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Causality in Power Delivery Network Extractions in Package & Printed Circuit Board

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Speaker

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His 11 years of experience in Signal Integrity & Power Integrity is with Seagate HDD, Nvidia Corporation & EchoStar Corporation. In 2018, Vinod A H joined Western Digital. In his current position as Principal Engineer, he is responsible for SI-PI co-simulations for parallel bus interfaces.

Mr. Vinod A H has numerous patents filed in Signal Integrity & Power Integrity domain.

Outline

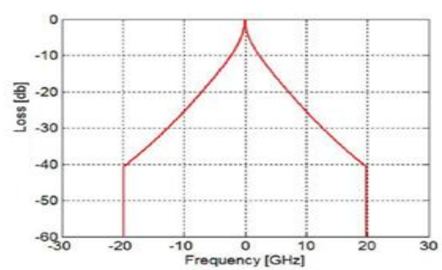
1. Introduction
2. Causality
3. Extracting Causal S-Parameter Models
4. Cascading Causal Channel Models
5. PDN Causality Effects on Time Domain Simulations
6. Conclusion

1. Introduction

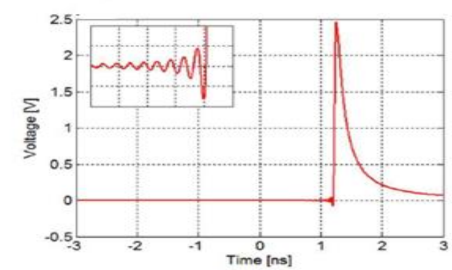
- S-parameters with multiple reference impedances have become the default standard for SI-PI co-simulation modeling of PCB traces and planes as they accurately capture impairments such as crosstalk, reflection and loss.

- It is assumed that the Fourier transform is precise means of converting data from frequency domain to time domain. This is true if S-parameters were continuous and spanned all frequencies. Unfortunately this is not the real world case. Real world S-parameters are bandwidth limited and sampled. So transformation into time domain might result in non-causal signals.

- Gibbs Phenomenon is one well known effects which causes a non-causal time domain signal and is due to finite bandwidth of S-parameter data set.



(a)



(b)

2. Causality

- Causality is the property whereby a system only produces a response after it has received a stimulus, but not before.

- To understand causality violations, we need to separate them into numerical and non-physical components.

- Gibbs Phenomenon is an example of a numerical non-causality.

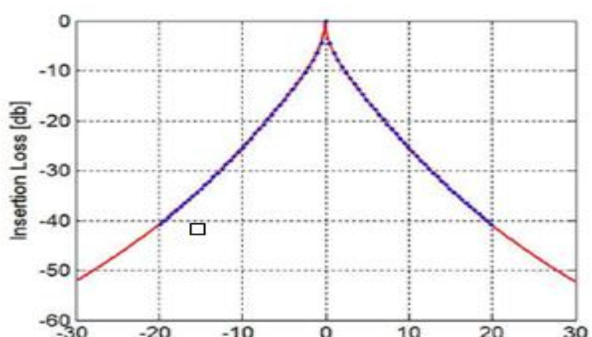
- Numerical non-causalities are caused by two separate attributes:
  - ✓ Real world S-parameters are bandwidth limited i.e. not infinity.
  - ✓ Real world S-parameters are sampled data sets i.e. data sets are discrete, not continuous.

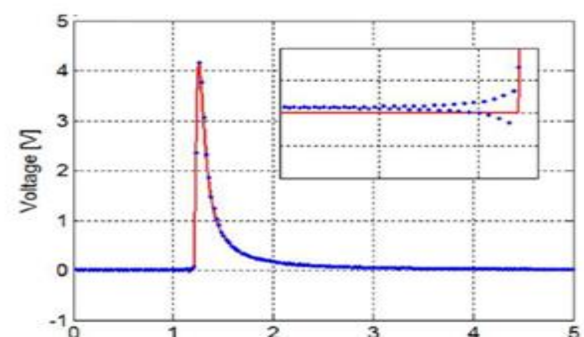
2. Causality..

- An example of a non-physical components is a case when a full wave simulation of a PCB trace that uses a non-physical dielectric model can result in a causality violation.

- To simulate signals, simulation tools cannot work with infinite continuous signals; therefore, the infinite signals must be discretized. Time and frequency domain representations of the signals are linked through the Discrete Fourier Transform (DFT). Non-causality effects are introduced if this is not done with care.

- Figure shows an infinite continuous signal and a bandwidth limited discretized signal and compares their impulse responses.





3. Extracting Causal S-Parameter Models

- The frequency spacing of the S parameter data can affect the causality of the data.
  - ✓ Closer is the frequency spacing; better is the S parameter model, in general. The maximum acceptable frequency spacing is determined by the delay and rise/fall time of the network being characterized.

- The maximum frequency of the S parameter data can also affect the causality of the data.
  - ✓ A higher maximum frequency will, in general, be better. It is sufficient to have data beyond the highest frequency that is relevant to the system bandwidth.

- Need to ensure frequency sweep begins at 0Hz, required by nature of causality, tied to IFFT requirement.

3. Extracting Causal S-Parameter Models..

- PDN of Package & Printed Circuit Board is usually modeled from DC to 1GHz (Die capacitance dominates around 1GHz) with reference impedance of 0.1 Ohm, while Signals are modeled based on their rise/fall times & data rates starting from DC with reference impedance being 50 Ohms.

- When both signal & power are extracted together, Fmax is dictated by signal Fmax for high speed parallel bus interfaces.

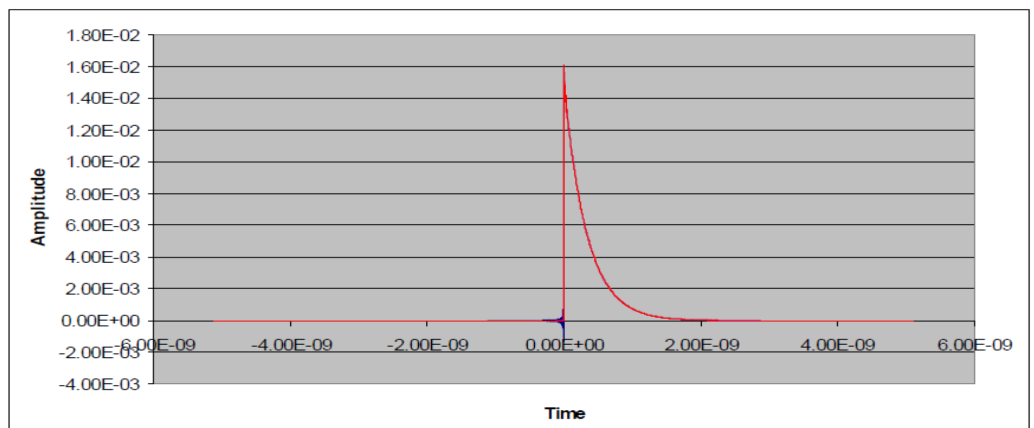
- It is bit tricky to follow same rule for PDN (delay computation) with respect to frequency step as it is done for signals because PDN needs more samples until 1GHz as compared to higher frequency region to ensure resonances are captured and PDN model is causal.

- This results in non-uniform step size for low frequencies as compared to high frequencies which is a problem for transient simulators.

3. Extracting Causal S-Parameter Models..

- The time domain response can be made completely causal by setting all samples before time equals delay to zero. Figure shows the time domain response with and without the non-causal part.

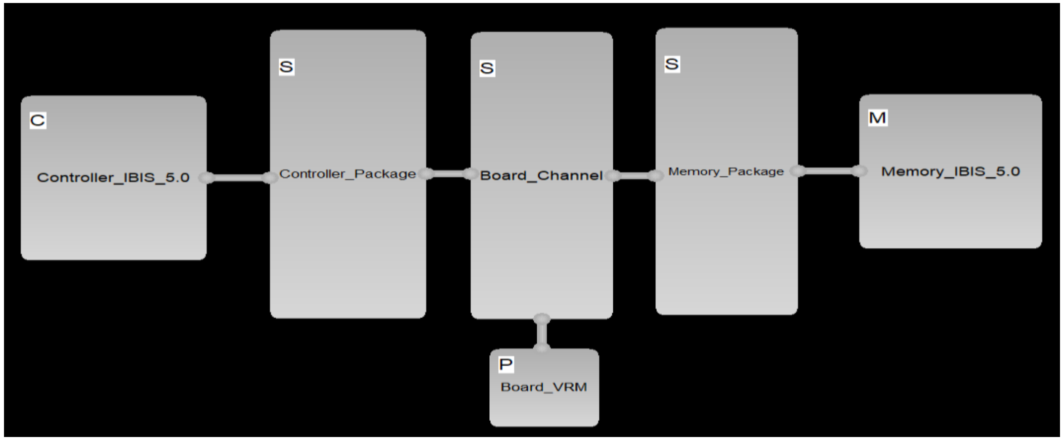
- Non-Causal part energy is dependent almost entirely on the frequency spacing and insensitive to the maximum frequency.



4. Cascading Causal Channel Models

- In power aware parallel bus simulations like DDR4 or Flash Interface, controller package S parameters are cascaded with Board S parameters along with Memory package S parameters.

- Ensuring each of the S parameters is causal is not sufficient. The time domain response can still be non-causal..



4. Cascading Causal Channel Models..

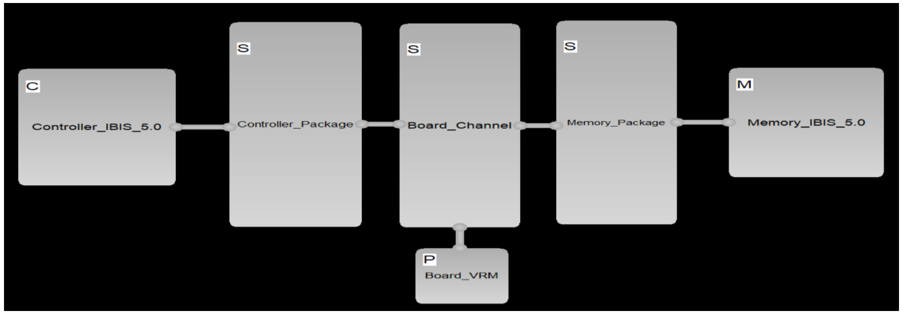
- It is recommended to cascade channel models with the exact same extraction settings with priority as follows;
  - ✓ Same maximum frequency Fmax
  - ✓ Same frequency step-size
  - ✓ Integer Fmax
  - ✓ Fmax should be an integer multiple of the step-size. This allows for ease of re-interpolation.

- While cascading multiple channel models, the challenge of re-interpolating to a common step-size and then extrapolate to a common Fmax for purposes of IFFT in time-domain is one of the many challenges related to causality issues.

5. PDN Causality Effects on Time Domain Simulations

- Example transient simulation setup considered is DDR4 1600MTps 8 bit wide PRBS7 50ps rise time data bus along with differential DQS flowing from controller (IBIS 5.0) to controller package (Touchstone 2.0) to Board (Touchstone 2.0) to memory package (Touchstone 2.0) to memory (IBIS 5.0).

- On-Die de-caps for controller & memory are not considered as part of simulation setup as the target is to capture the smallest effect of causality of PDN.



5. PDN Causality Effects on Time Domain Simulations..

- In the setup, controller package & board S parameter extraction are user controlled while memory package is used as is provided by memory vendor which is verified to be causal model.

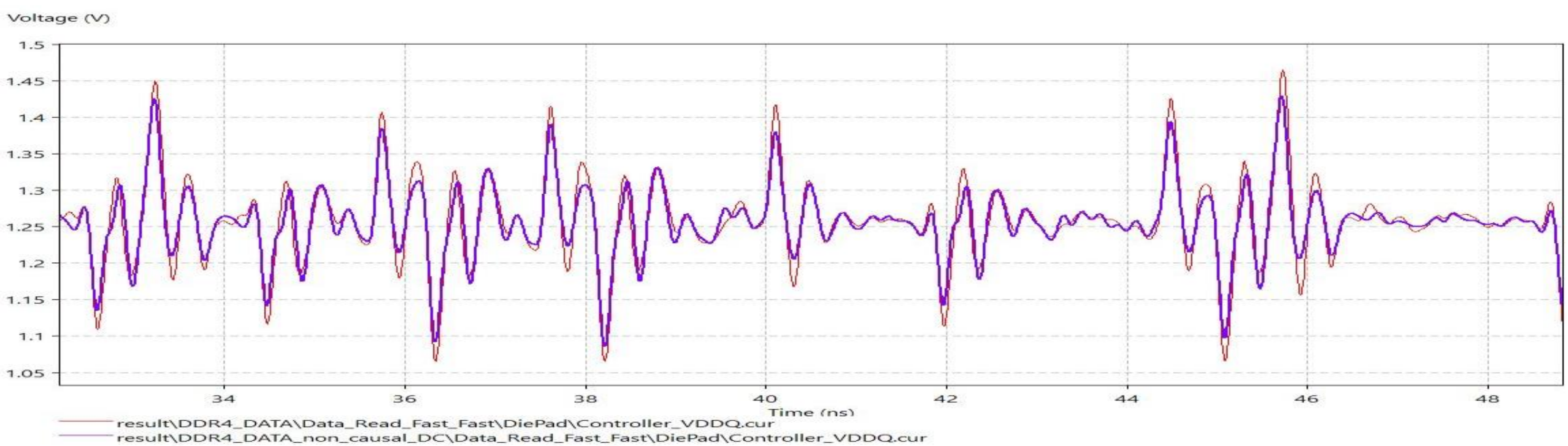
- As a case study, two S parameter models are generated; one of them has PDN causal & other has PDN non-causal. Note that signal extraction is still causal, just the PDN is altered.

- Non-causality as a mathematical artifact is used (extraction setting) to generate non-causal & causal models. Non-causality is introduced on IO supply rail PDN which connects controller IO supply pins & memory IO supply pins.

5. PDN Causality Effects on Time Domain Simulations..

- Waveforms show a comparison of ripple voltage on controller IO supply rail during READ transaction for causal (Red colored waveform) & non-causal (Blue colored waveform) IO PDN case.

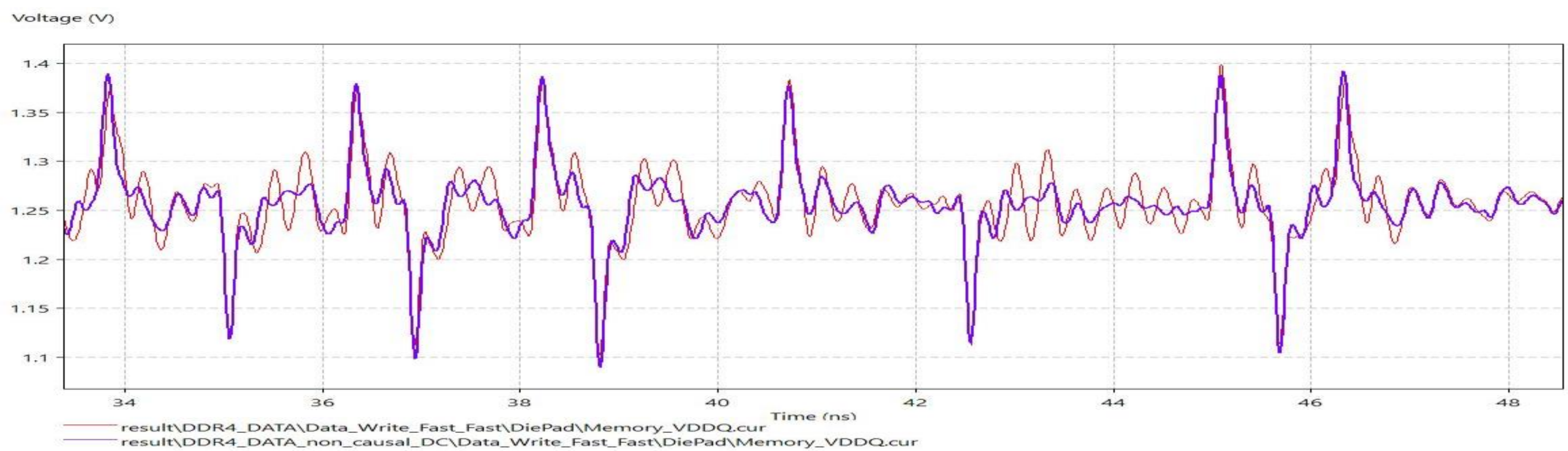
- Ripple waveforms are identical in term of shape but amplitude is slightly lower for non-causal as compared to causal case.



5. PDN Causality Effects on Time Domain Simulations..

- Waveforms show a comparison of ripple voltage on controller IO supply rail during WRITE transaction for causal (Red colored waveform) & non-causal (Blue colored waveform) IO PDN case.

- Ripple waveforms are pretty much identical in term of shape but amplitude is slightly lower for non-causal as compared to causal case.



6. Conclusion

It was shown; how to generate causal models, issues with causal model cascading & non-causal PDN effects on transient simulation output.

1) Non causal PDN results in incorrect supply ripple voltage.

2) As first order effect, incorrect supply ripple voltage will result in incorrect eye height on signal waveforms.

6. Conclusion..

3) It is crucial to qualify PDN causality before passing to next step. If causality check is not performed, simulations may be flawed unknowingly.

4) Causality enforcement techniques can be applied to numerical non-causalities, but will, in general, introduce unwanted errors in the S-parameters.

5) Results of such enforcement may not be reliable including the rational fitting process that many commercial tools perform either explicitly or implicitly.

Acknowledgment

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References

[1] Stefaan Sercu, "Causality Demystified", DesignCon 2015

[2] Madhavan Swminathan, "Causality Enforcement in Transient Co-Simulation of Signal and Power Delivery Networks", IEEE TRANSACTIONS ON ADVANCED PACKAGING, VOL. 30, NO. 2, MAY 2007

[3] Yuriy Shlepnev, "Quality metrics for S-parameter models", DesignCon IBIS Summit 2010.

[4] Peter J. Pupalaikis, "The Relationship Between Discrete-Frequency S-parameters and Continuous-Frequency Responses", DesignCon 2012

[5] "Kramers-Kronig relation", http://en.wikipedia.org/wiki/Kramers-Kronig_relations

[6] Philip A. Perry & Thomas J. Brazil, "Forcing Causality on S-Parameter Data Using the Hilbert Transform", IEEE MICROWAVE AND GUIDED WAVE LETTERS, VOL. 8, NO. 11, NOVEMBER 1998

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