Fundamentals of S-Parameter Modeling for Power Distribution System (PDS) and SSO Analysis

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The Myth of Ground Bounce

Basics about "Voltage" and "Ground" from an Electromagnetics Perspective

Power Delivery Modeling Basics

Motivation to Understand the Basics about Electromagnetics

- At high frequencies (when the wavelength is comparable to the circuit's size), electromagnetic (EM) phenomena form the basis for all Signal Integrity (SI) and Power Integrity (PI) issues in IC packages and PCBs. EM field theory must be applied, whereas lumped circuit theory may fail.

About Voltage

- Voltage is measured between 2 nodes, and these 2 nodes have certain restrictions for the measurement to be meaningful and valid:

1. Measuring voltage across a large distance (comparable to a wavelength) is not well defined. For example, defining the voltage between die-pad and the package-pin; or defining the voltage between a point in the middle of a PCB and a point at the edge of the PCB. These are not good if you are working in the hundreds of MHz range and beyond.

   Additional reading: Ray Anderson, SI-List, July 2004

2. Measuring AC voltage drop along the conductor itself is not defined. For example, we often measure the voltage at the ends of a transmission line (the 2 ports); we don't measure the voltage drop along the individual transmission line conductor. Voltage drop along the ground conductor (except at DC) cannot be defined based on EM theory.

   Additional reading: From Electromagnetics or physics text book

The Correct Way to Measure Voltage

1 ●━━━━━━━━● 3   Signal Trace

2 ● ━━━━━━━━━ 4   Ground Plane
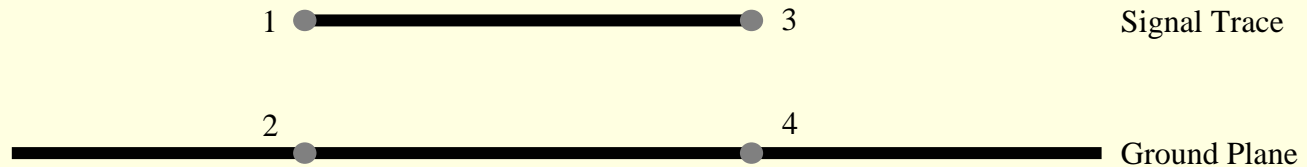
- V[1,2] and V[3,4] are meaningful; V[2,4] and V[1,3] are NOT meaningful.
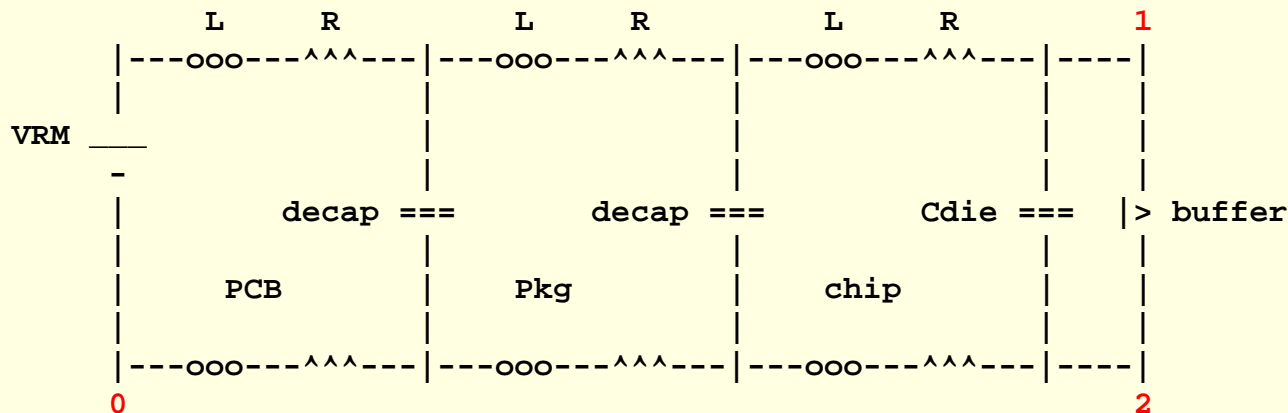
Chip

Package

PCB
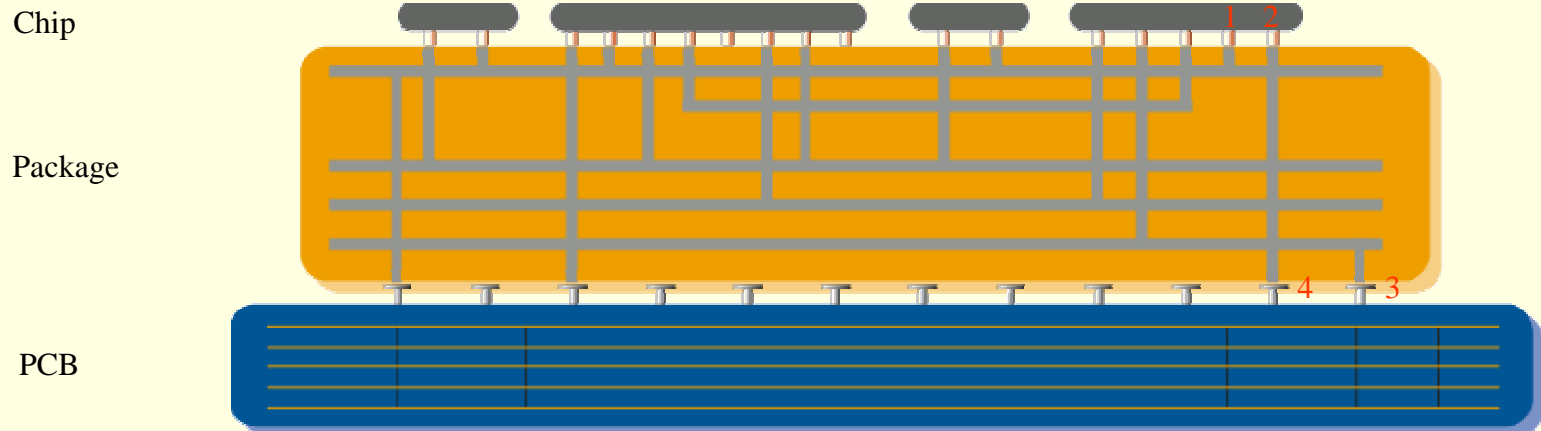
About the "Ground Bounce" Name

After all, the terminology of ground bounce itself can be misleading, because a lot of people think that ground bounce can be viewed ON the ground conductor, whereas actually ground bounce happens BETWEEN power and ground. The only time you can well define the voltage between 2 ground points is if these 2 ground points are physically very close (local port). For example, between two ground C4 bumps. At that time, most flux in this loop is well captured between these two points.

It is better to use the term Power/Ground fluctuation instead of ground bounce.

Now inspect the commonly used, one-dimensional power delivery system model:

```
            L      R           L      R           L      R           1
      |---ooo---^^^---|---ooo---^^^---|---ooo---^^^---|----|
      |               |               |               |    |
VRM ___              |               |               |    |
    -                 |               |               |    |
      |          decap ===       decap ===        Cdie ===  |> buffer
      |               |               |               |    |
      |     PCB       |     Pkg       |     chip      |    |
      |               |               |               |    |
      |---ooo---^^^---|---ooo---^^^---|---ooo---^^^---|----|
      0                                                    2
```

To a driver, what is important is the local supply voltage between node 1 and 2 (power and ground). Only V(1,2) can be well defined in the correct EM sense. The so-called "ground bounce" between node 2 and 0 is ill-defined and is meaningless to the driver.

Ground Reference

- SPICE, as a circuit simulator, has a node "0" to represent the reference node "ideal ground". You can always measure voltage between any specific node with respect to this node "0", while ignoring the time and distance that may separate these two nodes.

- In EM field simulation, there is no "ideal ground" that can be used as a global reference for voltage measurement. You always measure voltage locally between two closely-spaced nodes, using one node as the local reference.

HSPICE 2004.9 Update on Node "0"

- In previous versions of HSPICE, node "0", "GND", "GND!", and "GROUND" are reserved keywords and these nodes are global grounds. Node 0 in two different sub-circuits will be automatically shorted together.

- Starting from HSPICE 2004.9, when HSPICE detects it is running in co-simulation mode with SPEED2000, node 0 in every subcircuit will NOT be treated as global ground anymore. It will serve only as local ground for that subcircuit.

- This update enables HSPICE (with SPEED2000) to correctly simulate systems with non-ideal ground.

Driver subcircuit with node 0   Receiver subcircuit with node 0
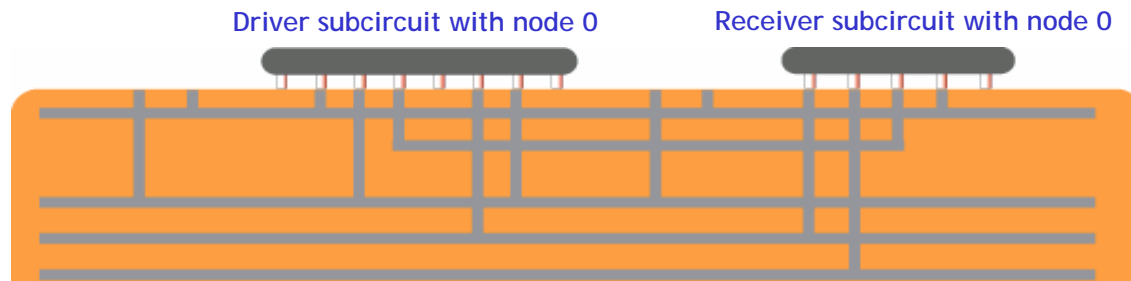
The Myth of Ground Inductance

About "Loop Inductance", "Partial Inductance" and "Ground Inductance"

Definition of Inductance (from any Physics or EM Text Book)

- Inductance L is magnetic flux through a loop area divided by the current.

- Self internal inductance, due to the flux inside the conductor body, approaches zero at higher frequencies because of the skin effect.

- The remaining inductance is the self external inductance, due to the flux outside the conductor body but within the loop area formed by the conductor, commonly known as loop inductance.

- Mutual inductance is the interaction between two loop areas.

Partial Inductance

- Partial inductance is a mathematical representation and has no physical meaning when comparing to loop inductance alone.

- Partial inductances are valid as long as they are defined in the context of a loop. Partial inductances by themselves have no meaning. But used in an inductance matrix, where they are combined with all partial self and mutual inductances in a loop, the extracted values (not unique) can be used to find unique voltages and currents within that loop.

Partial Inductance (Example)

Take the example of two connector pins, one used for a signal and the other used for ground. Loop inductance in this case is L1+L2-2*M12 (the sum of the partial self inductances minus two times the partial mutual inductance between them). The following partial self and mutual inductances might be obtained from two different electromagnetic extractors:

```
extractor         L1      L2      M12     Loop L   units
---------         -----   -----   -----   ------   -----
1                 10      10      9       2        nH
2                  2       2      1       2        nH
```

Which extractor got the right answer? They both did. Partial self and mutual inductances are meaningless outside the context of a loop. Both sets of extracted data give the same loop inductances and will lead to unique voltages and currents when the loop is simulated in a circuit analysis tool, even though the extracted partial self and mutual inductances are not unique.

Additional reading: Larry Smith, SI-List, April 2002

(http://www.freelists.org/archives/si-list/04-2002/msg00115.html)

Ground Inductance

" Many engineers try to use partial inductance (alone) in a circuit simulation. This is at best misleading and may give flat out wrong answers in the simulation." - Larry Smith, SI-List, April 2002
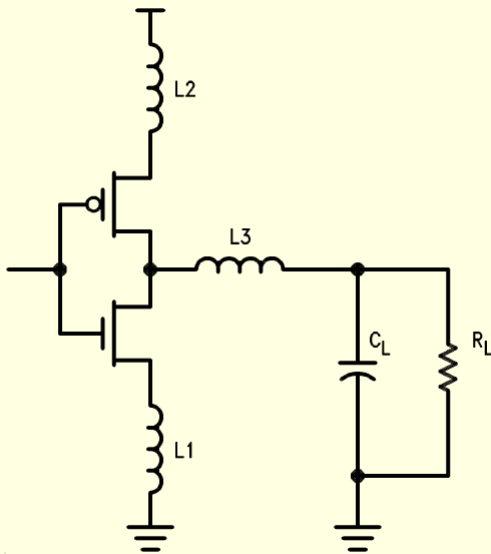
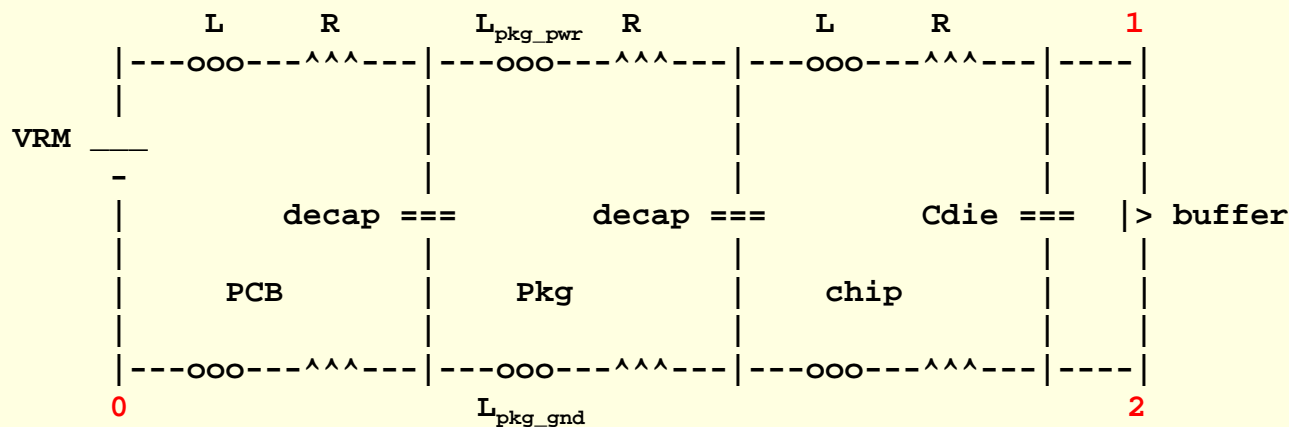
Misleading points for the model on the left:

1. L1 is the ground inductance. L2 is the power inductance.

2. Ground bounce is the voltage across L1, whereas power bounce is the voltage across L2.

Things to think about:

1. Which loop/flux L1 is representing?

2. Is voltage across L1 physically meaningful?

Ground Inductance (Case 2)

" Many engineers think about ground inductance and power inductance separately, and this is wrong. There is only one physical meaningful inductance, which is the power and ground loop inductance."

```
              L       R         L_pkg_pwr  R            L        R            1
     |---ooo---^^^---|---ooo---^^^---|---ooo---^^^---|----|
     |               |               |               |    |
VRM __              |               |               |    |
     -               |               |               |    |
     |          decap ===       decap ===        Cdie === |> buffer
     |               |               |               |    |
     |    PCB        |    Pkg        |    chip       |    |
     |               |               |               |    |
     |---ooo---^^^---|---ooo---^^^---|---ooo---^^^---|----|
     0                       L_pkg_gnd                    2
```

Misleading points for the model above:

1. I have ground inductance of Lpkg_gnd

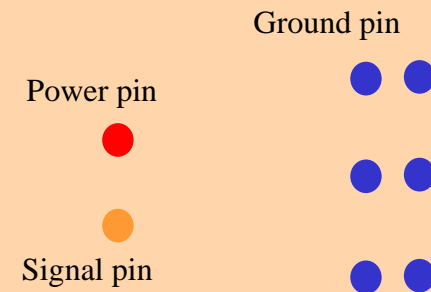2. I want to see ground bounce across Lpkg_gnd

Things to think about:

1. If Lpkg_gnd is loop inductance, then what is Lpkg_pwr?

2. If Lpkg_gnd is partial inductance, then where is the mutual inductance?

Ground Inductance (Case 3)

Design 1

Ground pin

Power pin

Signal pin

Design 2

Ground pin

Power pin

Signal pin
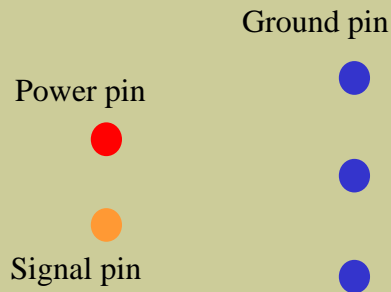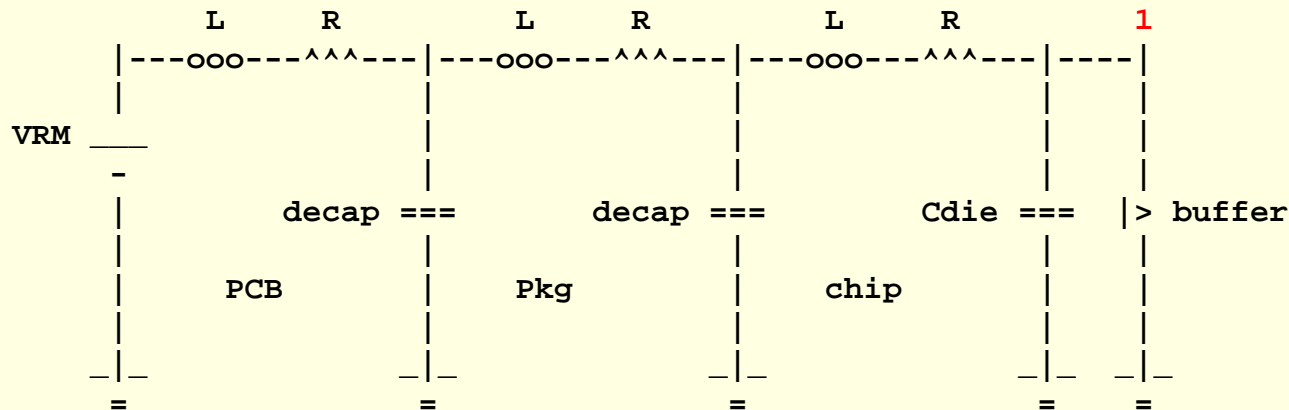
- Many engineers want to use ground inductance to measure the performance of the ground system design. Is it meaningful?

- Design 1 has three ground pins whereas Design 2 doubles the number of ground pins.

- Even though Design 2 seems to have much less "ground inductance," the overall power delivery system and signal delivery system are not improved. Because the distance between the nearest power and ground pins is not improved, the overall power and ground loop is not minimized.

- A better design would simply move the power and ground pins closer together, to minimize the overall inductance of the loop.

The Correct Power and Ground Circuit Representation

```
            L      R          L      R          L      R          1
        |---ooo---^^^---|---ooo---^^^---|---ooo---^^^---|----|
        |               |               |               |    |
  VRM ___               |               |               |    |
     -                  |               |               |    |
        |       decap ===       decap ===        Cdie ===  |> buffer
        |               |               |               |    |
        |    PCB        |    Pkg        |    chip       |    |
        |               |               |               |    |
       _|_             _|_             _|_             _|_  _|_
        =               =               =               =    =
```

Note: The circuit model above uses loop inductance to represent the power and ground parasitics. When I/O signals are added to this model, the actual current loops and/or return paths may be difficult to determine. In that case, using the partial inductance representation may have advantages – just make sure to include all partial self and mutual inductances.

Although this circuit model is conceptually correct, a realistic PDS response is more complex and very frequency dependent. If one wants to include the I/O signals for SSO simulations, a broadband model (an S-parameter matrix for example) is required to accurately represent the broadband response of the PDS and signal nets, as well as the interactions among them.

Frequency Dependant Broadband Representation
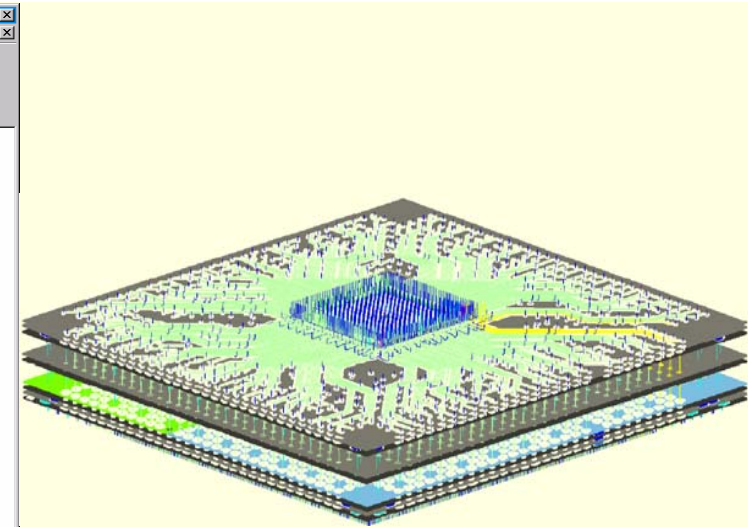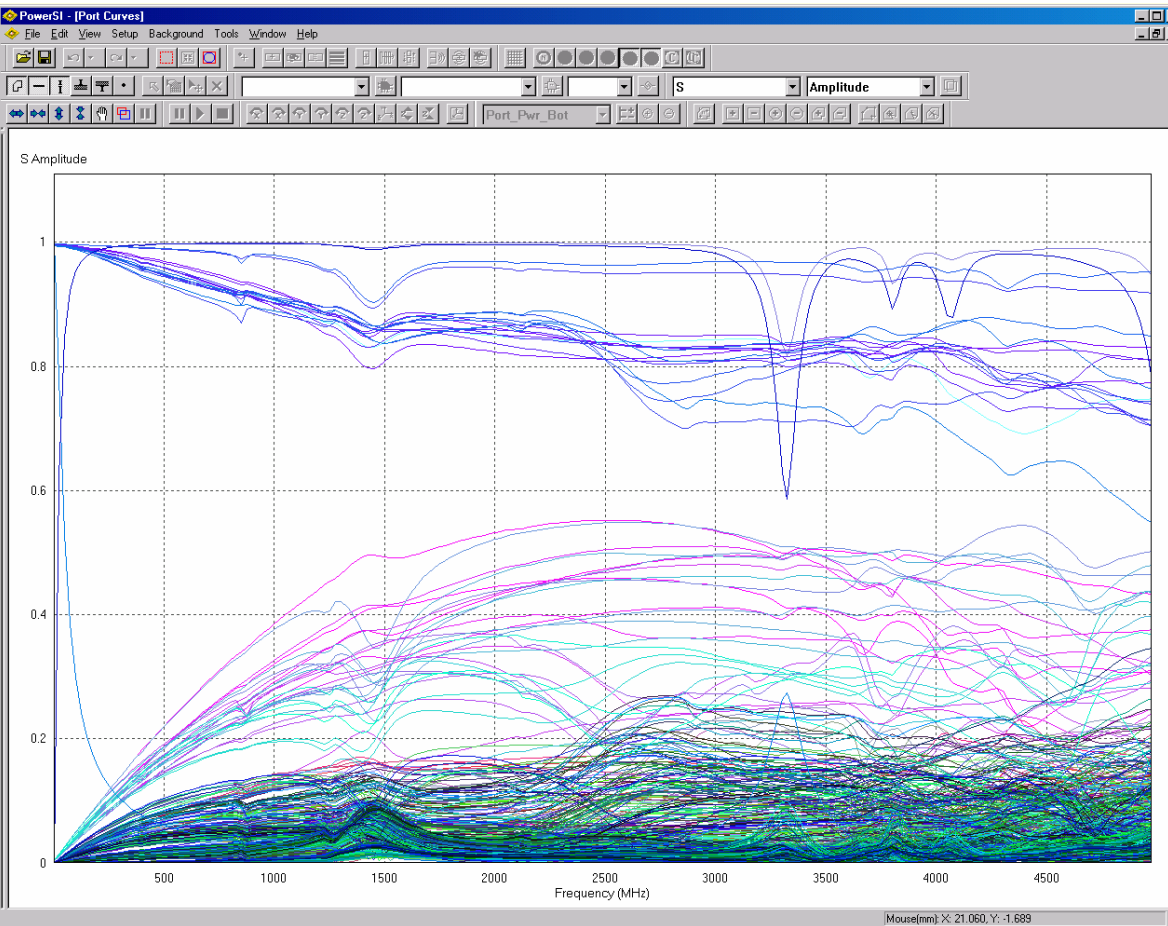
Mixed PDS and I/O S-parameters, 34 ports, 100Hz - 5GHz.

Power-Ground-Signal System Model

A Broadband Circuit Representation

Power Delivery Modeling Basics

Using S-parameters

- An S-parameter "black box" model allows complex physical structures to be simulated. Proper understanding of a few basic concepts such as "Port" and "Reference" is key to successful analysis.

- This document focuses on how an S-parameter model captures the behavior of non-ideal power and ground structures for SSO simulation, how S-parameters are extracted, and how to use S-parameter models in SPICE circuit-level simulations.

# Port Connections and the Reference Node
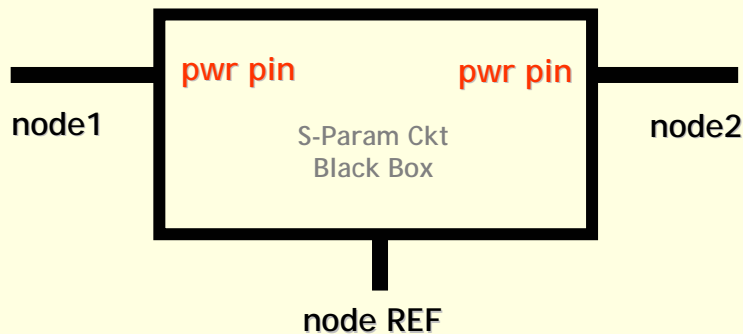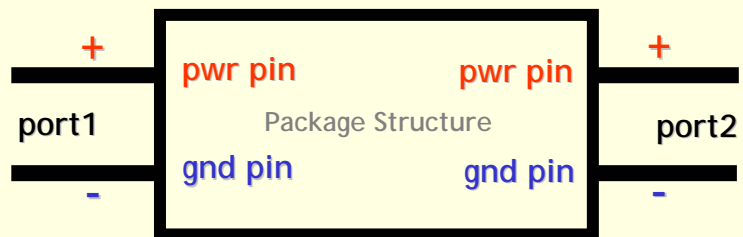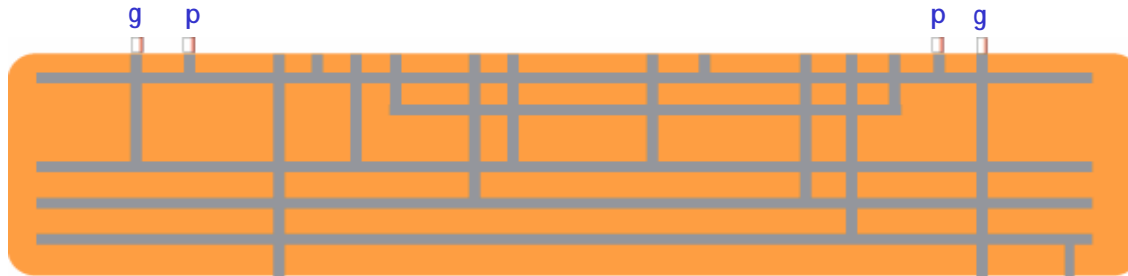
Correct and recommended
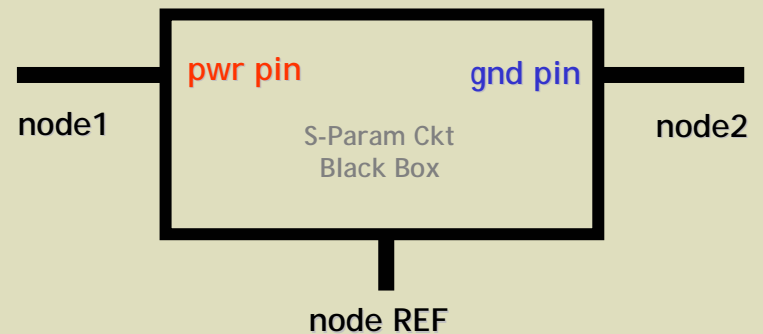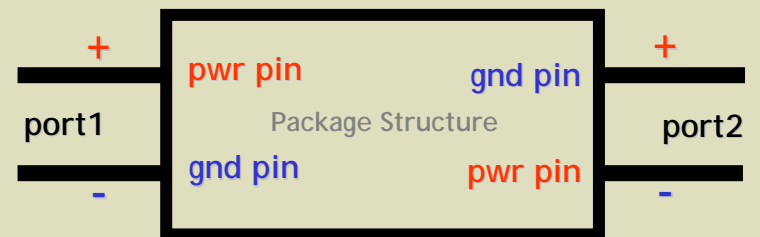
Correct but not recommended

Question on the Single Reference Node in the Circuit Model

- The physical structure has N ports. Each port has one "+" terminal and one "-" local reference terminal, resulting in a total of 2N physical terminals.

- The broadband circuit model has N+1 nodes. The N nodes correspond to the N physical "+" terminals, whereas the +1 node is a virtual reference node "REF".

- The "REF" node is not a physical ground node, nor a power node. Rather, the circuit is created such that the response or behavior at each node with respect to the REF node, models the response or behavior of each of the original "+" port-nodes with respect to their individual "-" port-nodes.

Circuit Connection Guidelines for S-parameter Models in SPICE

- When using the REF node with a specific "+" terminal, think of the REF node as that port's corresponding "-" terminal.

- If you don't already have node 0 in your circuit, you should connect REF to node 0 since SPICE requires as least one node 0. This also makes voltage measurement easy.

- If you already have node 0 somewhere in the driver or receiver circuits, then do not make the additional connection of REF to node 0. Measure voltage as V(n)-V(ref).

22
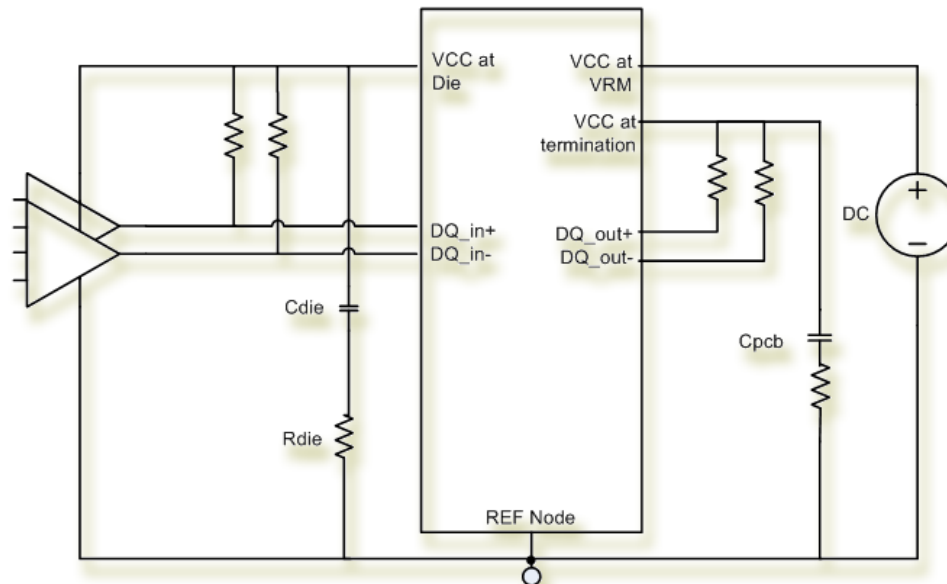
Additional Reading

Measure Voltage Across Distance

From : si-list on behalf of Ray Anderson [reanderson@sbcglobal.net]
Sent: Monday, July 19, 2004 8:55 AM
To: si-list@freelists.org
Subject: [SI-LIST] Re: How to measure voltage drop on plane

The measurement of power/ground noise is a differential measurement
(even if you use a single-ended probe) of the power voltage (Vdd) with
respect to the associated ground voltage (Gnd).

When making these sort of measurements you need to measure Vdd with
respect Gnd at the same XY spatial location for the measurement to make
sense. (i.e. vertically coincident). If you measure Vdd with respect to
Gnd where the Gnd node is physically offset some significant distance
(wrt lambda) then the measurement just doesn't make sense.

If the Gnd measurement point is offset from the Vdd measurement point by
only a small fraction of an inch instead exactly coincident with the
measured Vdd location that is probably an acceptably small error,
however if the offset is on the order of inches or more then the
measured voltage doesn't make sense. Why? Because you are measuring
voltages 'across time' where the time is the time-of-flight from the Gnd
node coincident with the Vdd node (which you should be using as a
reference) to the Gnd node which is distant (which you should NOT be
using as a reference). Measurements of voltage across time are
undefined, at least with respect to the measurement of power/ground
noise which you propose.

-Ray Anderson

Voltage Definition in Maxwell Equation

$$V = \oint_C E \cdot dl = -\frac{d\Phi}{dt} \qquad \text{(volts)} \qquad \textbf{Faraday's Law}$$

1. Voltage, between two points, is the integral of the E-field and dependent on the path of the integration loop.

2. This is why in lab measurement, the probe tips are very small (and have a small separation) to make sure you are measuring the loop (flux) of the DUT, and not the loop formed by the probe leads.

3. You don't measure voltage across a large distance.

4. And you don't measure voltage on a wire or a plane (the conductor itself) since the loop (flux) can't be defined.

Note

This IBIS summit short presentation is created from a simplified Sigrity application note. If you are interested in more details, please contact Sigrity.