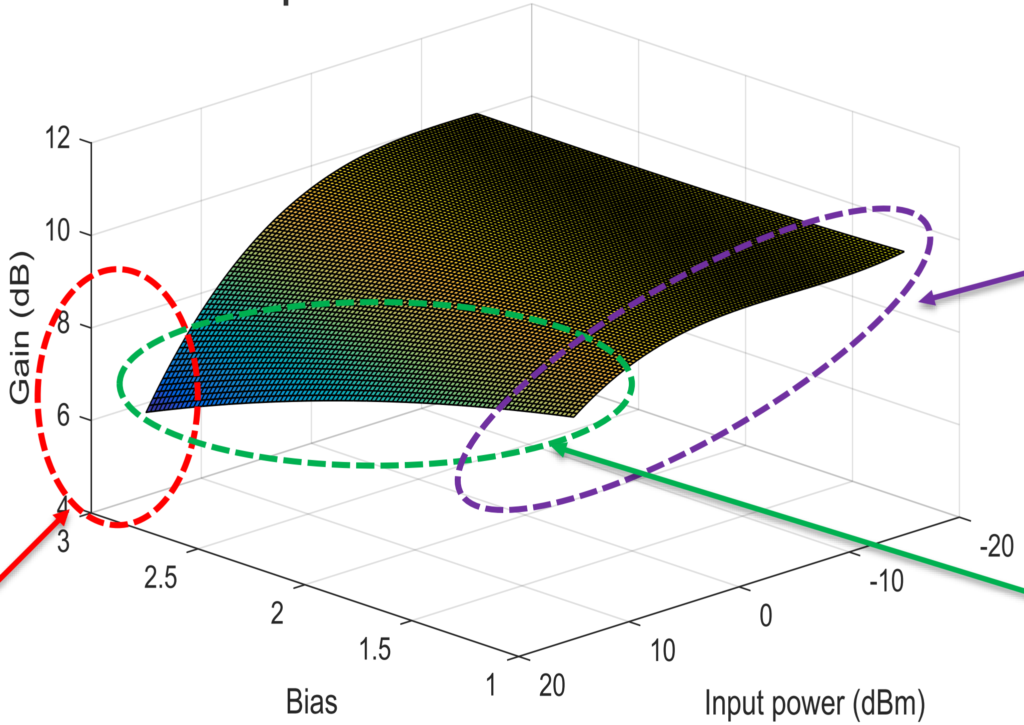
Behavioral models

- A black-box approach to modeling acquires parameters over frequency, power, bias, etc. and then uses that database (along with interpolation and extrapolation) to predict behavior elsewhere.

- How much data should be collected?
- How should interpolation and extrapolation be done?
- How do we fold in uncertainty knowledge over the response surface?

Behavioral models (2)

- A simple gain compression problem is sketched below where drive power and bias are the input variables.



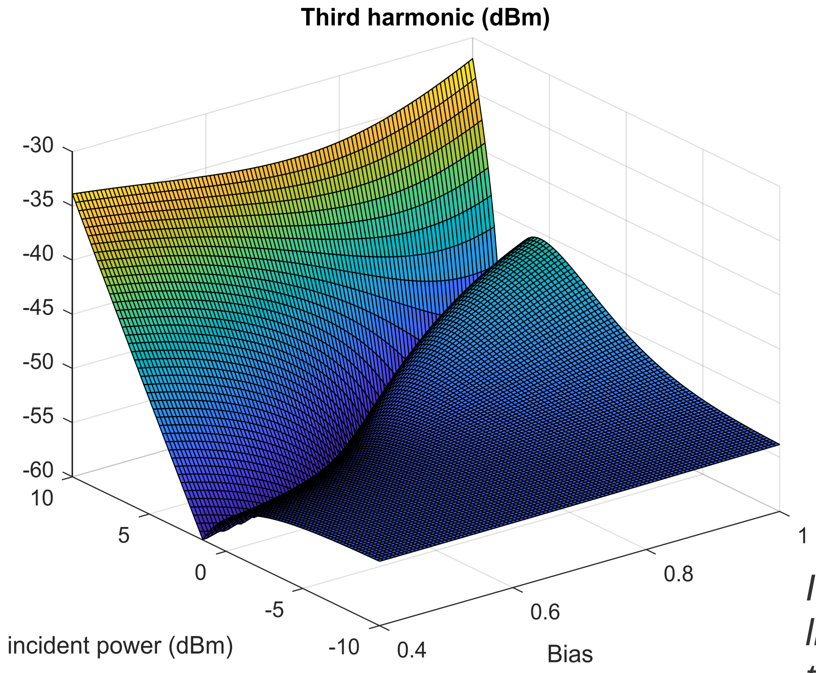
Uncertainty increase: bias instability

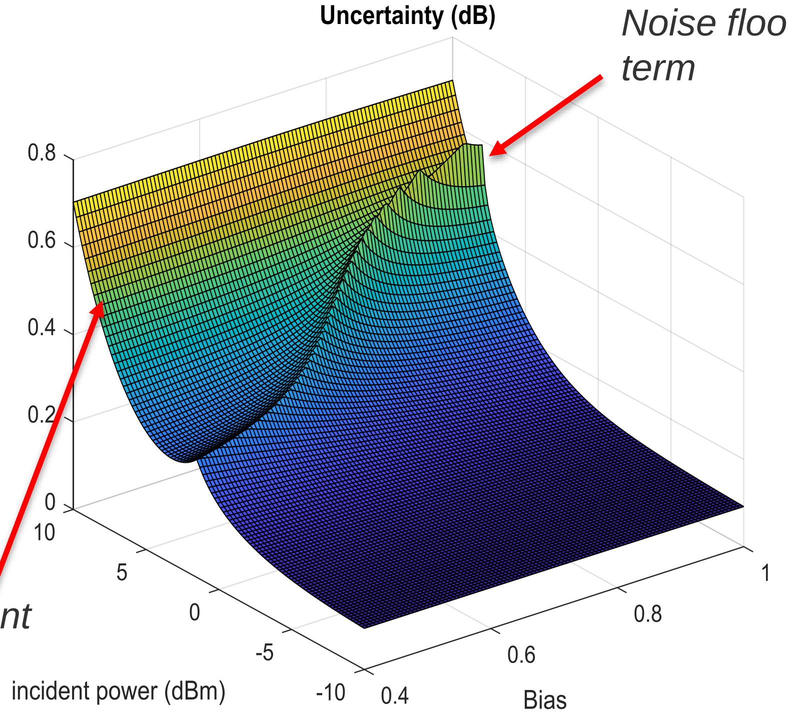
Steepest descent

Uncertainty increase: receiver compression and nonlinear match

Behavioral model example

- Interpolating/extrapolating on a complex surface can be a challenge and uncertainties may be moving differently.
- Measurement hardware configuration changes might help.



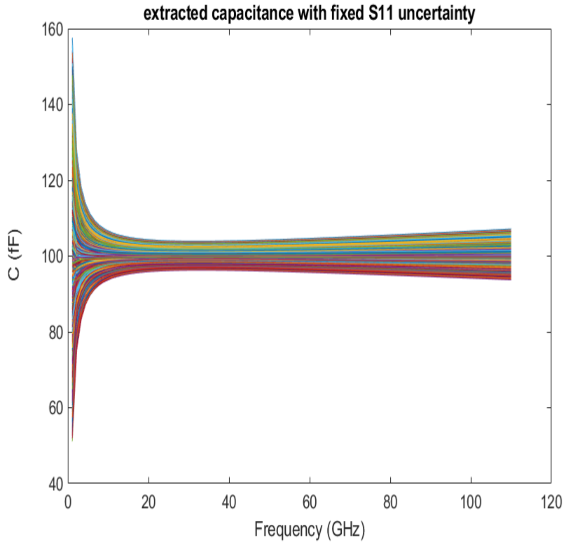


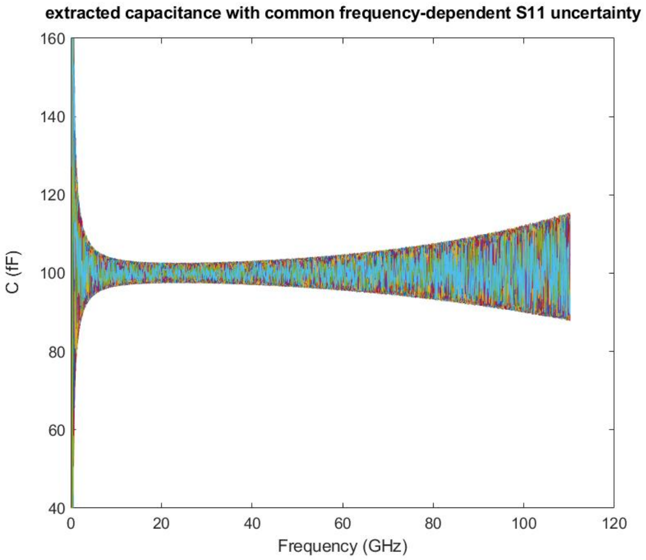
Noise floor term

Instrument linearity term

Uncertainty and sensitivity overlap

- Going back to the capacitor example with realistic uncertainties, the picture changes.
- Extreme frequencies have higher (usually) uncertainties which is where the sensitivities increase as well. Extrapolation-based processes can be impacted.


extracted capacitance with fixed S11 uncertainty

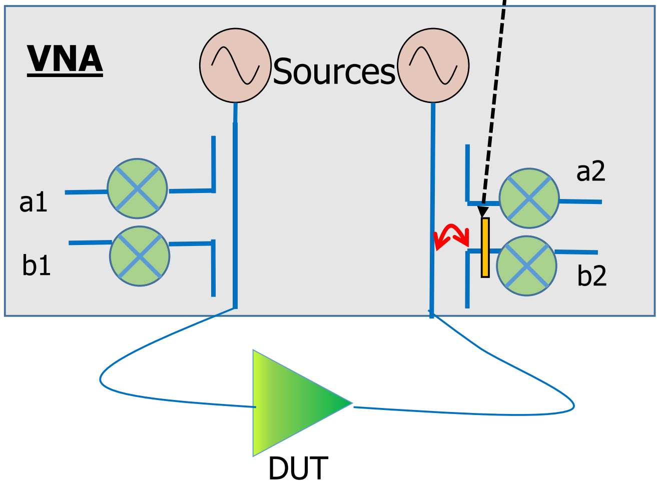

extracted capacitance with common frequency-dependent S11 uncertainty

Some mitigation strategies

- Some care may be needed when asymptotic or extrapolated values are of interest.
- Optimize the signal level, when free to do so, to improve uncertainties.
- Choose calibration/de-embedding processes that do not add correlation where it would be problematic. *(don’t always know in advance…)*
- Measurement hardware choices: may affect uncertainty directly or may change correlation levels.

Mitigation strategies: signal level control

- Passive devices:
  - Generally increasing drive level to near the point of trace noise-compression crossover can help
- Active Devices:
  - May be a cap on the drive level to ensure DUT linearity (dynamic range challenge: additive noise)
  - Receiver sensitivities can sometimes be altered (signal path changes, attenuation choices)
- Other measurement parameters that may be relevant: measurement bandwidth (of course), synthesis modes (that can affect phase noise)…

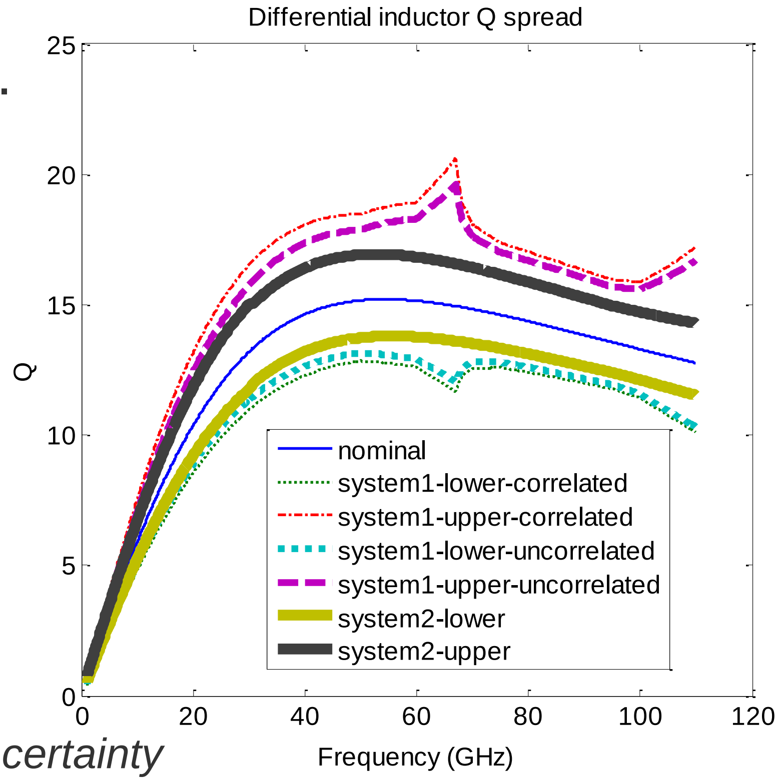


Coupling inversion and gain/attenuation addition are available tools.

Mitigation strategies: correlation control

- Some hardware uncertainty terms (drift and linearity) foster more correlation between parameters than others (noise).

- Certain calibration/de-embedding approaches also more tightly correlate individual parameters (TRL family more so than defined-standard family).

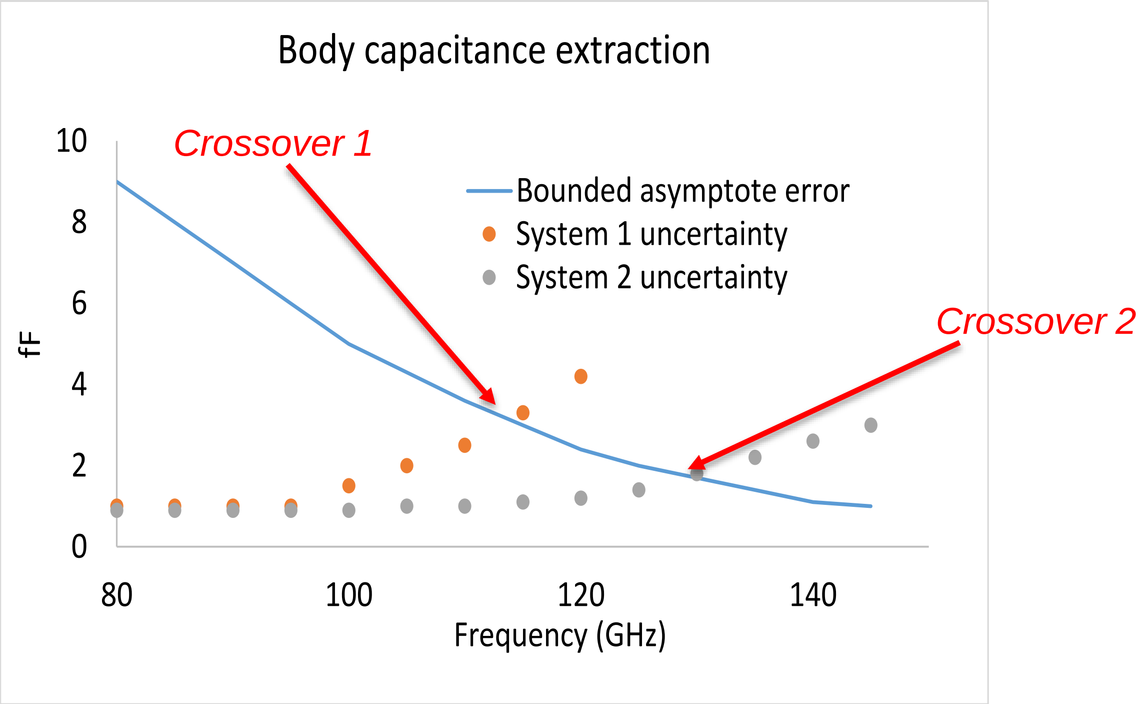


System 1 uncertainty was drift-dominated. System 2 uncertainty was noise-dominated and correlation had little effect.

Mitigation strategies: Asymptotic analysis

- Some extractions rely on 'high' or 'low' frequency data so other parasitics can be neglected.

- The measurement uncertainties might increase at those limits. Make a decision on what data to use.



Summary

- Many different model extraction techniques are popular and all interact with underlying data uncertainties in different ways.

- Mm-wave measurements are generally more challenging to begin with so the uncertainties may play a greater role.

- Quantifying those uncertainty mechanisms is somewhat easier than in the past and allows a better exploration of the parameter spaces and can improve model extraction.