Application Note

Simple Approach to Modeling of Power Delivery Networks and Components

Abstract

The digital system Power Delivery Networks (PDNs) have received increased attention in the electronics industry as a critical element in digital system design. The current generated by switching input/output buffers can produce significant voltage transients in the power and ground planes, which can result in unreliable operation of the system.

A power plane is a very low impedance structure that places high demands on measurement accuracy. Probes and cables used in the measurements must be carefully de-embedded. Substantial work on using frequency domain transmission measurements as an equivalent to 4-point resistance measurements to characterize PDNs has been done by Istvan Novak [1] and further developed in [2]. However, frequency domain measurements are not intuitive for digital engineers, and require expensive high-performance microwave probes. Even then, in order to accurately de-embed probes and cables, techniques developed in [1] and [2] require additional steps to obtain and interpret the data, further complicating the measurement.

In this paper, we will focus on using time domain measurement techniques, such as Time Domain Reflection and Transmission (TDR/T), for PDN analysis. These techniques are more intuitive and easier to understand for most digital designers, and the probes used are much less expensive and easier to use. In addition, this represents a simpler approach, with no loss in model accuracy. This TDR/T approach for PDN analysis produces models that will accurately represent the PDN behavior.

Power Plane Example and Probing

We will use the following test structure as an example. This test board consists of two planes, which have via connections to the bottom plane, and pad connections to the top plane at multiple locations on the board. Using these vias and pads, we can apply a TDR signal across the two planes at one point (the point of power application), and measure the response across these same planes at another point (the point of power delivery).

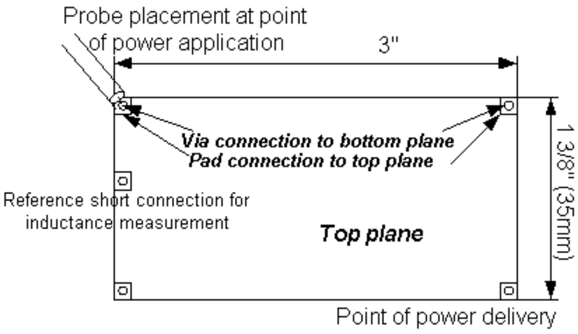


Figure 1. Power plane test vehicle

For applying TDR signals to the planes, we used a semi-rigid coax-based QuickTDR™ probe from TDA Systems, with the Cascade Microtech EZ-Probe™ as the probe holder. The QuickTDR probe with EZ-Probe positioner allows easy access to the probe points on the test vehicle.

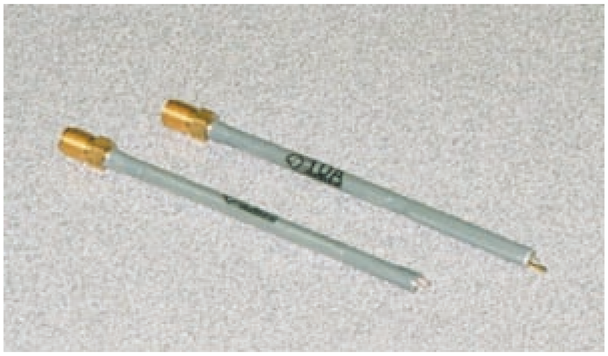


Figure 2. QuickTDR™ probes - a simple and convenient probing solution

A more accurate probing setup, available from several vendors and employing precision microwave probes would provide better measurement accuracy - however, at the expense of ease of use.

PDN Equivalent Models

The simplified PDN can be viewed as a transmission line of very low impedance. Alternatively, it can be viewed as a parallel plate capacitor, with additional equivalent series inductance and resistance (ESL and ESR). These two approaches do not contradict each other, since a low impedance transmission line is equivalent to a capacitor with low ESL and ESR values.

The following are typical equivalent circuit models used for PDN and PDN components [2].

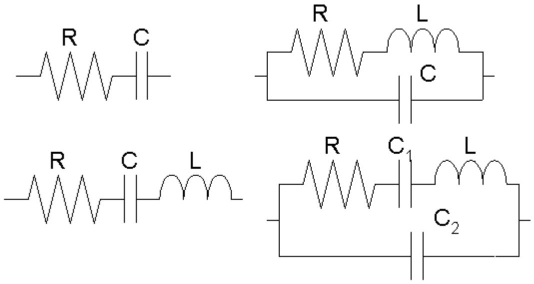


Figure 3. Typical equivalent models for the PDN

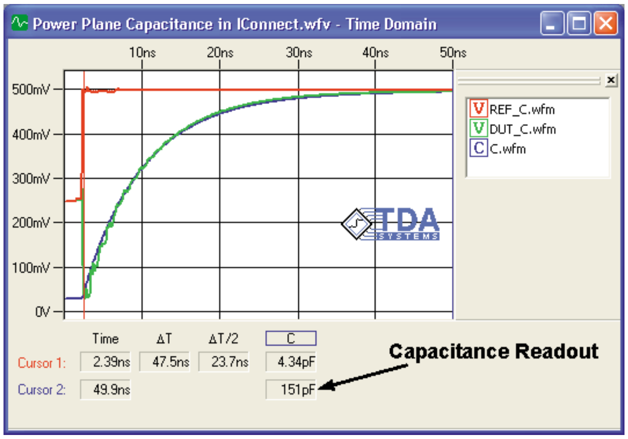
The series RLC model can be applied to parallel plate plane pairs, from DC to the first parallel resonance, as well as to many bypass capacitors. The parallel RLC model can be applied to shorted plane pairs, and to capacitors mounted on plane pairs around their resonance.

There are well-established techniques for measuring C and L of a circuit, and they are based on the JEDEC standard for electrical characterization of electronic packages [3]. These techniques can be extended to PDN modeling. Moreover, because the JEDEC standard defines a comparative technique for measuring L and C with and without the probe in place, the probe is de-embedded from the measurement. This allows the designer to achieve modeling accuracy that is comparable to the accuracy obtained using the 2-port VNA measurements discussed in [1] and [2], while keeping the modeling process very fast and simple.

PDN Capacitance

For the PDN capacitance measurements, the power plane must be left unconnected from the ground plane. Two measurements are required: the DUT and the reference open. The DUT waveform is obtained by placing the probe at the point of power application (Figure 1). The reference open measurement is obtained simply with the probe left open-ended, not connected to anything.

The resulting two waveforms - reference and power plane DUT waveforms are shown in the figure below. The capacitance is computed in TDA Systems' IConnect TDR software using C_{self} computation, as specified in the JEDEC standard [3], and is shown in the figure as well. You can observe the cumulative capacitive curve, with the cursor readout providing the final value of capacitance, equal to 151pF. Note that it is important to read the asymptotic inductance value, as required by the JEDEC standard.



	Time	ΔT	ΔT/2	C
Cursor 1:	2.39ns	47.5ns	23.7ns	4.34pF
Cursor 2:	49.9ns			151pF

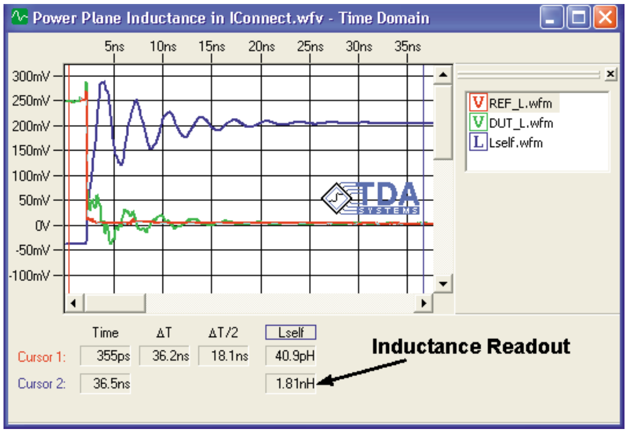
Capacitance Readout

Figure 4. Measurement of capacitance for the PDN

We can also estimate the capacitance of the two planes using the basic equation: $C=\varepsilon\varepsilon_r\, lw/t$, where ε and ε_r are the absolute and relative permittivity of the board material, and l, w, and t are the length, width and thickness of the board, respectively. With l=3", w=13/8, t=0.7mm, and ε_r=4.2 (FR4), we compute a capacitance value of 141pF, which is in excellent correlation with the measured value, considering the substantial t and ε_r measurement uncertainties.

PDN Series Inductance

Two measurements are required for the power plane series inductance measurements. For the DUT measurement, the power plane is shorted to ground at the point of power delivery using a piece of metal foil (see Figure 1 above), and is measured at the point where the power is applied to the board. In this measurement, we obtain a waveform that includes inductance of the probe, via to the bottom plane and the PDN. The second measurement is a reference short, which is used to de-embed the probe inductance and the inductance of the via. For the reference short, we need to have another power-ground connection, such as the reference



	Time	ΔT	ΔT/2	Lself
Cursor 1:	355ps	36.2ns	18.1ns	40.9pH
Cursor 2:	36.5ns			1.81nH

Inductance Readout

Figure 5. Measurement of inductance for the PDN

short connection for inductance measurement in Figure 1. Since there is practically no inductance between the power application point and the reference short connection, a TDR measurement at the power application point, with the planes shorted at the reference short connection, provides us with primarily inductive signature of the probes and vias. Note that in a real board, providing a similar connection would require some forethought in the board layout. Now, computing L_{self} in IConnect using this measurement as a reference allows us to accurately obtain the inductance value of the PDN of 1.8nH.

Since we are measuring very small inductance values, care must be taken to ensure measurement repeatability. This is the only measurement in the sequence where a precision microwave probe may be required to ensure the required repeatability level.

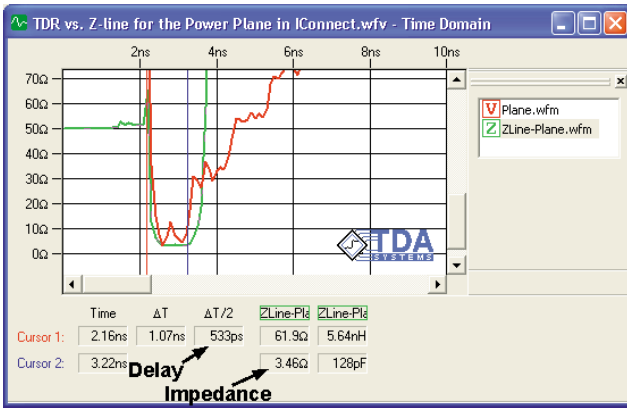
Power Plane Resistance

Here we are measuring a small resistive value between the point of power application and the point of power delivery. A 4-point probe method or another method, which would allow the designer to remove the resistance of the cables and probes from the measurements, should provide more than adequate accuracy for such measurements. In our example, using a 4-point probe method we measured resistance of 0.02 Ohms for the test case power delivery system.

Power Plane Impedance Value

TDR is the traditionally accepted technique for measuring transmission line impedance. The true impedance profile peeling algorithm, discussed in [4] and implemented in IConnect TDR software, allows the designer to remove the effect of multiple reflections and get a much more accurate readout for impedance and electrical length of the power plane. Note that with the impedance profile algorithm applied, we can observe not only the impedance, but also the time delay required for the signal to travel across the plane, from the point of power application to the point of power delivery (approximately 3.46 Ohm and 533ps, respectively). The time delay is read as ½ of the round-trip delay observed from the TDR measurement.

The impedance value measured here is on the order of several ohms. In a case where the power plane impedance is on the order of milliohms or less, this technique may not provide sufficient accuracy when applied directly. The JEDEC approach for computing C and L of the plane will provide better accuracy.


TDR vs. Z-line for the Power Plane in IConnect.wfv - Time Domain

	Time	ΔT	ΔT/2	ZLine-Pla	ZLine-Pla
Cursor 1:	2.16ns	1.07ns	533ps	61.9Ω	5.64nH
Cursor 2:	3.22ns			3.46Ω	128pF

Figure 6. With the impedance profile algorithm applied, we can observe not only the impedance, but also the time delay required for the signal to travel across the plane. Delay is read as ½ of the round-trip delay observed from the TDR measurement.

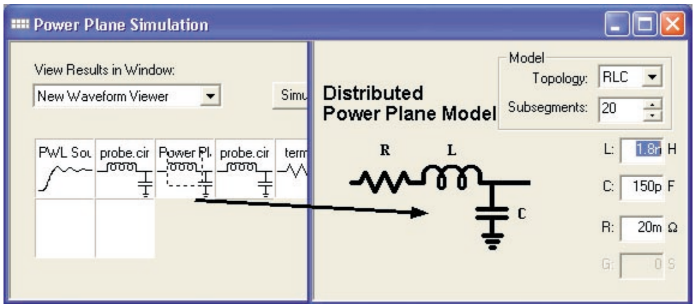
The impedance and delay of the plane can be estimated from computed L and C values using the following equations:

$$Z = \sqrt{\frac{L}{C}} \qquad t_d = \sqrt{LC}$$

Applying these equations to the L and C values of 1.8nH and 151fF obtained using the JEDEC technique, we obtain Z=3.45 Ohm and t_d=521ps. This is in excellent correlation with the numbers obtained using the impedance profile approach.

Model Validation

To validate the resulting model, we set up a simulation in IConnect, using a model configuration shown on Figure 7. The TDR source is simulated based on the reference open waveform obtained when performing the capacitance measurement sequence. The measurement probe was modeled separately using the impedance profile approach [5] and included in the simulation. Since the power plane is, in reality, a distributed inductance and capacitance, we split the total extracted RLC values into 20 subsegments in the simulation, so that each subsegment is shorter than the rise time of the signals propagating through the plane.


Power Plane Simulation

View Results in Window: New Waveform Viewer

Model
Topology: RLC
Subsegments: 20
L: 1.8n H
C: 150p F
R: 20m Ω
G: 0 S

Figure 7. Composite circuit for simulating PDN

The measurements with a 50-Ohm termination are shown with excellent correlation observed. Please note that correlation in both time and frequency domain (past the first resonance) is obtained.

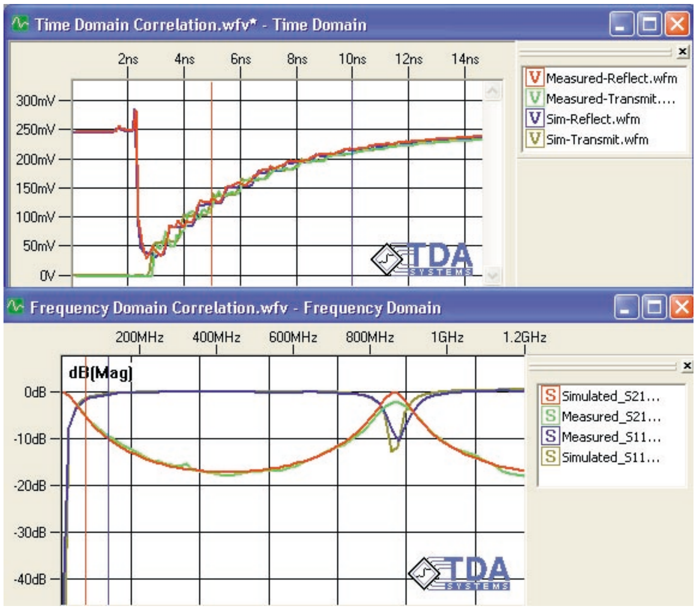


Figure 8. Correlation of the extracted model and measurements for the PDN

PDN Component Measurements

Techniques similar to those described above can be applied to measurement of other PDN components, such as vias, bypass capacitors, and voltage regulators. For example, consider the via inductance. In addition to the JEDEC approach discussed above, the inductance of a single via can be extracted using the impedance profile approach discussed in [5]. More importantly, inductance of a via pair, located close together and coupled, can be extracted using the technique based on differential TDR measurements and presented in [6] and [7]. The "even" and "odd" inductances of the via pair are extracted using either the JEDEC approach, or the coupled line impedance profile approach, and then the self and mutual inductances of the via can be extracted using the following equations if the JEDEC approach was used for "even" and "odd" mode measurements:

$$L_{self} = \frac{L_{even} + L_{odd}}{2} \qquad L_{mutual} = \frac{L_{even} - L_{odd}}{2}$$

If the differential impedance profile approach [7] was used, the following equations will apply:

$$L_{self} = \frac{1}{2}\left(Z_{even}t_{even} + Z_{odd}t_{odd}\right) \qquad L_{mutual} = \frac{1}{2}\left(Z_{even}t_{even} - Z_{odd}t_{odd}\right)$$

Consider the following via example: We performed differential and common mode TDR measurements, and acquired odd and even mode waveforms. Then the waveform is partitioned in IConnect, and the via inductance is obtained. IConnect calculates the L values directly. The extracted values are L_{self}=1.9nH, and L_{mutual}=0.38nH, or a coupling coefficient of 0.2. The simulation of this via model correlates well with the measured data, as shown on Figure 9 below.

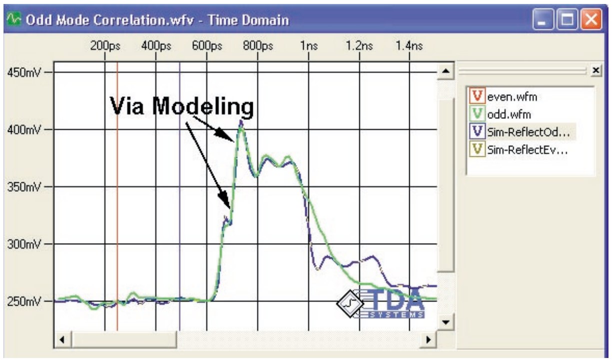


Figure 9. The correlation between the via model simulation and the measurement

Summary

We have demonstrated in this paper that TDR/T measurements with IConnect TDR software produce models that are sufficiently accurate to correctly reproduce the PDN behavior in both time and frequency domains. The simplicity and ease of use and interpretation of TDR/T measurements provide additional advantages for a PDN designer.

Bibliography

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