New Interconnect Models Removes Simulation Uncertainty

Fangyi Rao, Agilent Technologies
Chad Morgan, Tyco Electronics
Vuk Borich, Agilent Technologies
Sanjeev Gupta, Agilent Technologies

Tyco Electronics

Agilent Technologies

IBIS Summit, 7th Feb' 2008

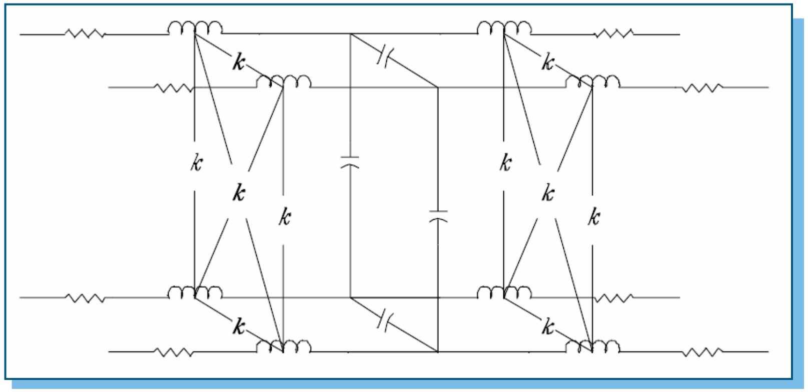
Presentation Outline

- Tyco Electronics:
  - Passive Component Model Review
  - Simulation Tools and Methods Review
  - Simulation Advantages from Using Impulse Responses
  - Getting Impulse Responses Directly
  - Converting Band-Limited S-parameters to Impulse Responses
  - Practical Implementation Needs for Impulse Response Models

- Agilent Technologies:
  - A New Method to Convert Band-Limited Spectrum to Impulse Responses
  - Method Validation Data
  - Proposed Time Domain Impulse Response Model Methodology
  - EDA Support for Exporting/Importing Impulse Response Data File

Passive Component Models: Traditional

- Quasi-Static 2D & 3D solvers used to derive inductance (L), mutual inductance (k), and capacitance (C) for component cross sections. Models typically lossless with the exception of series DC resistance (R)

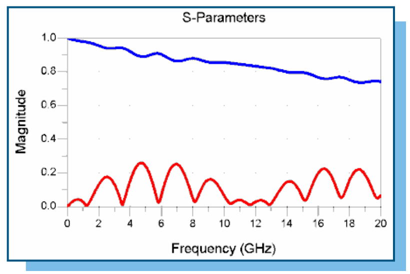


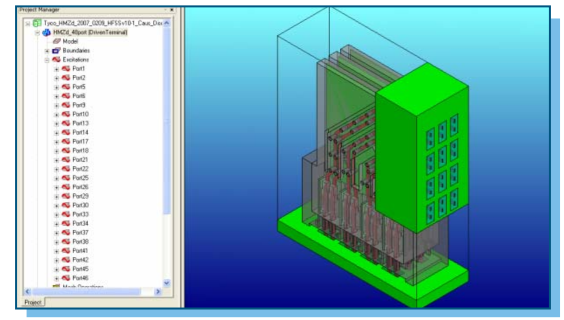

```
** SERIES ELEMENTS
*
* row a
RS111 111   211   3.00E-03
LS211 211   311   1.88E-09
*
** CAPACITANCE MATRIX
*
* row a
C1311 311   331   1.50E-14
C2311 311   321   1.38E-13
C3311 311   322   2.00E-14
C4311 311   312   8.50E-14
C5311 311   313   1.00E-14
*
** MUTUAL COUPLINGS
*
* row a
K1211 LS211 LS231 0.030
K2211 LS211 LS221 0.310
K3211 LS211 LS222 0.050
K4211 LS211 LS212 0.160
K5211 LS211 LS213 0.020
```

- Advantages: Sub-circuit models use generic SPICE elements
  – Can be run in transient simulations with non-linear active device models
  – Can be run in AC-sweep simulations to compute linear S-parameters
  – Models are inherently causal and passive
- Disadvantages: At high data rates, models become complex and inaccurate
  – Model complexity and run-time increase with shorter cross-section lengths
  – Frequency-dependant loss & dispersion not adequately modeled
  – Longitudinal modes and transverse currents not adequately modeled

Passive Component Models: Modern

- Scattering parameters (S-parameters):
  - Measurable by modern vector network analyzers (VNAs) with or without device under test (DUT) fixturing
  - Generated by parametric equations, 2D field solvers (frequency-dependant RLGC tables), 2.5D field solvers, and 3D full-wave field solvers

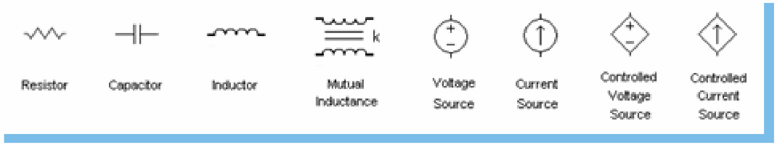




- Advantage: Frequency-domain simulations
  - Flexible…can be directly used with linear simulations and deembedding
  - Accurate…frequency-dependant losses and higher-order modes included
  - Portable…can be transferred between simulators using Touchstone format
- Disadvantage: Time-domain simulations
  - Must be converted to pole/residue macro-models or impulses for SI analysis
  - Conversion to impulse data requires significant expertise (more than iDFT)
  - Many SI engineers struggling to use S-parameters efficiently in simulations

Simulation Tools: Traditional SPICE

- Generic SPICE (i.e. Berkeley SPICE v3): Can only solve transient simulations through time-stepping of differential equations from 'traditional' elements – must convert S-parameters into lumped element circuits:



  - Genetic algorithms: Given a structure, can determine lumped element values that will fit given S-parameters…difficult to know structure ahead of time
  - Macro-modeling: 'Vectfit' procedure fits S-parameters to a pole/residue function, passivity is enforced, and a lumped element circuit is produced
- Laplace domain simulation
  - Uses recursive convolution (usually faster than time integration of the lumped element approximation) to evaluate the model in
    - Pole/residue (1), pole/zero (2) or rational polynomial (3) form

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

$$H(s) = \frac{a\cdot(s+\alpha_{z1}-\omega_{z1})(s+\alpha_{z1}+\omega_{z1})\ldots(s+\alpha_{zn}-\omega_{zn})(s+\alpha_{zn}+\omega_{zn})}{b\cdot(s+\alpha_{p1}-\omega_{p1})(s+\alpha_{p1}+\omega_{p1})\ldots(s+\alpha_{pn}-\omega_{pn})(s+\alpha_{pn}+\omega_{pn})} \quad (2)$$

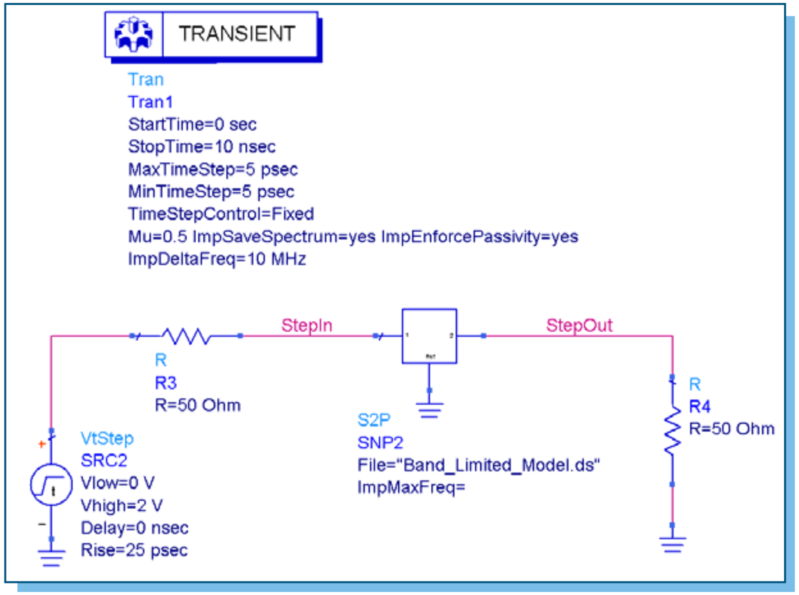
$$H(s) = \frac{k_0+k_1 s+\ldots+k_n s^n}{d_0+d_1 s+\ldots+d_m s^m} \quad (3)$$

Simulation Tools: Custom & Commercial

- Math programming languages:
  - Frequency-domain multiplication
    - Take DFT of source waveform
    - Multiply by system S-parameters
    - Take iDFT of result to get output*
  - Time-domain convolution
    - Take iDFT of system S-parameters*
    - Convolve with source waveform

```
% Find the input signal (Tx.iSignal) spectrum
    Tx.PSD = fft(Tx.iSignal);

% Multiply the input signal spectrum by the channel response (idata.s)
    Rx.PSD = idata.s.* Tx.PSD;

% Find the output signal (Rx.iSignal) time response
    Rx.iSignal = real(ifft(Rx.PSD));
```

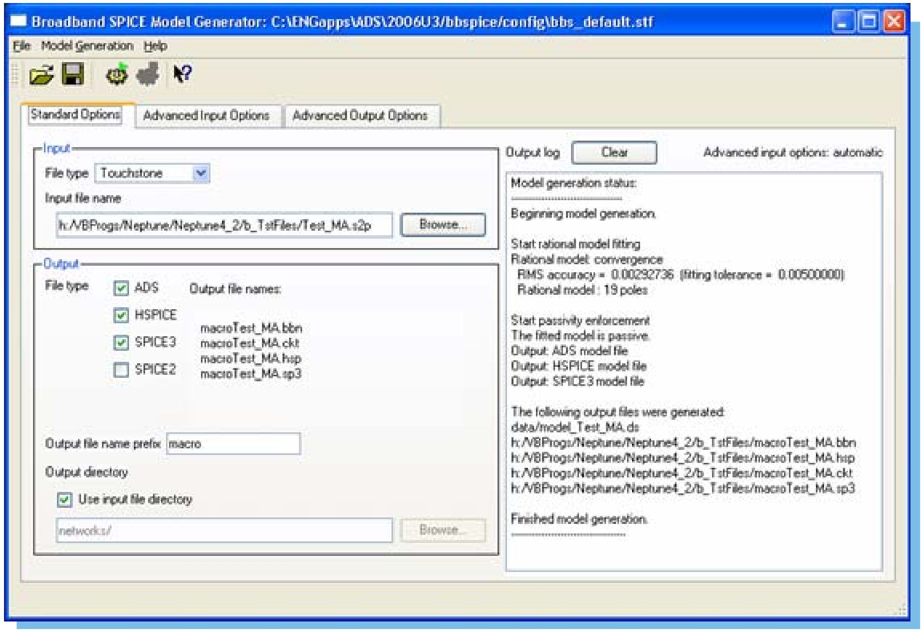
- Commercial tools:
  - Advanced algorithms to complete S-parameter-to-impulse response conversion, along with convolution
    - Passivity and causality are enforced
    - Data validity maintained to Fmax



*Completing a valid iDFT of band-limited S-parameters is not a trivial task (will be shown)

Simulation Tools: Method Summary

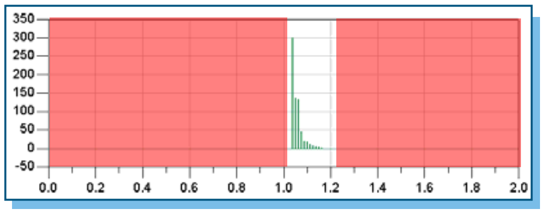
- Macro-modeling:
  - – Pole-residue curve fit and passification for all frequencies
  - – Produces strictly causal and passive models for SPICE usage
  - – Difficulties:
    - Consistent passification
    - Time-domain data validity

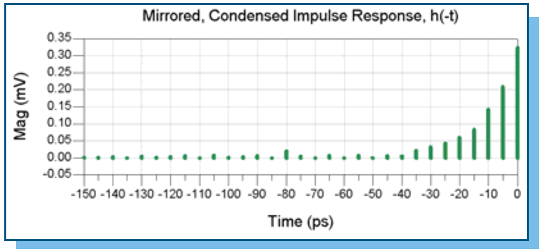


- Transient convolution:
  - – Must have accurate impulse responses to complete procedure
  - – One must overcome iDFT difficulties to compute impulse responses
- **The focus of this paper will be on transient convolution**
  - **– Converting band-limited S-parameters to causal, passive impulses**
  - **– Discussing a standard impulse response file format**

Impulse Response Advantages: Convolution

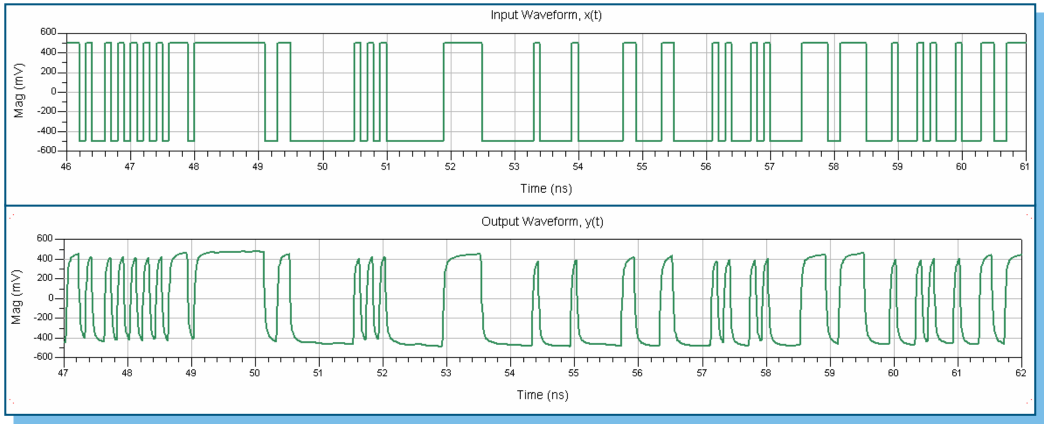
- If one has the impulse response, convolution is simple to accomplish:
  - Consistent impulse response time steps make convolution easier
  - Separated ‘base delay’ makes convolution more efficient
- Convolution can then be easily coded by doing the following:





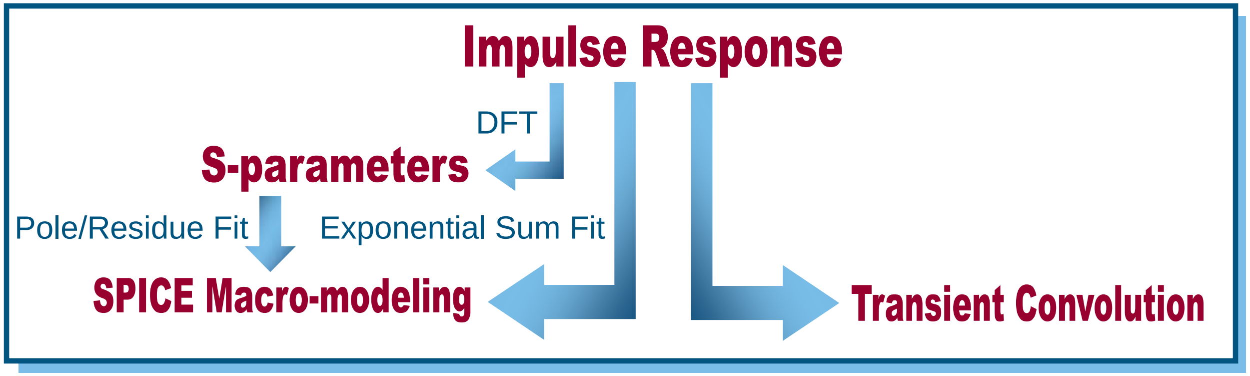
- Reduce the impulse response to its shortest length:
  - Remove all zero points before the impulse ‘base delay’
  - Remove all zero points after the impulse has settled
- Mirror the shortened impulse response
- Generate the input waveform (same time steps as impulse)
- Complete transient convolution:
  - Step the impulse through the input waveform
  - Multiply all overlapping points
  - Add the multiplication results to get the output at each time
- Shift the output waveform forward in time by the ‘base delay’

$$y(t) = h(t) * x(t) = \sum_{n} x(n)h(t-n)$$



Impulse Response Advantages: Conversion

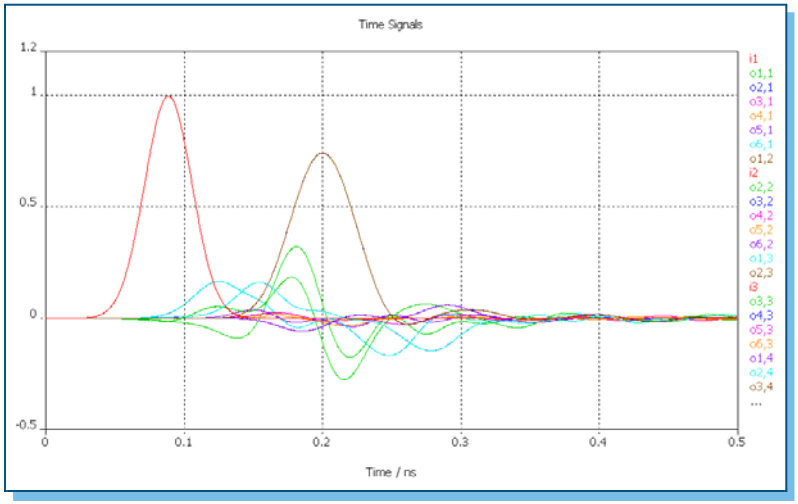
- Impulses can be easily converted to S-parameters using a DFT
  - If impulse has settled (starts/ends at 0 volts), there are few transform issues
  - S-parameters can be determined up to $F_{max}=1 / (2*T_{step})$
  - Impulse can be zero-padded to get any desired frequency resolution
- Impulse can be used to generate SPICE macro-models
  - Sum of exponentials approximation can be used to get models directly
  - Pole/residue approximation of S-parameters can be used to get models



- Impulse response models represent ‘golden source’ for model distribution
  - Impulse response model can be directly used in math tool convolution
  - EDA tools should easily be able to handle an impulse response model

Getting Impulse Responses Directly

- If one has impulse responses, they can be used directly in transient convolution without inverse transform issues
- Impulse response sources:
  - Several time-domain modeling tools (FIM, FDTD, TLM)
  - Component manufacturers (let experts deal with the iDFT issues)
- Problem: No standard file format for model distribution
- Solution: Create a new time-domain impulse file format
  - File format allows multiple tools to exchange information
  - A specific file format is proposed later in the paper



Converting S-parameters to Impulses: Difficulties

- If one only has band-limited S-parameters, one must use the inverse discrete Fourier transform (iDFT or iFFT) to get time-domain impulse responses:

$$x(n) = \frac{1}{N}\sum_{m=0}^{N-1} X(m)\cdot e^{j2\pi mn/N} = \frac{1}{N}\sum_{m=0}^{N-1} X(m)\cdot\left[\cos(2\pi mn/N) + j\sin(2\pi mn/N)\right]$$

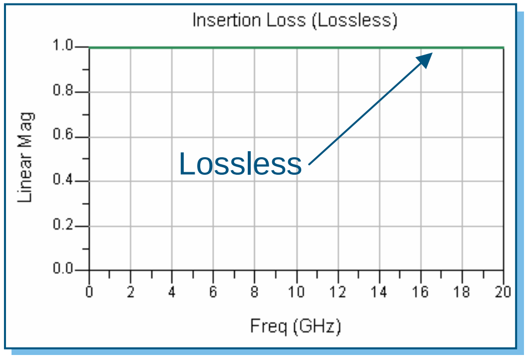
x(n) is the discrete time-domain sequence
X(m) is the discrete frequency-domain sequence
N is the total number of samples in x(n) and X(m)*

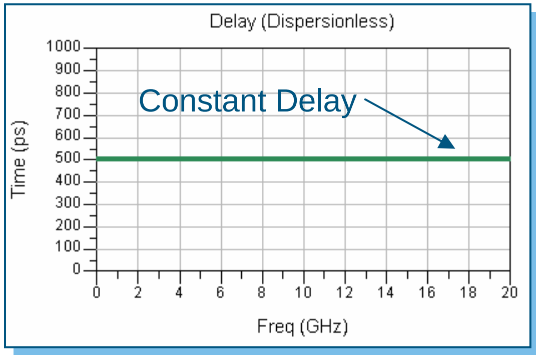
- The major source of error in calculating time-domain impulse responses from band-limited S-parameters is termed iDFT *LEAKAGE*
  - The iDFT has ZERO leakage only if a structure is lossless/dispersionless such that its delay is constant at all frequencies and a multiple of $1/2F_{max}$ (i.e. Delay(f) = Constant = $m/2F_{max}$ → Fmax can be tuned to eliminate leakage)
  - Real physical structures have loss & reflections, so delay varies across frequency – iDFT leakage CANNOT BE AVOIDED entirely
    - Time-domain energy existing between discrete iDFT time steps will manifest error on ALL available discrete time points as a sync function
    - Frequency-domain windowing can greatly minimize iDFT leakage error, but there are issues with this (discussed later)

**Given band-limited s-parameters with N/2 points (Ranging from 0 to F_{max} in steps of F_{step}), X(m) is usually created with N points by mirroring the initial spectrum. The iDFT of X(m) then yields a real-valued time-domain signal, x(n), where the time step is defined as $1/2F_{max}$ and the stop time is defined as $1/F_{step}$.*

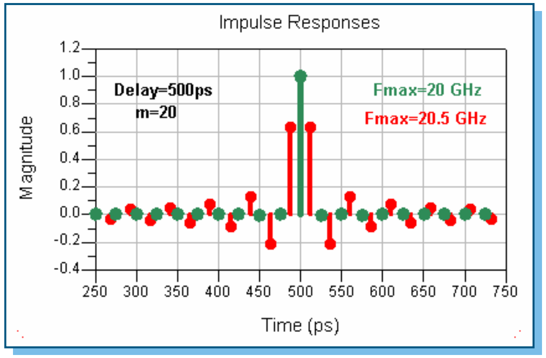
Converting S-parameters to Impulses: Difficulties

- Lossless, constant delay example of iDFT LEAKAGE:
  - In this case, leakage can be avoided by selecting (F_{max} = m / 2*Delay, m = integer)
  - Green waveform shows no leakage when data falls on a discrete time point
  - Red waveform shows sync leakage when data falls between discrete time points

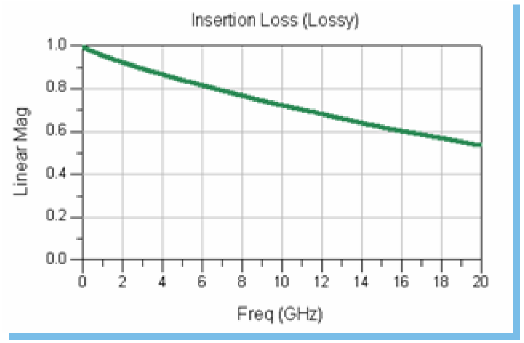


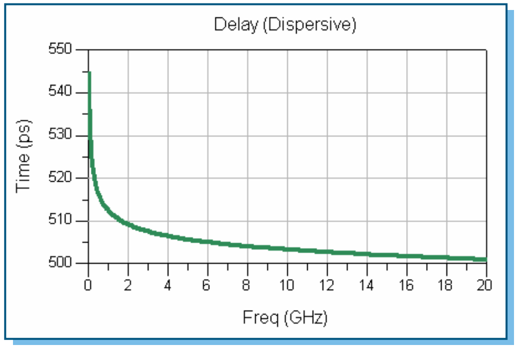


iDFT



- Lossy, varying delay example of iDFT LEAKAGE:



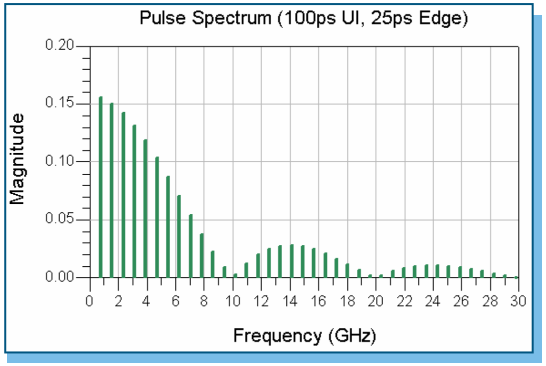


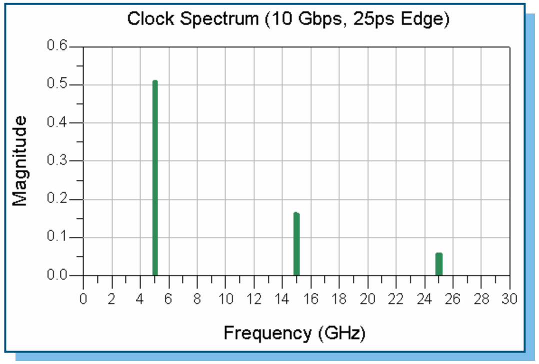
iDFT

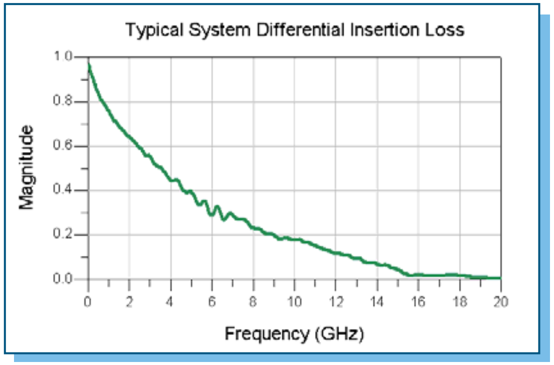
Eliminating LEAKAGE *at all time points* is IMPOSSIBLE, because energy is coming out of the system at different times for different frequencies

Converting S-parameters to Impulses: Difficulties

- Frequency-domain windowing: S-parameters are multiplied by common window shapes to decrease output magnitude with increasing frequency
  - Advantage: iDFT sinusoid 'pulsation' is minimized (less time leakage)
  - Disadvantages:
    - Many window functions are non-causal
    - High-frequency data is not preserved (time-domain signal is damped)
- 'Natural windows' have helped many SI engineers get good simulation data:
  - Step, pulse, and bit pattern responses all have spectra that roll-off with increasing frequency (defined by edge rate)
  - System simulations typically examine highly lossy insertion loss responses, which roll off dramatically with increasing frequency



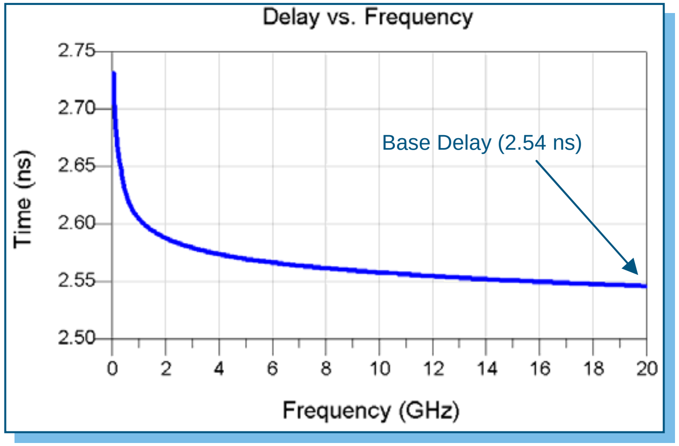


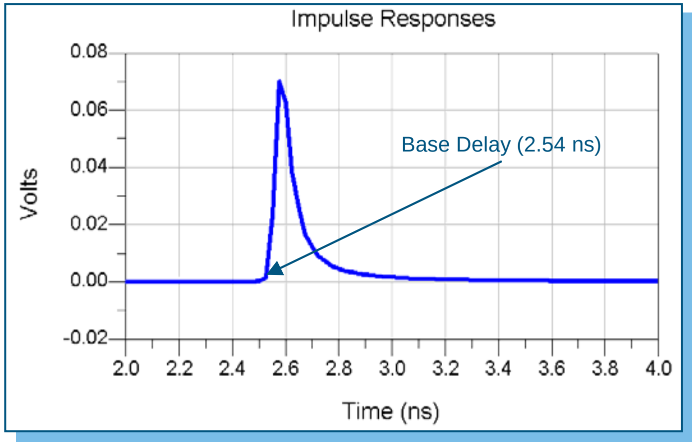


Converting S-parameters to Impulses: Difficulties

- Causality enforcement is a good goal for any sophisticated iDFT conversion
- 'Base delay' causality enforcement better…must find structure's 'base delay':
  - Delay versus frequency can be plotted using the equation below
    - For a reflectionless system, this is the true delay versus frequency
    - If a system has reflections, delay is distorted above & below the true delay
  - One can use the minimum value of delay vs. frequency as the 'base delay'

$$Delay(f) = (Time\ for\ 1\ \lambda)\cdot(\#\ of\ \lambda s) = \left(\frac{1}{f}\right)\cdot\left(\frac{-unwrap(phase(IL))}{360}\right)$$





- Note: Group delay is NOT a true measure of delay…only of phase linearity!!!

Converting S-parameters to Impulses: Difficulties

- ‘Base delay’ causality can be enforced using phase shifting and the discrete Hilbert transform:

$$Phase\ Shifting = e^{+j\omega t}\ or\ e^{-j\omega t}, where\ 't' = base\ delay$$

$$\tilde{X}_I[k] = \frac{1}{N}\sum_{m=0}^{N-1} \tilde{X}_R[m]\cdot\tilde{V}_N[k-m] \qquad \tilde{X}_R[k] = \frac{1}{N}\sum_{m=0}^{N-1} j\tilde{X}_I[m]\cdot\tilde{V}_N[k-m] + \tilde{x}[0] + (-1)^k\tilde{x}[N/2]$$

$$\tilde{V}_N[k] = \begin{cases} -j2\cot(\pi k/N), & k\ even \\ 0, & k\ odd \end{cases}$$

- The Hilbert transform is usually calculated as follows:
  - Take the iDFT of the real frequency data to get the time signal’s even component
  - Since the signal is real/causal, one can calculate the time signal’s odd component
  - Take the DFT of the time signal’s odd component to get imaginary frequency data

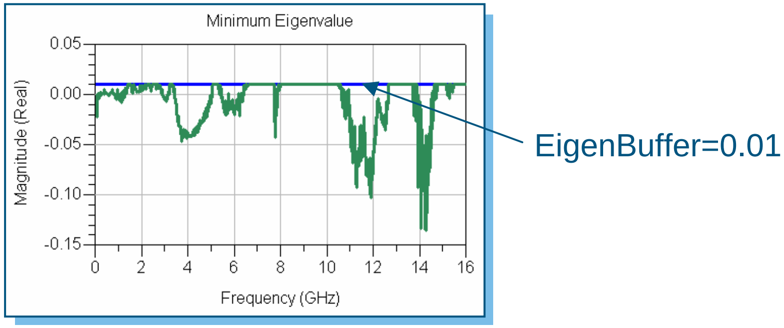
- Note: Completing an accurate Hilbert transform can be difficult since it requires calculation of the iDFT, which has leakage for band-limited S-parameters.

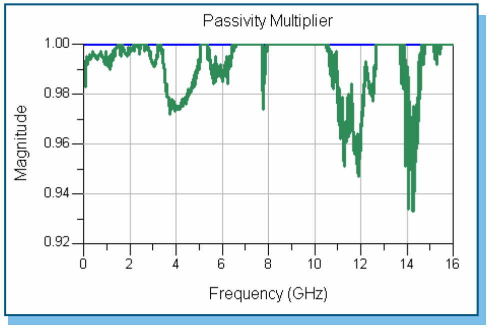
Converting S-parameters to Impulses: Difficulties

- Checking & enforcing passive component physical passivity
  - At each frequency, an s-parameter matrix is passive only if the minimum eigenvalue of I-S'S* is greater than or equal to zero (semi-positive definite)
  - A small 'EigenBuffer > 0' value can be used for over-passification
  - One can multiply the entire [S] matrix by a scalar multiplier at each frequency to force passivity

$$\min\left[eig\left(\left[I\right]-\left[S^{'}\right]\cdot\left[S^{*}\right]\right)\right]\geq EigenBuffer$$

$$Multiplier(f)=\sqrt{\frac{1-EigenBuffer}{1-MinEigen(f)}},if\ \ MinEigen(f)<EigenBuffer$$

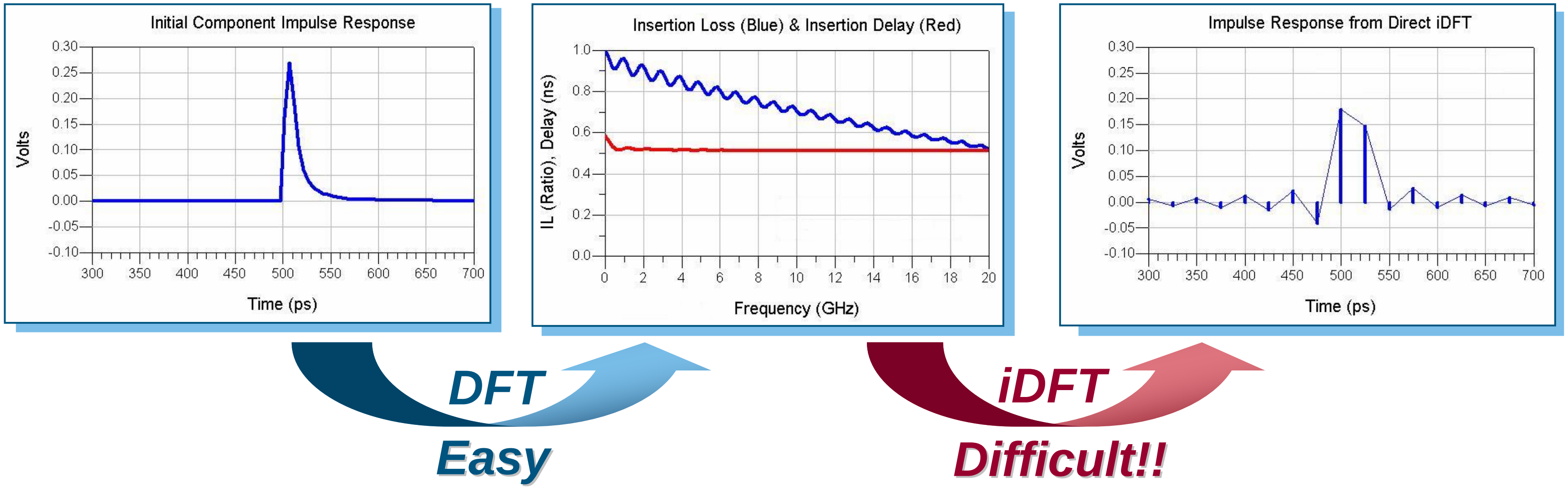




- Other frequency-domain model issues:
  - F_{max} must be large enough to ensure adequate time step ($T_s = 1 / 2F_{max}$)
  - DC extrapolation & frequency interpolation must be handled

Converting S-parameters to Impulses: Difficulties

- Bottom Line…it is easier to get valid frequency-domain data from time-domain data than it is to get valid time-domain data from band-limited frequency-domain data:
  - – DFT of settled impulse response yields accurate S-parameter data
  - – iDFT of band-limited S-parameter data yields impulse response with leakage



- It is desirable to have a tool that can complete the iDFT properly:
  - – Tool must eliminate leakage with minimal change to initial S-parameters
  - – Tool must enforce ‘base-delay causality’ and passivity

Impulse Response Model Implementation Needs

- There are advantages to directly using impulse responses in time-domain simulations, and there is a need for a standardized file format
- Given band-limited S-parameters, it is difficult to directly calculate accurate time-domain impulse responses, and there is a need for a tool to do so
- Concludes Tyco Electronics portion of the presentation:
  - chad.morgan@tycoelectronics.com
  - www.tycoelectronics.com/documentation/spiceelectricalmodels/
  - modeling@tycoelectronics.com
- Agilent Technologies up next:
  - Fangyi Rao, Vuk Borich, & Sanjeev Gupta
  - New approach for calculating valid impulse responses
  - Impulse response model methodology and Agilent support

Tyco Electronics → Agilent Technologies

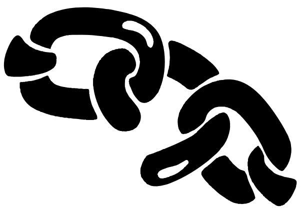
Time Domain Convolution Challenges

Causality

- Causal condition: Kramers-Kronig (K-K) relations

$$u(\omega) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{v(\omega')}{\omega - \omega'} d\omega'$$

$$v(\omega) = -\frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{u(\omega')}{\omega - \omega'} d\omega'$$

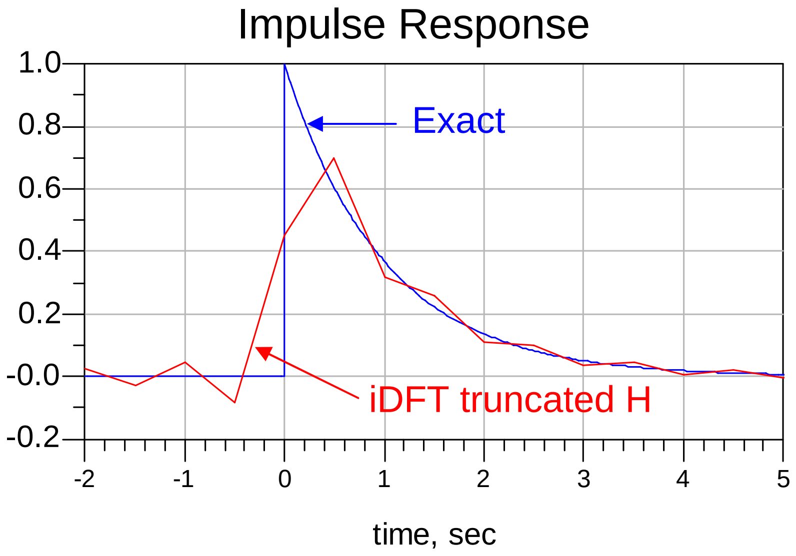


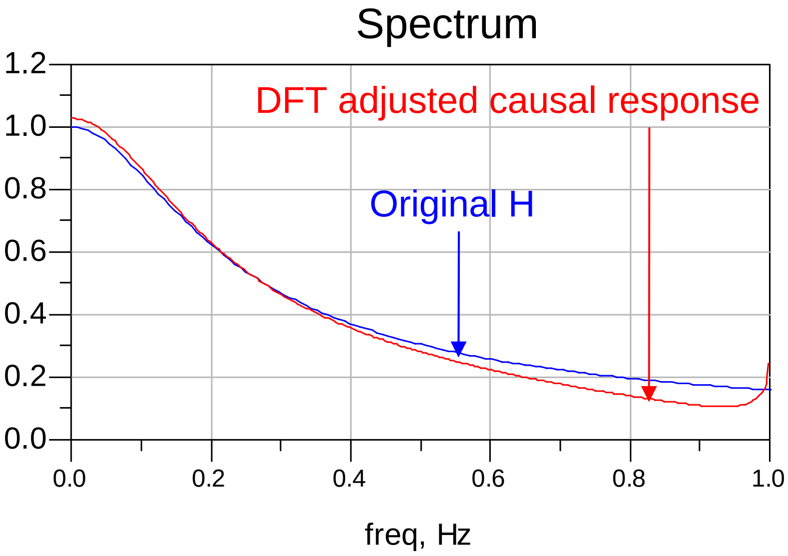
- Real and imaginary parts are not independent.
- Hilbert integrals involve entire spectrum.
- Truncation in band-limited spectrum breaks K-K relations. Direct iDFT is non-causal.

Case Study: A Simple Response Function

$$H(\omega) = \frac{1}{1 + j\omega\tau} \quad \xrightarrow{\text{IFT}} \quad h(t) = \begin{cases} 0 & (t < 0) \\ e^{-t/\tau} & (t \geq 0) \end{cases}$$

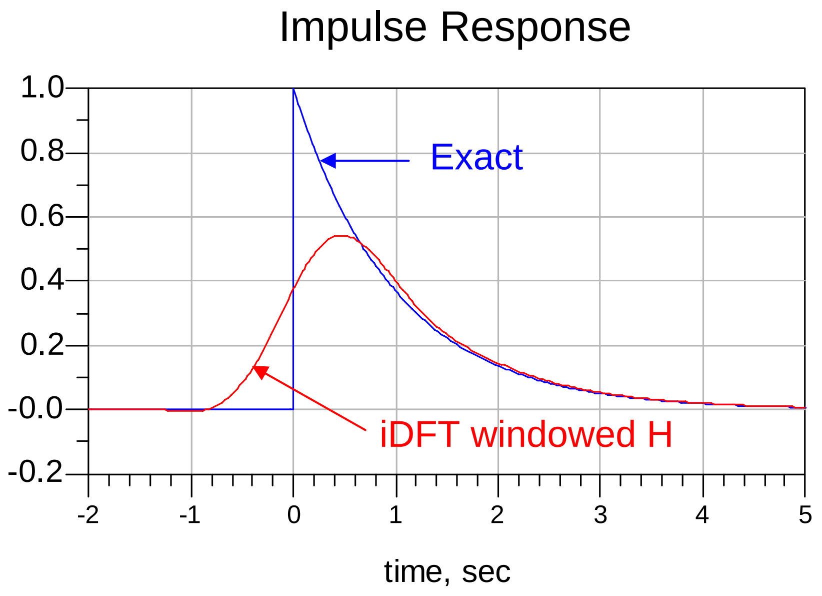
- Truncate H at 1 Hz ($\tau = 1$). Compute impulse response by iDFT. Result is non-causal.
- Restore causality by adjusting response to 0 at $t < 0$. Spectrum is altered.

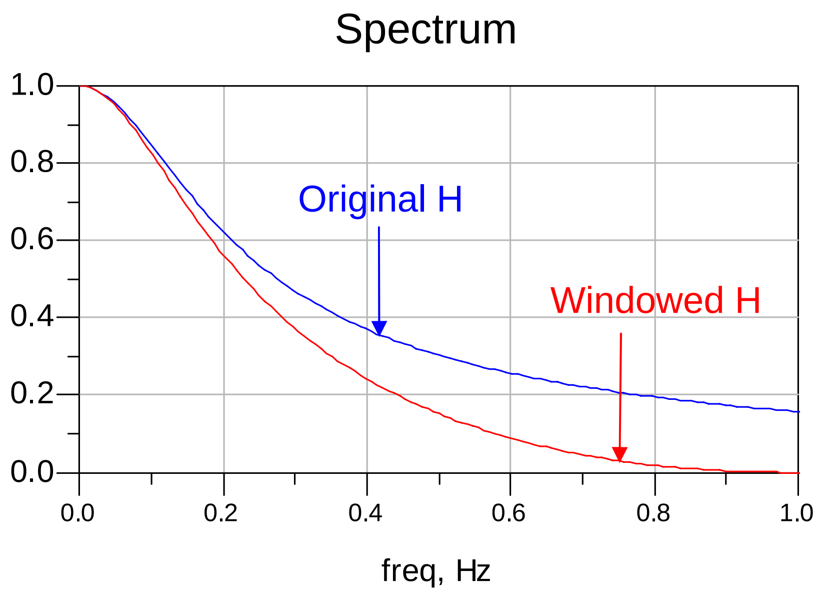




Problems with Windowing

- Standard window functions are non-causal
- Equivalent to convolving h(t) with LPF. Leads to non-causal response at t < 0.
- Spectrum roll-off at truncation frequency
- Example: apply Hanning window to H





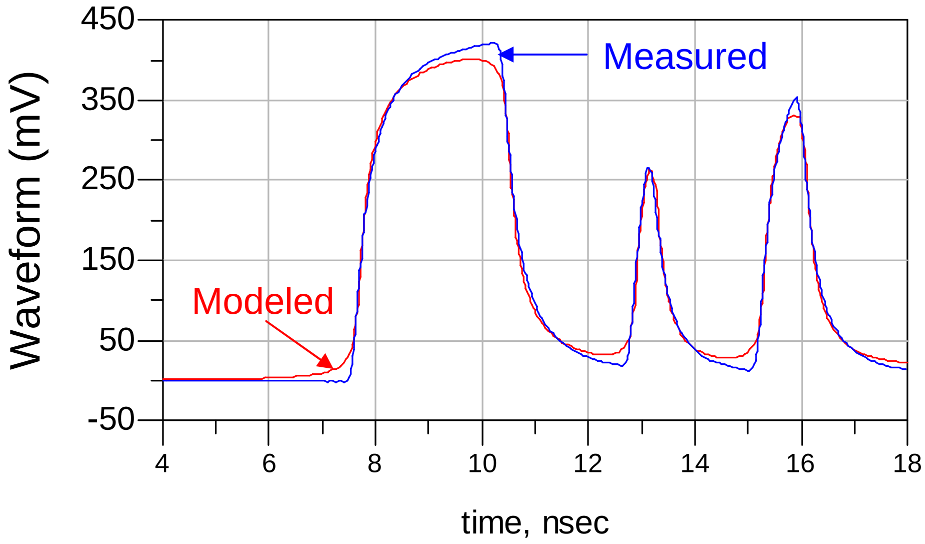
Delay Preservation

- Delay causality: no response before system base delay time
- Common sources of violation
  - Substrate dielectric constant model

$$\varepsilon(\omega) = \varepsilon_R(\omega) \cdot (1 - j \tan\delta)$$

Does not satisfy K-K relations if tanδ is constant

  - Skin loss model: sqrt(f) dependent loss is non-causal without imaginary part.



Passivity

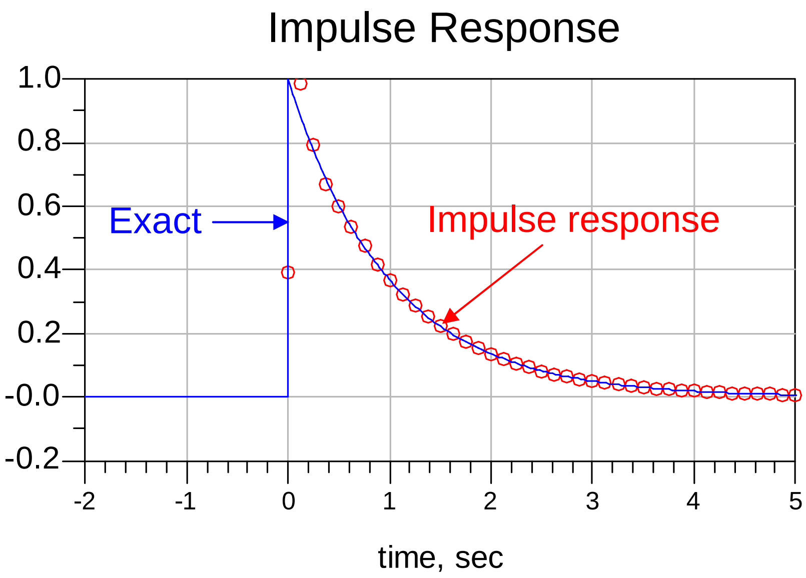
- Measurement or numerical modeling error cause non-passive S-parameters
- Passivity can be corrected frequency-by-frequency
- Requirement for passivity correction
  - minimum impact on original data, avoid over-damping
  - preserve causality in corrected S-parameters

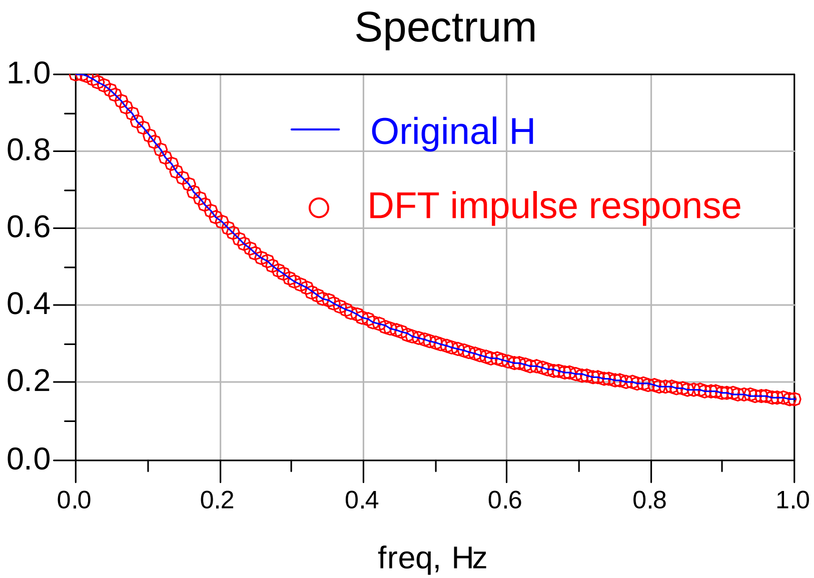
Rigorous Approach for Impulse Response Calculation

- Calculate impulse response from band-limited spectrum
- Automatic causality enforcement with respect to time zero and delay
- Correct passivity violation in S-parameters while maintaining causality
- Impulse response matches original spectrum to highest possible accuracy

Revisit Simple Response Function

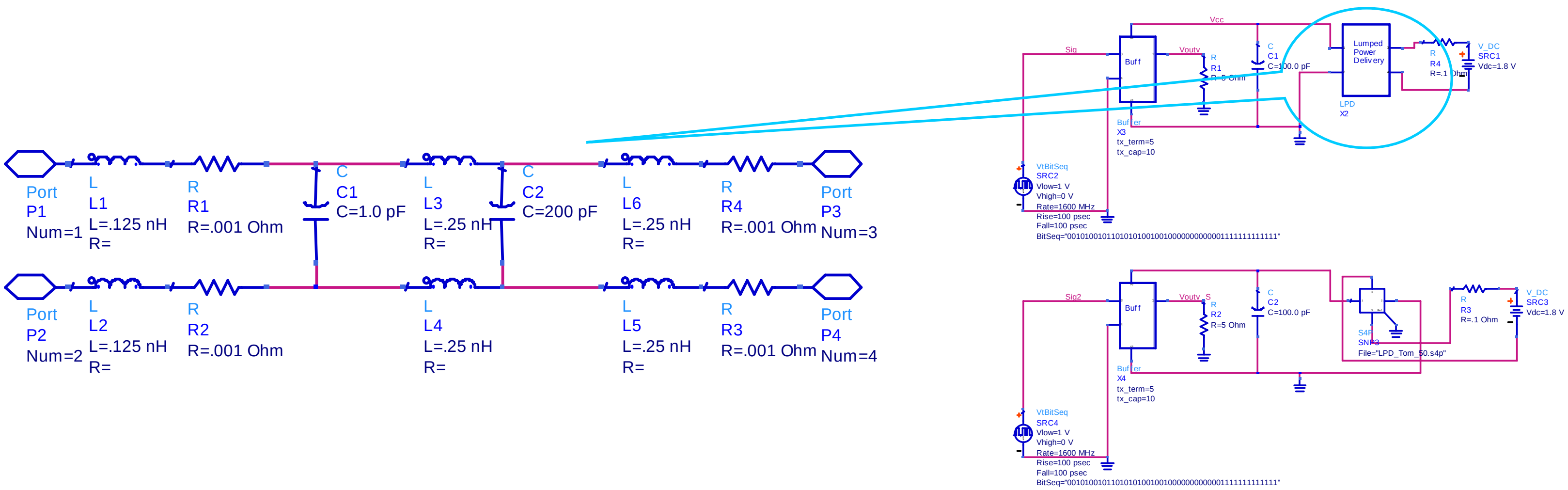
- Use new approach to compute impulse response from truncated H
- Response is causal
- FT of impulse response matches original H
- No roll-off at high frequency





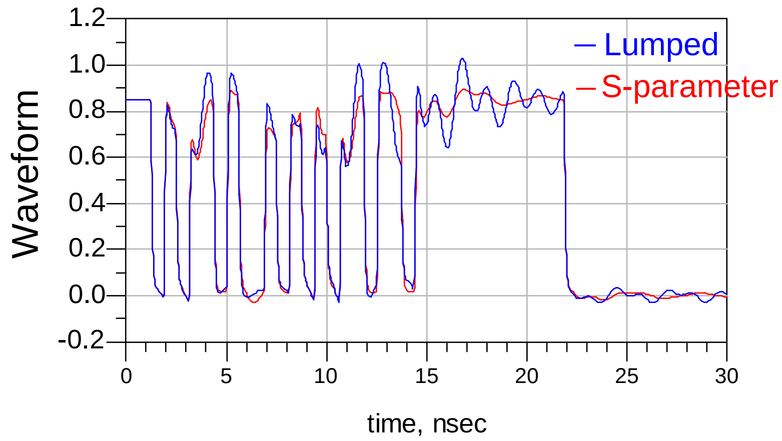
S-parameters of Low Impedance RLC Network

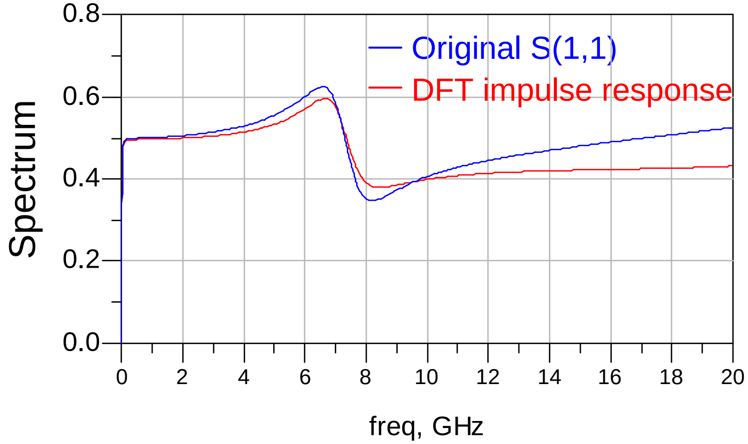
- Extract S-parameters of RLC sub-network
- Compare waveforms between lumped network and S-parameter convolution
- Tough case for convolution: Ohm impedance network normalized to 50 Ohm
- Narrow dynamic range in S-parameters. Requires highly accurate impulse response.



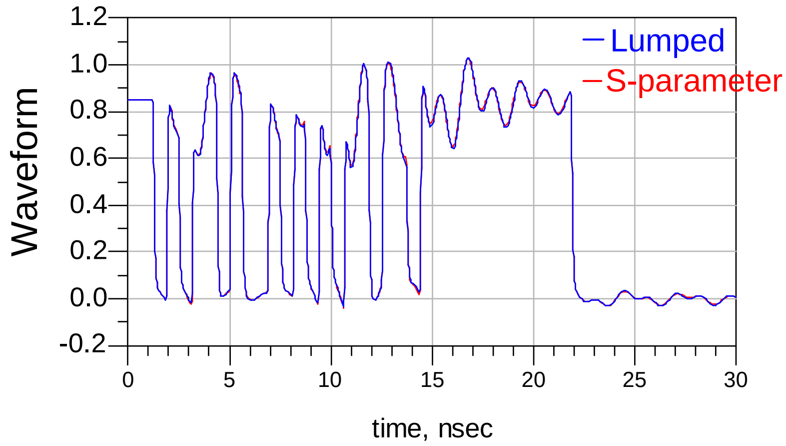
Lumped vs S-parameter Convolution

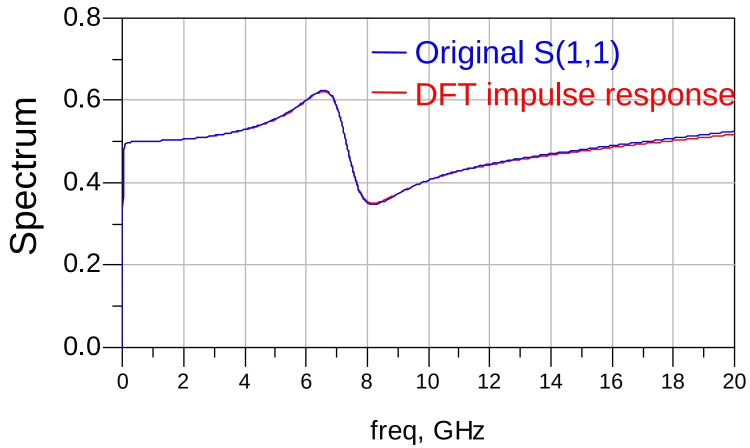
Direct iDFT Approach: poor agreement





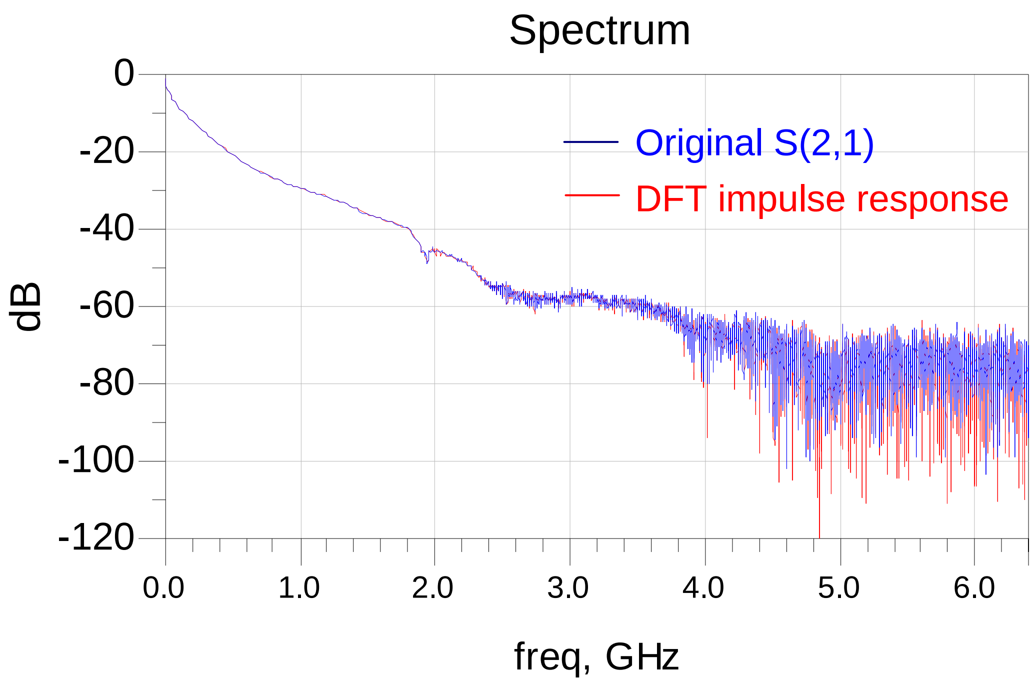
New Approach: perfect agreement





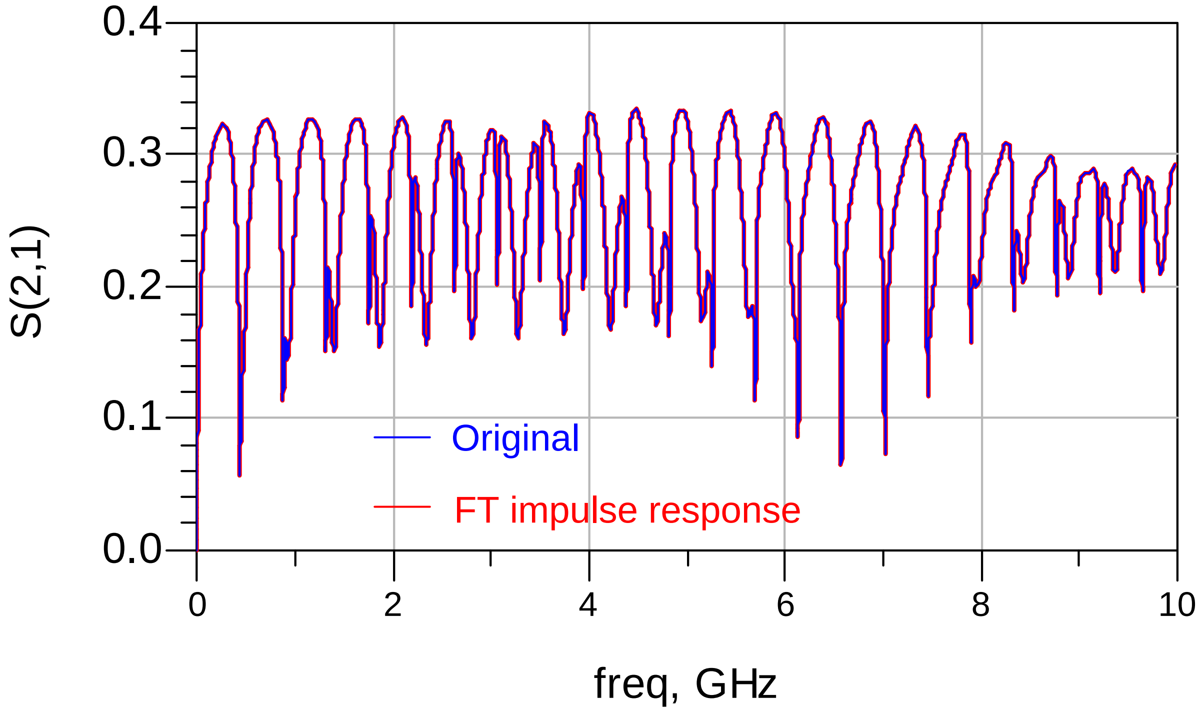
S-parameters of 30 Meter Coaxial Cable

- Data measured up to 6.4 GHz
- Noisy data at high frequency
- Impulse response accurately represent original spectrum even in noisy region



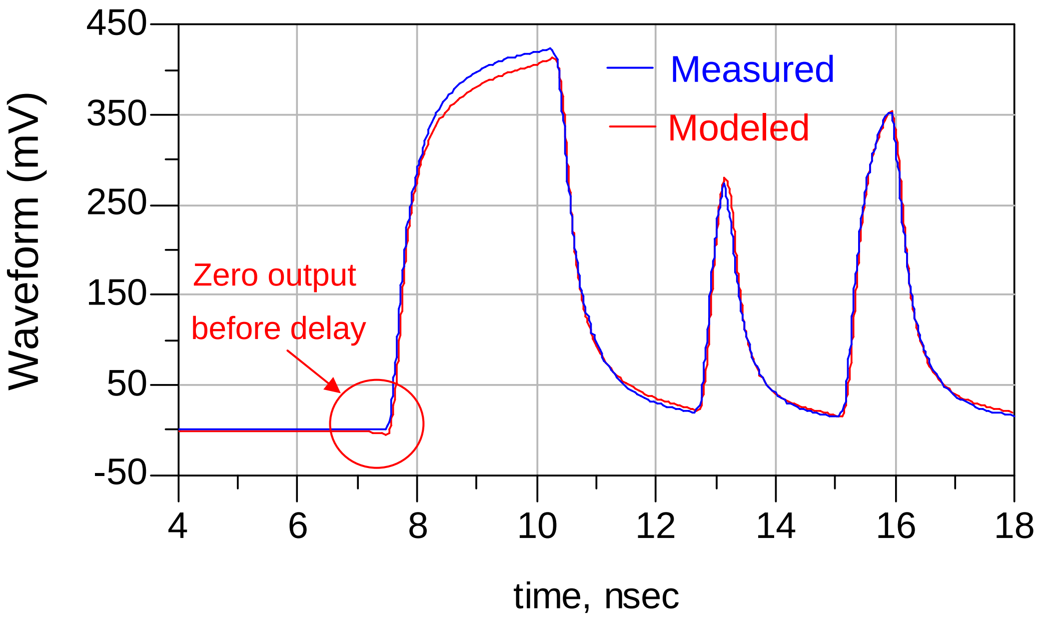
S-parameters of 20 cm Multilayer Line

- 8-layer transmission line
- Complex structure in spectrum due to coupling between layers
- Excellent match between impulse response and original spectrum



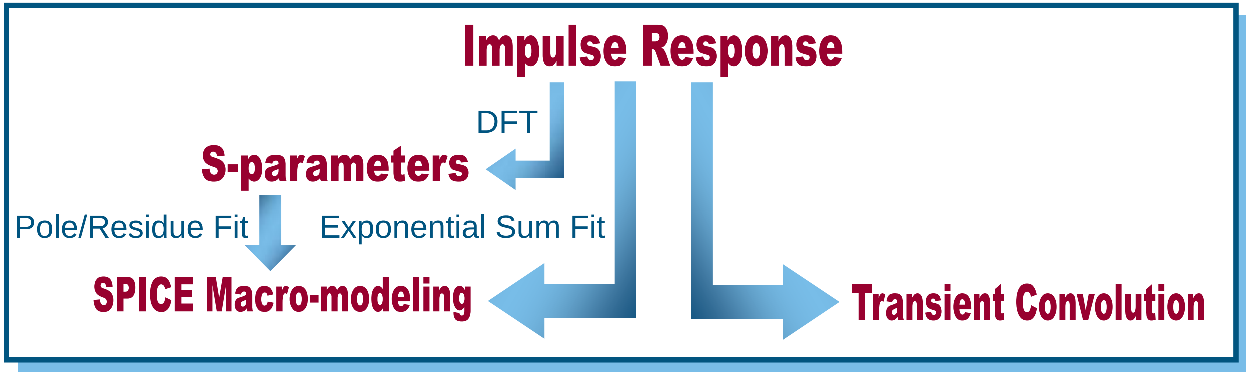
Delay Modeling

- Analytic transmission line model optimized to match measured S-parameter
- Non-causal lossy substrate dielectric constant is used
- Results in non-physical response before delay time
- In new approach, delay causality violation is automatically corrected in impulse response



Impulse Response Model Methodology

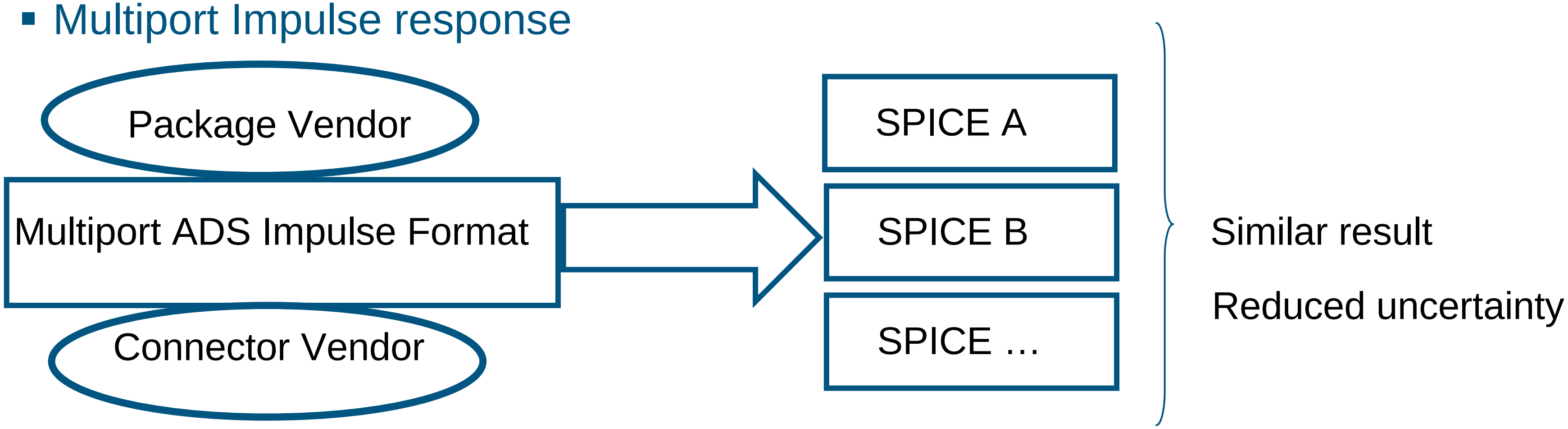
- It is not straightforward to calculate impulse response from band-limited S-parameter
- Must consider not only accuracy, but also causality, passivity and delay preservation
- Much easier to start with impulse response models for convolution. Spectrum can be easily recovered by DFT.



- Need standard time domain file format for impulse response
- Allows interoperability and distribution of causal/passive impulse response obtained by our new approach or other methods
- Eliminates EDA vendor-proprietary treatment of S-parameter convolution

Interconnect Model Exchange

- Current
  - S-parameters
    - No standard simulation methodology results in variation of simulation results between different EDA tools
  - Lumped SPICE models
    - Difficult to extract for long and complex channel
- Future vision
    - Multiport Impulse response

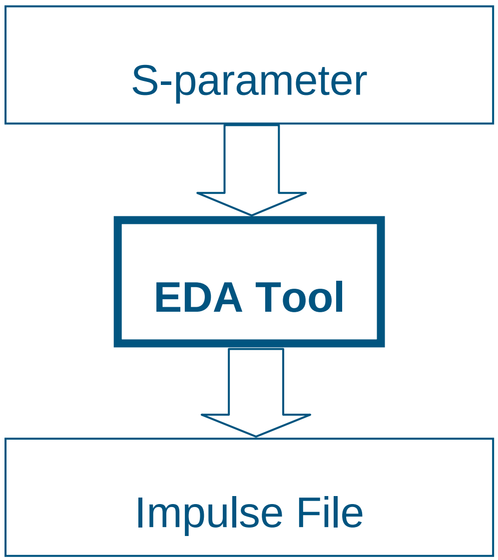


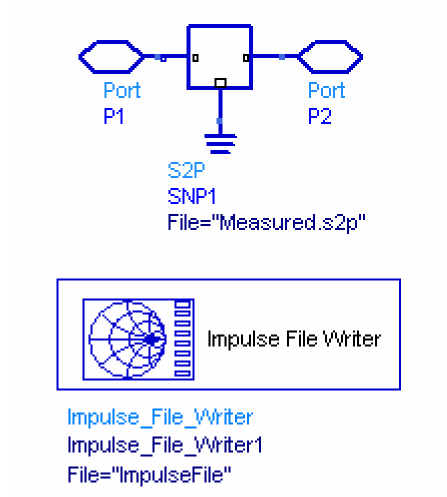
Vendor ensure the quality of the models

ADS Time Domain Impulse Format

Easy to use: 2 simple steps

- Create Impulse response from S-parameter (connector and package vendors)
- Use impulse response within ED Tools





Step 1: input S-parameter

Step 2: run

Proposed ADS Impulse Response Format

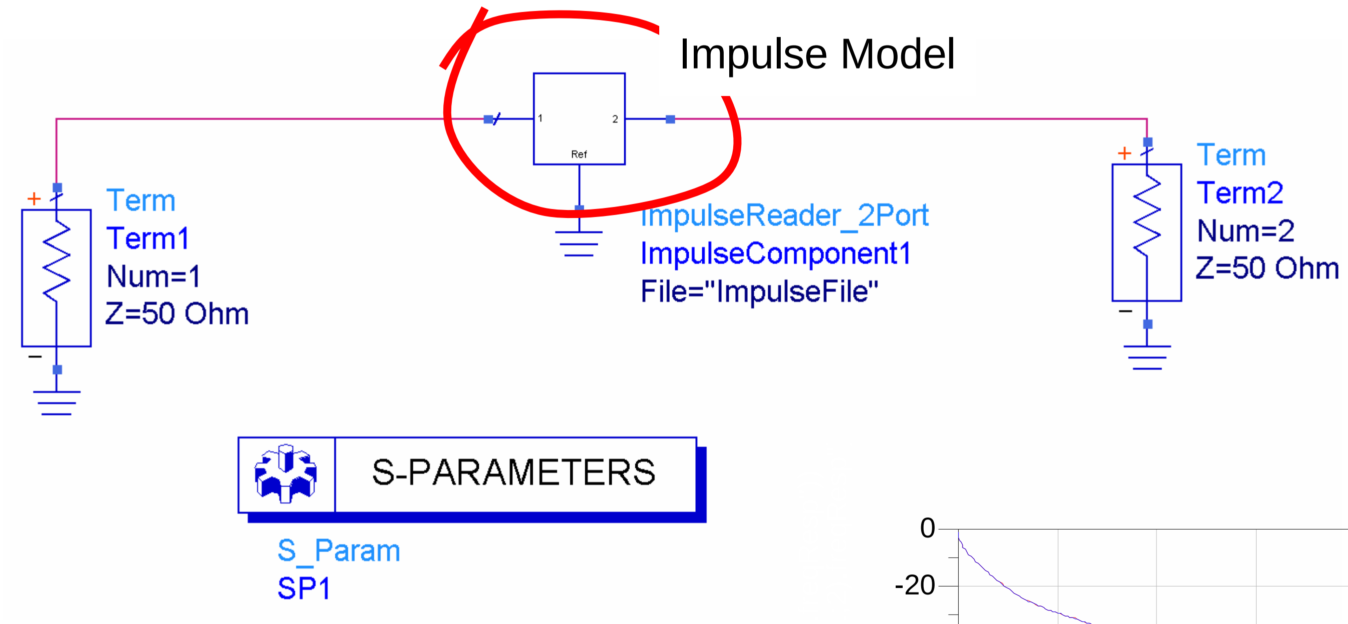
```
!2-port impulse response of S-parameter
[Version] 1.0
#S R 50.0
[Number of Ports] 2
[Reference] 75.0 75.0

[Time Step] 0.005 nsec

[Base Delay] 0.0 5.21 5.21 0.0

Number of Time Points 200
-0.51 -0.94 -0.86 ...

Number of Time Points 150
0.32 0.78 0.43 ...

Number of Time Points 150
0.32 0.78 0.43 ...

Number of Time Points 200
-0.51 -0.94 -0.86 ...
```

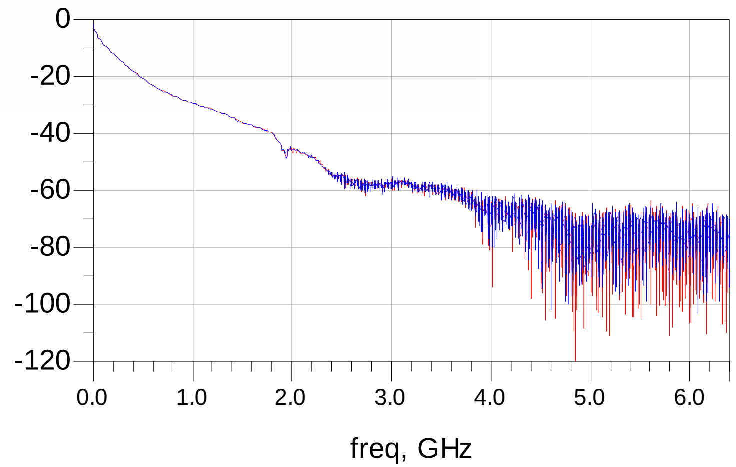
- #S R 50.0 ← support S/Y/Z form
- [Time Step] 0.005 nsec ← uniform time step and time unit
- [Base Delay] 0.0 5.21 5.21 0.0 ← base delay of S(I,J)
- Number of Time Points 200 ← number of time point for S11
- -0.51 -0.94 -0.86 ... ← impulse response of S11
- Number of Time Points 150 ← number of time point for S12
- 0.32 0.78 0.43 ... ← impulse response of S12

- Impulse data is real number.
- Data starts from delay time (0 before delay)

- Initial version. Format is opened to modification.

S-parameter Simulation

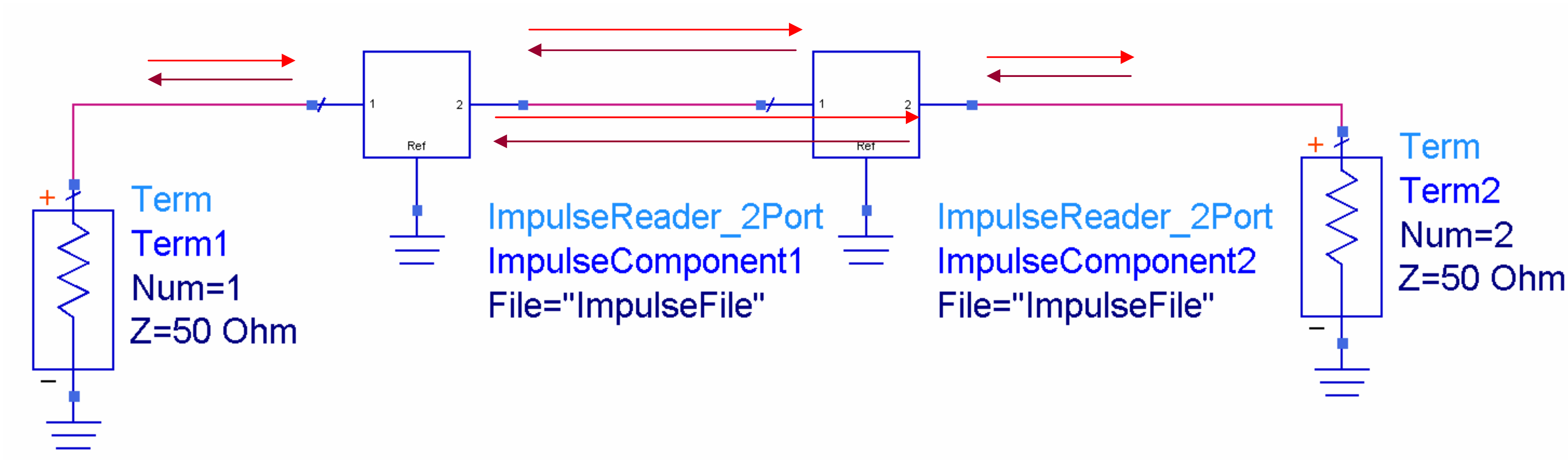




S-parameter simulation of impulse response

can be compared with original measurements

Cascaded Impulse Models



All reflections, crosstalk, insertion loss are accounted for.

Provides voltage and current at every node

Allow frequency, time and envelope domain simulations

Summary

- Fundamental difficulties due to causality and passivity in impulse response calculations and effects on time domain convolution
- New approach for accurate and causal impulse calculation from band-limited spectrum
- Validation in various SI applications
- Propose a new impulse response model methodology
- Need for time domain data format of impulse files