Some Results for General K-table Extraction Proposal Using SPICE

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Updated Material

- More derivation detail: January 30, 2015, “General K-Table Extraction Proposal Using SPICE”
  - Contains Summit references
- Some results and other observations here
- Purpose – Use SPICE for PROTOTYPING IBIS extraction algorithms (with general C_comp, on-die, package structures and fixture loads)
Overview

- Fixed C_comp to local GND for extraction
- Detailed C_comp model from S-parameters or IBIS-ISS allowed
- IBIS Interconnect BIRD proposal adds on-die and package models
- SPICE-based extraction proposal supports total path measurement with more detailed C_comp/on-die/package structures
- Limitations exist
Standard IBIS Model

Drivers

[Pullup]

[Rise & Fall Transitions]

[Pullup Reference]

[Pulldown]

[Rise & Fall Transitions]

[Pulldown Reference]

[Power Clamp Reference]

[Power Clamp and C_comp]

[Fixed Clamps and Reference]

[Rise & Fall Transitions]

[Pin]

[Package]

Die

L_pin

R_pin

C_pin

C_comp

GND

GND
Calculate \( V(t) \) and \( I(t) \) from load information
Direct V(t), I(t) Solution

• Xuefeng Chen, Asian IBIS Summit (China), September 11, 2007: V(t), I(t) extracted directly for L/R/C/V_fixture by applying $i = C \frac{dv(t)}{dt}$ and $v = L \frac{di(t)}{dt}$

• Extension can include L/R/C_dut (where L/R/C_dut replaces the L/R/C_pin values for the measured pin)

• Ku(t) and Kd(t) tables extracted using the 2-equations/2-unknowns (2EQ/2UK) method (later)
Indirect Feedback Solution Next

- Avoids encoding equations for complex structures
- Calculates $K$-tables with high-gain (e.g., $1E7$) feedback loop multiplier
  - $K_{ur}(t), K_{dr}(t)$ from two rising $V$-$T$ waveforms and fixtures
  - $K_{uf}(t), K_{df}(t)$ from two falling $V$-$T$ waveforms and fixtures
- Calculated and specified responses converge
- Requires vendor-specific SPICEs (versus IBIS-ISS)
  - Tables
  - Feedback loop issues with tables
Partial SPICE Circuit Showing 2EQ/2UK K-Table Extraction

* FEEDBACK TABLE ADJUSTMENT

GDET NDET GND CUR='(I(VDN2)*I(VUP1)-I(VDN1)*I(VUP2))/(1E7)'

GKUR NKU GND + CUR='((V(IN2)-V(PIN2))*I(VDN1)-(V(IN1)-V(PIN1))*I(VDN2))/I(VDET)'

GKDR NKD GND + CUR='((V(IN1)-V(PIN1))*I(VUP2)-(V(IN2)-V(PIN2))*I(VUP1))/I(VDET)'

\[ I_1(t) = K_u(t)*I_u(V_1(t)) + K_d(t)*I_d(V_1(t)) \]
\[ I_2(t) = K_u(t)*I_u(V_2(t)) + K_d(t)*I_d(V_2(t)) \]
SPICE Encoding

- I-V tables: G elements (VCCS)
- V-T tables: PWL voltage sources
- Voltage rails: Entered
- SPICE interpolation
  - Allows higher resolution time steps in V-T tables
  - Interpolates G table currents
- I-V and V-T tables extended from final values
- Convergence criteria adjustable
- K-tables printed for Kur(t), Kdr(t); Kuf(t), Kdf(t)
- Simulation done with K-table drivers:
  - G elements for K-tables
  - Scaled controlled ramp (1V/nS)
  - Step stimuli (0 to 1, 1 to 0)
Part of SPICE Encoded IBIS Prototype for Simulation

* HIGH SIDE
XUP OUT1 VCC NU1 PULLUP
VUP NU1 VCC 0
GUP OUT1 VCC CUR='-(I(VUP)*((I(VKUR)*I(VON))+(I(VKUF))*(1-I(VON))))'
XPC OUT1 VCC POWER_CLAMP

* LOW SIDE
XDN OUT1 GRD ND1 PULLDOWN
VDN ND1 GRD 0
GDN OUT1 GRD CUR='-(I(VDN)*((I(VKDR)*I(VON))+(I(VKDF))*(1-I(VON))))'
XGC OUT1 GNDC GND_CLAMP

* C_COMP AND DUT PACKAGE
XCAP OUT1 GRD C_COMP
XPKG OUT1 GRD PIN1 PACKAGE

* LOAD
TLOAD PIN1 GRD PIN9 GRD Z0=50 TD=1N
RLOAD PIN9 GND 50G

* VOLTAGE CONTROL (AMPLITUDE (0 TO 1), PULSE WIDTH & PERIOD)
VPULSE STEP GRD 0 PULSE (1 0 0P 1P 1P 5N 10N)

Kur, Kdr
Kuf, Kdf

Table switching control

Enter simulation load

Ideal Step Stimulus
General Proposed Single-ended C_comp Subckt Model

- (Notation and details under development)
- C_comp_I: If needed for series path
  - Resistance needs to be de-embedded from I-V tables
- A_signal: Output
- Extend model for differential connections
SPICE Extraction of V(t), I(t) Setup and C_comp A_signal Node

V(t), I(t)

Vsense = 0V

V(t), I(t) node and I(t) are calculated using an ideal high gain (e.g., K=1e7) amplifier

V-T table (originally extracted at the Fixture) is now a PWL driver

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2EQ/2UK SPICE Setup to Generate Ku(t), Kd(t) Tables

2EQ/2UK Module

V(t), I(t)

V sense = 0V

PC

C_comp Subckt

On-die Subckt

Package Subckt

L/R/C/V Fixture

Load 1

K

V-T

Load 2

V(t), I(t)

V sense = 0V

PC

C_comp Subckt

On-die Subckt

Package Subckt

L/R/C/V Fixture

K

V-T
Ideal Ramp Test Cases

- **Reference Waveforms**
  - 1 ns ramp (0% to 100%) into 50 Ω-to-gnd and 50 Ω-to-vcc loads
  - 5 V supply
  - 2 ns duration

- **C_comp cases**
  - 0 pF (0p)
  - 4 pF (4p)
  - 4 pF || (4 pF – 50 Ω) (4p_4p-50)

- **Pullup/Pulldown I-V tables**
  - 50 Ω straight lines

- **1001 point extractions (not critical)**
K-tables Shapes Versus Time (s)

No L_fix, C_fix

C_comp:
- 0 pF
- 4 pF
- 4 pF || (4 pF - 50 Ω)

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K-tables Versus Time (s) – With $L_{\text{fix}}=10$ nH, $C_{\text{fix}}=4$ pF Fixtures

New shapes with ideal ramp and reactive fixtures

- $C_{\text{comp}}$:
  - 0 pF (without $C/L_{\text{fix}}$)
  - 0 pF
  - 4 pF
  - 4 pF || (4 pF - 50 Ω)
4 ns Cycle Simulations for 4p_4p-50 C_comp Model

K-tables for C_comp model reproduces ideal ramps (50 Ω to gnd, 50 Ω to vcc)
No C_comp, no clamps, just a Package model which could be a C_comp model or an on-die model

PU, PD Vout(t) node and Isense(t) are calculated using an ideal high gain (e.g., K=1e7) amplifier

V_T table (originally extracted at the Fixture) is now a PWL driver
Lpkg = 0 nH, Cpkg = 0.004 nF

Closed-form references (50 Ω to GND)

Continuous V(t) and dV(t)/dt
Extractions using Laplace Element

Same as closed-form references

K-tables
Lpkg = 2 nH, Cpkg = 0.004 nF

VOUT discontinuities: Feedback loop fails

Closed-form references (50 Ω to GND)
Observations and Conclusions

• Result accuracy
  o K-table extraction insensitive to K=1e5 to K=1e9 feedback multipliers
  o Requires SPICE maximum accuracy settings
  o Not sensitive to number of extraction points

• Severe test cases
  o Sharp waveform derivative discontinuity in ideal ramp
  o Large C_comp model load can be used
  o Large L_fixture, C_fixture reactive loads are ok
  o BOTH L_pkg, and C_pkg do not converge (even with smooth waveforms) – therefore topology limited and must use tool-dependent methods
  o Fails for T-line models (delay in feedback loop)
  o Works for S-parameter, Laplace transform, lumped models