Proposed Touchstone Improvements for Optimization of Mixed PDS and I/O Models

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Sam Chitwood

Sigrity, Inc.

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Outline

- Motivation for using Broadband models
- Characteristics of ideal Touchstone models
- Limitations of Touchstone models in SPICE
- An alternative approach to utilize Touchstone models in time-domain SPICE applications
- How to optimize the alternative approach for mixed PDS and I/O models
- A proposed Touchstone enhancement based on this optimized methodology

Why do we use Touchstone models?

- Today's designs have broadband frequency content (DC to tens of GHz)
  - Lumped RLC models are a low frequency approximation – they offer insufficient bandwidth and accuracy when measuring picosecond margins
  - Frequency-dependent, broadband coupling is mandatory at GHz switching frequencies
  - PDS impedance is highly frequency dependent; must identify and reduce resonances
- Power / ground structures affect the I/O signal's performance
  - Large, parallel busses create huge current transients (large dI/dt)
  - PDS noise degrades the signal quality of a driver's output (SSO pushout for example)
  - Resonance in the PDS significantly increases via crosstalk and supply impedance
  - An accurate model not only includes the PDS, but also the interactions with the I/Os (signal return current on the PDS creates further fluctuations on the supply voltage)
- Touchstone models provide all of this and more…
  - Captures the frequency dependent response and coupling of the power / ground structures and I/O signals
  - Easier to correlate frequency domain than time domain (less unknowns)
  - Touchstone is another type of behavioral model – no IP is divulged
  - Widely used to model many structures: connectors, packages, PCBs, RF, etc.

Characteristics of Ideal Touchstone Models

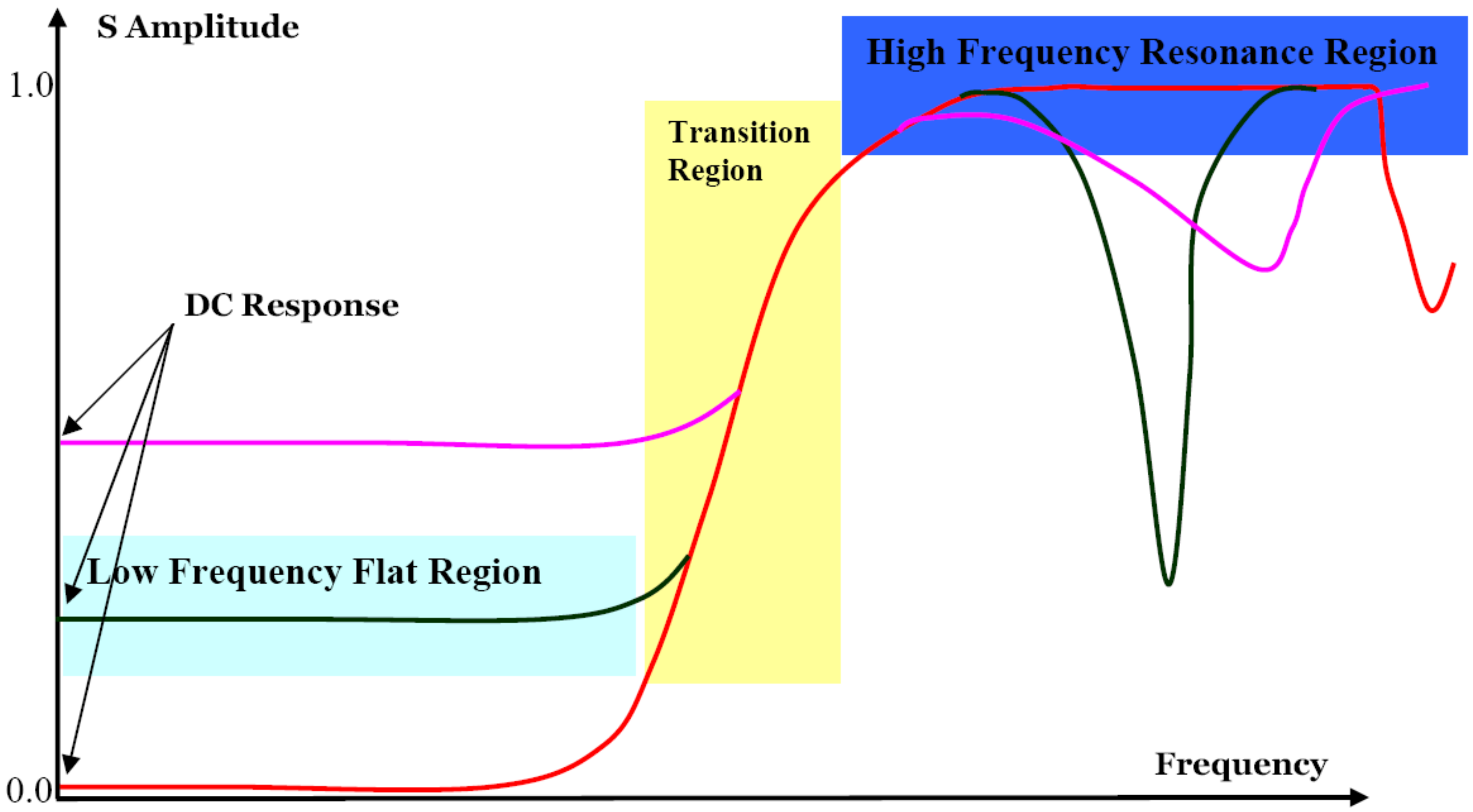
Tip 1: Minimize the number of ports whenever possible!

- **Only extract the nets of interest (don’t extract the PCI bus if you’re only interested in DDR; only extract the necessary PDS voltages as well)**
- **Don’t create multiple ports for the chip’s PDS terminals if your on-die model is a single, lumped R-C circuit. You’re not gaining a spatial distribution this way.**
- **Be realistic about how many I/O circuit models you can simulate (if you have convergence problems with 10 drivers, a model built for 20 doesn’t help matters)**

Tip 2: A proper frequency sweep is key for time domain sims.

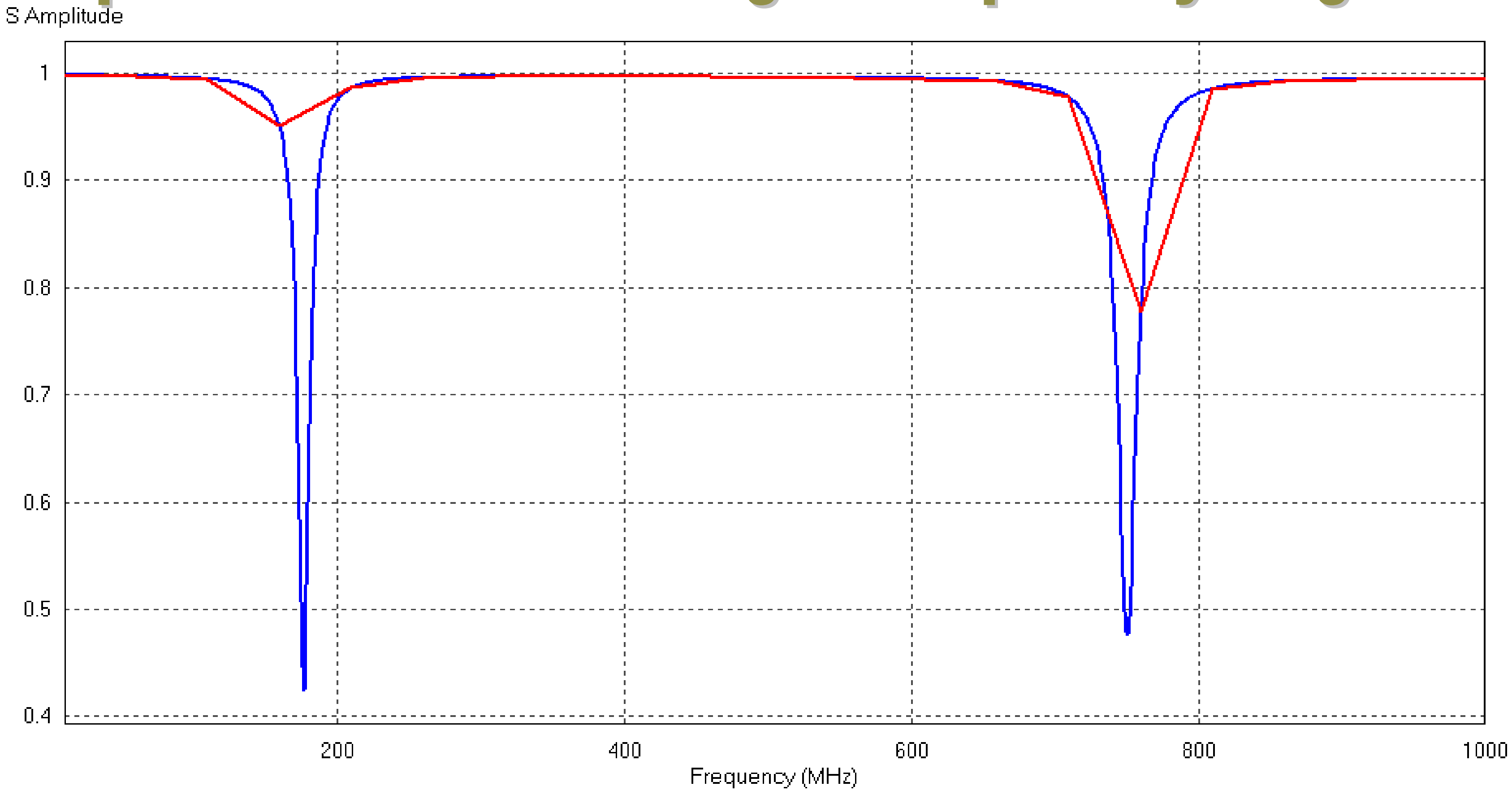
- **The low frequency data is important! Typically, a log sweep is used in the low frequency region with at least 5 pts/dec (more is better in the transition region).**
- **DC values are allowed, but are uncommon (not many tools can accurately do it; also, the DC value is undefined for the Z-parameter of conventional models).**
- **The time domain simulator must extrapolate the DC point for the first timestep.**

Extrapolation of the DC Value



The low frequency flat region must have a sufficient number of data points. This enables the final simulator to accurately extrapolate the DC value that is used for the initial DC operating point calculation.

Tip 3: Use as dense of a linear sweep as possible for the high frequency region



These curves show the difference between 50 MHz and 1 MHz increments. Regardless of the interpolation method used, an under-sampled curve cannot be accurately restored. Accurately capturing resonances requires dense sampling.

Limitations of the S model in SPICE

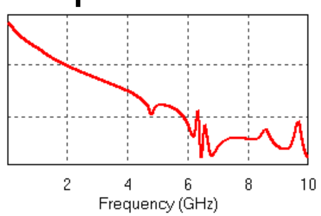
- A number of SI tools enforce the de facto standard's limit of 99 ports
  - For SSO analysis, this limits the total number of possible I/Os to ~48. Obviously many users need Touchstone to support 100+ ports.
  - An IR drop application gaining popularity is to use the Z-parameter to analyze (model) the resistance between the bumps and balls of a specific net (such as GND or VDD). Although not a broadband model, this Touchstone application requires 1000+ ports.
- Convolution is used in many SPICE tools for time domain simulation
  - These algorithms are typically extremely slow (prohibitively slow in many cases).
  - If a convergence problem is encountered (timestep too small error) when an S model is added to an otherwise working simulation, what should the user do to correct the problem? What option(s) to tweak? Sometimes this problem cannot be solved.
- Handling models with bad data (from simulation or from measurement)
  - Touchstone models built from multiple port measurements commonly have passivity problems (S magnitude > 1). This is a primary source of convergence problems. (This can also happen in simulation if data points are extrapolated.)
  - Do we expect users to manually correct passivity problems for 1000+ samples?
  - How do you correct the problem? "Whack-a-mole" isn't very scientific. ☺ (Passivity is a black art – sometimes it's a problem, sometimes it's not.)

An alternative approach to SPICE's convolution-based S model

- The "curve fit approach" is becoming an increasingly popular alternative
  - For time domain simulations, an alternative solution is needed for numerous reasons: 100+ ports, faster simulations, handle passivity problems, etc.

- **Step 1:** The curve fit approach scans the Touchstone data and builds a transfer function that accurately fits the original data.
  - A transfer function is built for each entry in the S matrix. (The curve fit is performed on the S-parameter because Z typically doesn't exist at DC.)

$S(i,j) =$



$$> \ Hij(x) = \frac{4x^3 + 2x + \ldots}{5x^6 + 3x^4 + \ldots}$$

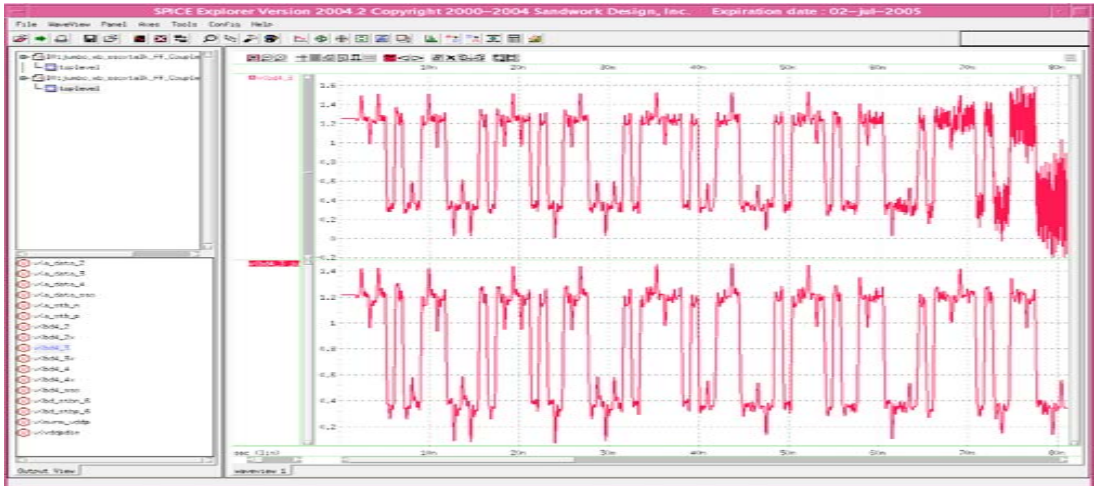
- **Step 2:** An equivalent sub-circuit model is then constructed with time domain SPICE elements (typically RLGCEFGH and optionally Laplace).
  - These elements are not physical in any way – they merely serve to create the mathematical transfer function.
  - Note that the Laplace element is not supported by all SPICE tools. If available, its use can significantly reduce the size of the sub-circuit model.

Benefits of the Curve-Fit Approach

- Tremendous gains in simulation efficiency are realized
  - Because the new model contains only time domain circuit components, costly convolution is no longer required. The typical speed improvement is ~50X.

- The equivalent circuit model is compatible with all SPICE simulators and has no limitation on the number of supported ports.
  - The new model is a standard SPICE sub-circuit; it may contain any number of external nodes. This solution is necessary for applications needing 100+ ports.
  - Vendors can provide this model to customers without compatibility concerns.
  - No IP is divulged in this behavioral model. (The elements are not physical.)

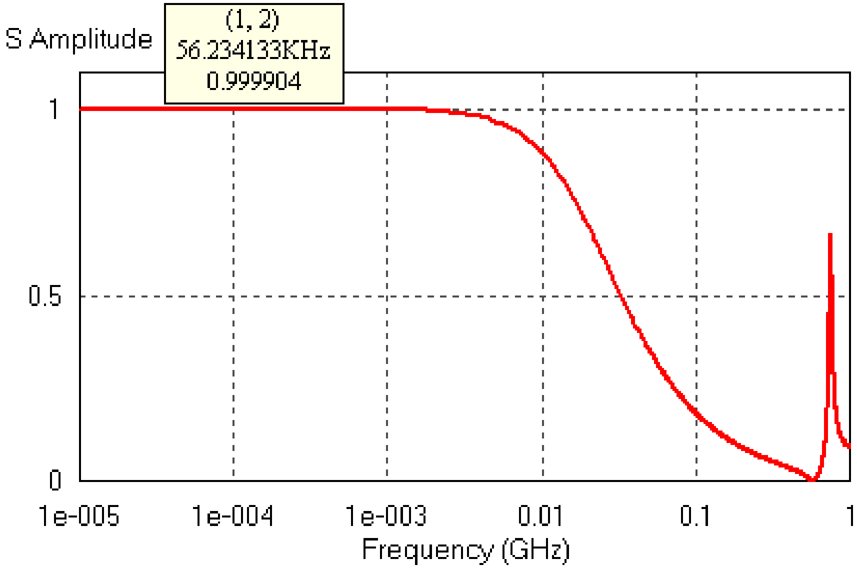
- Passivity issues can be eliminated during the conversion

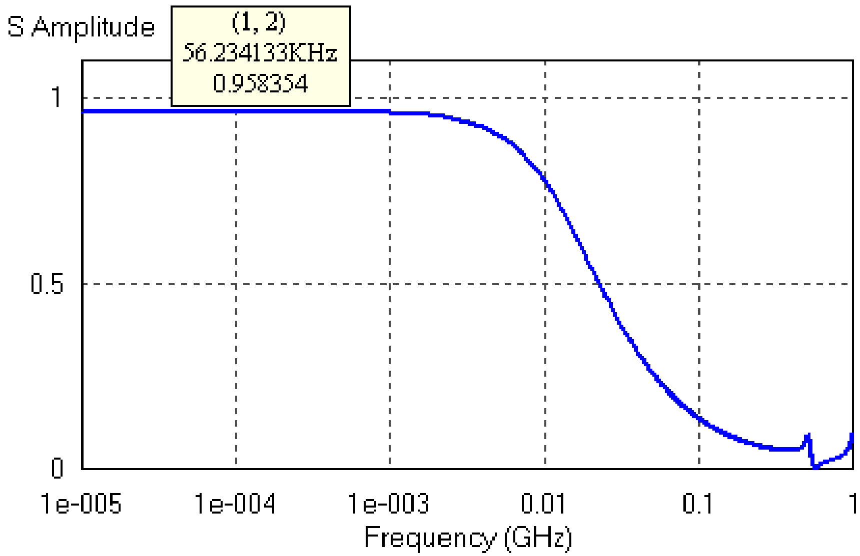


Limitations of the Curve-Fit Approach

- Sufficient low frequency data is necessary to accurately extrapolate the DC value of each S-parameter curve.
- Accuracy of the curve fit process is EXTREMELY important
  - Fit inaccuracies may introduce passivity issues into passive Touchstone models.
  - Many PDS S entries very closely approach 1 in the low frequency range – if the magnitude of the fitted curve goes above 1, this is a blatant passivity violation.
  - However, if a small reference impedance is used during the extraction (instead of the de facto 50Ω), the S curve will approach a value comfortably less than 1.

The figures below compare S(1,2) for a PDS extracted with 50Ω vs 0.1Ω ref Z.

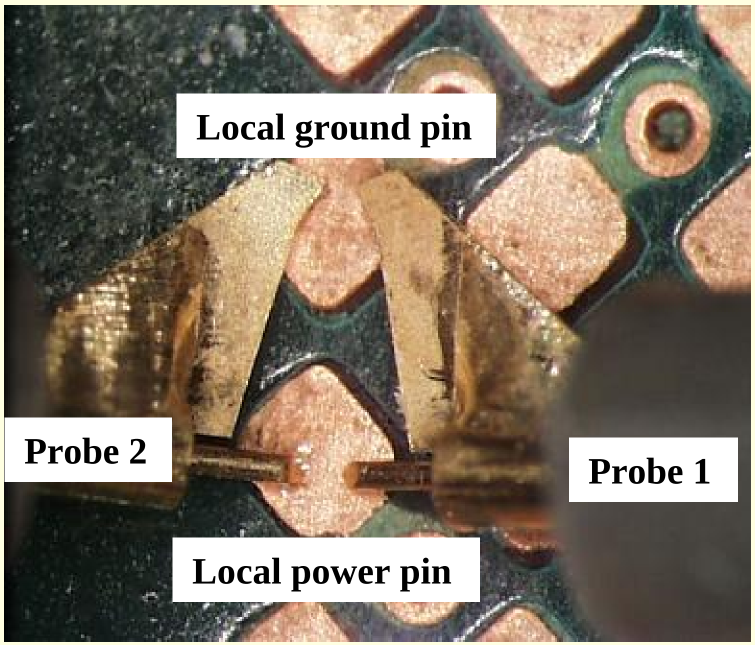


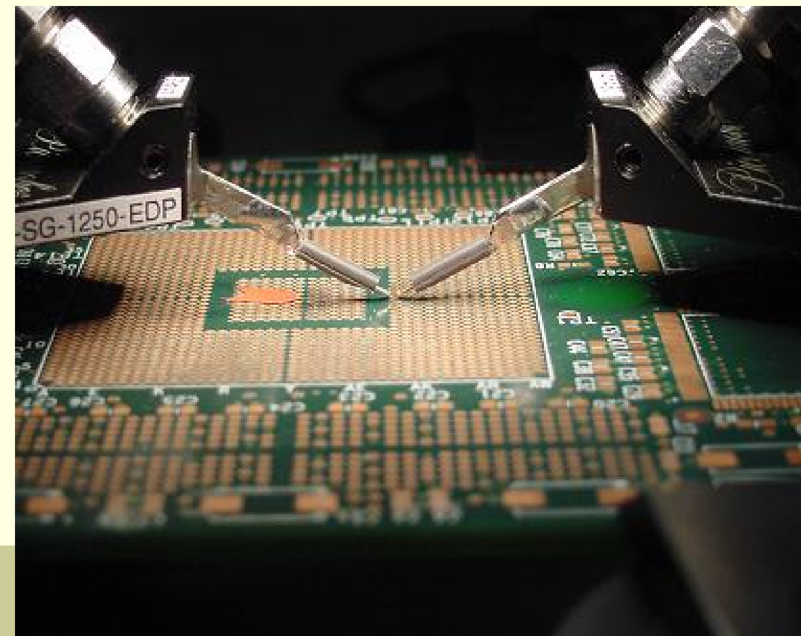


Why is <1 Ω reference impedance not commonly used in measurement?

- <1 Ω reference impedance for measurement is not practical
  - A probe with such a low ref Z may be difficult (and expensive) to construct
  - End users would have to buy another set of (expensive) probes with limited usefulness (mainly PDS measurement)
- The common practice is to use two conventional 50 Ω probes in parallel when measuring the PDS
  - Two 50 Ω probes in parallel effectively reduces the ref Z to 25 Ω.
  - Although not an ideal solution, this method does improve the resolution of the measurement.
- Keep in mind these physical limitations do not exist in simulation…
  - Simulation tools allow any reference impedance to be used. The limitations of probe technology should not constrain simulation techniques if better methodologies exist.

Detailed View of Two Probes in Parallel





Optimizing the Curve-Fit Approach

- Curves can be made to approach smaller magnitudes and the number of "important" (significant) digits in the S-parameter can be reduced
  - By intelligently choosing reference impedances, S-parameters can be mathematically conditioned so that the curve-fit approach is optimized.
  - A previous slide showed S values of 0.9999 for 50 Ω ref Z and 0.9853 for 0.1 Ω ref Z. The latter case is much more tolerant to a fit error of 0.002…
- A port's reference impedance should be chosen to roughly match the distribution's target impedance
  - 50 Ω is not a magic number, but it's close to the target Z of most traces.
  - The reference impedance for PDS extractions should be <1 Ω. Note: there is no "correct" choice. Values between 0.01 Ω and 1 Ω typically work well.
- Important – the "ideal" choice of reference impedance for I/Os and for the PDS are VERY DIFFERENT. But Touchstone supports only one ref Z…
  - Therefore, to optimize the curve-fit approach for S-parameter models that contain both I/Os and the PDS, a simple Touchstone enhancement is needed.

Proposal – Support Multiple Reference Impedances in the Touchstone Spec.

- In order to achieve optimum results with the curve-fit approach, different reference impedances are needed for the I/Os and the PDS
  - A reference impedance for each port should be listed on the header line with respect to the ordering of the ports in the data.
  - If the number of reference impedances is less than the number of ports in the data, the last reference impedance value applies to all remaining ports.

This is an example of a six port model with two PDS and four I/Os ports:

```
!Example of a multiple reference impedance S-parameter file
!Port list:  Bump_D1  Bump_D2  VDD_Bumps  Ball_D1  Ball_D2  VDD_Balls
# Hz       S       RI      R       50.0  50.0  0.1  50.0  50.0  0.1
100        -0.998609317665        0.0106141993482 ...
```

- This proposal can only be applied to S- and Y-parameter models
  - The de facto standard for Z-parameters mandates that they be normalized by the reference impedance. It is unclear what to divide by for the off-diagonals.

Benefits of the Proposed Enhancement

- The multiple reference impedance technique allows mixed PDS and I/O models to be optimized for use with the curve-fit approach
  - The curve-fit approach is here to stay: numerous vendors already support it
  - The improved simulation speed and passivity enforcement are huge benefits
  - When combined with the BIRD95 technique, this methodology facilitates extremely wide SSO analysis and realistic simulation times
- Standardization allows multiple reference impedance models to be compatible with all industry tools
  - Regardless of whether a particular vendor uses the curve-fit approach, users will no longer be concerned with model compatibility between vendors.
  - At least two tools already support this technique… The list will grow.
  - Standardization prevents creation of another unofficial, de facto standard.
- The proposed improvement is easy for tool vendors to implement
  - Converting from multiple reference impedances to a single reference is trivial for tools that prefer a single reference

Thank You!

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