Fixture De-embedding Techniques and Tools using VNA

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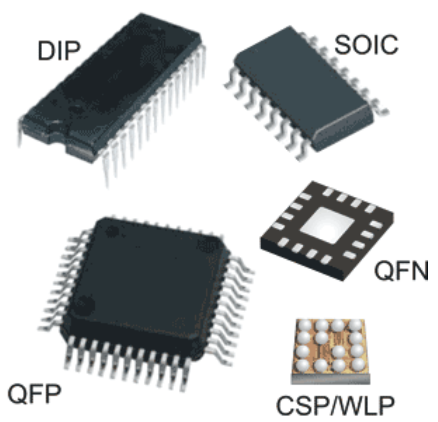
03/16/2023

Agenda

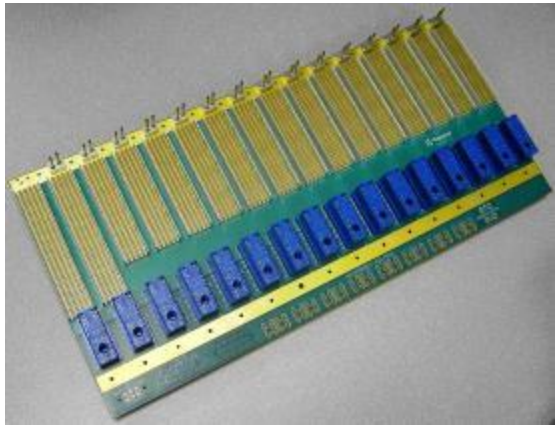
- Background and Simple “fixes”
- Calibration Techniques
- De-embedding Techniques
- Results
- Keysight Automatic Fixture Removal (AFR)
- Analysis Software: Keysight Physical Layer Test System (PLTS)

Measurement Challenges



IC packages

USB connector



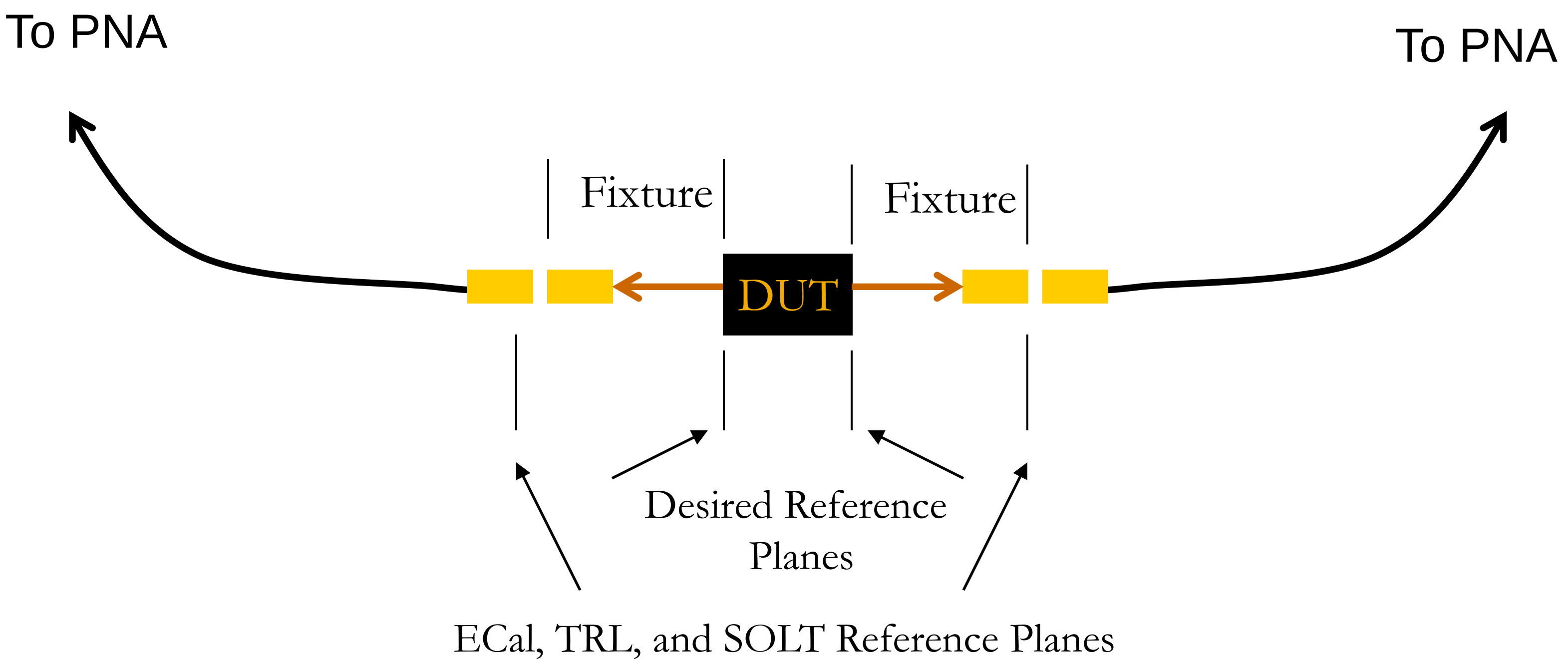
Backplane

- Linear passive interconnect devices often have non-coaxial connectors, so they cannot be connected to test instruments with coaxial port connectors

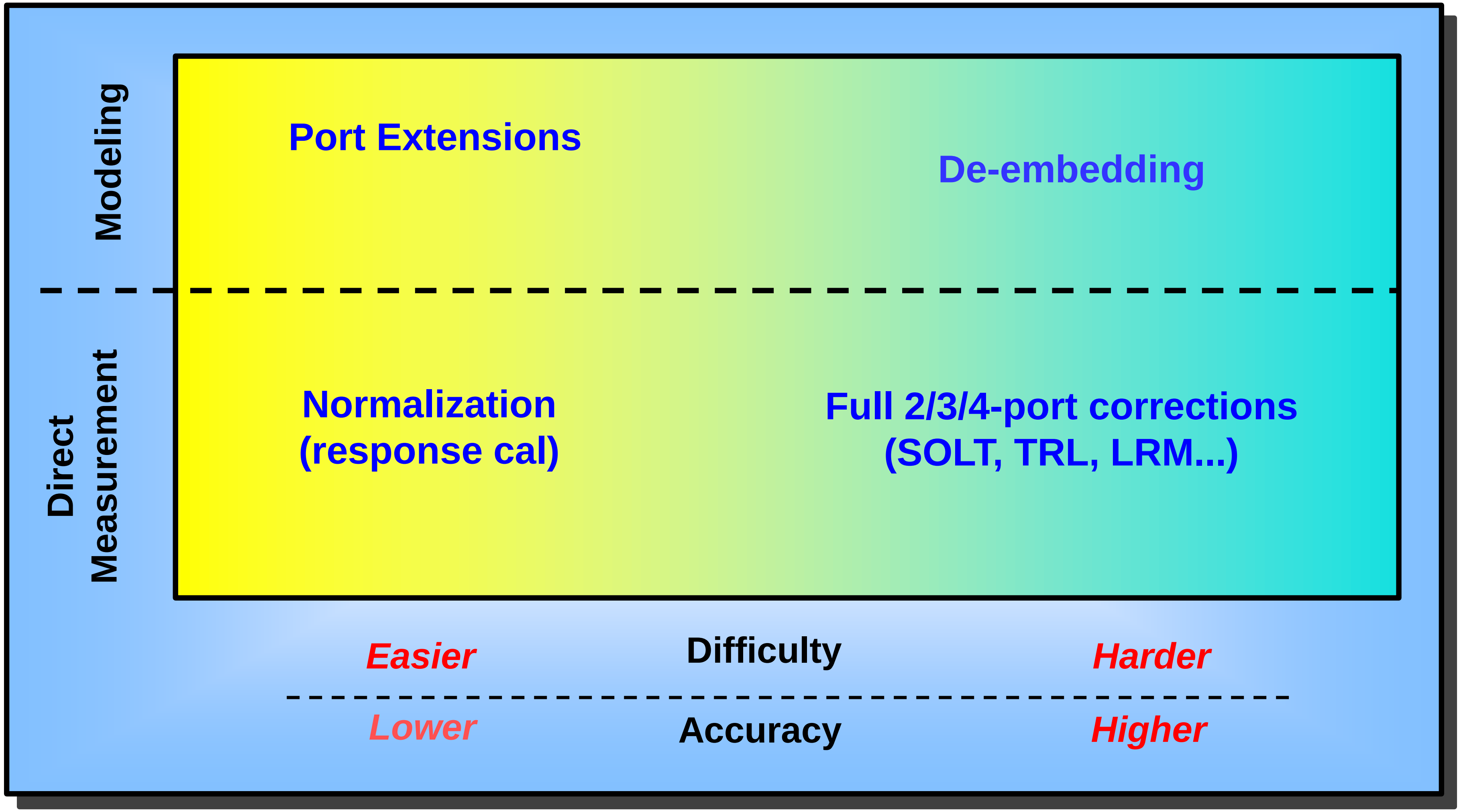
Why Remove Fixtures?

- Understand the performance of a device that needs a fixture to be measurable
- Model correlation
- Reduce overall test time

Calibration Reference Planes



Reference Plane Adjustment Techniques



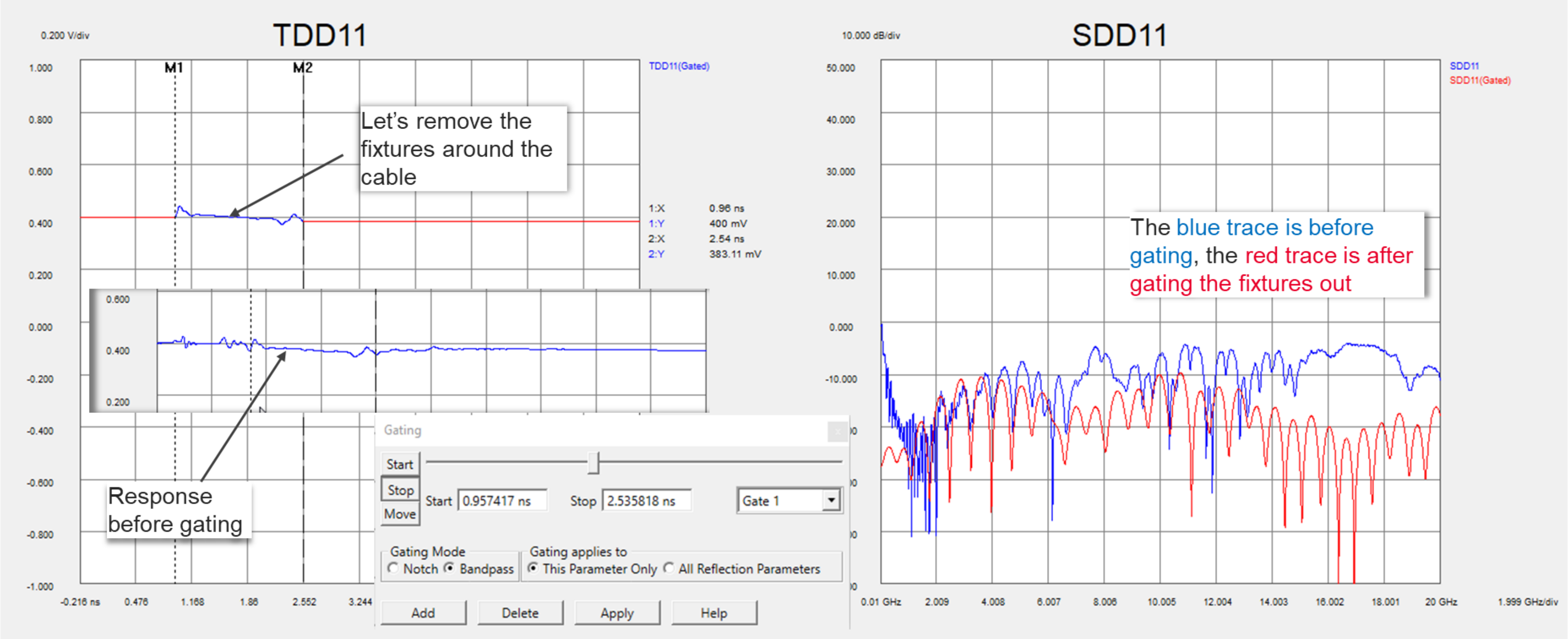
Background and Simple “fixes”

Normalization

- Data & MEMORY OPERATIONS
  - A very quick way to zero out a reference or remove the loss associated with cables from
  - Able to see variations between a reference and other samples
  - In most cases equivalent to Data ÷ Memory
  - Advantages
    - Quickly see variations between devices
  - Disadvantages
    - Only a single term correction
    - Does not usually interpolate well if frequency range is changed

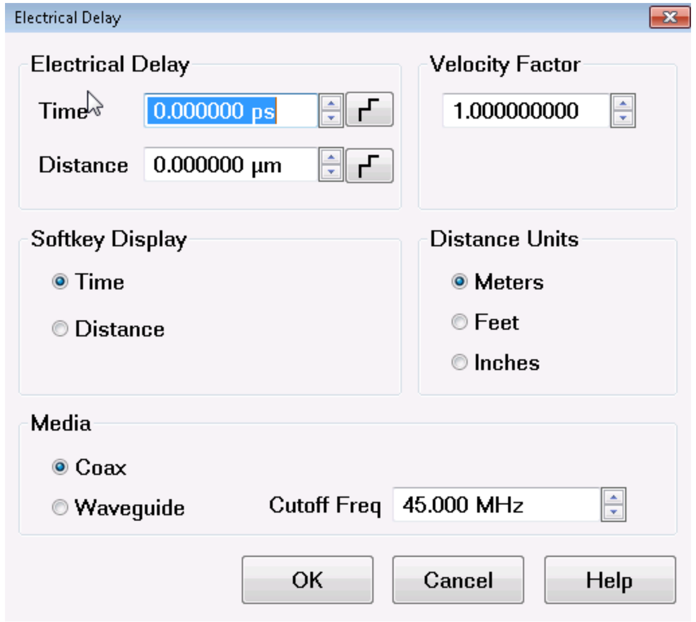
Time Domain Gating

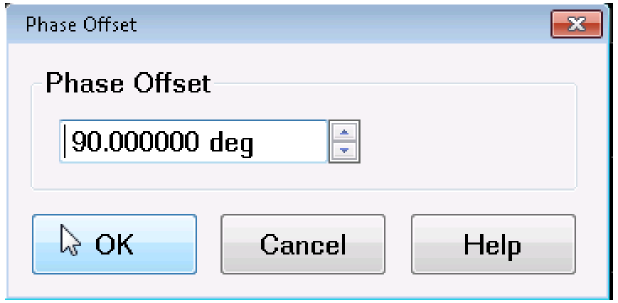
- Gating is a process in which the frequency domain data is converted to time domain and the user can select to either gate in a specific region or gate out a specific region in time and replace the rest with a perfect transmission line
- The gate only applies to the specific measurement parameter that is being acted upon
- Saving a file after gating for modeling will lead to erroneous results since the other parameters have not be adjusted to account for the what has been removed using the gate
- This is a decent “what-if” analysis tool, but repeatability in gate placement leads to measurement uncertainty

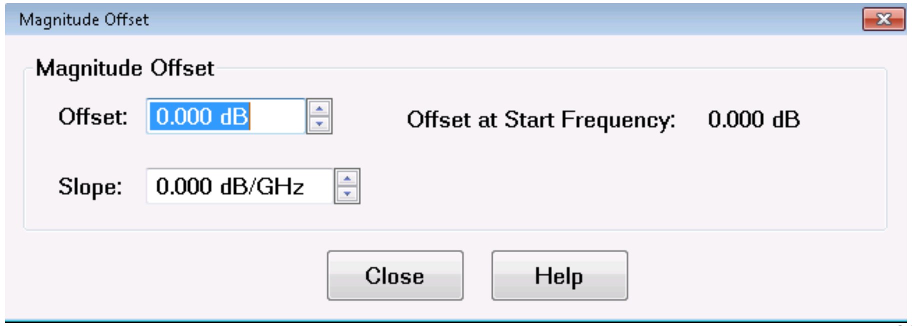


Offsets

- Manual offset of Amplitude, phase, & Electrical delay
- A brute force offset for either phase or amplitude
  - e.g. correcting for a 10 dB attenuator offset
- Magnitude offset is usually a single scalar value with an optional slope on a measurement
- Phase offset is a single value up to 360 degrees on a measurement
- Electrical Delay specifies the value of delay added or removed, in Time or Distance. This compensates for the linear phase shift through a device. Each measurement can have its own value.





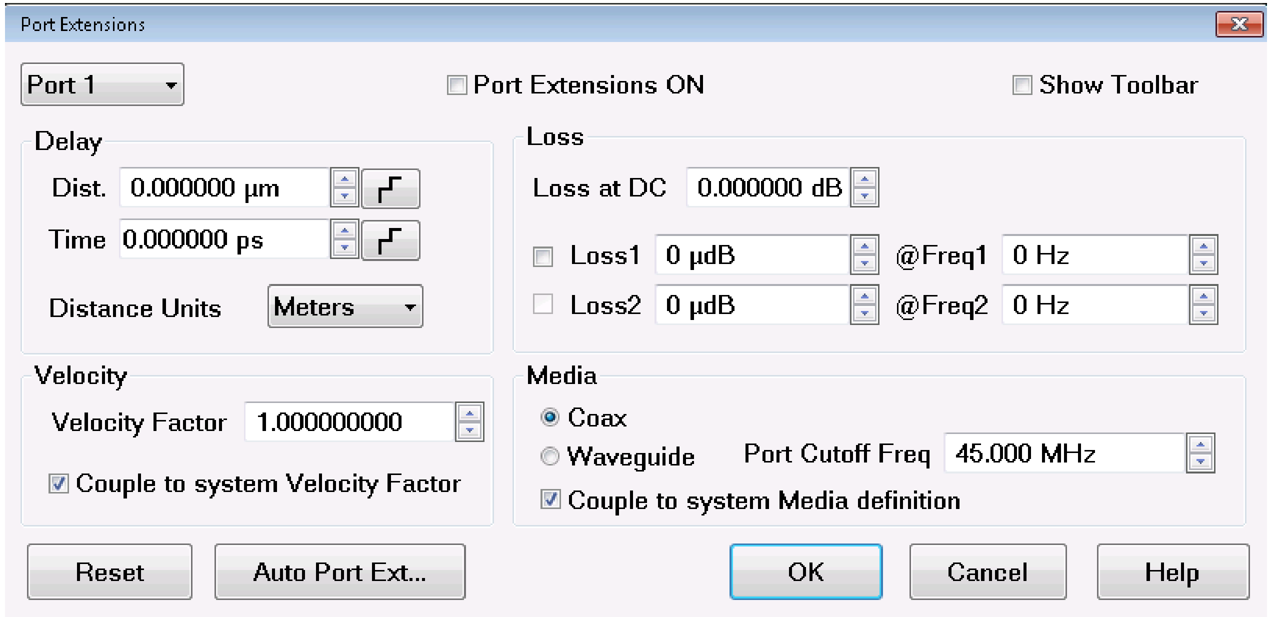


Summary of Offsets

- Advantages
  - Extremely easy to use
  - No standards needed
  - Available on VNAs that are fairly old
- Disadvantages
  - Prone to user error
  - No real standards used to verify performance
  - Only an offset that may or may not allow for a slope

Port Extensions

- The manual type
- Allows the user to manually set the distance or time to extend from the calibrated reference plane.
- The extension is based on a linear phase response
- User can include single or two point loss calculation
  - Two point calculation assumes a linear slope



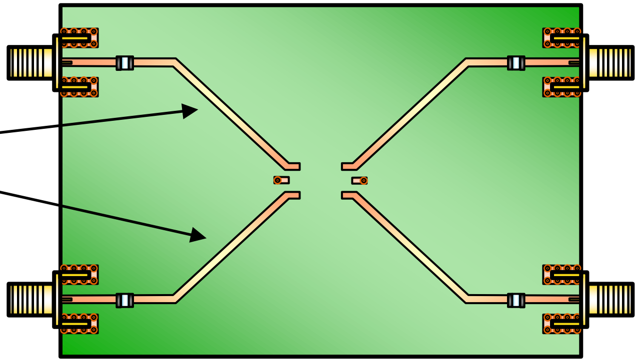
Summary of Port Extensions

- Advantages
  - Extremely easy to use
  - No standards needed
  - Available on VNAs that are fairly old
  - Can include insertion loss and return loss corrections
- Disadvantages
  - Prone to user error
  - No real standards used to verify performance
  - Error associated with linear assumptions for loss

APE = Automatic Port Extensions

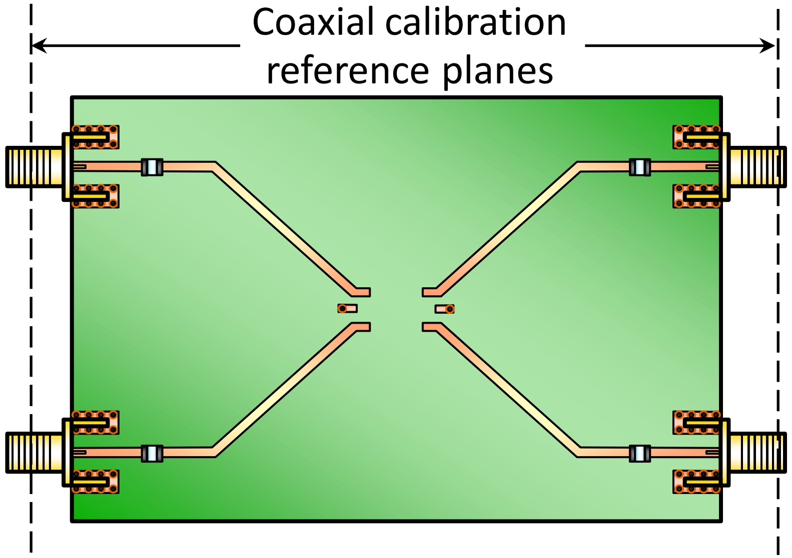
- First solution to apply both electrical delay and insertion loss to enhance port extensions
- First approach to give reasonable alternative to building in-fixture calibration standards or de-embedding fixture

APE accounts for loss and phase of fixture transmission lines

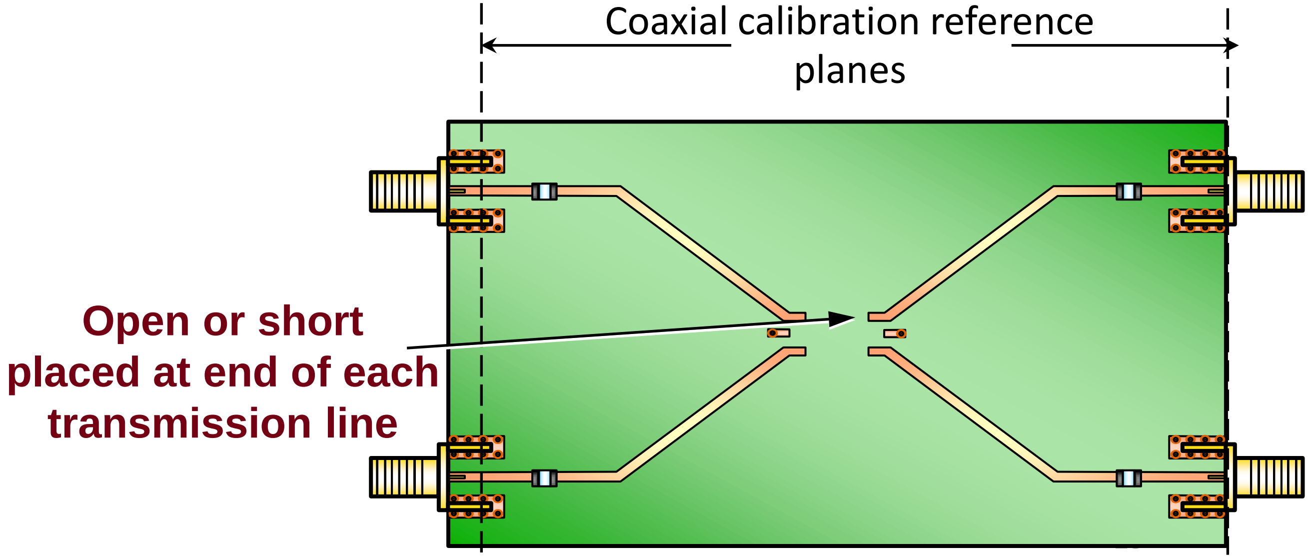


Automatic Port Extensions

- First, perform coaxial calibration at fixture connectors to remove errors due to VNA and test cables
- At this point, only the fixture loss, delay and fixture mismatch remain as sources of error.



- After coaxial calibration, connect an open or short to portion of fixture being measured
- Perform APE: algorithm measures each portion of fixture and computes insertion loss and electrical delay
- Values calculated by APE are entered into port extension feature
- Now, only fixture mismatch remains as source of error (dominated by coaxial connector).



Summary of Automatic Port Extensions

- Advantages
  - Ideal for in-fixture applications where
    complete calibration standards are not available
  - Eliminate the need to design and build difficult load standards
  - Applicable to a wide range of fixture designs
  - Works with probes too
  - Easy to use and quick to get results
- Disadvantages
  - Does not correct fully for mismatch
  - Loss profile has to have a linear response
  - Does not yield a way to use in other tools
  - Number of standards necessary depends on bandwidth of the device

Calibration Techniques

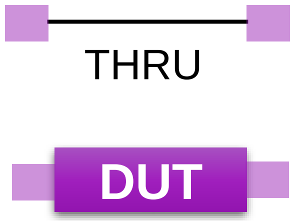
SOLT Calibration

- Types of Calibration

UNCORRECTED

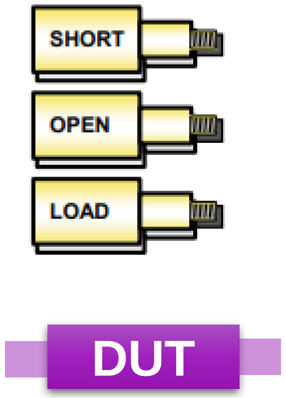
- Convenient
- Generally not accurate
- No errors removed

RESPONSE



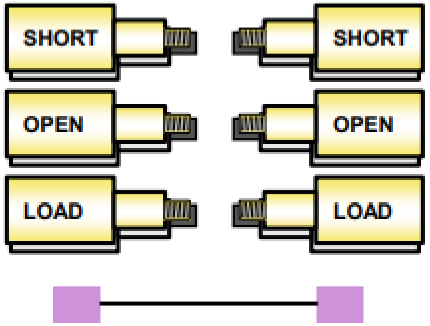
- Easy to perform
- Use when highest accuracy is not required
- Removes frequency response error

1-PORT



- For reflection measurements
- Need good termination for high accuracy with 2-port devices
- Removes these errors:
  - Directivity
  - Source match
  - Reflection tracking

FULL 2-PORT



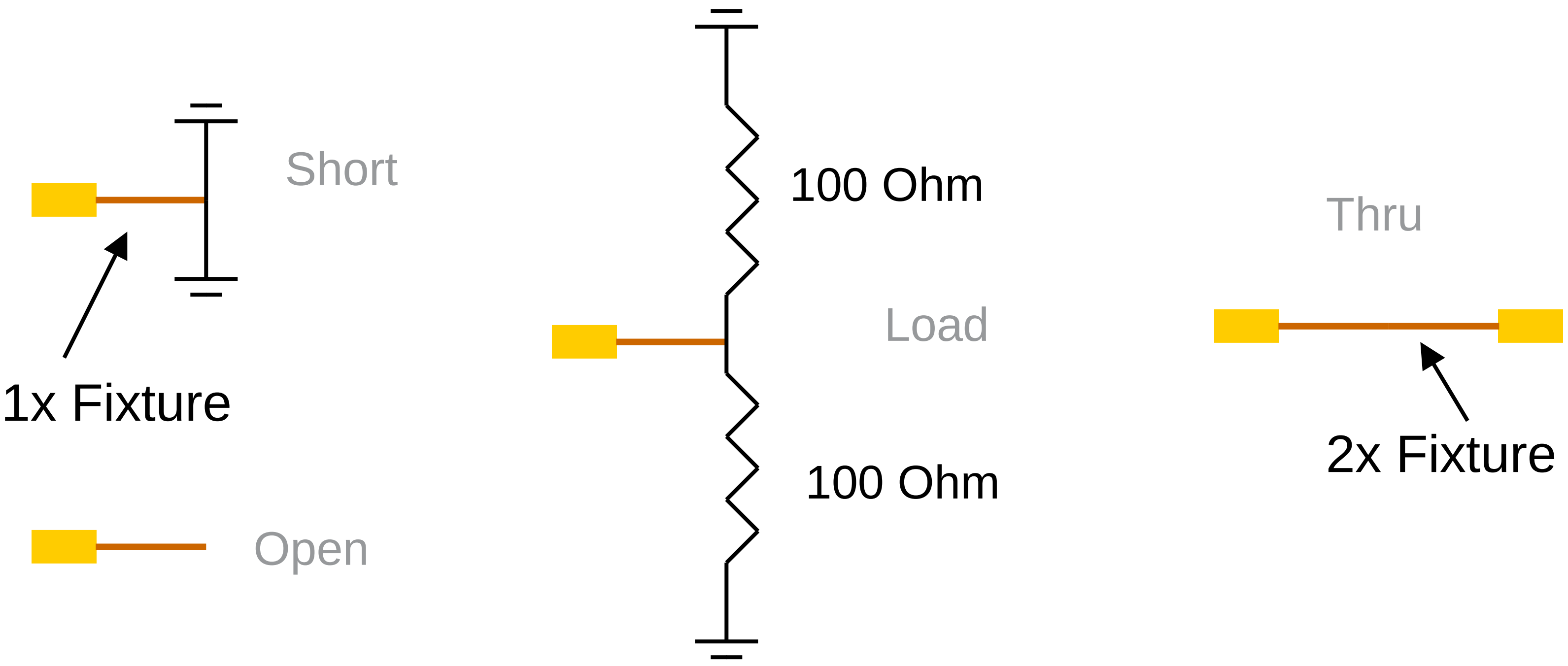
Defined Thru or Unknown Thru

- Highest accuracy
- Removes these errors:
  - Directivity
  - Source/load match
  - Reflection tracking
  - Transmission tracking
  - Crosstalk (limited by noise)

ENHANCED RESPONSE

- Combines response and 1-port
- Corrects source match for transmission measurements

SOLT Fixture Cal Kit

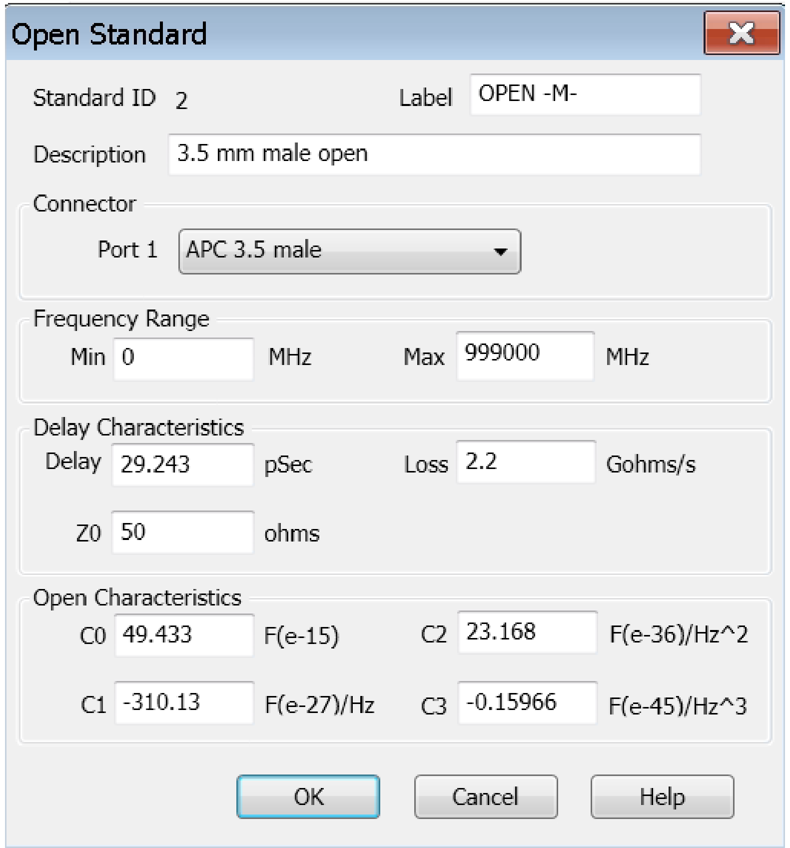


- Model JUST the fringing Capacitance and Inductance from via
- The higher the frequency the more difficult this is – especially in PCB material.

SOLT Calibration

- Short Open load thru

- In the simplest world: $\Gamma = 1\angle 180$, $\Gamma = 1 \angle 0$, $\Gamma = 0$, IL = 0 dB $\angle$ 0
- In reality (modeled with polynomial):
  - Short: $L_0 + L_1 * freq + L_2 * freq^2 + L_3 * freq^3$
  - Open: $C_0 + C_1 * freq + C_2 * freq^2 + C_3 * freq^3$
  - Load: Hard to make a good high frequency load.
    - Either suffer uncertainty at higher frequencies,
    - model with an additional Inductor,
    - or use sliding load.
  - Databased:
    - More accurate than polynomial



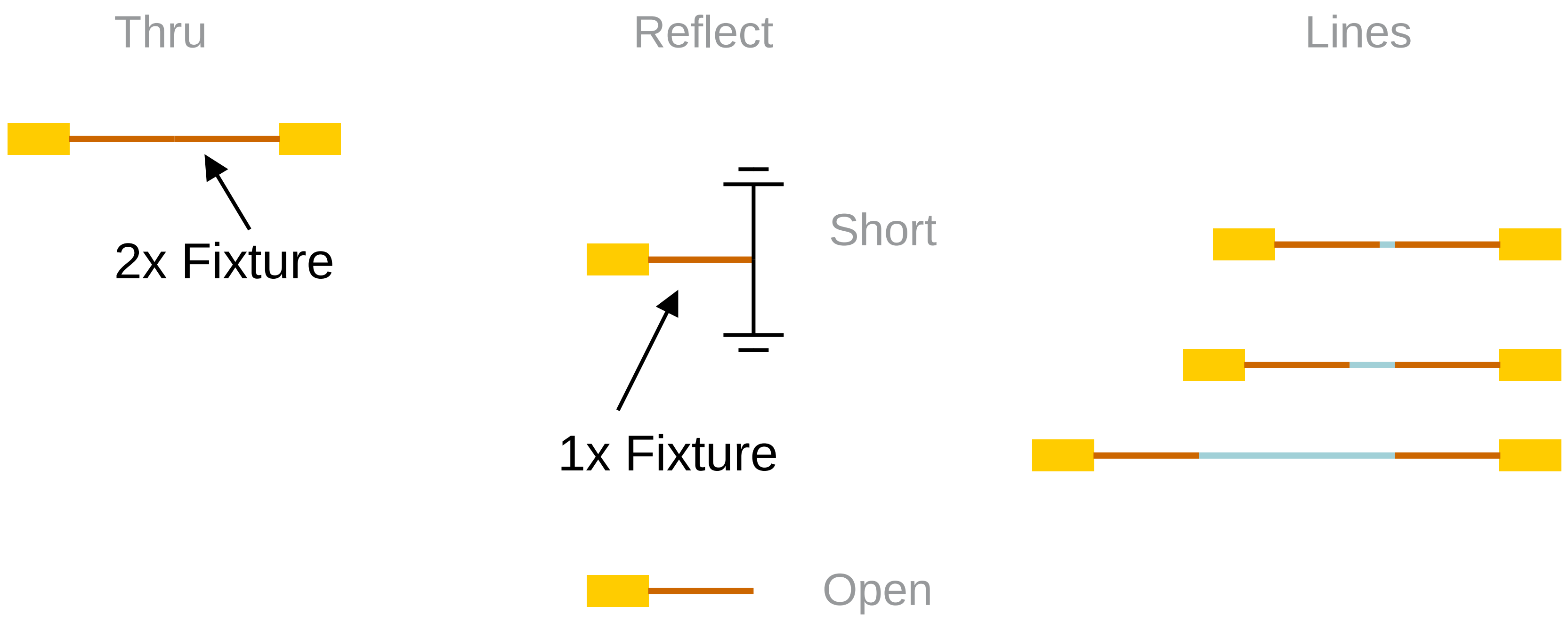
Summary of SOLT Fixture Cal Kit

- Advantages
  - Simple first order model can be completed with ease, but not as accurate
  - Good for low frequency fixtures (< 1GHz)
- Disadvantages
  - Difficult to model standard parameters for polynomial model
  - Hard to build a broadband termination in most fixtures

TRL Calibration Kits

- Generally preferred over SOLT for non-coaxial fixtures
  - Modeling on the open, and short is not required
- Cal kit must be fabricated on the same panel as the fixtures.
  - Assumes identical connectors and launches
  - Lines are identical except for length
  - Lines are useable from 20 to 160 degrees (8:1). More common: 30 to 150 deg (5:1)
  - Thru is 2x Fixture
  - Reflect is 1x Fixture
  - Typically set the reference plane in middle of thru

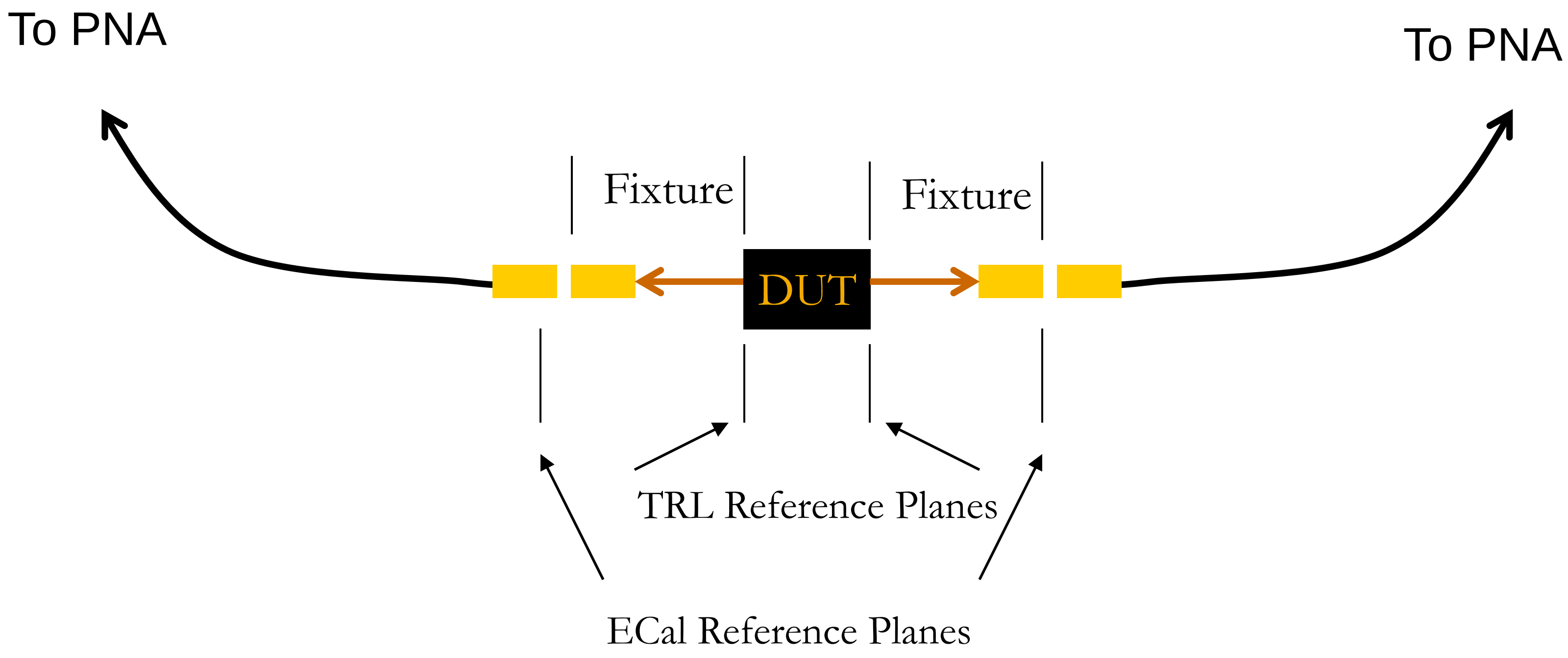
TRL Fixture Cal Kit



Reflect – Usually does not need to be modeled
Load - Is used for low frequencies only (< 200 MHz)

Calibration Reference Planes

- TRL Calibration



Summary of TRL

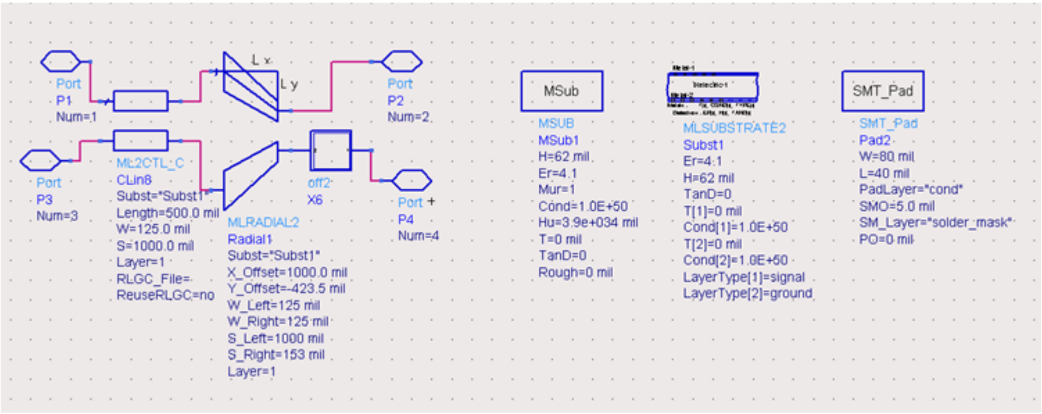
- Advantages
  - Open and/or Short models are not required
  - Fairly simple to define, build, and characterize
  - Preferred over SOLT
  - Can morph into TRM, LRL, and LRM mixed calibrations based on available standards
  - Can be utilized for both low frequency and high frequency fixtured applications
- Disadvantages
  - Non matching standards per port can be an issue with consistent performance
  - Consistency between line standard impedances can cause steps in return loss data
  - Consistency between line standard impedances will add measurement uncertainty
  - TRL kit not matching fixture will add uncertainty and can create non-causal responses

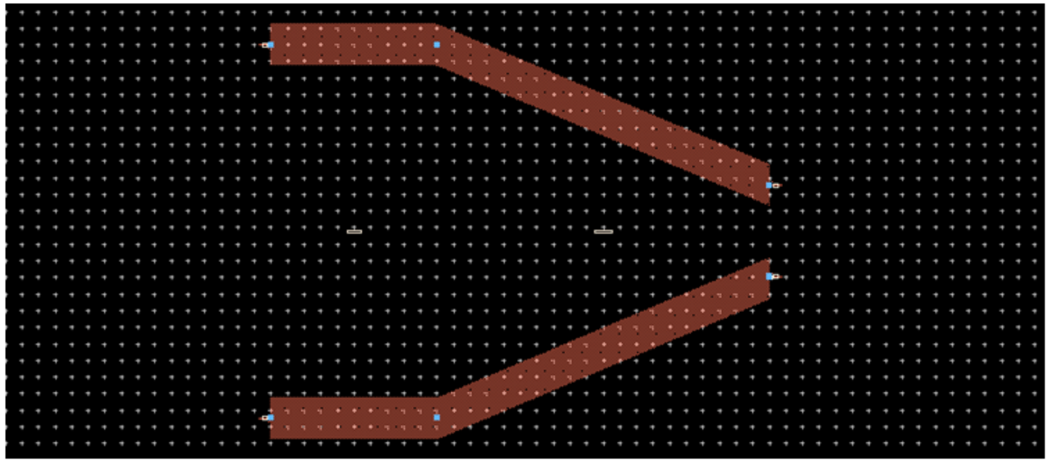
De-embedding Techniques

De-embedding Techniques

- Simulation based de-embedding

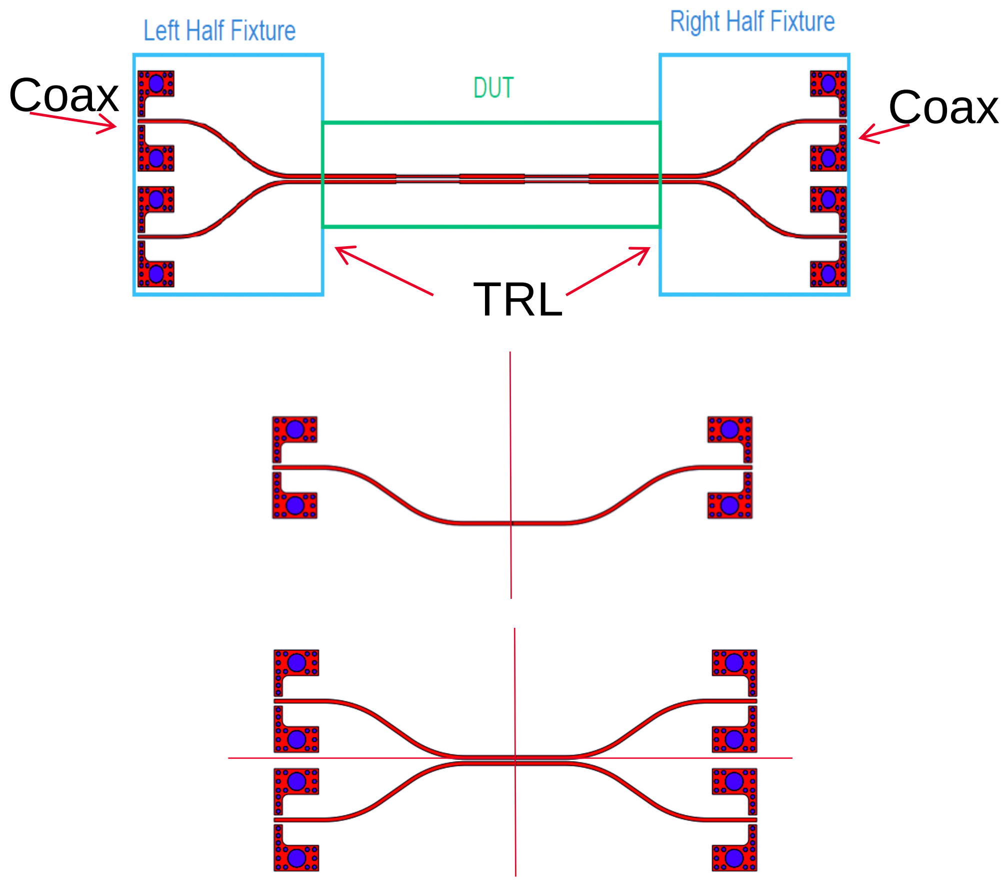
- When measurements of the fixture(s) are not available and the fixture was simulated, the simulator can create S parameter files that can be used to de-embed the fixture(s).
- The accuracy depends on the accuracy of the simulation matching the actual built fixtures.
- This is a very good way to test out different algorithms.
- This should be an iterative process until the model matches the initial measurements or the continue turning devices until the fixture matches the model





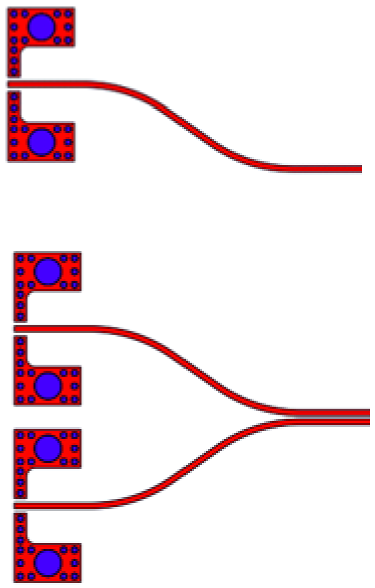
De-embedding Techniques

- 2x Thru de-embedding
- There are methods for taking a single ended or differential 2X Thru and mathematically “cutting the measurement in half” and creating accurate S parameter models for each fixture.
- Traditionally, it required symmetric fixtures and low mode conversion for differential fixtures. These are no longer requirements due to advancements in de-embedding methods such as AFR.
- Recent versions also used the actual fixtured DUT to improve the model when it is different from the 2x Thru.



De-embedding Techniques

- 1x Reflect de-embedding
- 1X Reflect (open or short) was developed after the 2X thru.
- Note the Open must not radiate
- It is slightly less accurate at the current development than the 2X thru, but the accuracy is generally more than enough for most cases.
- It is very convenient. A board with multiple “fixtures” can be quickly characterized before loading the DUT

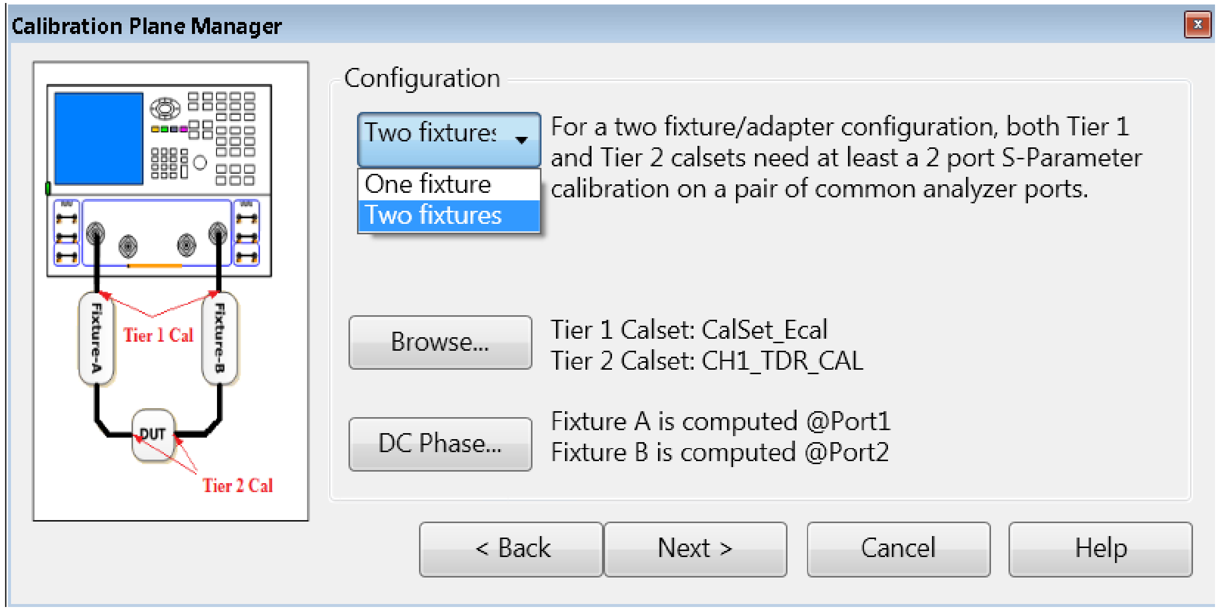


Open or Shorted Fixtures

De-embedding Techniques

- Cal Set Subtraction – Calibration Plane Mgr

- The Calibration Plane Manager (CPM), subtracts 2 calsets to create a S parameter file of the fixture(s).
- The first tier calibration is done at the end of the cables – before the fixture.
- The second tier calibration is done at the DUT reference planes. Usually this is either a TRL cal or Probed cal.
- Once you have the fixture de-embed files, simple calibrate at the end of the cables, measure the fixtured DUT and then de-embed the fixtures. Resulting in just the measurement of the DUT.
- Post processing de-embedding can also be done with Keysights PLTS Software.



Results

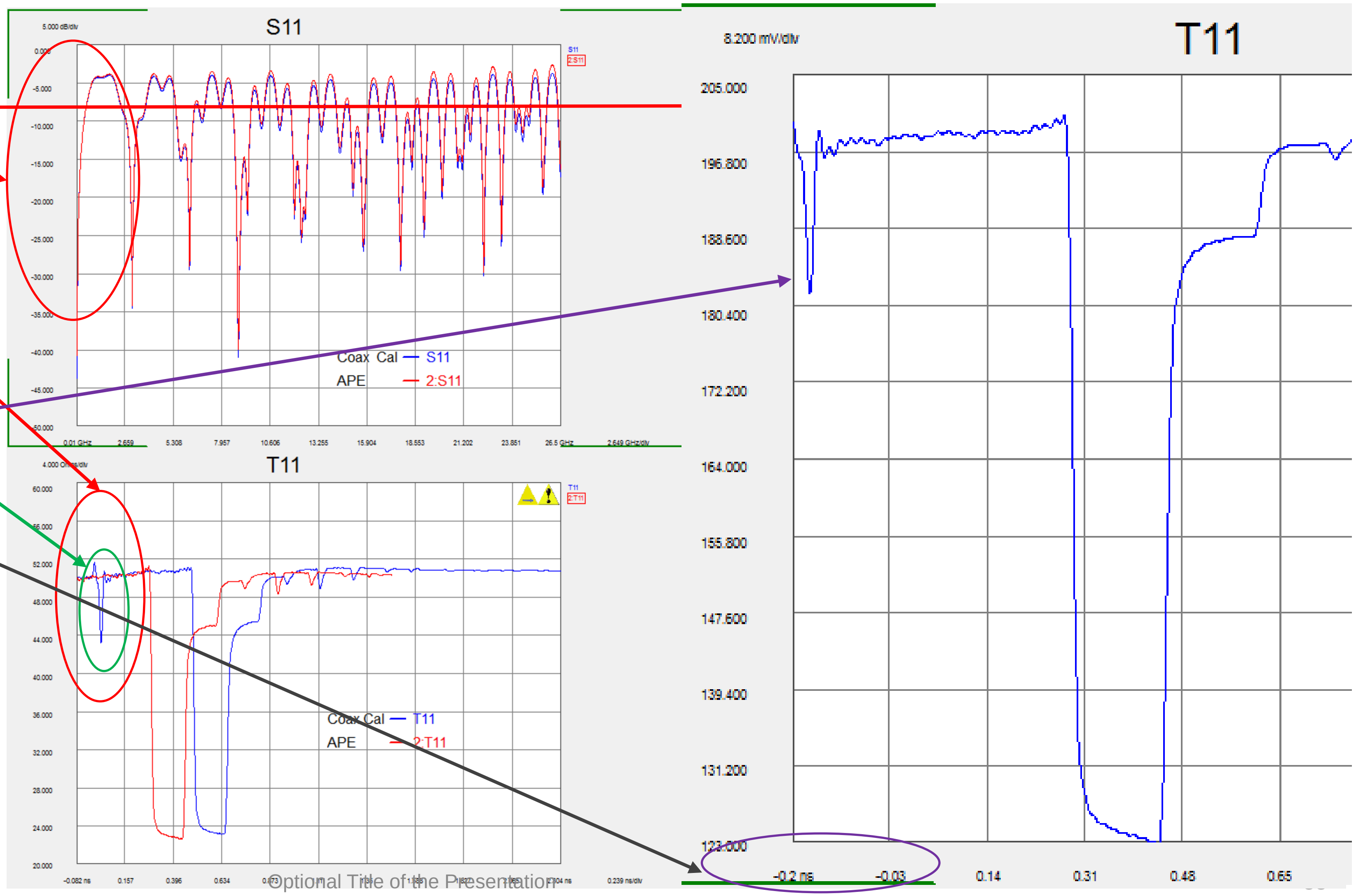
Accuracy and Repeatability Concerns

- When using a file to de-embed, the response is only valid as long as the de-embedded structure remains constant
  - For devices that have return loss changes due to multiple connections or excessive wear, the de-embed file creation process needs to be completed more often
  - It helps to have an understanding on when the de-embedding tolerance change will impact the measurement of the device to a point where the data is no longer useful
- The de-embed is only as good as the file (e.g. garbage in – garbage out)
- Take time to make sure the de-embed file makes sense
  - Watch for radiation on the 1x reflect based de-embedding
  - Verify calibrations with the cal set subtraction process
  - Watch for symmetry and excessive loss with the 2x thru based de-embedding

Comparison (measurement based)

- Stripline Beatty – Automatic Port Extensions

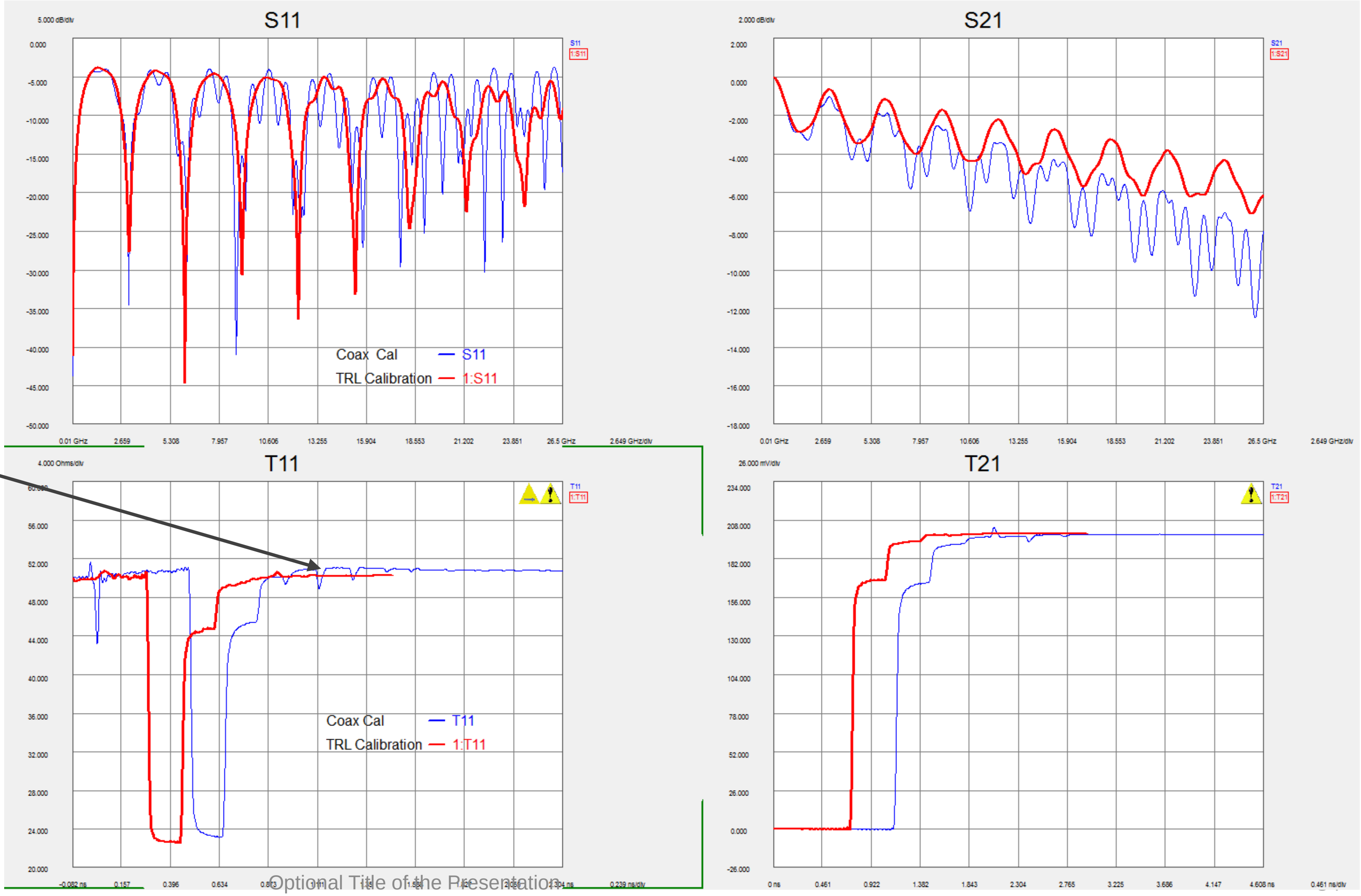
- Fixture Loss and length removed.
- Via appears to be gone but effects were Not removed
- Via was moved to negative time



Comparison (measurement based)

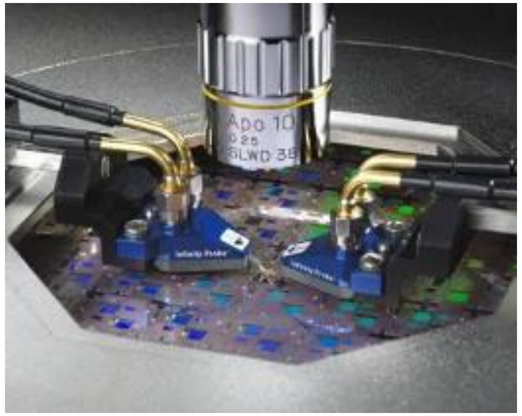
- Stripline Beatty – TRL Calibraton

- Fixture has been removed. More recognizable Frequency domain ripple patterns.
- Time domain much cleaner without the glitches.



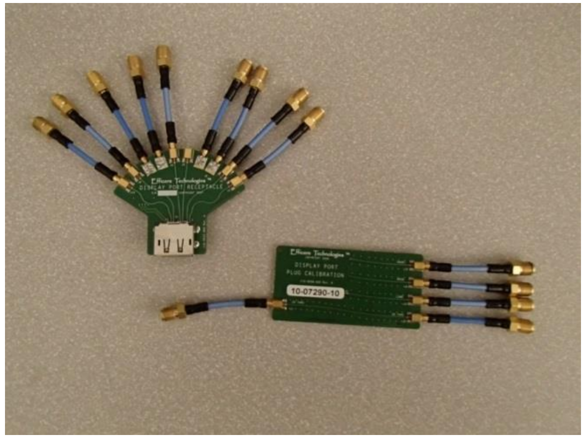
Keysight Automatic Fixture Removal (AFR)

Traditional Methods of Measuring Non-coaxial Devices



Probing on the device for measurement

Drawback:
1. Probe station is expensive
2. Need probe cal kit and models for probe calibration



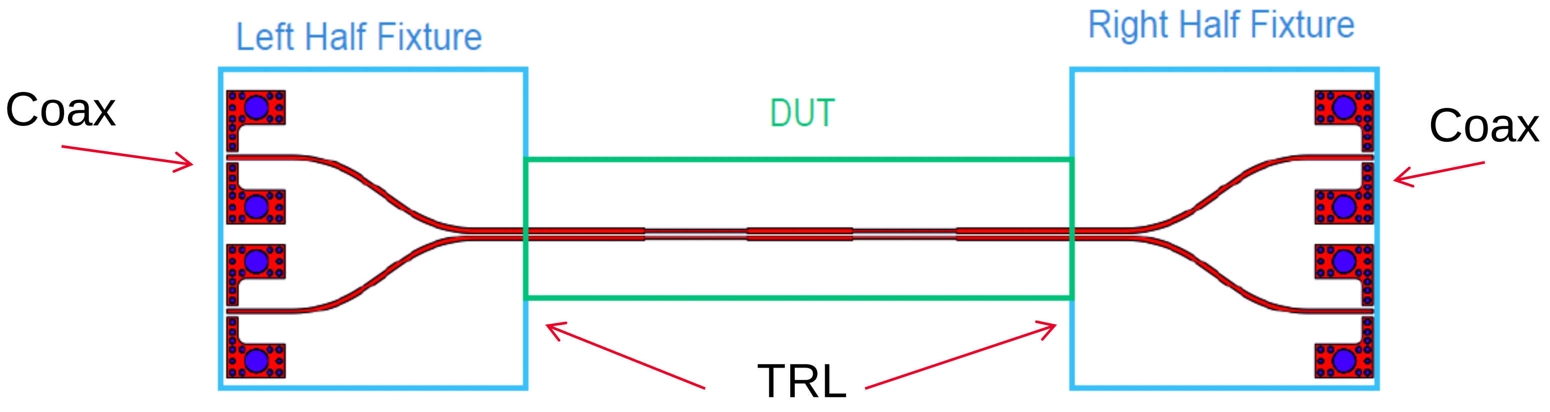
Building test fixtures for coaxial to microstrip/stripline transition

Drawback:
1. The fixtures are not electrically transparent, they have mismatch, loss and delay, they need to be characterized and removed from the DUT measurement
2. The fixtures also have non-coaxial connectors and cannot be measured directly

We'll focus on solving fixturing problem in this presentation

Traditional Fixture Removal Techniques

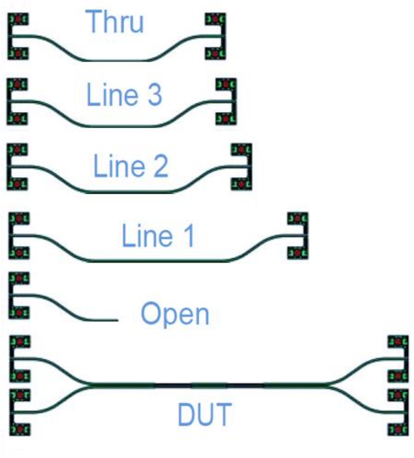
- Historically – 2 methods:
  - Model fixture using EM Simulation and de-embed the fixtures from the measurement
  - Use a TRL calibration technique to move measurement reference planes to the DUT.



TRL Calibration

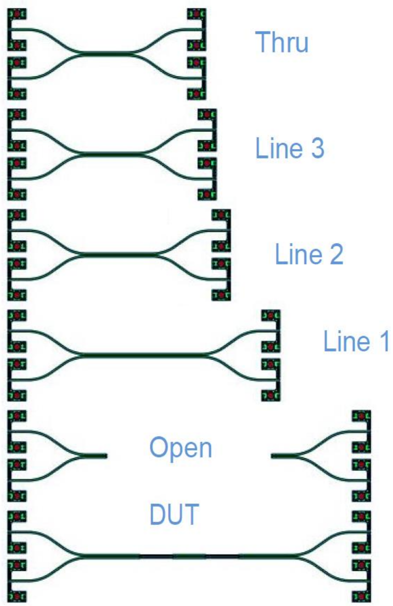
Assumptions for single ended TRL

- Connectors and launches are identical
- All lines have same Transmission Line characteristics
  - Impedance, loss, propagation
  - Only differ in length
- Lines are usable 20 to 160 degrees relative to thru
- Usually 2-4 lines depending on frequency range
- For differential fixtures
  - No coupling in fixture is removed



Even more complicated - Differential Cross talk calibration

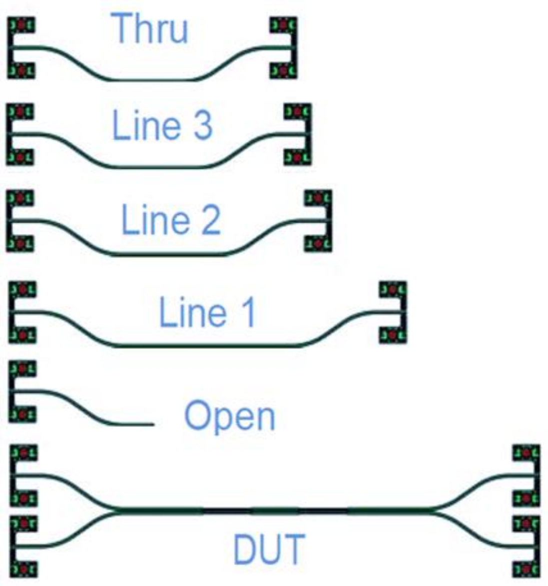
- **Fixture may be asymmetric**
- **Similar assumptions to single ended TRL**
  - Repeatability of connector, launch, and line
  - lines are usable 20 to 160 degrees relative to thru
- **Additional differential constraints**
  - SDCnm and SCDnm < -30 dB
  - Skew between lines < 10 degrees
  - Coupling in fixture is removed



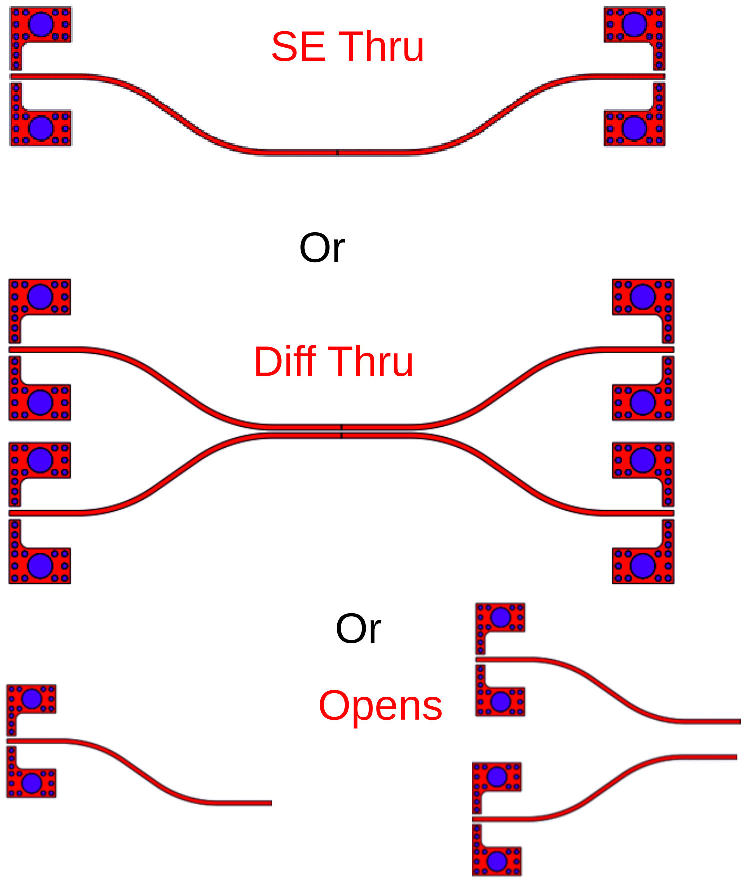
New method：Automatic Fixture Removal

Based on simple cal standards, using time domain gating and signal flow calculations to extract fixtures and do de-embedding.
Much simpler but same accuracy as TRL calibration.

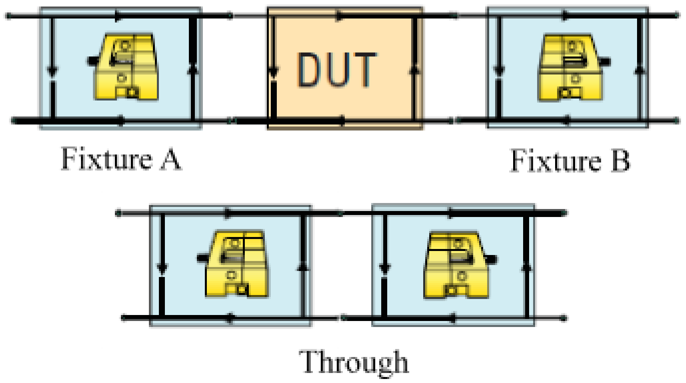
Yesterday's Method: TRL

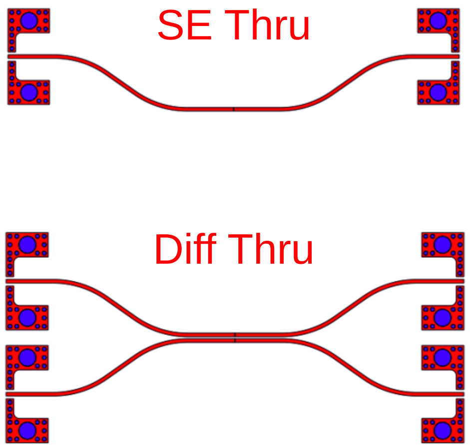


Today's Method: AFR



AFR with 2xThru





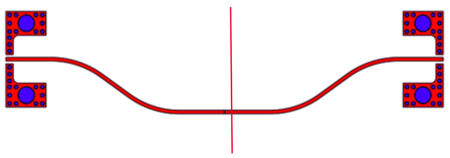
Concept:

1. Measure the 2xThru with VNA after coaxial calibration
2. Mathematically divide the 2xThru to two halves (based on Time Domain Gating and Signal Flow diagram calculations) to acquire the S-parameters of the two fixtures
3. De-embed the fixtures from the DUT measurement to achieve the real DUT characteristics

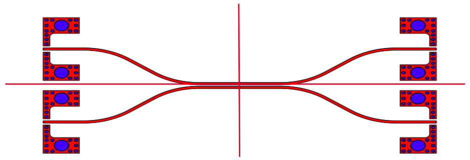
In Differential case: Coupling in fixture is removed

AFR with 2xThru – limitations and best practices

SE Thru



Diff Thru



- The left and right fixtures should have the same delay and insertion loss, but match (launch impedance) doesn't need to be the same
- The fixtures in the 2xThru should be consistent with that in the 'fixtured' DUT (left to left, right to right)
- The Thru cannot be too short: should be at least 4x system step rise time
- The Thru cannot be too long: the fixture bandwidth should be higher than the DUT measurement bandwidth
  - the return loss and insertion loss of the 2xThru cannot cross each other in **DUT** measurement frequency range, often >5 dB separation is required
  - Needs good control on the impedance mismatch on the connector, launch and PCB traces

For Diff Thru:

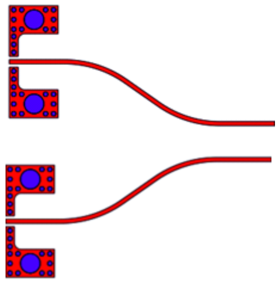
- Top-bottom symmetric
  - SDCnm and SCDnm < -30 dB
  - Skew between lines < 10 degrees

One-port AFR using Open or Short

Concept:

1. Measure the Open or Short fixture with VNA after standard coaxial calibration
2. Mathematically extract the fixture S-parameters from the Open / Short measurement (based on Time Domain Gating and Signal Flow diagram calculations)
3. De-embed the fixtures from the DUT measurement to achieve the real DUT characteristics

In Differential case: Coupling in fixture is removed



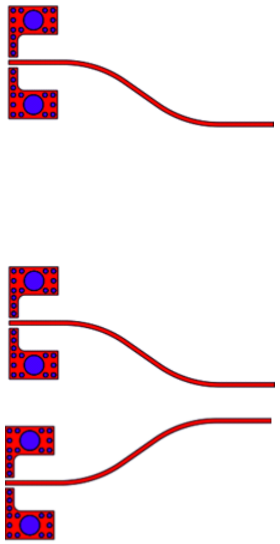
One-port AFR Applications

- Probes – especially GSGSG (coupling)
  - measure open and shorted
- Fixtured packages –
  - measure open fixture
  - measure loaded part
- PC board –
  - measure unloaded board
  - load part and measure

Smallest footprint

Easy to fabricate

One-port AFR : Limitations and Best Practices



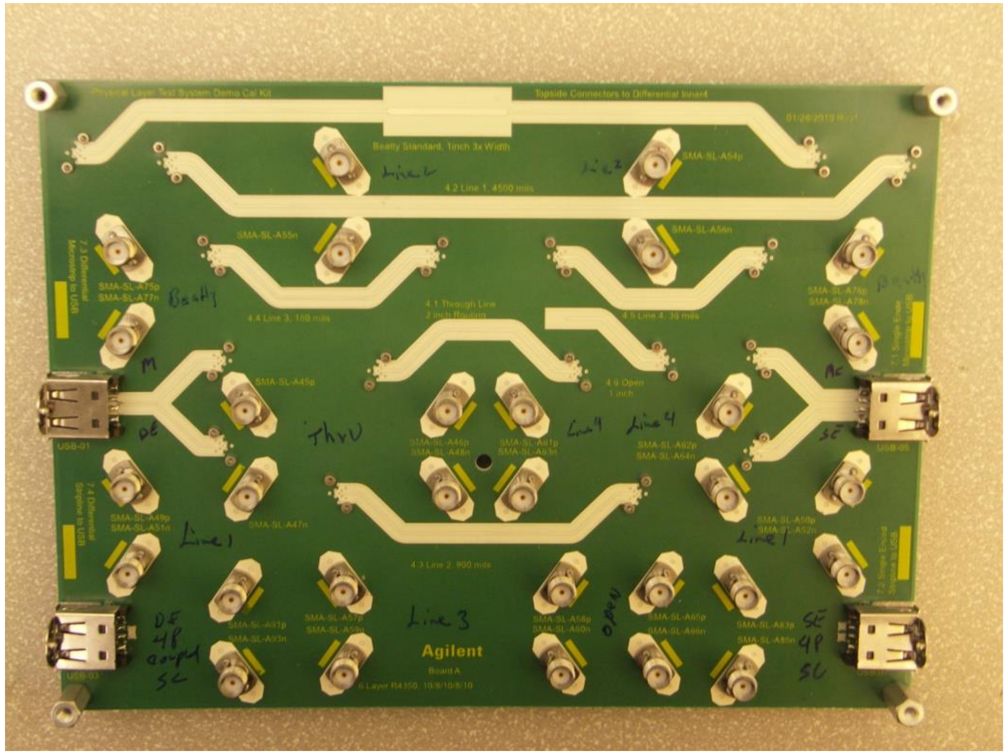
- No apparent radiation (open)
- Good reflect (for insertion loss accuracy)
- The open fixture should be consistent with that in the fixtured DUT. Typically, the same fixture can be used for both
- The fixture length should > 4x system rise time
- The fixture bandwidth should be higher than the **DUT** measurement bandwidth
  - Needs good control on the impedance mismatch on the connector, launch and PCB traces

For Diff Open:

- Top-bottom symmetric
  - SDC11 and SCD11 < -30 dB
  - Skew between lines < 10 degrees

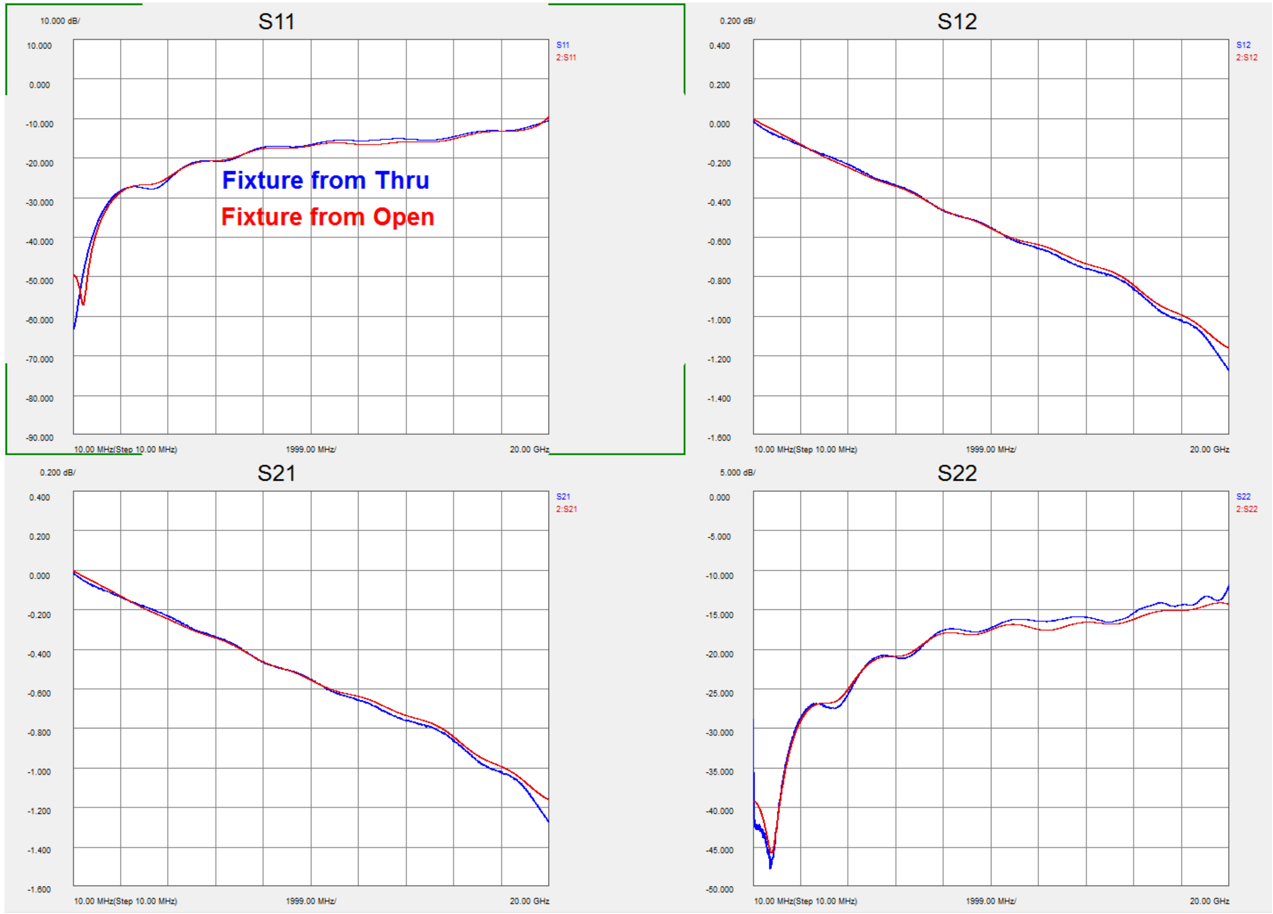
Case Study Example Rodgers 4350 PCB

- Low loss material
- Minimized weave variations
- Vias were not back drilled
- DUT is a mismatched line
- Compare AFR to TRL



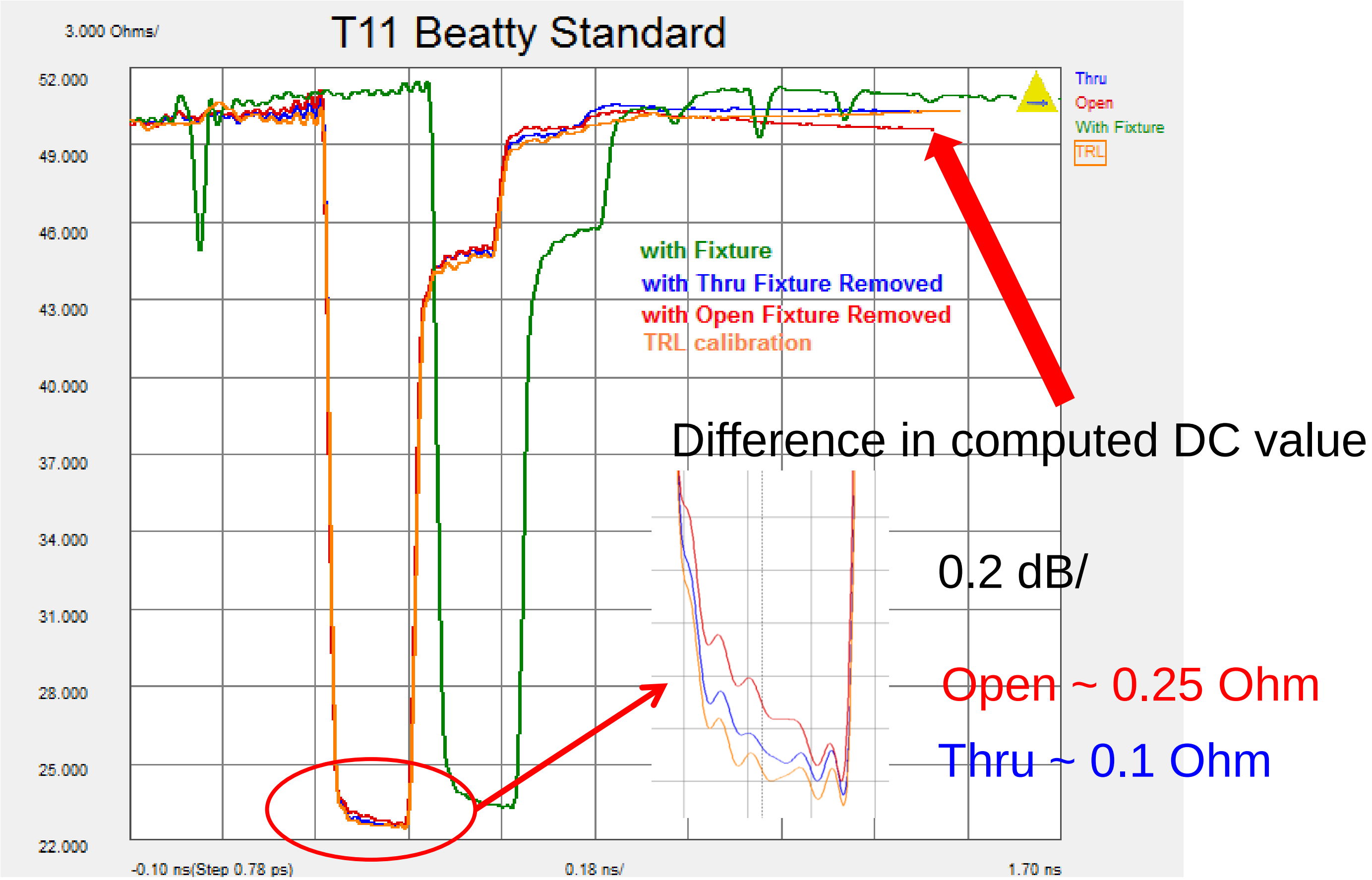
Rodgers 4350 Fixture

Comparing the fixture models from the 2X thru standard and the open standard, we see very good agreement.



Rodgers 4350 Beatty DUT

Comparing DUT measurements after removing the fixtures from the 2X thru standard and the open standard, we see very good agreement.

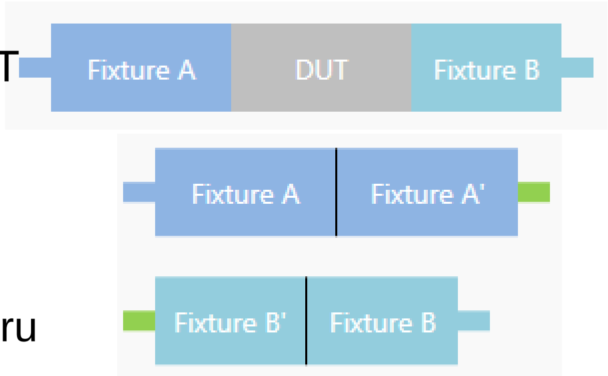


AFR for Asymmetric Fixtures – 3 methods

‘Fixtured’ DUT

First 2xThru

Second 2xThru

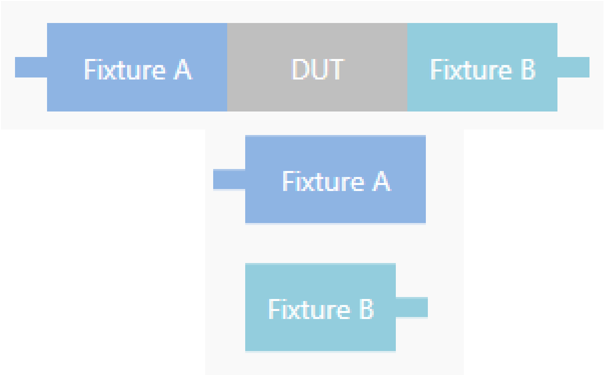


Using two 2xThrus, one for Fixture A, the other for Fixture B

‘Fixtured’ DUT

First Open

Second Open



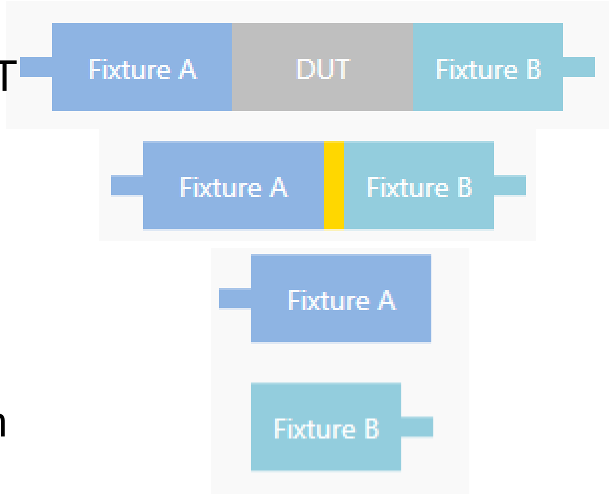
Using two Open fixtures

‘Fixtured’ DUT

2xThru

First Open

Second Open



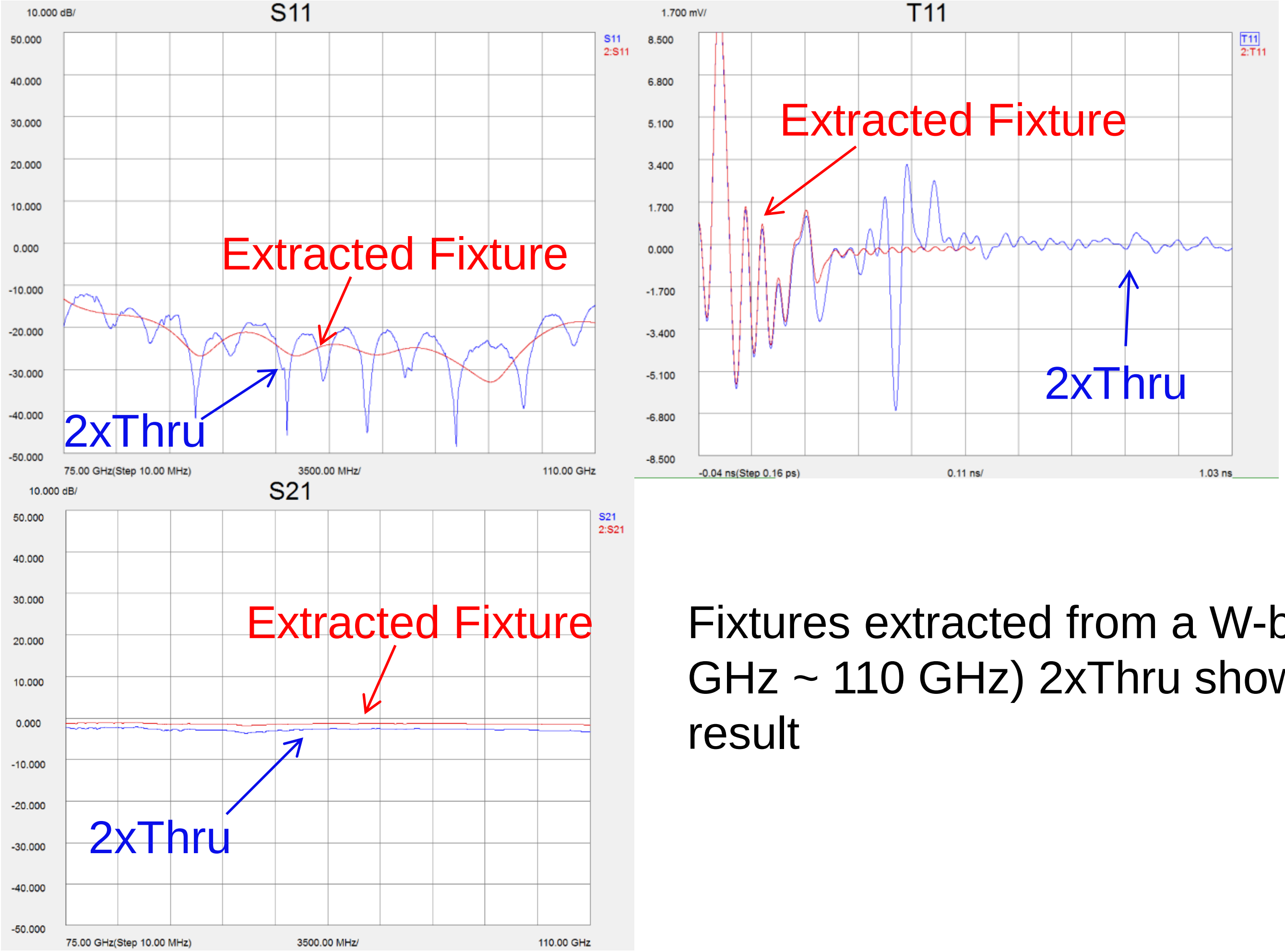
Using a Thru and two Open fixtures

- Open is used to determine the fixture electrical lengths
- Then the fixtures are extracted from the 2xThru

Limitation: the insertion loss and phase shift of the fixtures are proportional to that of the whole Through according to the electrical lengths

Bandpass AFR

- AFR algorithm works for bandpass devices with bandpass time domain gating
- Limitations are similar to those of low pass mode



Fixtures extracted from a W-band (75 GHz ~ 110 GHz) 2xThru show perfect result

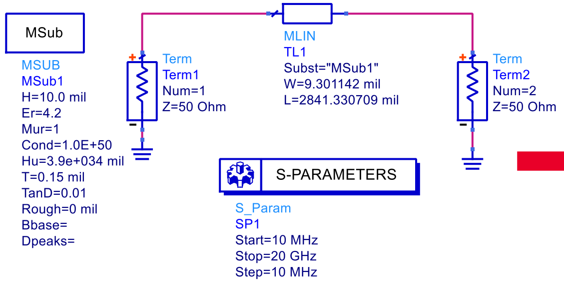
AFR for Non-50 Ohm Reference Impedance

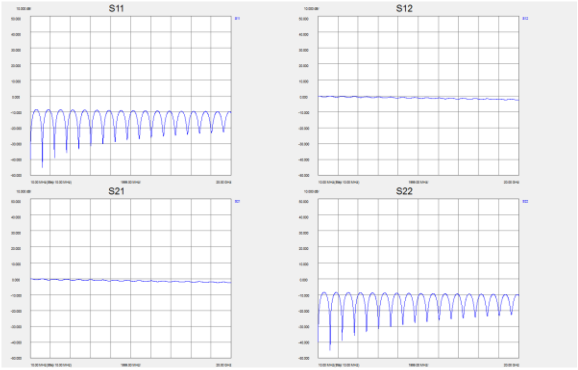
Can we use AFR for non-50 Ohm DUT reference impedance?

A similar question to

Can we use 50 Ohm VNA and cal kit to measure DUT with non-50 Ohm Z0?

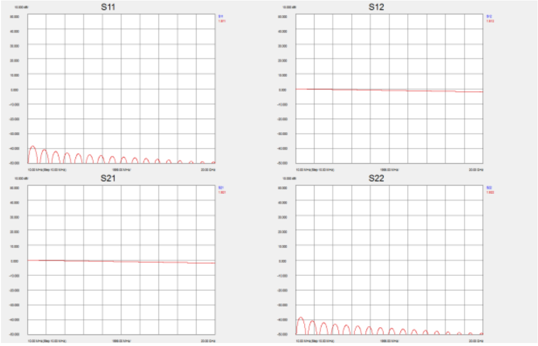
Example: measure a 75 Ohm device with 50 Ohm system

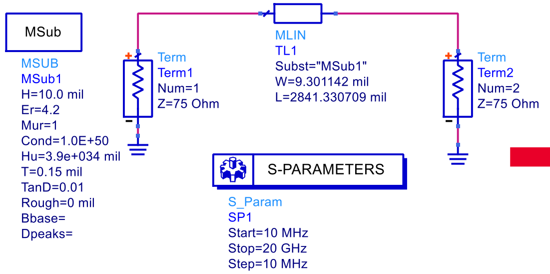


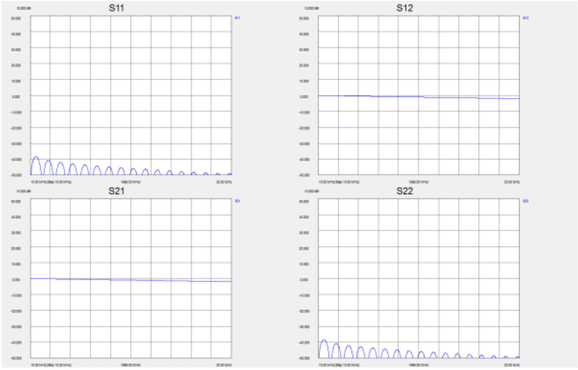


Measured with 50 Ohm system

Measured with 50 Ohm system and converted to 75 Ohm Z0 with Port impedance conversion, set System Z0 to 75 Ohm







Same device, measured with 75 Ohm system

Exactly the same with the S-parameters measured with 75 Ohm system

Summary

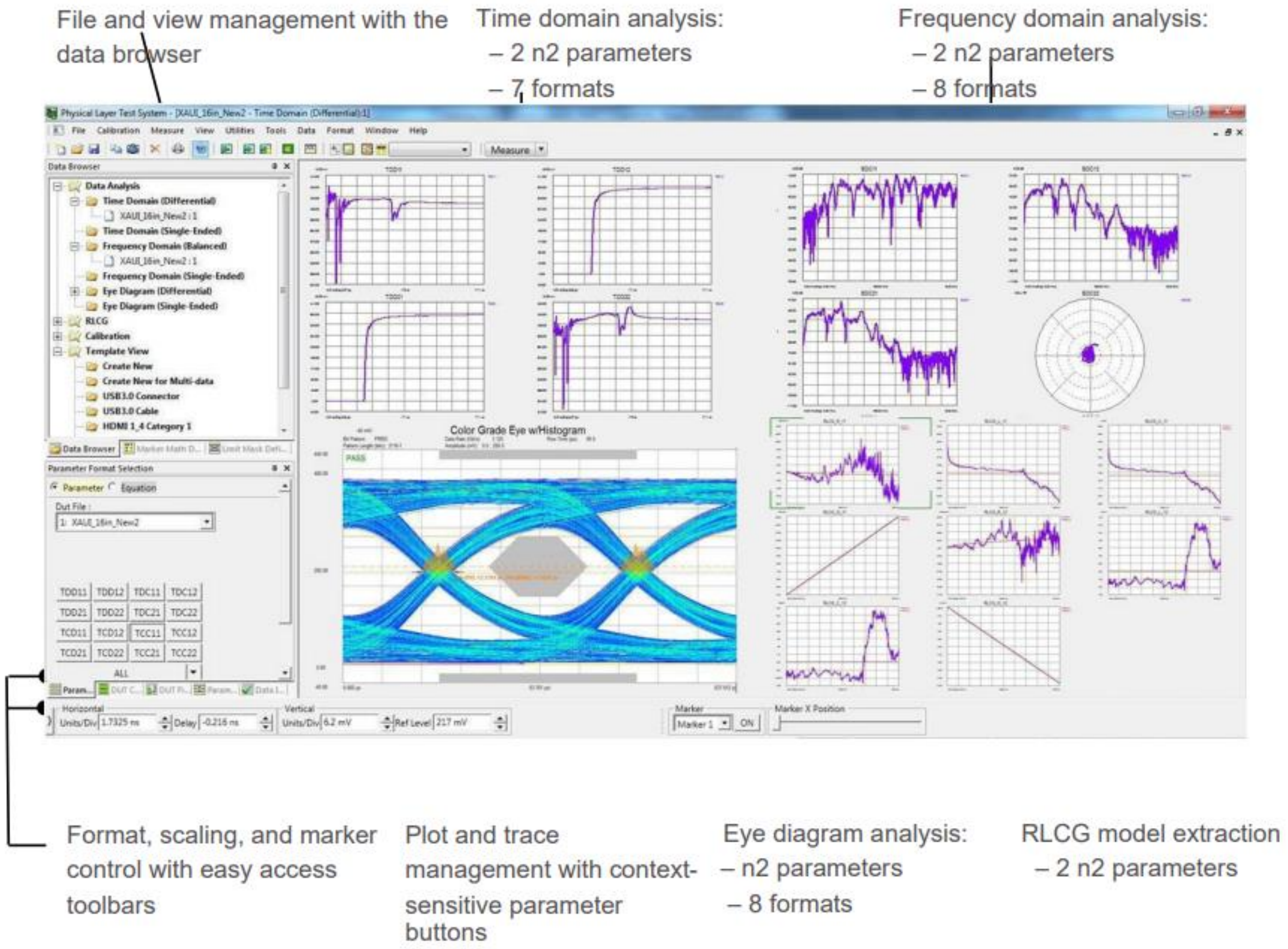
- Fixture removal can take many different paths with varying degrees of complexity and accuracy
- Choosing the correct method is essential in understanding the true (desired) performance of the DUT
- There are many cases when the simple and legacy techniques will work well for generally understanding a device
- The more advanced calibration and full de-embedding techniques are better when generating data to be used in a model or to verify model behavior
- Don’t be afraid to compare different methods (if feasible) if you have the standards or analysis tools that allow for continued processing

Keysight Physical Layer Test System (PLTS)

PLTS Major Features

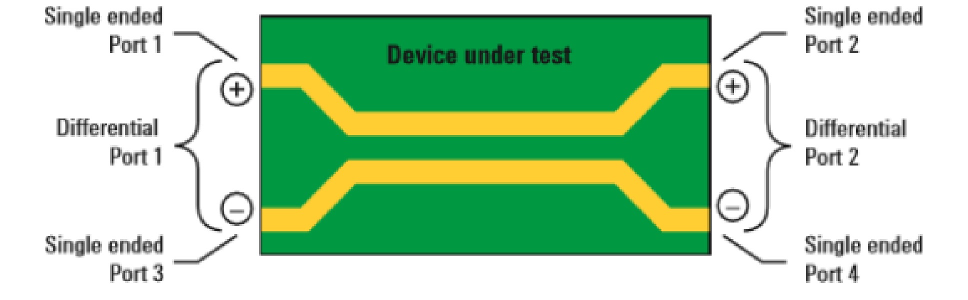
- The most advanced and flexible TDR from Keysight
- TDR to any frequency. Only limited by the VNA max frequency.
- Mates with most current VNA products.
- Swept frequency method followed by IFFT.
- Imports S parameter files.
- Displays S parameters and TDR.
- contains AFR as an option.
- Can do eye diagrams
- Can do multiport

Data analysis with n-port PLTS



Complete Characterization

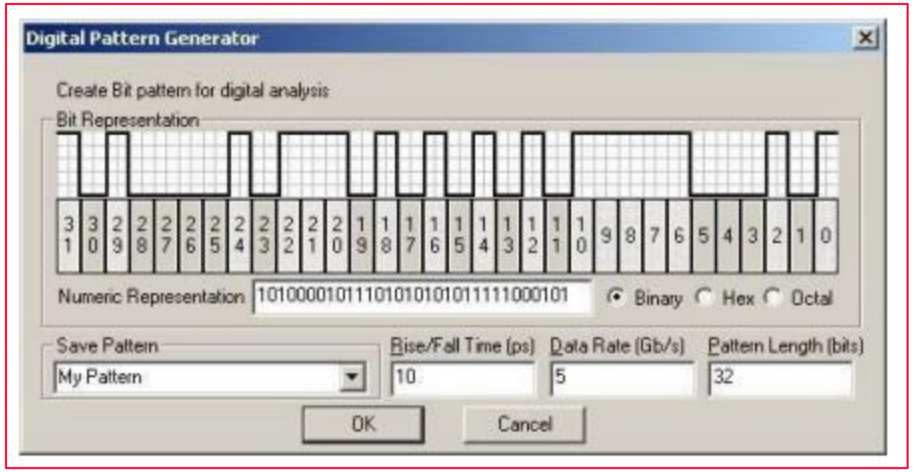
Mode	Time Doman		Frequency Domain	
	TDR	TDT	Reflection	Transmission
Differential	TDD11 TDD22	TDD21 TDD12	SDD11 SDD22	SDD21 SDD12
Diff-to-comm	TCD11 TCD22	TCD21 TCD22	SCD11 SCD22	SCD21 SCD12
Comm to diff	TDC11 TDC22	TDC21 TDC12	SDC11 SDC22	SDC21 SDC12
Common	TCC11 TCC22	TCC21 TCC12	SCC11 SCC22	SCC21 SCC12
Single-ended	T11 T22 T33 T44	T21 T31 T41 T12 T32 T42 T13 T23 T43 T14 T24 T34	S11 S22 S33 S44	S21 S31 S41 S12 S32 S42 S13 S23 S43 S14 S24 S34

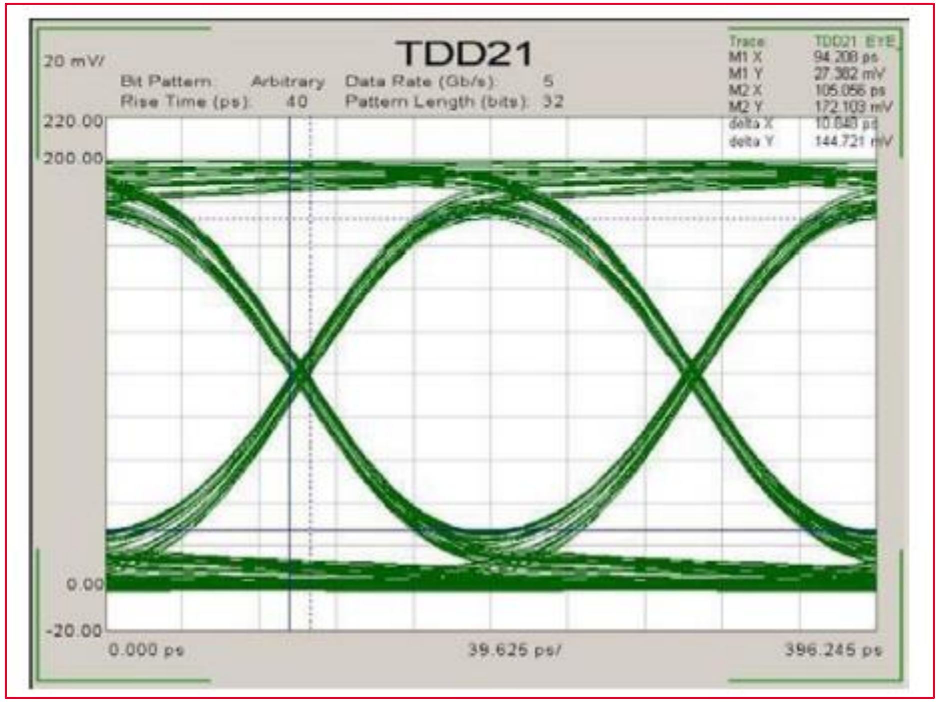


- The chart is showing the characterization for a 4 port
- The number of ports analyzed can be extended up to 32 ports.

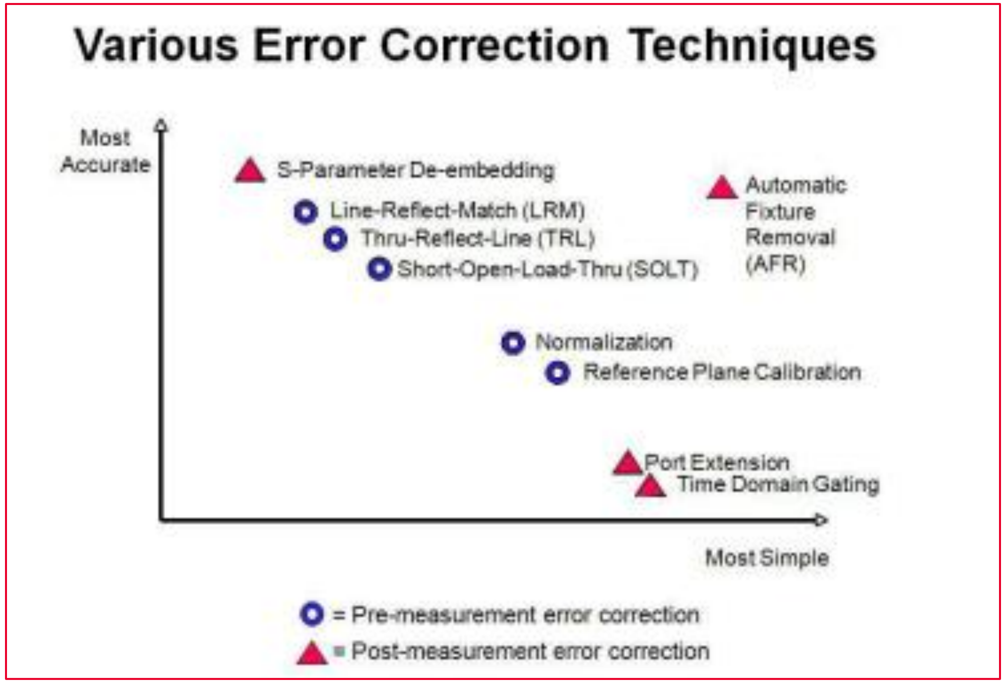
Data Analysis

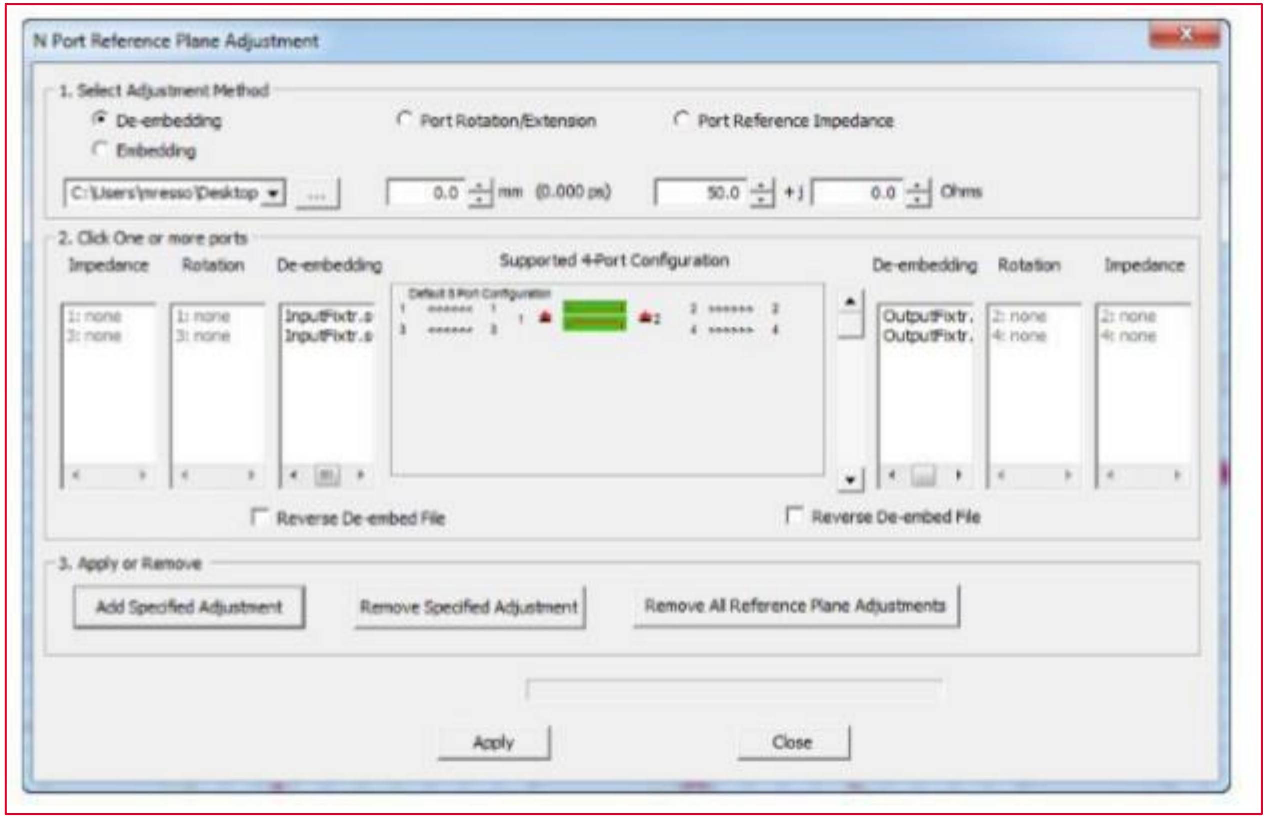
Measurement Based Eye Diagram





PLTS Calibration





Thank you

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KEYSIGHT