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The Need for Impulse Response Models and an Accurate Method for Impulse Generation from Band-Limited S-Parameters

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Abstract

In the signal integrity industry, S-parameters have become the most commonly distributed models for simulating passive components. Because S-parameters are frequency-domain values, many signal integrity engineers are finding it difficult to accurately implement these parameters in time-domain simulations. Addressing transient convolution specifically, this paper shows the need for a new impulse response model and proposes a methodology for its inclusion in time-domain simulations. The paper also solves another difficult problem by presenting a new technique for converting band-limited S-parameters into 'base-delay' causal and passive impulse response models that preserve accuracy to the maximum frequency of the original S-parameters.

Authors Biographies

Fangyi Rao received his Ph.D. degree in physics from Northwestern University in 1997, for research in quantum theory of magnetism and transport. He joined Agilent EEsof in 2006 as a Senior Development Engineer, where he works on Analog/RF simulation technology in ADS and RFDE. From 2003 to 2006 he was with Cadence Design Systems, where he made key contributions to the company's Flexible Balance technology and perturbation analysis of nonlinear circuits. Prior to 2003 he worked in the areas of EM simulation, nonlinear device modeling, and optimization.

Chad Morgan earned his degree in Electrical Engineering from the Pennsylvania State University, University Park, in 1995. For the past 12 years, he has worked in the Circuits & Design group of Tyco Electronics as a signal integrity engineer, specializing in the analysis & design of high-speed, high-density components. Currently, he is a Member of Technical Staff with Tyco Electronics, where he focuses on high-frequency measurement & characterization of components & materials, full-wave electromagnetic modeling of high-speed interconnects, and the simulation of digital systems. Mr. Morgan's responsibilities at Tyco Electronics include numerous research activities, and he has presented multiple papers at both DesignCon & IMS.

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Introduction

In the signal integrity industry, S-parameters are quickly replacing traditional lumped-element SPICE models to become the most commonly distributed models for simulating passive components. Although S-parameters are more accurate than lumped-element SPICE models, they are composed of band-limited, frequency-domain data that can be difficult to use properly in time-domain simulations. Increasingly, signal integrity (SI) engineers are expressing frustration in using S-parameter models to quickly and accurately complete time-domain simulations of digital systems. This paper presents a two-tier solution to the band-limited S-parameter problem that allows fast and accurate time-domain simulations.

To begin, the paper discusses current methods that are used to simulate frequency-domain, S-parameter data in time-domain simulations. A brief discussion of macro-modeling techniques that convert S-parameters into pole/residue transfer functions (and ultimately dependent-source SPICE models) is included. However, the paper then shifts its focus to transient convolution methods that have become popular not only in several commercial EDA tools, but also in custom computer algorithms for completing fast and accurate time-domain simulations.

Considering transient convolution, the paper discusses specific properties of the Fourier transform in order to justify the need for a new, time-domain model format. In essence, the paper shows that direct Fourier transforms of impulse responses are easier than inverse transforms of band-limited S-parameters. Therefore, by starting with impulse response data, an end user can directly complete transient convolution without needing to complete inverse transforms. Further, it is relatively simple to use the impulse response data to calculate S-parameters.

Once the need for new impulse response models has been established, the paper presents a two-tier solution for enabling fast and accurate time-domain convolution simulations. First, the paper describes a technique for converting band-limited S-parameters into ‘base-delay’ causal and passive impulse response models that preserve accuracy to the maximum frequency of the original S-parameters. The method for accomplishing this is new, so a significant amount of data is presented in order to prove the validity of the method. The paper then presents an impulse-response modeling methodology that will allow passive component data to be easily distributed.

Traditional and Modern Model Distribution

Since the very early days of signal integrity engineering, passive component models have been distributed via lumped-element sub-circuits, as shown in Figure 1. Typically, quasi-static 2D or 3D solvers have been used to derive inductance (L), mutual inductance (k), and capacitance (C) for multiple cross sections of a part. Sometimes, a small DC resistance (R) is added to the model, but otherwise, the models are lossless vs. frequency.

One of the major advantages of traditional lumped element models is that they can be run in any generic SPICE simulator. Within SPICE, these models can be run in transient simulations with non-linear active device models, or they can be swept versus frequency to compute the linear S-parameters of the component. Traditional lumped element models are inherently causal and passive, and their accuracy has proved adequate for the slower edge and data rates of the past.

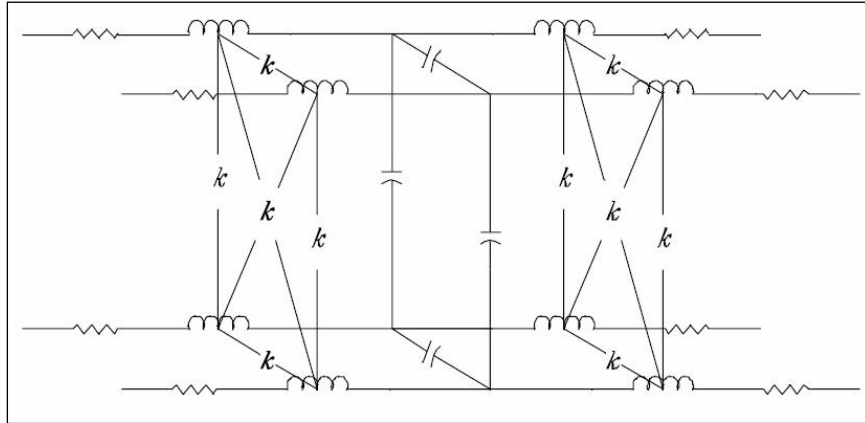


Figure 1: Traditional Lumped Element Model.

Today's gigabit data rates, however, highlight the weaknesses of traditional lumped element models. Specifically, fast edge rates require that lumped element models be sectioned finely, which in turn, makes the models extremely complex. These complex models then require extremely long run times to produce simulation results. Besides long run times, traditional lumped element models also suffer from inaccuracies at fast data rates. These models cannot account for frequency-dependent loss, frequency-dependent phase dispersion, higher-order longitudinal modes, or transverse currents.

As a result of lumped element model weaknesses at higher speeds, most SI engineers have now transitioned to using distributed S-parameter models to simulate passive components. These models are comprised of measured or modeled complex data versus frequency, as shown in Figure 2. S-parameters can be measured, with or without test fixturing, by the vector network analyzer (VNA). They can also be modeled via parametric equations, lossy 2D field solvers, 2.5D field solvers, or full-wave 3D field solvers.

S-parameters easily characterize the frequency-domain behavior of passive components, and they offer other advantages as well. S-parameters are flexible because they can be used in frequency-domain linear solvers, and they can be used for deembedding and calibration algorithms. S-parameters are accurate, because they can account for all high-frequency component effects, including frequency-dependent losses and higher-order modes. S-parameters are also portable, because they can be distributed in the industry-standard Touchstone format.

Although S-parameters are currently the model of choice for passive component distribution, they pose significant problems to SI engineers trying to complete time-domain simulations. Ultimately, S-parameters must be converted into either pole/residue macro-models or time-domain impulse responses in order to be used in time-domain simulations. As will be shown in this paper, both of these techniques require significant expertise. As a result, many SI engineers are struggling to use S-parameters properly in time-domain simulations, and it would be ideal to have a new model that would ease the problem.

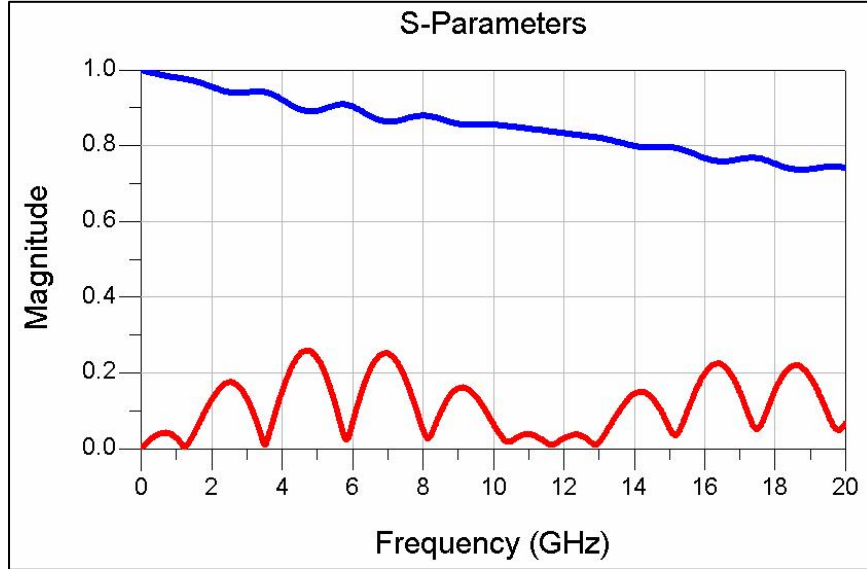


Figure 2: Modern S-Parameter Data (Insertion & Return Loss Shown).

Time-Domain Simulation Tools and Methods

Given that S-parameters are the current model of choice, it is useful to review the tools and methods that are commonly used by SI engineers when simulating them in time-domain simulations.

The most common tool used by SI engineers is SPICE. In its traditional form, SPICE performs transient simulations through the time-stepping of differential equations from lumped elements, such as resistors, inductors, capacitors, and independent/dependent sources. As a result, S-parameters must be converted into lumped element models in order to be simulated in traditional SPICE. There are two popular methods to do this. The first method defines an element structure ahead of time and then uses an optimization algorithm to find the best component values that will match the given S-parameters. The problem with this method is that it is often very difficult to know a model's lumped component structure ahead of time. The second method, that has gained increasing popularity in recent years, is termed pole/residue macro-modeling. In this method, S-parameters are approximated by a Laplace-domain expression [1], as shown in Equation (1), to the given S-parameters:

$$H(s) = c + \sum_{m=1}^M \frac{k_m}{s - p_m} \quad (1)$$

Several passivity enforcement methods have been proposed to make the final approximation passive, stable, and causal so that it can be converted into a state-space equation and ultimately a lumped macro-model for SPICE. One complication with this approach is that complex S-parameter responses require high-order approximations that involve a large number of circuit elements and take a long time to run. To circumvent this problem, some SPICE simulators allow

direct inclusion of Laplace-domain models, eliminating the need for lumped element conversion and taking advantage of fast recursive convolution for their evaluation.

Whether Equation (1) is converted to a lumped macro-model or evaluated directly by means of recursive convolution, the underlying difficulty remains the same: fitting S-parameters to passive Laplace-domain transfer functions is difficult and failure-prone, especially when fitting complicated S-parameter responses or noisy data.

Another approach is to convert frequency-domain S-parameters to impulse responses and compute output waveforms using time-domain convolution. This method is the focus of this paper, and specifically, the calculation of an impulse response model to make this simulation process easier and more accurate.

The principle of time-domain convolution is well known and is illustrated in Figure 3. It involves time-mirroring the given impulse response, and then stepping that reversed impulse response through the input waveform while multiplying and adding all overlapping points to produce the output waveform at each time point.

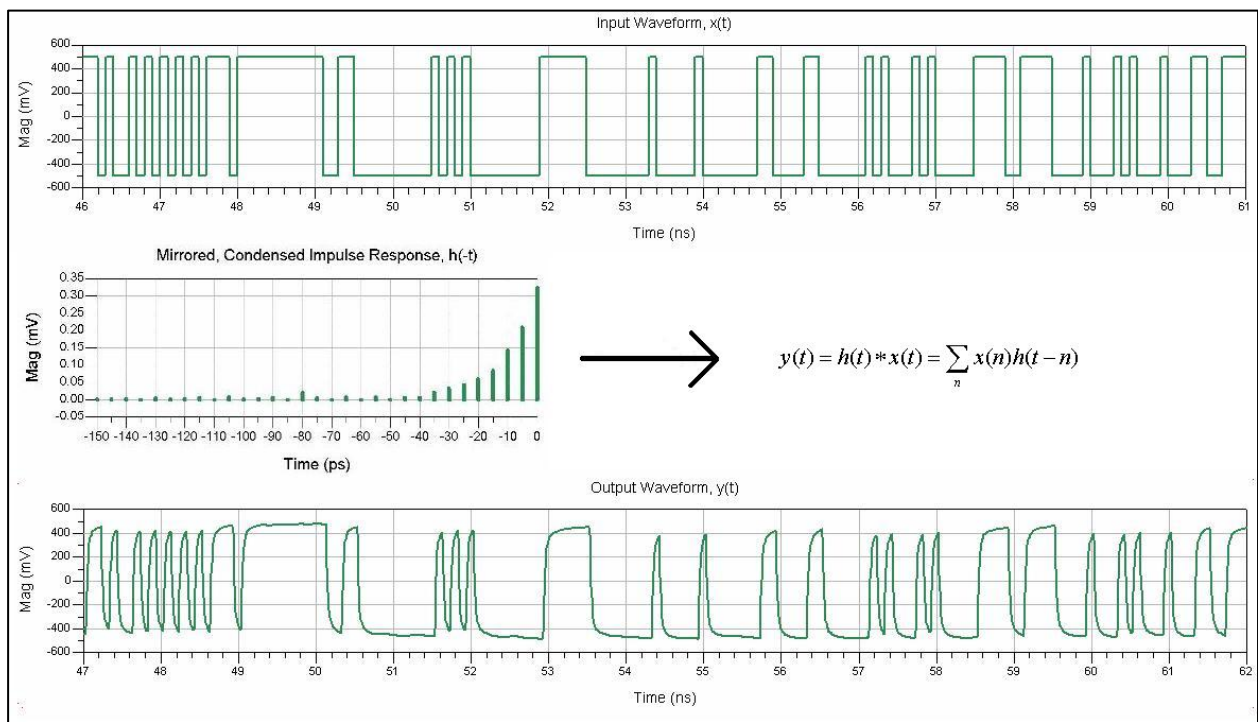


Figure 3: Time-Domain Convolution.

Impulse response calculation is central to the application of convolution methods. Though the inverse discrete Fourier transform (iDFT) provides a theoretical framework for conversion of frequency-domain data to time-domain impulses, obtaining accurate impulse responses from band-limited S-parameters will be shown to require considerable attention beyond direct application of the iDFT.

Time-Domain Convolution Challenges

System causality, passivity, and delay preservation pose significant challenges to obtaining accurate, robust, and reliable impulse response models for use in time-domain convolution. The next few paragraphs qualitatively describe these technology challenges and illustrate their effect on time-domain simulations.

Causality

Band-limited (i.e., truncated) S-parameters can violate causality conditions even when in-band data is accurate and physical. Recall that causal systems satisfy Kramers-Kronig (K-K) [2] relations:

$$\begin{aligned} u(\omega) &= \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{v(\omega')}{\omega - \omega'} d\omega' \\ v(\omega) &= -\frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{u(\omega')}{\omega - \omega'} d\omega' \end{aligned} \quad (2)$$

where $u(\omega)$ and $v(\omega)$ are the real and imaginary part of the frequency response and P is the Cauchy principle value. As Equation (2) shows, K-K relations impose the following strict constraints on causal systems:

- a) The real and imaginary components of the frequency response (e.g. S-parameter matrix entries) are interdependent and related by the Hilbert transform.
- b) The K-K relations involve integration over all frequencies.

As a consequence, truncated frequency responses of otherwise causal systems, typical of measured S-parameters, generally break K-K relations and lead to non-causal responses.

To gain an appreciation for this phenomenon, consider a simple response function:

$$H(\omega) = \frac{1}{1 + j\omega\tau} \quad (3)$$

representing the conductance of a series RL circuit with $R = 1 \Omega$ and $\tau = L/R$. Its impulse response $h(t)$ is causal and given by:

$$h(t) = \begin{cases} 0 & (t < 0) \\ \exp(-t/\tau) & (t \geq 0) \end{cases} \quad (4)$$

Consider next the impulse response obtained by direct application of the iDFT when the conductance function is truncated beyond an upper limit, as is typical in measurements and electro-magnetic simulations. Figure 4 compares the exact, causal impulse response given by Equation (4) (assuming $\tau = 1$) to the iDFT of the conductance function truncated at 1 Hz.

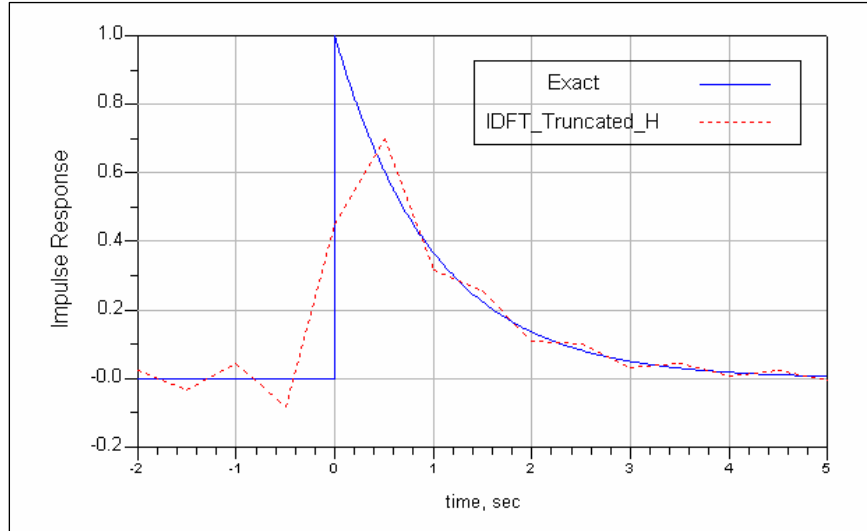


Figure 4: Exact Impulse Response of $H(\omega)$ and $iDFT$ of $H(\omega)$ Truncated at 1 Hz.

Spectrum truncation, as shown in the figure and as argued earlier, induces a non-causal response in this example. It also produces Gibbs ripples in the time domain, as illustrated in Figure 4.

To obtain physically meaningful responses from convolution simulations, one applies a correction technique to enforce causality. Consider a hypothetical causality correction method that simply truncates the non-causal ($t < 0$) part of the impulse to zero. Figure 5 compares the given $H(\omega)$ to the DFT of the truncated impulse, to gain insight into the effect of simple causality correction methods on the accuracy of convolution simulations. As Figure 5 shows, the spectrum of the truncated impulse does not match the original frequency response and, consequently, time-domain simulation accuracy is poor.

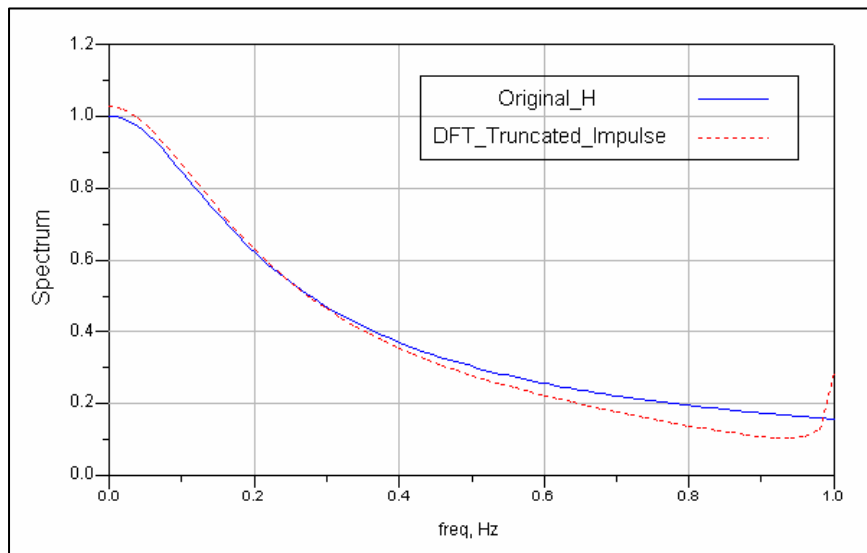


Figure 5: Magnitude of $H(\omega)$ and DFT of Truncated Causal Impulse.

To deal with Gibbs ripples, one is tempted to apply windowing techniques commonly used in signal processing applications [3]. Windowing has an adverse affect on causality because most of the popular window functions, such as Bartlett, Hanning and Hamming, are non-causal themselves. For example, Figure 6 highlights the effect of Hanning windowing on the impulse response of the truncated conductance function. Ripples are smoothed out, as expected, but significant energy appears at $t < 0$.

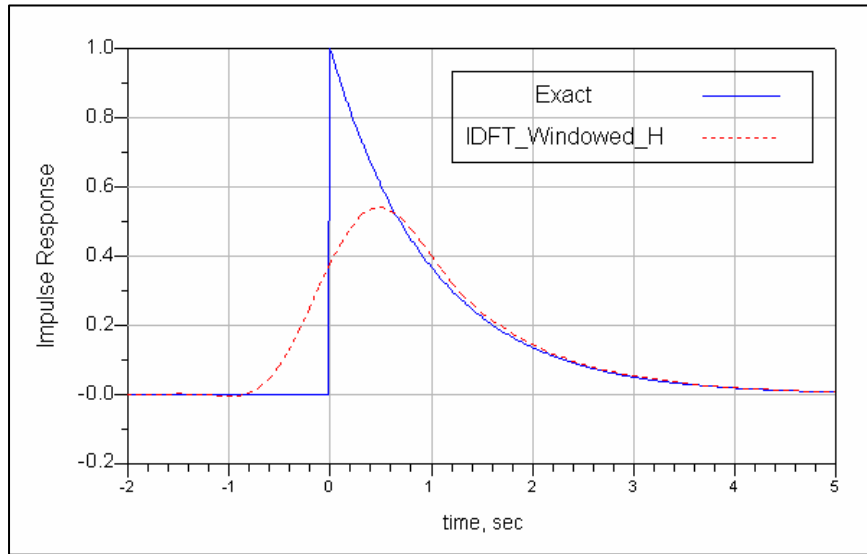


Figure 6: Exact Impulse Response of $H(\omega)$ and iDFT of Windowed $H(\omega)$.

Delay Preservation

While in a strict sense causality and causality enforcement methods deal with system response in relation to absolute time zero, another important consideration is the response with respect to a minimum propagation delay. Physical systems produce no output before the system's base propagation delay (i.e. they are 'base delay' causal), a constraint that is frequently violated in numerical simulation. Traditional substrate and skin loss models are a common source of 'base delay' causality violations [4,5], as are the numerical effects of spectrum truncation and the resulting violation of K-K relations. Figure 7 shows a typical manifestation of 'base delay' causality violations.

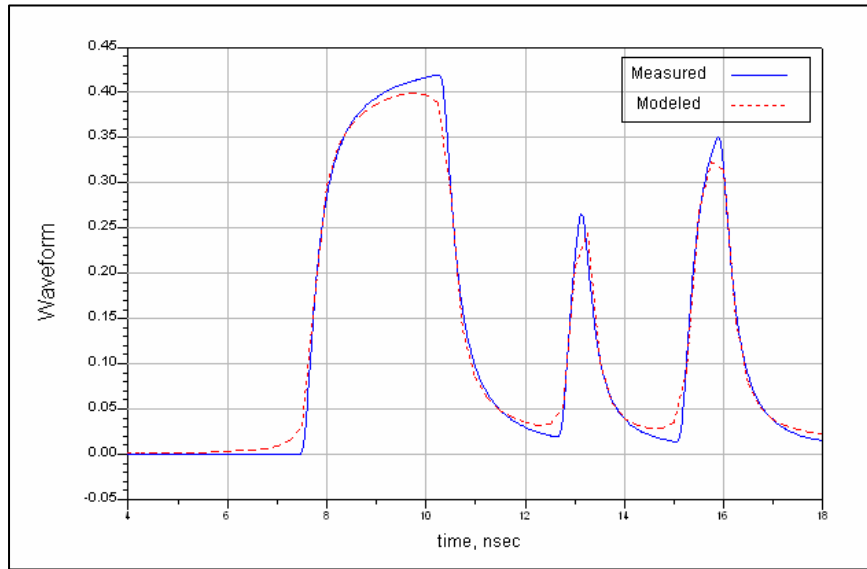


Figure 7: ‘Base Delay’ Causality Violation (Propagation Delay is ~ 7.5 ns).

While in this case the expected system delay is approximately 7.5 ns, simulations incorrectly predict finite output at approximately 6 ns.

Passivity

Models of passive components often appear non-passive because of measurement or numerical modeling errors. Passivity enforcement is therefore a key requirement for any simulation approach, including impulse response convolution.

A system is passive if the magnitude of each eigenvalue of its S-parameter matrix is less than or equal to one. This definition suggests a straightforward method to enforce passivity in the frequency domain, e.g., by scaling the matrix at the offending frequency by $1/\lambda$, where λ is the magnitude of the largest matrix eigenvalue.

In practice, any approach to passivity correction requires considerable attention. As Equation (2) suggests, S-parameter manipulation in the frequency domain may violate causality. Thus, once again, careful consideration of causality plays a key role in obtaining reliable time-domain results.

Accurate Impulse Response Calculation for Robust Time-Domain Convolution

Impulse calculation for accurate time-domain convolution is a non-trivial task, requiring careful attention to the principles of system causality, passivity, and delay preservation. A rigorous new approach to time-domain convolution has been developed to address these fundamental challenges [6], offering the following important features:

- Automatic causality correction with respect to delay and with respect to absolute time zero.
- Passivity correction that ensures causal impulse response of the passivity-enforced S-parameters.
- Optimal or near-optimal preservation of the original frequency response; i.e., impulse response DFT matches the given S-parameters data to the highest possible degree following passivity and causality enforcement.

In the next few paragraphs, these important properties of the new method are validated via several time-domain simulation examples.

Low Impedance RLC Network

The simplest way to gauge the accuracy of time-domain convolution is to compare it to traditional lumped circuit simulation, as is commonly available in SPICE. This example starts from an RLC model, applies AC simulation to extract its S-parameters to a realistic upper limit, and compares results of time-domain convolution to RLC transient simulation. The example circuit is shown in Figure 8.

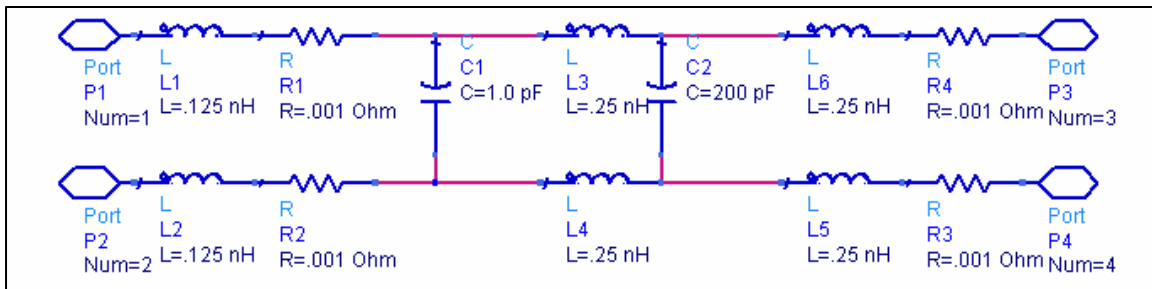


Figure 8: Lumped RLC Network.

Despite its apparent simplicity, the benchmark circuit illustrates two problems encountered in more complicated cases. The first is that S-parameters are band-limited and therefore non-causal. The second is that the network is low-impedance and extracted into 50 Ohms, requiring high impulse response accuracy in order to match RLC transient results.

Typically, straightforward application of time-domain convolution (e.g., by direct application of the iDFT, as illustrated in Figure 3) fails to produce acceptable results. Typical results of direct iDFT application are shown in Figure 9.

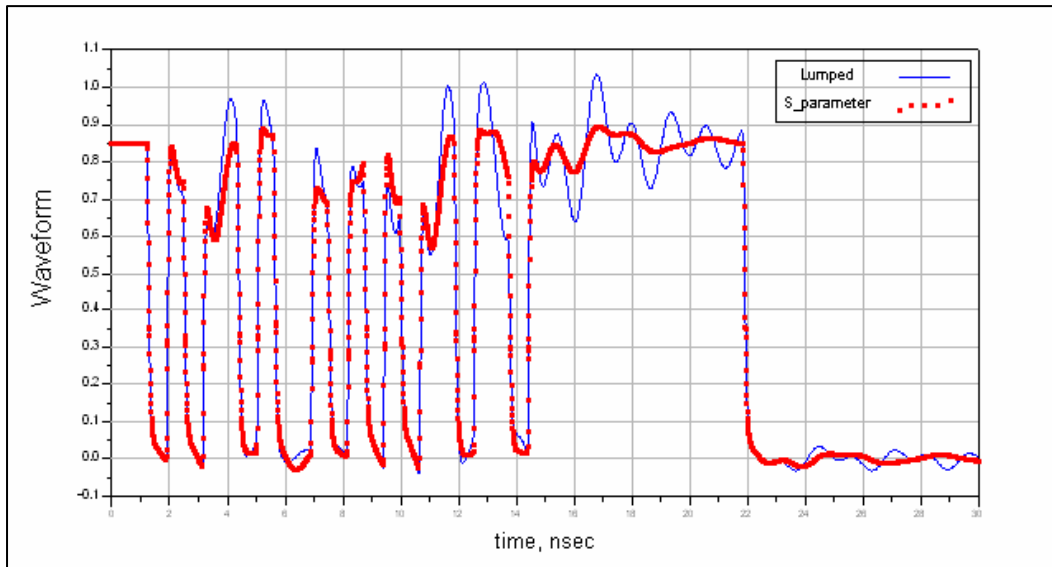


Figure 9: Waveforms Calculated by Lumped Circuit Simulation and by iDFT-based S-parameter Convolution.

Another way to look at simulation accuracy is to compare the impulse's DFT to the original S-parameters. As discussed earlier, causality violations, among other factors, contribute to discrepancies between the given band-limited data and the impulse response's DFT. Figure 10 shows frequency-domain simulation error for parameter $S(1,1)$.

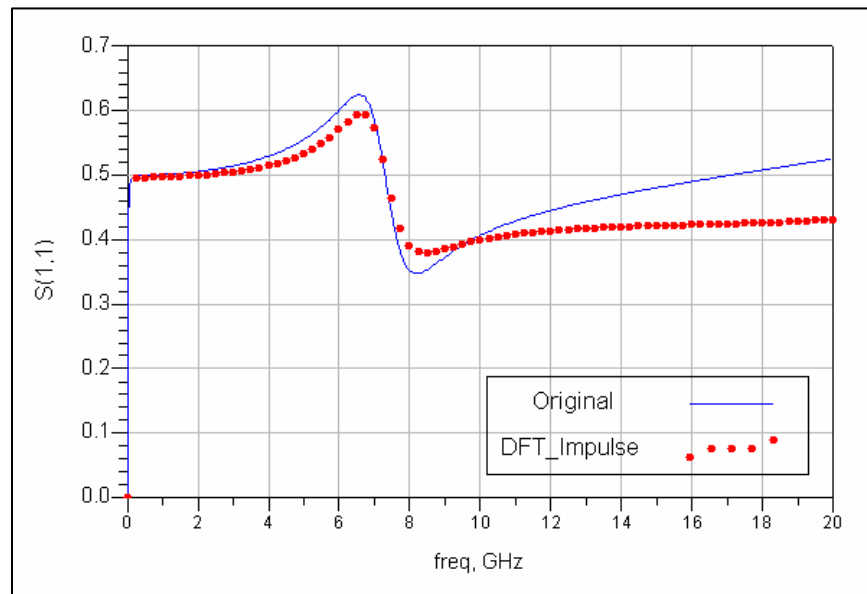


Figure 10: Magnitudes of Original $S(1,1)$ and DFT of Impulse Response of $S(1,1)$.

Turning attention to the proposed, rigorous approach to causal impulse calculation, the new method is applied to the circuit in Figure 8 and another comparison between time-domain convolution and lumped RLC simulation is performed. Figure 11 shows the results.

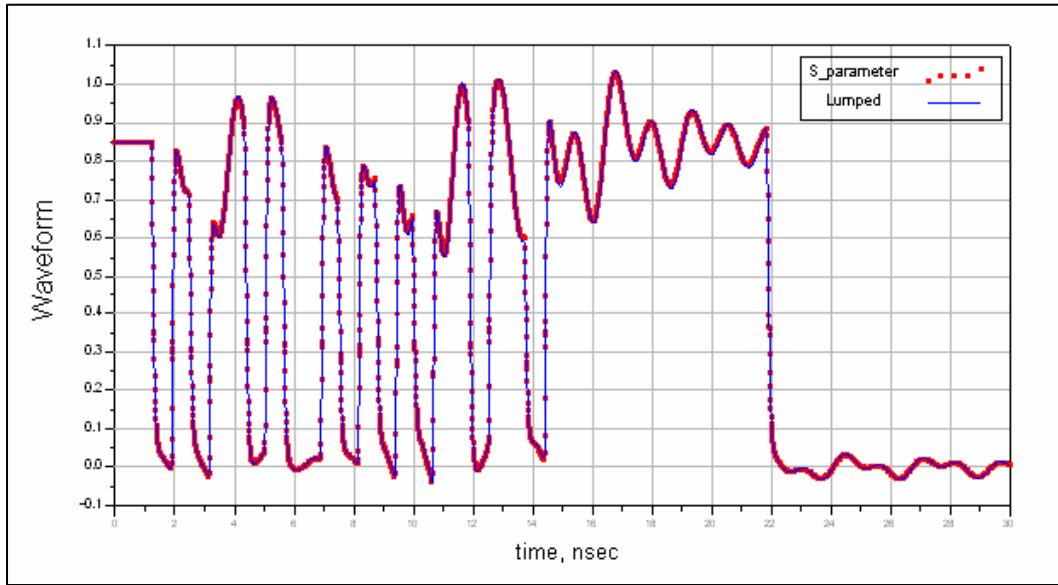


Figure 11: Waveforms Calculated by Lumped Circuit Simulation and by Equivalent S-parameter Convolution.

Observe the near perfect agreement in the time domain. Revisiting spectral-domain comparisons in Figure 12, the excellent level of accuracy offered by the new approach is confirmed once again.

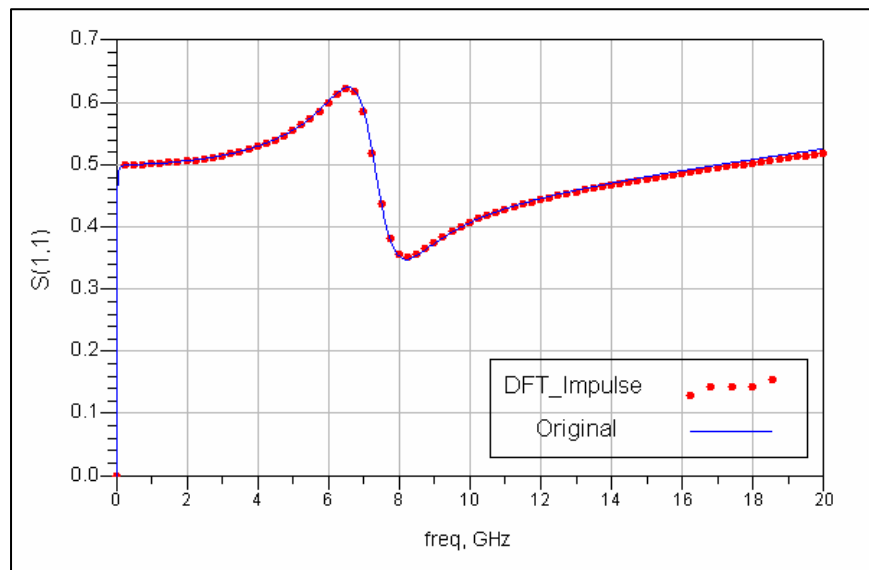


Figure 12: Magnitudes of Original $S(1,1)$ and DFT of Impulse Response $S(1,1)$.

Long Coaxial Cable and Multilayer Transmission Line

A 30 meter coaxial cable described by measured S-parameters up to 6.4 GHz is simulated as another, more realistic example. The new impulse calculation method is applied and its accuracy examined by comparing the impulse's DFT to the measured S-parameters. This comparison is shown in Figure 13 for parameter S(2,1). Note that the simulated impulse closely tracks the measurement even in the region dominated by measurement noise.

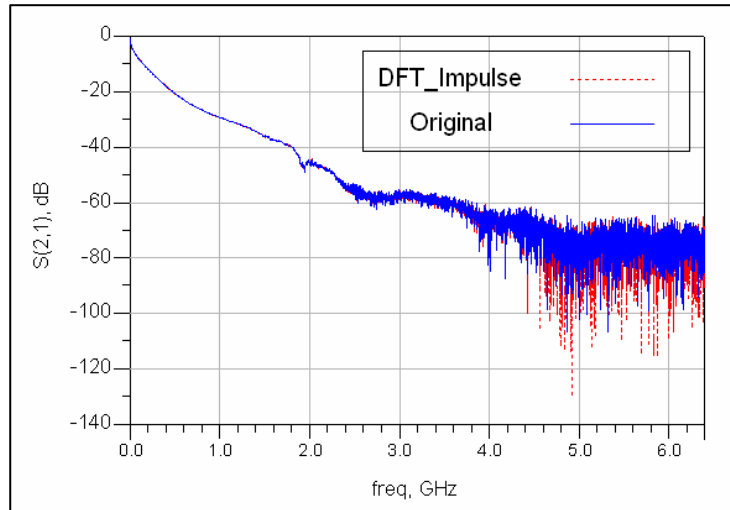


Figure 13: Magnitudes of Original S(2,1) and DFT of Impulse Response of S(2,1).

To showcase the ability of the impulse calculation method to tackle a variety of passive structures, consider the simulation of a 20 cm 8-layer transmission line driven by a 1 GB/s pulse train. Despite the complex frequency spectrum due to coupling between metal layers, the new approach generates a highly accurate representation. Figure 14 is a spectral-domain comparison of the impulse's DFT and the original model response for parameter S(2,1), showing near perfect agreement between the two.

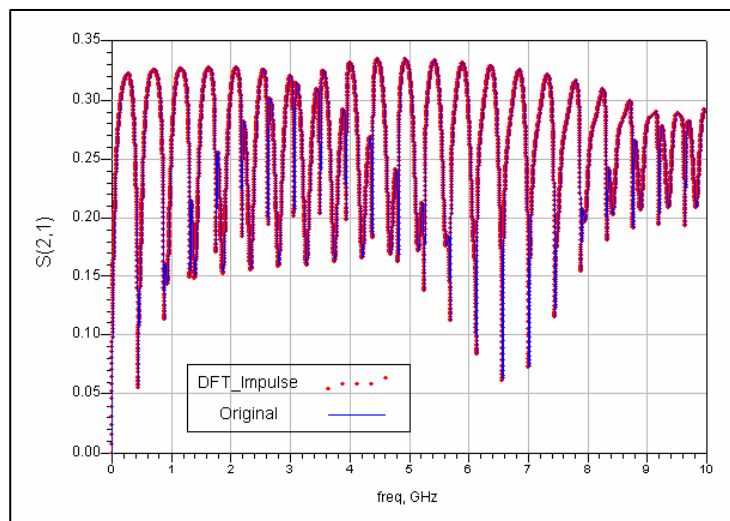


Figure 14: Magnitudes of Original S(2,1) and DFT of Impulse Response of S(2,1).

Delay Modeling

This section concludes by revisiting the example of Figure 7, and examining the ability of the proposed method to model delay and address delay causality violations. In this example, parametric (analytical) transmission line models were optimized to match measured S-parameter data in the frequency domain. A non-causal substrate loss model utilized by the frequency-domain parametric model introduces ‘base delay’ causality violations. Figure 7 showed an example of delay errors when a 2.5 GB/s PRBS sequence drives the transmission line structure.

The result of applying the new impulse calculation method is shown in Figure 15. Observe that it accurately models delay, even if the underlying frequency-domain model is not ‘base delay’ causal.

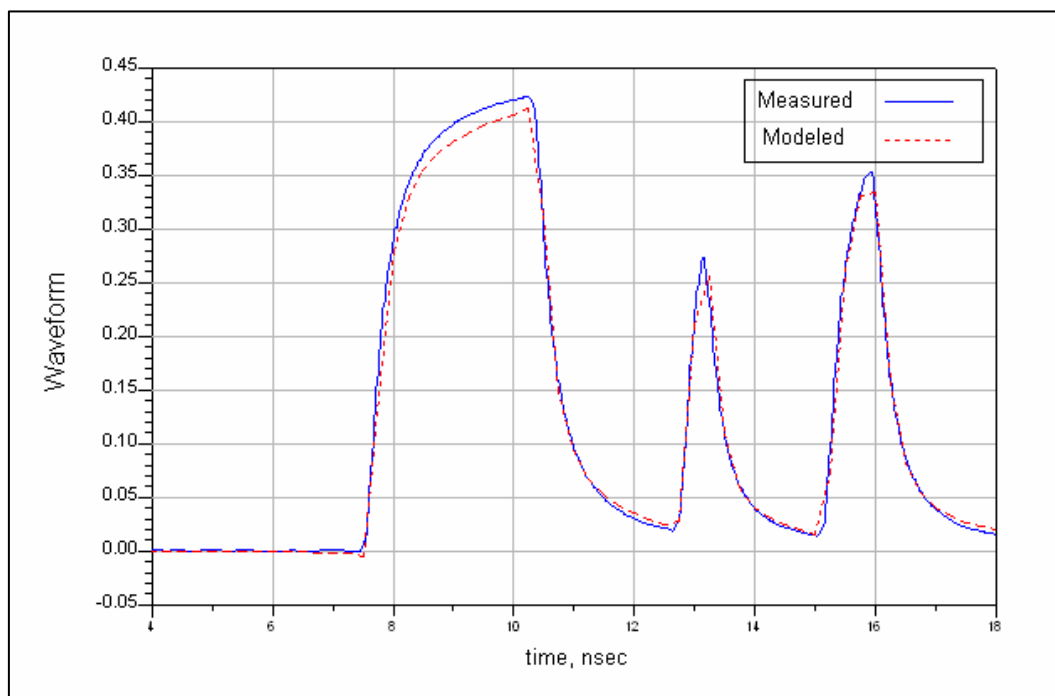


Figure 15: Delay Causality Correction.

The Need for Impulse Response Models

Time-domain convolution is a robust, general-purpose method for time-domain simulation of frequency-domain S-parameter models. Obtaining accurate impulse responses from S-parameters is not straightforward and requires considerable attention to the fundamental principles of passivity, causality, and delay preservation. The paper has outlined the typical obstacles to accurate impulse characterization and has reported a new technique that overcomes those difficulties, demonstrating its validity in a variety of challenging SI applications. In regards to time-domain convolution, the paper has shown that it is highly desirable to avoid direct iDFT calculations whenever possible. If a user is able to start with impulse responses, rather than S-parameters, the iDFT is avoided, and time-domain convolution can be performed directly.

To build on the ubiquity of time-domain convolution and to make use of the new method for obtaining accurate, causal, and passive impulse responses, a new time-domain simulation methodology, relying on impulse response model distribution and direct inclusion of impulse response models in convolution simulators, would be ideal.

Under this methodology, impulse responses are distributed directly (e.g., by component model suppliers) using a time-domain file format similar to the industry standard Touchstone format for frequency-domain S-parameters. Distributing models in impulse response format offers at least two advantages. First, it ensures consistent results by eliminating EDA vendor-proprietary treatment of frequency-domain S-parameters for inclusion in time-domain simulations. Second, it ensures robust time-domain simulations in all commercial simulators when accurate, passive, and causal models are distributed by component vendors. An upcoming version of Agilent Advanced Design System (ADS) will support the proposed methodology by providing tools for exporting and reading time-domain impulse data files.

Note that, as shown by Figure 16, the proposed methodology does not exclude the application of time-domain simulation methods that are not based on convolution, as classical S-parameters can be supplied alongside impulse response files or easily and accurately recovered from time-domain models.

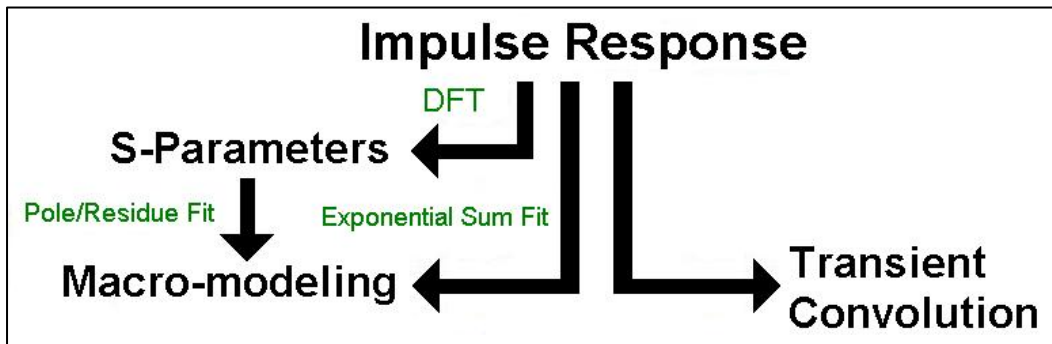


Figure 16: Time-Domain Modeling Methodology.

Summary

The paper has presented a new method for accurate impulse calculation from band-limited S-parameters and demonstrated its validity in several practical applications. The paper has also established the need for impulse response models and proposed a new simulation methodology based on direct inclusion of time-domain model files in convolution simulators. The proposed methodology relies on advanced techniques for impulse response calculation, such as the method introduced in this paper, to effect accurate and robust time domain simulations that are consistent and interoperable among disparate commercial simulators. A near-future release of commercial software tools that supports the proposed modeling methodology is planned in an effort to accelerate its adoption in the SI community.

References

1. B. Gustavsen and A. Semlyen. "Rational approximation of frequency domain responses by vector fitting," *IEEE Trans. PWRD*, vol. 14, no. 3, pp. 1052-1061, Jul. 1999.
2. G. Arfken and H. Weber, *Mathematical Methods for Physicists*, Academic Press, 2005.
3. R Lyons, *Understanding Digital Signal Processing*, Addison-Wesley, 1997.
4. C. Svensson and G. Dermer, "Time domain modeling of lossy interconnects," *IEEE Trans. Adv. Packaging*, vol. 24, no. 2, pp. 191-196, May 2001.
5. T. Arabi, A. Murphy, T. Sarkar, R. Harrington, and A. Djordjevic, "On the modeling of conductor and substrate losses in multiconductor, multielectric transmission line systems," *IEEE Trans. Microwave Theory Tech.*, vol. 39, no. 7, pp.1090-1097, Jul. 1991.
6. US Patent 11/747007 to Agilent Technologies, Patent pending.