DIGITAL INDUSTRIES SOFTWARE

Comprehensive S-parameter verification coverage by Analog FastSPICE

Analog mixed-signal

Executive summary

In this white paper, we focus on the value of S-parameters in circuit verification and their efficient and accurate processing by the Siemens Analog FastSPICE™ (AFS) engine during analysis. The fundamentals of S-parameters and associated physical properties are explained. The importance of rational fitting and its flow are described, in addition to an alternative flow that does not require fitting. Furthermore, we describe the latest AFS XT advancements in various S-parameter focus areas for enhanced performance, convergence, memory consumption, feature support, usability and debugging.

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Introduction

IC design is transforming at an accelerated pace along with fabrication technology. The need to incorporate more functionality has led to denser dies, multi-die chips, stacked 3D ICs and advanced packaging. Furthermore, design technology continues to progress towards supporting higher data rates to address the increasing demand for more and enhanced connectivity. We now must deal with much more power and ground signals and their distribution. The same goes for clocks and other signals routes on die, between dies, on package and on board. To boost performance in SoCs, frequencies continue to reach new heights for high-speed serial link and memory protocol standards, and so do CPU frequencies. Signal transmission and reflection needs to be well understood to properly design for signal integrity in various signal conduits. Furthermore, custom passive structures such as inductors, T-coils, capacitors, and resistors are being innovated in each technology progression to meet design challenges and specifications related to frequency synthesis, noise filtering and bandwidth extension. S-parameters (scattering parameters) play a crucial part in IC design, and in this paper, we focus on their importance for accurate design considerations and how AFS simulation technology can broaden your IC design verification scope.

S-parameter fundamentals

Signals operating in the radio frequency (RF) realm between 3 kHz to 300 GHz are an inherent part of processing by circuit components within and outside an IC. Linear characteristics of RF circuits can be well represented by S-parameters by which important characteristics such as impedance, gain, loss and voltage standing wave ratio (VSWR) can be calculated. The term scattering implies how voltages and currents in a transmission line are affected due to a discontinuity of an inserted network into it. As shown in figure 1, the two-dimensional S-matrix for an electrical component is a frequency specific data that provides a relationship between the incident, reflected and transmitted waves at each port over a range of frequencies. It provides an amplitude-phase feel in frequency domain rather than transient voltages and currents.

S-parameters describe linear time-invariant (LTI) systems in the frequency domain. By linear, we mean commutative, associative, and distributive mechanisms that do not include clipping or mixing and only involves amplitude and delay variations. Time invariant means a certain input will give the same output regardless of when the input was applied to the system wherein $Y(n)=H(x(n))$ is equivalent to $Y(n-t)=H(x(n-t))$. LTI systems further imply causality and passivity of a bounded input to a bounded output system. Causality means that an output is a reaction to present and past events but not future input, where a model only responds after being excited. Passivity is a measure for stability, and a passive system does not generate energy across all frequencies.

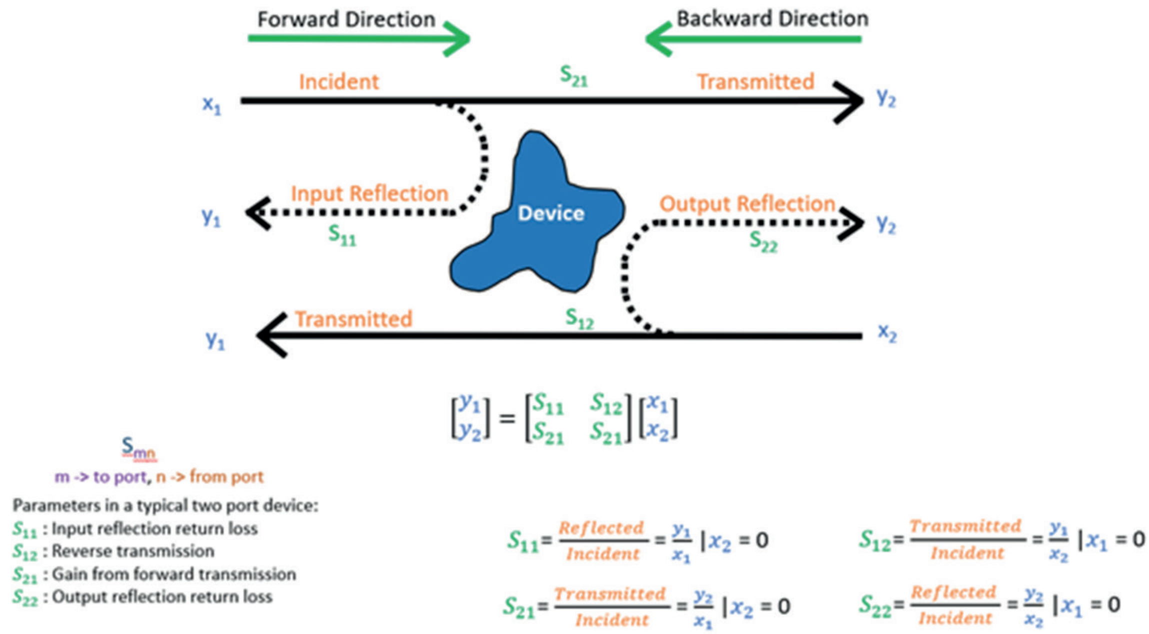

Figure 1: S-parameter basics.

Industry EM field solvers can generate S-parameters. In the lab, vector network analyzers (VNAs) can be used to measure them. Since S-parameters change with frequency, the frequency specification is a necessity in addition to characteristic impedance. In essence, they should be viewed as a black box abstraction of the electrical system (simple or complicated) with frequency characterized parameters for input-output port relationships.

Benefits of S-parameters

There are many benefits of S-parameters.
For starters, they can be easily converted to Y, Z, H or T parameters for a circuit analysis. And then, S-parameters are more reliable. While S-parameters require matched loads, the other listed types require open and short circuit terminations that are difficult to maintain at RF frequencies. Furthermore, the portability of S-parameters with standard file formats such as Touchstone and Citi enables compatibility with most simulators. S-parameter files can be easily included in a testbench with other circuit blocks with appropriate connectivity to simulate that cross section with necessary stimuli.

Systems using S-parameter modeling

S-parameters are mostly used to model passive systems such as inductors, capacitors, T-lines, cables, packages, bond wires, microwave distributed circuits, etc. LC VCO designers specifically indulge in experimenting various inductor architecture types modeled with S-parameters for easy inclusion into VCO analysis before attempting physical layout. S-parameters are also used to model high-speed digital interconnects and channels including PCB traces, vias, connectors, and packages to characterize the effects of impedance mismatches, reflections, losses, dispersion, and crosstalk. SerDes designers also put them to heavy use in early design stages for formulating budgets for power, gain and noise where it is crucial to know frequency-induced effects and impedance mismatch effects. Low noise amplifier (LNA) designers find S-parameters valuable to design input and output matching systems to optimize the tradeoff between gain uplift and noise figure minimization.

Types of S-parameters

There are different types of S-parameters. The most common is the small-signal S-parameters, where signals have only small linear effects on the network and where gain compression or other non-linear effects are not prevalent. This is the case for passive networks. Large signal S-parameters differ in that they will vary based on input signal strength.

And then there are mixed mode S-parameters for analyzing the response of balanced circuits using common mode and differential stimulus signals. Signal integrity engineers are often required to compare mixed-mode SP against industry-standard measures. Pulsed S-parameters are another variant that represent the system before it heats up, mostly applicable to power devices.

Physical properties of S-parameters

Circuit simulators incorporate S-parameters under the form of tabulated data that come in various formats, whether being extracted by an EM solver or measured at the lab. Such tabulated data, irrespective of the format, will always be of discrete and band-limited nature as well as prone to non-physical properties, which potentially gives rise to unwanted side effects due to quality issues. Consequently, handling S-parameter requires careful inspection and debugging. Such quality issues can be seen in passivity, causality, reciprocity, as well as data range, and if not addressed correctly, users will suffer from inconsistencies among different simulators in time and frequency domains response.

Passivity

Passivity is a property of paramount importance to circuit simulators. Given the nature of structures that are being modelled by S-parameters, passivity should be granted by construct as such since structures are only capable of dissipating energy rather than generating it.

Let us represent our system by the equation below[2,3], where "S" denotes the Scattering matrix relating the incident travelling wave vectors "a" and the reflected wave vectors "b,"
$\bar{b} = S.\bar{a}$

Accordingly, $\|a\|_2^2$ represents the total power entering the system while $\|b\|_2^2$ is the total power leaving the system. If the system is passive, then the following condition must be satisfied, $\|b\|_2 \leq \|a\|_2$ which leads to the condition $\frac{\|Sa\|_2}{\|a\|_2} \leq 1$. By the definition of induced 2-norm, the S matrix passivity criteria must satisfy $\|S\|_2 \leq 1$. Non-passive models cannot guarantee a bounded output and may lead to unstable simulations where the currents/voltages keep building up, accumulating power over time till convergence and accuracy issues appear on the horizon. Thus, a passive model is needed to ensure stable simulations irrespective of the adjacent external connections. This drives the need for a simulator that checks and optimally enforces passivity while minimizing perturbations to the original data. On a similar note, designers and lab technicians are advised to ensure at no point in their flow, non-passive models are being created.

It is inconvenient for a user to go through complicated mathematical calculations every time they wish to check the quality of their data. Hence, warnings on passivity violations with the ability to visualize and inspect them across frequency in a seamless manner can highly benefit users.

We describe later in the paper how AFS has invested into high-quality passivity enforcement along with a user-friendly debugging capability.

Causality

Causality can be intuitive to grasp, yet not straight forward to detect. A system is deemed to be causal if it reacts only after being stimulated, i.e., the cause must precede the effect. The time domain definition of causality is rather simple and can be demonstrated by the following for a causal system H, $h(t) = 0 \quad \forall t < 0$
where h(t) is the impulse response of system H.

Reciprocally, for a system to be causal in the frequency domain, Kramers-Kroning relations[8,9], which link the real and imaginary parts of the complex response, need to be fulfilled. However, such relations cannot be used to verify for causality, nor can they help provide an insight regarding the quality of S-parameter over band-limited discrete data due to the improper integrals as denoted in the equation below,

$$S_r(w) = \frac{1}{\pi} PV \int_{-\infty}^{+\infty} \frac{S_i(w')}{w - w'} . d w'$$

$$S_i(w) = \frac{-1}{\pi} PV \int_{-\infty}^{+\infty} \frac{S_r(w')}{w - w'} . d w'$$

Where PV is Caushy principal value,

$$PV \int_{-\infty}^{+\infty} = \lim \epsilon \longrightarrow 0 \quad \left(\int_{-\infty}^{w-\epsilon} + \int_{w+\epsilon}^{+\infty} \right).$$

Several other methods exist in literature proposing means and methods for causality estimation over band-limited data; however, they still suffer from many uncertainties. A simplified method to check for causality based on a heuristic was proposed[4] where the data's complex trajectory is being monitored, as illustrated the in figure 2 below, and a causality measure gets computed as a ratio of clockwise rotations to the total rotations. The idea behind such heuristic is that any real physical system can only impose a positive group delay, which appears as a clockwise trajectory. An anti-clockwise trajectory, on the other hand, means that your system is introducing a negative group delay, and accordingly, is capable of preceding the cause, which is of course not physical.

2a.

2b.

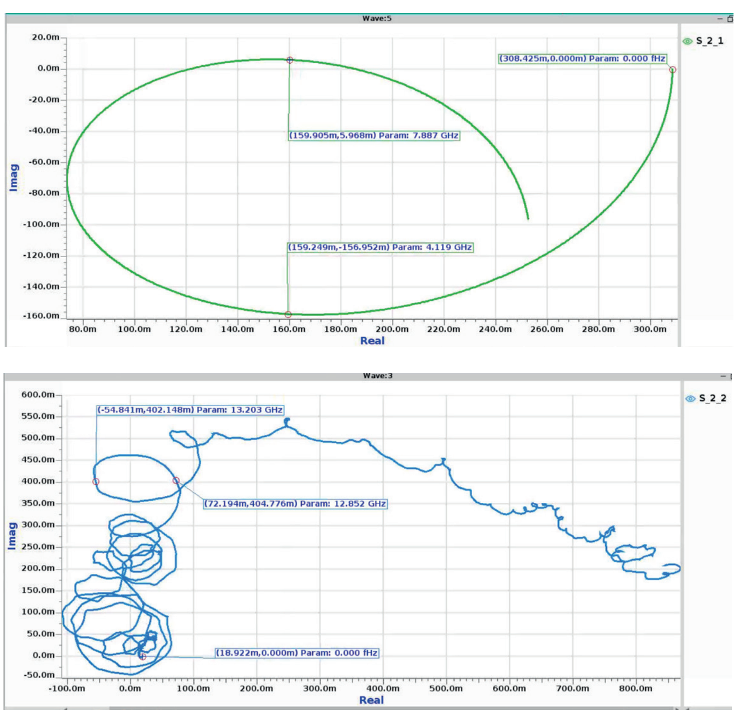

Figure 2. Complex/Polar trajectory for S-parameter response where (a) is a clockwise causal behavior, and (b) is anti-clockwise noisy non-causal behavior.

Many pitfalls can make a system appear as non-causal[5,6], starting from the discrete nature of the data and its sampling frequency. If the extracted data is too sparse, this can lead to time-domain leakage in case of an impulse response that exhibits a long duration. Also, the band-limited data can lead to some ringing in the impulse response, making it to appear as non-causal, which is known as the Gibbs phenomenon; and it can lend itself to be more severe if the data's maximum frequency is not large enough to contain most of the signal's energy.

Non-physical behavior can also be the outcome of a careless full-wave EM simulation setup and approximations. Measuring S-parameters at the lab is also a major contributor to poorly behaved data, especially when de-embedding, fixture removal, stitching and calibration aren't properly configured, ending up with noisy data that is hard to recover from.

Reciprocity

For a reciprocal DUT, the S matrix satisfies the following,

$S=S^T$

For a two-port network, reciprocity entails exhibiting identical transmission and reflection characteristics from port 1 to port 2 or vice versa. This is guaranteed if your model is linear with reciprocal materials. Such assumption of interchangeability no longer holds true when dealing with non-linear models or non-reciprocal materials, e.g., magnetic materials, which lay the basis for the realization of isolators and circulators.

Extracting a good S-parameter model

The more the frequency points, the better the accuracy of raw data. This applies to low- and high-frequency areas, especially if the points are well placed to capture the model’s dynamic behavior across frequency. Not having a DC value (frequency=0) can be problematic where simulators will have it extrapolated in the frequency domain with assumptions that can be prone to inaccuracies in low frequencies or will be calculated by the rational fit without any constraints. Sometimes DC points could be estimated and manually overridden by the user, which can cause discontinuity to the data trajectory on low frequency, or badly extracted by the EM solver due to unreliable approximations or numerical errors.

For higher frequencies, it is best to extract up to at least the fifth harmonic, or one decade higher than the fundamental frequency. Choosing adaptive sampling in the extractor’s settings is the best option where the EM solver would inject frequency points around the regions of high activity such as resonances. Logarithmic sampling with typically 100 points/dec has proven to be sufficient across the board.

For a well-behaved S-parameter model, the real parts must undergo zero slope at DC, i.e., the real parts have the characteristics of an even function. Contrarily, the imaginary parts must have a zero value at DC but can have a non-zero slope, i.e., the imaginary parts have the characteristics of an odd function.

Finally, it's advised to carry a set of sanity checks to inspect the model's passivity, reciprocity, and have a rough estimate of its causal properties, which in return ensures seamless integration with circuit simulators and allows different pieces to interface in harmony.

S-parameter handling aspects

Dealing with tabulated discrete data presents a real challenge to circuit simulators. One possible flow is to get the impulse response of the S matrix, and have it convolved with the time-domain stimulus. However, such a method has its own demerits and constraints when it comes to time-domain simulations. Another potential flow is to create passivated, continuous, rational macro-models in the frequency domain that are easier to interpret and handle when converted to the time domain. AFS has heavily invested in the latter method, as will be shown throughout the rest of the paper. Finally, Rational Function Models (RFM) that are directly generated by EM solvers have recently risen as a means to resolve the dilemma of ill-defined S-parameter models.

Rational fitting

Fitting is a common term in the S-parameter world. Discrete raw data in the frequency domain needs to be fitted to get a continuous representation across the frequency, and in return, facilitates time-domain simulations. S-parameters generated from industry field solvers will need to be "fitted" by the simulator with rational functions (like Laplace transfer functions) to create an equivalent circuit representation of the black box that needs to work at any frequency. This is used for calculating equivalent pole-residue representations.

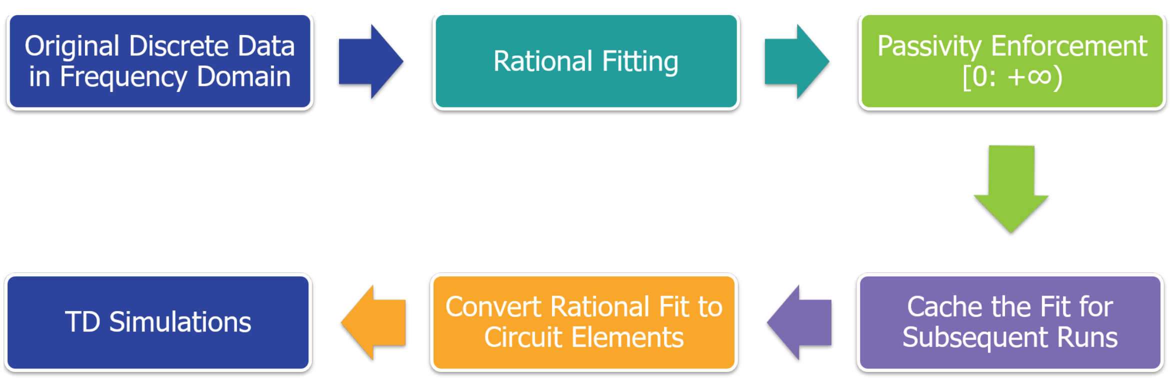

Figure 3: Rational fitting flow incorporated in time-domain simulation.

The rational function created in the process can be non-passive, i.e., it creates energy (like unintended extreme voltage or current spikes at nodes) and won't converge. Conversion to passive nature is required. However, it can cause damage to the model and hence loss of accuracy. Consequently, the need for an efficient passivation algorithm arises, one that can guarantee a passive behavior up to infinity while causing minimum perturbations to the vector fitted data. Non-passive data will impose complications on time-domain analysis and will eventually lead to "time step too small" issues. Vector fitting also aids in enforcing causality and creating reduced order models.

One of the major perks of rational fitting is exposing ill-behaved and badly characterized data, as while the raw data is being fitted into a set of complex poles/residues, the engine will trigger red flags whenever a physical mathematical representation is not able to capture the model dynamics accurately, making it visible to the user that a re-extraction and a revision for the model is needed to avoid unwanted consequences on the long run. Moreover, rational fits do not impose limiting constraints on the time steps when simulated in time domain, allowing for a faster performance compared to convolution.

Rational function model

RFM is a pole/residue format that is directly generated by EM solvers and guarantees a unified baseline across circuit simulators. The S-parameter fitting process can be avoided if the EM extractor has the ability to create a rational function model (RFM) that the simulator can directly use without doing any sort of fit, essentially taking all of the guessing out of the equation. This paves the way for an equivalent baseline among different circuit simulators. RFMs are passive and causal by construct. The poles and residues for each port pair are already pre-calculated, so no fitting or passivity enforcement is required, saving prep time for simulations.

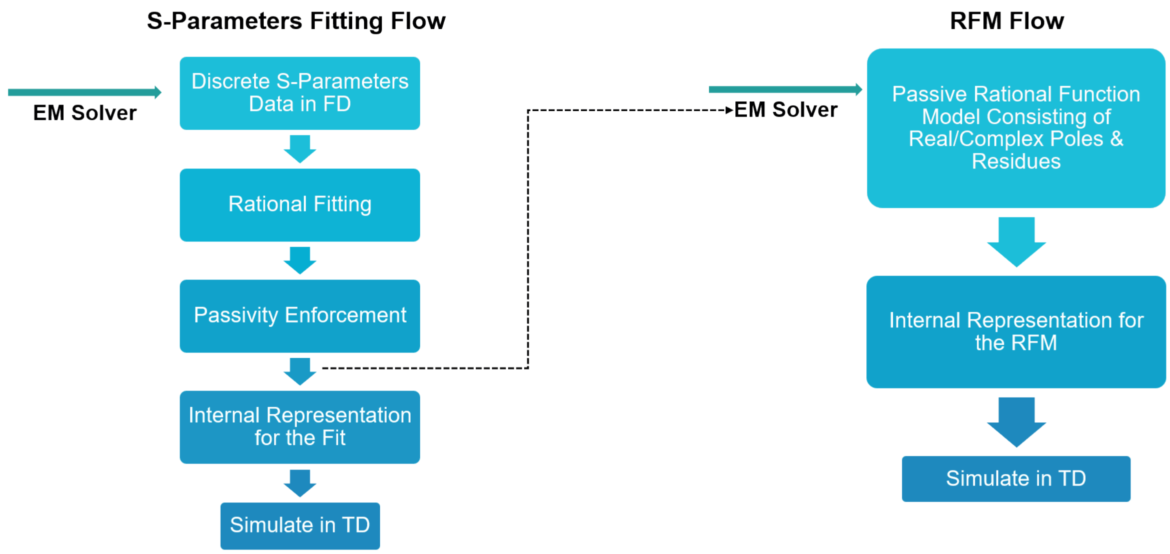

Figure 4: S-Parameter versus RFM flow

Analog FastSPICE platform

Siemens EDA's Analog FastSPICE platform (AFS) is an industry-leading simulation technology that provides superior nm-accurate circuit simulation, mixed-signal simulation, and full-spectrum device noise analysis. AFS is foundry-certified by the world's leading foundries, and it delivers SPICE accuracy. AFS is a single executable platform that supports high capacity and functionality with high performance. It supports industry-standard netlist syntax and is seamlessly integrated into industry EDA design environments. The AFS RF engine supports Shooting Newton and Harmonic Balance analyses with recent innovations. For silicon-accurate characterization, the AFS platform includes the industry's only comprehensive, full-spectrum device noise analysis and integrates with Solido™ Variation Designer to deliver full variation-aware design coverage in orders-of-magnitude fewer simulations, but with the accuracy of brute force techniques.

Analog FastSPICE eXTreme (AFS XT) technology further enhances performance drastically for large post-layout netlists. There is no additional cost to existing and new customers. AFS XT can handle over 300 million element transient capacity and delivers the fastest mixed-signal simulation with Symphony™ mixed-signal platform.

AFS S-parameter enhancements

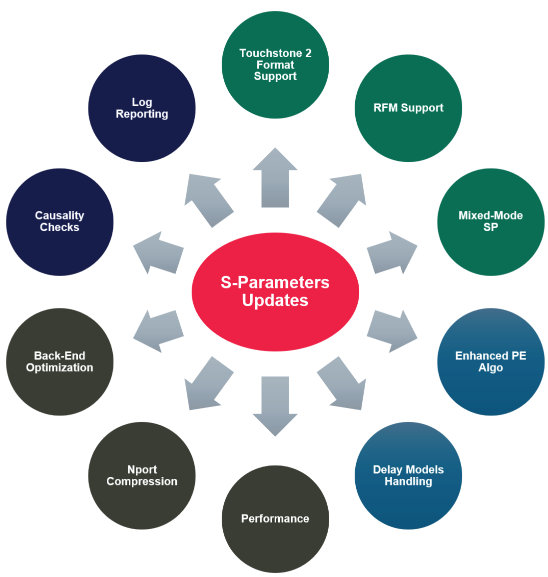

Figure 5: S-Parameter focus areas in AFS.

Recent investments by Siemens EDA into S-parameter handling for enhanced usability and performance is showcased in figure 5.

Touchstone 2 support

An extension of Touchstone 1 - with additional set of features - that is used to describe an n-port network parameter data. You may refer to IBIS specifications and standards[7] for more details regarding Touchstone-2 format and extended features set.

RFM support

This feature provides the ability to read a RFM model as an alternative to touchstone, citi or spectre format S-parameter files. Such a flow has started to gain high traction among the IC design community as it can eliminate ambiguities and inconsistencies across different circuit simulators in comparison to its S-parameter counterpart.

A standard RFM file consists of two parts. The first one is a header that specifies information about the model itself, such as the number of ports, matrix type, and characteristic impedance. While the second part has the data that constitutes the transfer function of each pair of ports comprising of real and complex poles and residues in addition to constant, reactive, and propagation delay terms, as demonstrated in the generic rational function below. Incorporating RFM models in a simulation is analogous to S-parameter where a user just has to point to the model of interest while specifying the type; then AFS does its magic.

$$S_{ij}(s) = Const + sC + \sum_{n=1}^{N_r} \frac{r_{r,n}}{s - p_{r,n}} + \sum_{n=1}^{N_c} \left(\frac{r_{c,n}}{s - p_{c,n}} + \frac{r^*_{c,n}}{s - p^*_{c,n}} \right)$$

Mixed-mode support

Mixed-mode support extends S-parameter analysis capabilities to enable automated transformations from single-ended S-parameter to differential, common and cross-mode S-parameter, which are often required by SI/PI engineers to ensure compliance with industry standards. For given 2N ports, the generalized mixed-mode S-parameters can be given as,

$$[S_{dd}]_{i,j} = \frac{1}{2}\left(S_{2i-1,2j-1} - S_{2i-1,2j} - S_{2i,2j-1} + S_{2i,2j}\right)$$

$$[S_{cc}]_{i,j} = \frac{1}{2}\left(S_{2i-1,2j-1} + S_{2i-1,2j} + S_{2i,2j-1} + S_{2i,2j}\right)$$

$$[S_{dc}]_{i,j} = \frac{1}{2}\left(S_{2i-1,2j-1} + S_{2i-1,2j} - S_{2i,2j-1} - S_{2i,2j}\right)$$

$$[S_{cd}]_{i,j} = \frac{1}{2}\left(S_{2i-1,2j-1} - S_{2i-1,2j} + S_{2i,2j-1} - S_{2i,2j}\right)$$

where:

- Sdd is the differential-mode S-parameter sub-matrix
- Scc is the common-mode S-parameter sub-matrix
- Sdc is the common-to-differential mode S-parameter sub-matrix
- Scd is the differential-to-common mode S-parameter sub-matrix

Passivity enforcement

Passivating a model undergoes an unavoidable series of steps, starting from identifying the regions of passivity violations. The magnitude of maximum violations must be determined next within those regions. Finally, minimal perturbation ΔS takes place to satisfy the passivity constraint according to $\|S - \Delta S\|_2 \leq 1$. This flow can introduce significantly unwanted runtime overhead, and can endanger the integrity of the original discrete raw data, and this is where novelty and optimizations kick in. AFS now incorporates a new optimized algorithm for passivity enforcement that guarantees the fitted models are passive from DC to infinity while preserving the accuracy of the original data. This prevents convergence issues (time step too small), alleviates any constraint bounding the transient time steps, and guarantees correlation to silicon measurements.

The passivity aspect of AFS is illustrated in figure 6 below. The end-goal would be that, at any given point in frequency, the passivity norm should be <=1.

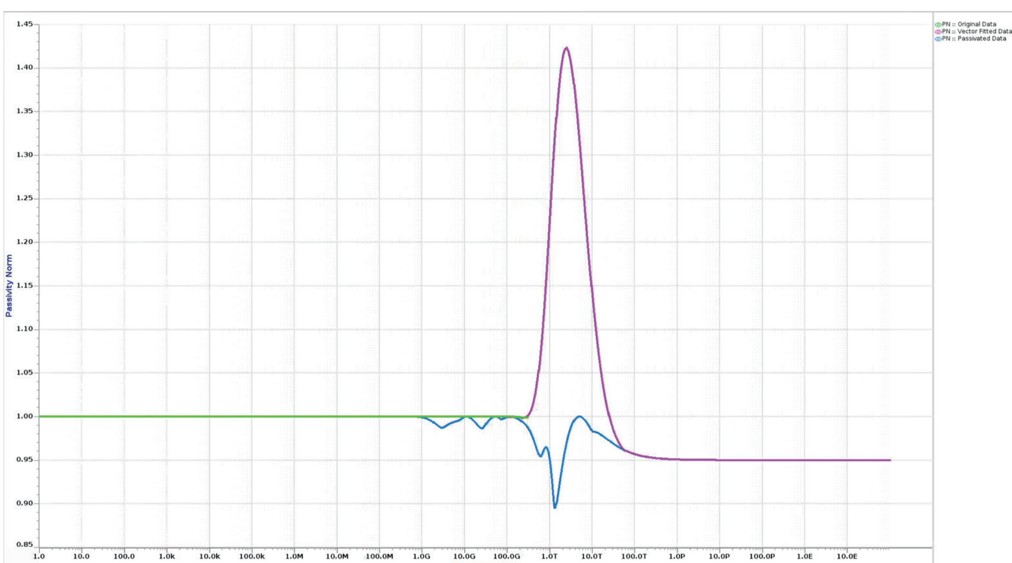

Figure 6: Illustration of Passivity Norm across frequency at different fitting stages.

Delay line handling

Many applications would employ distributed layout structures exhibiting medium to long electrical delays, e.g., long traces, and various kinds of transmission lines. Such structures in their most basic lossless lumped representation can be thought of as a cascade of LC sections, as illustrated in figure 7. A long delay manifests itself as a set of circular trajectories on a polar plot, where each complete circle represents a delay of 360°.

It's very common to end-up with a high-order, complex I/O transfer function according to the length and geometry of the line. The constraints that stem from such transfer functions can impose cumbersome and stringent requirements on rational fits to accurately generate continuous passivated models. AFS has the ability to address such accuracy-performance tradeoffs to help users navigate through the continuum as they see fit.

It's also worth noting the highly dynamic behavior across frequency, induced by the high-order transfer function, makes any kind of direct extrapolation in frequency domain for the discrete data totally non-physical and can lead to inaccurate results once correlated to silicon measurements. Accordingly, it's crucial to have a DC data-point extracted or estimated in such models.

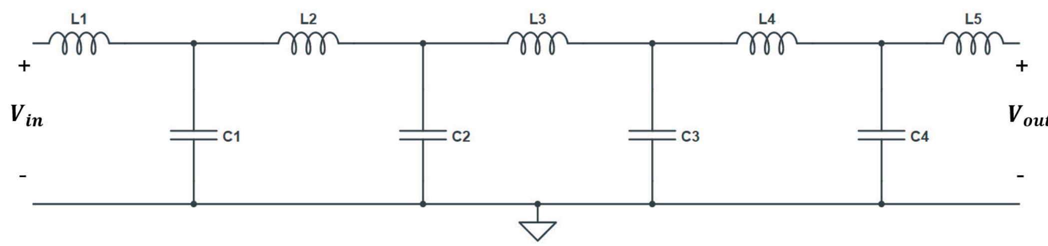

Figure 7: Lossless lumped representation for an electrically long line.

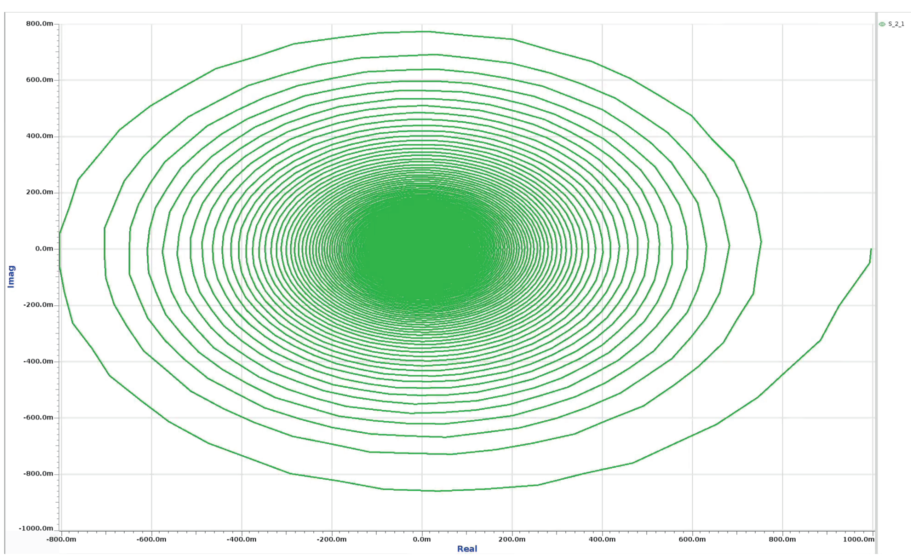

Figure 8: Circular complex/polar trajectory for long delays.

Causality checks

Causality checks apply to detecting causality for band-limited data based on the causality metric heuristic that was previously described. The automated checks will notify the user about potentially ill-extracted models and highlights exactly where the user needs to look. Furthermore, there is enhanced log reporting that elaborates on warnings and errors to ease the debugging process. When the designer is notified about data being non-causal, it can help them re-extract the S-parameters with more accuracy.

Figure 9 below illustrates the importance of a well-fitted S-parameter model as well as the direct RFM alternative. A 24.5GHz VCO with a multi-port S-parameter for the inductor was simulated for four scenarios: 1) RFM model with AFS; 2) well extracted S-parameter model with AFS fitting; 3) well extracted S-parameter model with bad fitting; and 4) poorly extracted S-parameter model. Scenarios 1 and 2 yield matching and highly accurate results, unlike scenarios 3 and 4. The large discrepancy in scenario 4 is an inevitable side effect to extracting models without DC, and/or without low- or high-frequency data, and/or sparse datapoints in frequency bands of interest.

Backend optimization

Backend optimization applies to converting rational functions to circuit elements using proprietary devices for better convergence, capacity, and memory footprint.

Nport compression

The rising complexity of IC modules, the shift towards higher frequencies, increasing high-yield requirements and faster time-to-market constraints are imposing cumbersome challenges on design cycles. S-parameter models are growing in number, size and complexity. NPORT compression comes into play when dealing with large models, where a pre-defined percentage of their ports can deem to be unused, as illustrated in figures 10 and 11 below.

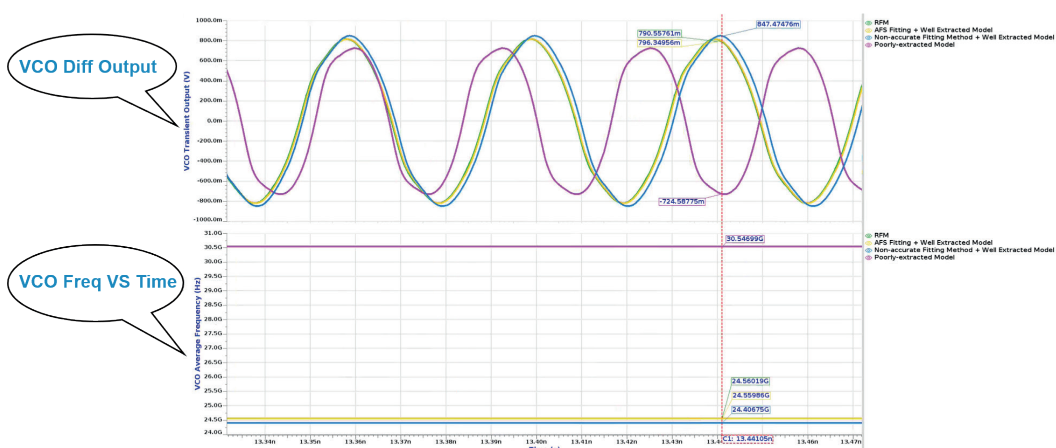

Figure 9: Example of high frequency clock with varying extraction quality, fitting and RFM alternative.

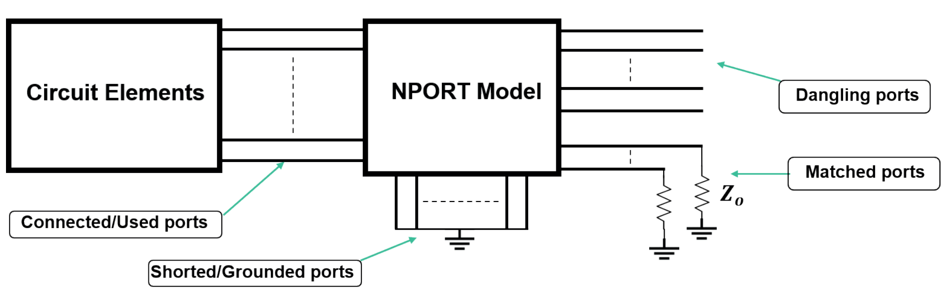

Figure 10: Eligible scenarios for port compression.

Figure 11: Nport compression flow.

Nport compression applies mathematical transformations over the S matrices and can safely remove shorted, open, and matched ports with no loss in accuracy while preserving the integrity of the overall model. Such compression results in an improved fitting performance, reduced back-end representation for the model, and it prevents any kind of leakage that may arise from dangling ports.

Performance

Performance applies to speed-up on fitting algorithms with a 4.5X YoY trend. Figure 12 (below) illustrates a sample of AFS fitting speedup over the past year across many S-parameter models of varying port sizes and frequency band complexity.

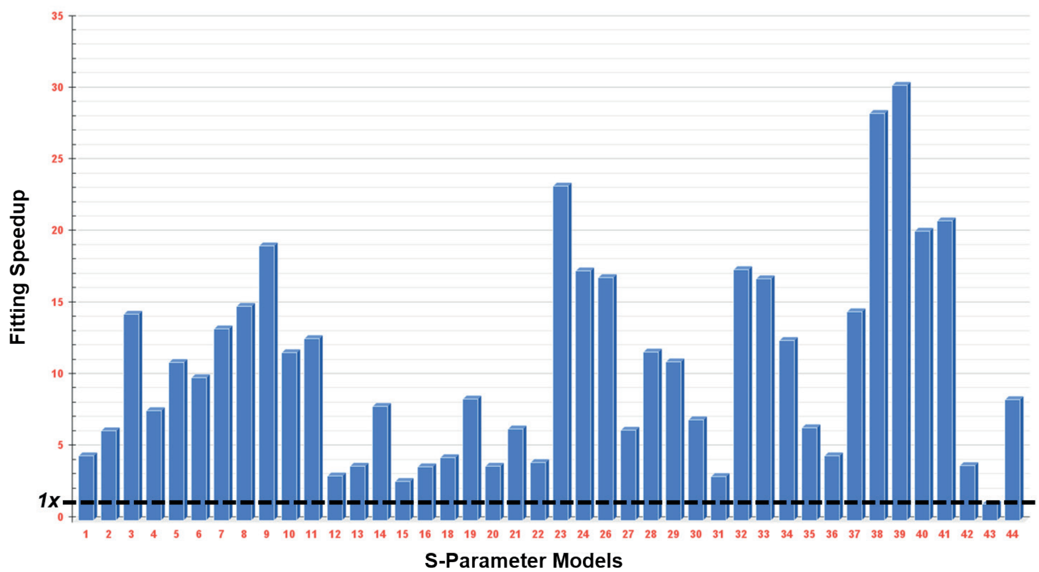

Figure 12: YoY AFS fitting performance speedup.

As S-parameter usage becomes increasingly complex in IC development, technical support for guidance on proper S-parameter handling as well as debug for anomalies becomes equally important, and Siemens EDA is committed to prompt support.

Conclusion

For circuit simulation involving S-parameter files, choose your simulation engine wisely, since its expected frequency behavior cannot be compromised. Siemens EDA's Analog FastSPICE platform (AFS) is an industry-leading simulation technology that provides best-in-class, nm-accurate circuit simulation, mixed-signal simulation and full-spectrum device noise analysis and is foundry-certified by the world's leading foundries delivering SPICE accuracy. Take advantage of the latest AFS offering that provides best-in-class S-parameter handling performance and accuracy along with the many features it supports including RFM support, enhanced fitting, backend optimization, mixed mode support, delay handling, causality checks and N-port compression. Furthermore, you will benefit from the multi-threaded capability AFS offers for additional speedup for designs needing extensive sweeps, corners, and statistical analysis.

Come talk to us regarding your S-parameter verification issues and try out our AFS engine to get through the hurdles of convergence and accuracy, while benefiting from industry proven performance!

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