Causality in Power Delivery Network in Package & Board

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Abstract

In power aware parallel bus simulations, signal and power S parameters are extracted together. Extracting signals without causality is well known in literature. Extracting power being causal with signal also being causal is challenging task as signal & power by its nature are way too different (different reference impedances).

Non-causal PDN will possibly cause incorrect supply ripple voltage & incorrect signal swing during transient simulations. This makes SI engineer to incorrectly design PDN which has cost impact to product as well as design cycle impact.

This paper is a case study on causality problems in Power Delivery Network (PDN) in power aware signal integrity (SI) simulations. With power aware IO buffer models like IBIS 5.0 used very commonly in simulations, extraction (S parameters) of package & board signals with power is becoming a challenge. Power integrity checks (DC Drop or AC Impedance analysis) will ensure PDN offers low impedance to IC drawing current to ensure ripple voltage is under control. This paper talks about causality of PDN and impact on design if causality check is not done on PDN of package or board.

Author(s) Biography

Vinod Arjun Huddar received his B.E. from University Visvesvaraya College of Engineering (U.V.C.E) Bangalore as Electronics & Communication Engineer in 2007.

His past experience is with Seagate HDD, Nvidia Corporation & Echostar Corporation with 11 years of experience in Signal Integrity & Power Integrity. 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.

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, reflections and loss.

For example, resonant behavior in systems is captured when working with S-parameters for Signals & impedance behavior is easily seen when working with Z parameters (converted from S parameters). While there are many advantages to using S-parameters for SI-PI co-analysis, there are certain problems associated with using them in time domain simulations.

It is assumed that the Fourier transform is precise means of converting from the frequency domain to the time domain. This is true if the 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 the time domain will result in non-causal signals.

Gibbs Phenomenon is one well known effect which causes a non-causal time domain signal and is due to finite bandwidth of the S-parameter data set. Figure 1 below illustrates the same.

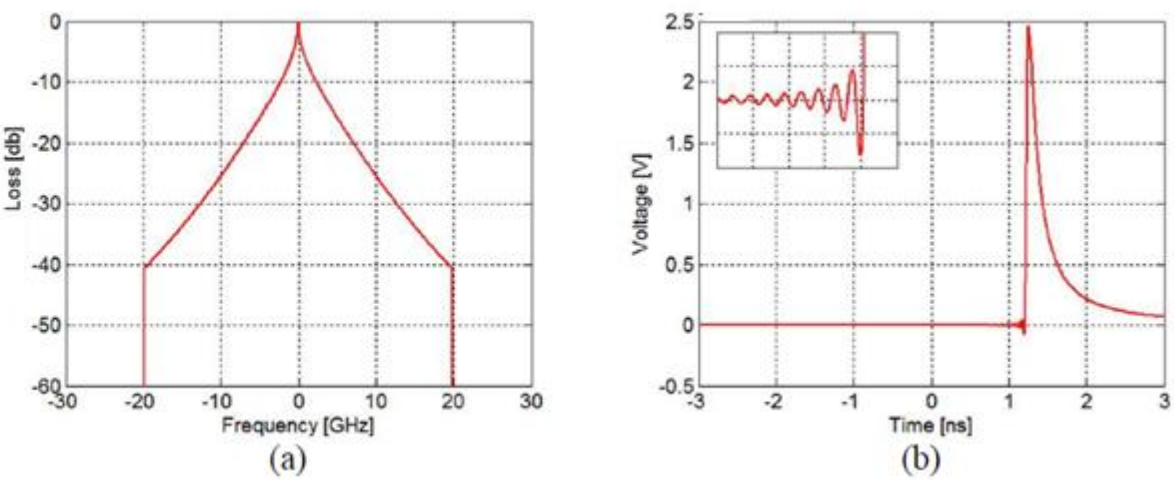

Figure 1: (a) Bandwidth limited insertion loss of PCB Trace (b) Corresponding impulse response with ringing.

2. Causality

Causality is the property whereby a system only produces a response after it has received a Stimulus but not before. The goal of this work is to understand how causality violations arise in PDN networks during S parameter extraction when signals are extracted along with power and impact on PDN in power aware transient simulations.

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:

1. Real world S-parameters are bandwidth limited i.e. not infinity.

2. Real world S-parameters are a sampled data set i.e. it is not continuous; it is a discretized data set.

Non-physical components can be for example 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 2 below compares the impulse response of an infinite continuous signal with the impulse response of a bandwidth limited discretized signal.

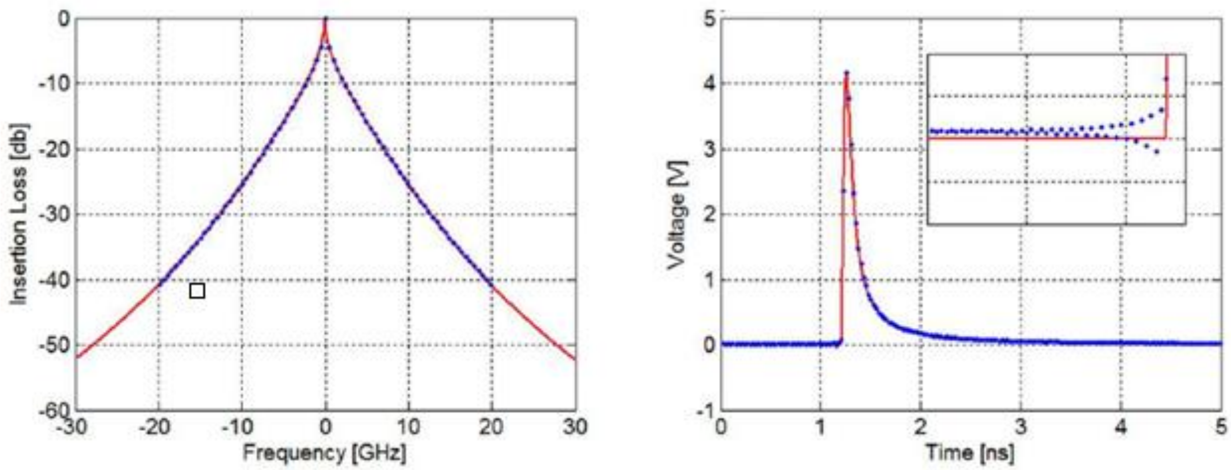

Figure 2: IFT & DIFT of Continuous & Sampled Bandwidth limited S-parameters.

3. Extracting Causal S-Parameter Models

The frequency step/spacing of the S parameter data can affect the causality of the data. Closer is the frequency spacing; better is the S parameter model. 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 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) a true DC point.

PDN of Package & Board is usually modeled from DC to 1GHz (Die capacitance dominates beyond 1GHz) with reference impedance of 0.1 Ohms, 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 as PDN needs more samples until 1GHz as compared to higher frequency region (beyond 1GHz) to ensure resonances (high impedance) are captured and PDN model is causal. This results in non-uniform step size for low frequencies as compared to high frequencies. Need to verify the causality of PDN using industry standard simulation tools or Polar plots trajectory.

The time domain response can be made completely causal by setting all samples before time equals delay to zero. Figure 3 below 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.

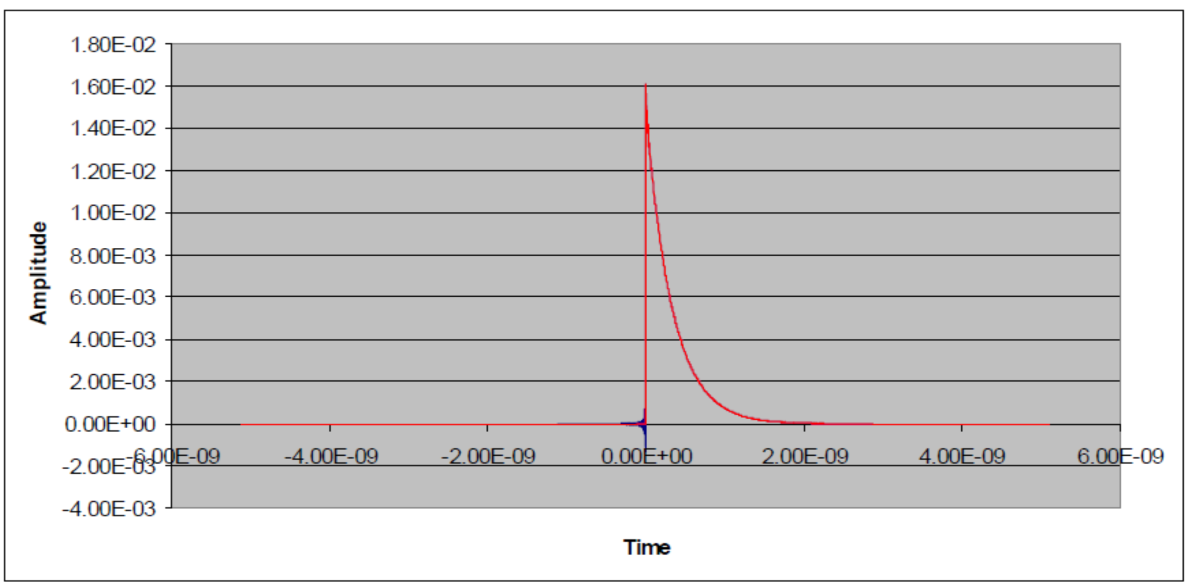

Figure 3: Time domain response with and without non-causal part.

4. Cascading Causal Channel Models

In power aware parallel bus simulations like DDR4 or Flash Interface, Controller package S parameters (Touchstone 2.0 version) are cascaded with Board S parameters along with Memory package S parameters as shown in Figure 4 below.

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

It is recommended to cascade channel models with the exact same extraction settings with priority as follows:

1. Same Maximum frequency Fmax
2. Same Frequency step-size
3. Integer Fmax i.e. No non-integer Fmax.
4. 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.

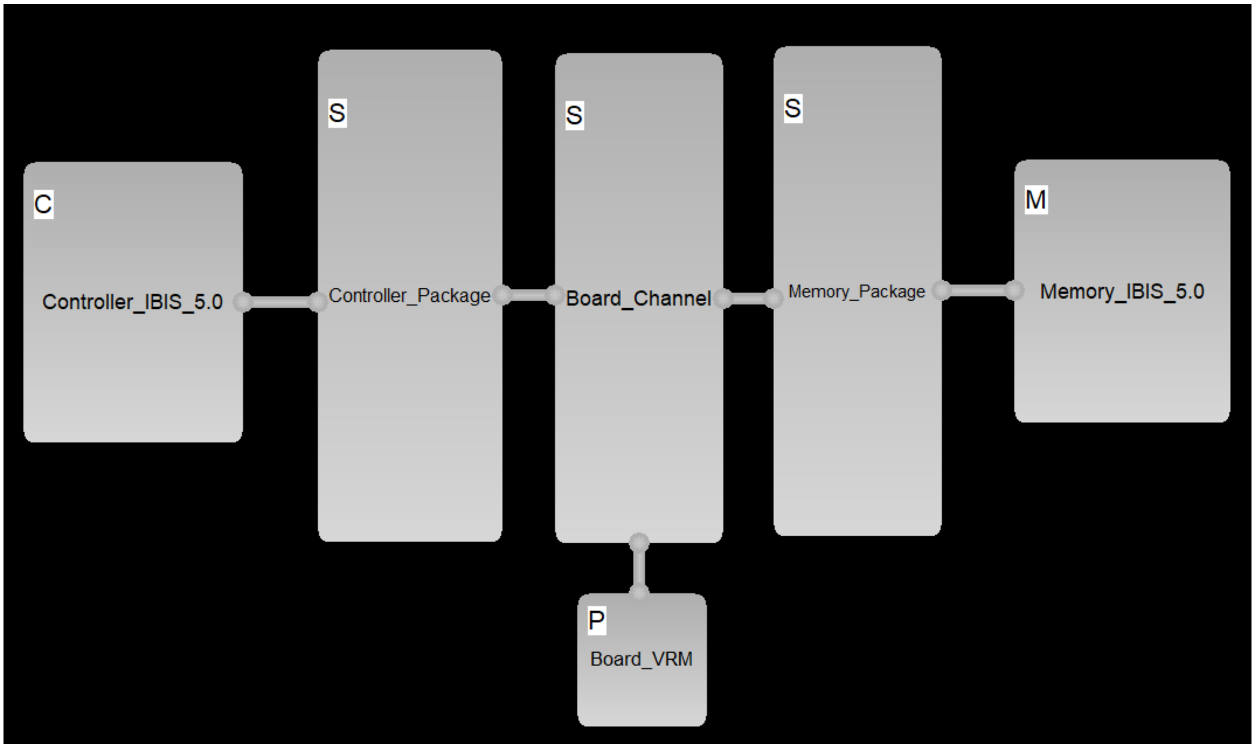

Figure 4: Cascading Causal Channel Models.

5. PDN Causality Effects on Time Domain Simulations

The previous sections showed on how to extract causal models & challenges in cascading multiple causal channel models. This section takes a closer look at impact of non-causality of PDN on supply ripple in time domain.

Transient simulation setup as shown in above Figure 4 is DDR4 1600MTps 8 bit wide PRBS7 50ps rise time data bus along with differential DQS (Data Strobe) 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). Note that On-Die de-caps for controller & memory are not considered as part of simulation setup to capture the smallest effect of causality of PDN.

In this 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.

Below Figure 5 shows the 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.

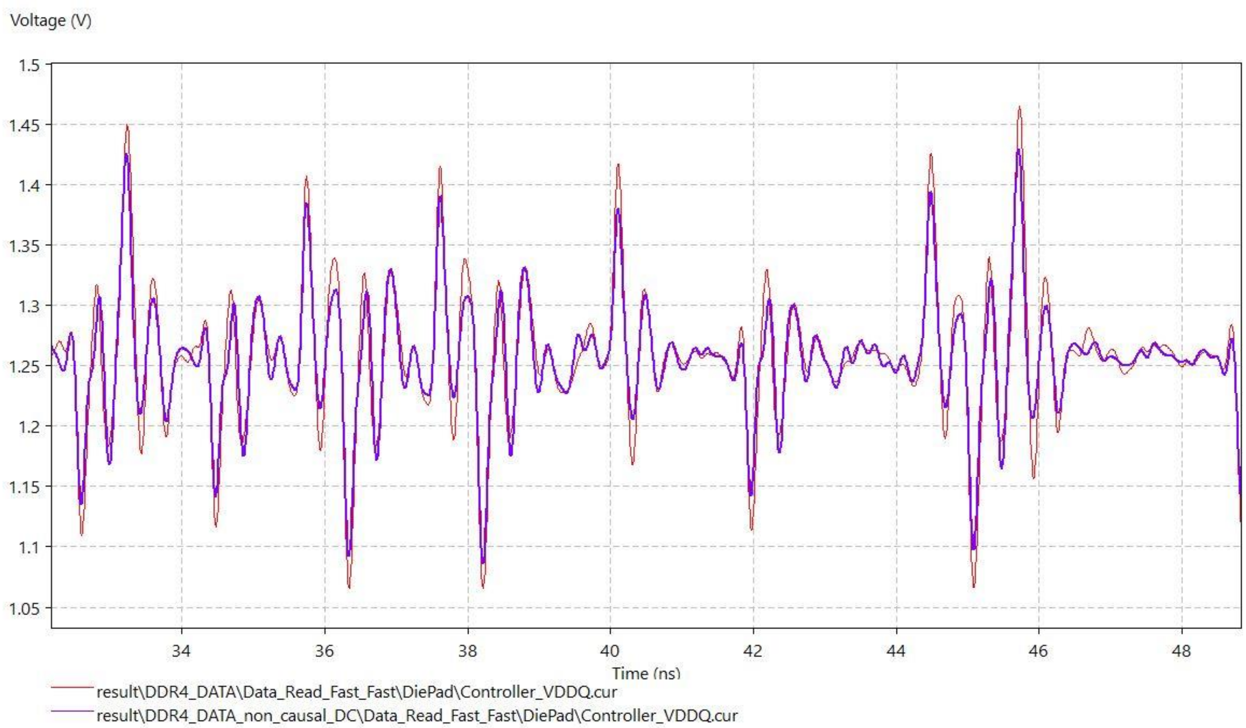

Figure 5: IO Supply ripple comparison for Causal & non-Causal PDNs during Reads.

Below Figure 6 shows the 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.

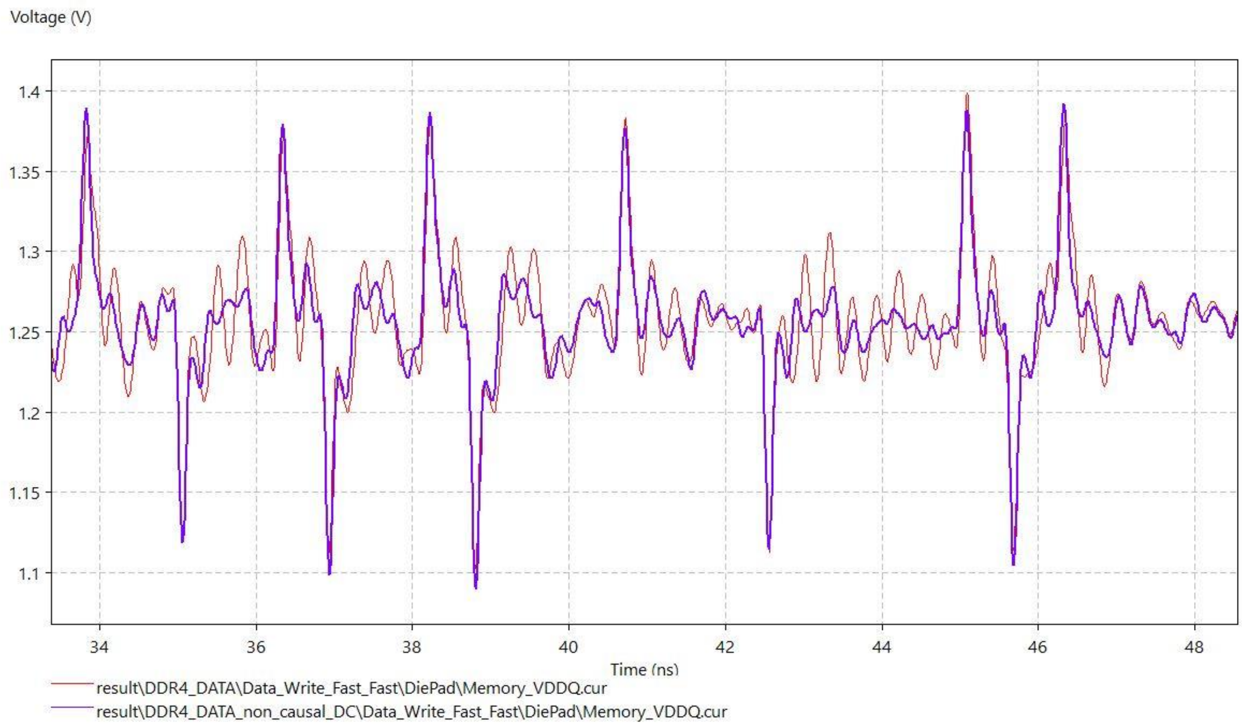

Figure 6: IO Supply ripple comparison for Causal & non-Causal PDNs during Writes.

6. Conclusion

This case study paper dealt specifically with causality for PDN. It was shown; how to generate causal models, issues with causal model cascading & non-causal PDN effect on transient simulation. Non causal PDN results in incorrect supply ripple voltage. As first order effect, incorrect supply ripple voltage will result in incorrect eye height on signal waveforms.

It is crucial to qualify PDN causality before passing to next step. If causality check is not performed, simulations may be flawed unknowingly. Causality enforcement techniques can be applied to numerical non-causalities, but will in general introduce unwanted errors in the S-parameters. Results of such enforcement may not be reliable including the famous rational fitting process that most of the commercial tools perform either explicitly or implicitly.

7. Acknowledgements

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8. 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