High Accuracy Behavioral Modeling for Frequency and Time Domain Simulations

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Part I

Introduction
Why frequency domain analysis?

Some times it is easy to tell that there is a signal quality problem by looking at the waveforms (in time domain), but often it is very easy to miss problems or it may take too long to find them.

We need a methodology that can reliably and quickly tell us whether there is a problem and what it is.

• The waveforms of time domain simulations may change when we run the simulation at different frequencies even if we don’t change anything in the circuit (due to reflections and resonance)
  ➢ this frequency dependency can be studied much easier with frequency domain analysis to uncover problems
  ➢ FD simulations run much faster than TD simulations, so more work can be done in less time

Once we are done optimizing for signal quality in the frequency domain we still need to run simulations in the time domain to find best/worst timings for the design.
The bottom line is time

The timing of our designs is determined by the shape of the waveforms.

The shape of the waveforms, however, are very strongly effected by the resonance effects.

Eliminating resonance results in more precise, stable and predictable timings. So our goal is to find and remove resonances.

In order to be able to do that we need buffer models which are accurate at all frequencies.
What makes these waveforms so unpredictable?
Waveforms without resonance are predictable

- 100 MHz
- 375 MHz
- 500 MHz
- 750 MHz
The circuit of the previous two sets of waveforms

R L C

1 Volt pulse source}

output voltage

underdamped R = 5 Ω or critically damped R = 63.25 Ω

f_{clock} = 100, 375, 500, 750 MHz

Resonant \( \omega_0 = 503.3 \) MHz NOT resonant

\[
\begin{align*}
   s_{1,2} &= -\frac{R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}} \\
   s_{1,2} &= -\alpha \pm \sqrt{\alpha^2 - \omega_0^2} \\
   R &= 2\sqrt{\frac{L}{C}} = 2\sqrt{\frac{10 \text{ nH}}{10 \text{ pF}}} = 2\sqrt{1000} = 63.25 \Omega
\end{align*}
\]

L = 10 nH
C = 10 pF

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Part II

Frequency response of an IBIS model
Looking into an IBIS buffer - $Z_{11}$

$Z_{11} = \frac{V_1}{I_1}$

Where $Z_{11}$ is a complex quantity (Real + Imaginary)

1 mV AC voltage Source ($V_s$) with a DC offset

Measure current magnitude and phase

Must be kept small due to non linear IV curves

PWL Current source (IV curve)

C_comp (1.25 pF)

IBIS buffer
Frequency response at 0.1 V DC bias

- IV curve with 0 pF
- IBIS model
- SPICE model (FET)
Frequency response at 2.0 V DC bias

**Graph:**
- **IV curve with 0 pF**
- **IBIS model**
- **SPICE model (FET)**

**Notes:**
- Frequency response
- Bias condition
- Model comparison

*Other brands and names are the property of their respective owners*
Facts and problem statement

- **Voltage dependent impedance ($Z_{11}$ vs. bias)**
  - this is the steady state DC behavior
  - IBIS uses IV curves to describe this
  - good match (at very low frequencies)

- **Frequency dependent impedance**
  - we use $C_{comp}$ to describe (part of) it
  - $C_{comp}$ matches a single parallel RC circuit well
  - series-parallel RC combinations not accurate
  - cannot model voltage (bias) dependency

- **Time dependent impedance**
  - this is the transient (switching) behavior
  - IBIS uses $V_t$ curves to describe this
  - need to find a method to analyze AC response during transients
Part III

New modeling proposal
Some theory

Complex number = Real part + Imaginary part

\[ Z = R + jX = R \parallel \frac{1}{j\omega C} \]

\[ Y = G + jB = G + j\omega C \]

(for a parallel RC circuit)

To express this as a function of voltage, we can write

\[ Z(V) = R(V) \parallel \frac{1}{j\omega C(V)} \]

\[ Y(V) = G(V) + j\omega C(V) \]
Transfer functions and the Laplace element

The $Y_{11}$ transfer function of a resistor:

$$H(s) = \frac{1}{R}$$

The $Y_{11}$ transfer function of a capacitor:

$$H(s) = sC$$

The $Y_{11}$ transfer function of a parallel RC circuit:

$$H(s) = \frac{1}{R} + sC = \frac{1+sCR}{R}$$

In HSPICE this can be modeled with a Laplace element the following way:

```
G1 node1 node2 Laplace node1 node2 1 'R*C' / 'R'
```
An undocumented(?) HSPICE feature

The same transfer function can also be expressed with parameters who’s value depends on another variable. The $Y_{11}$ transfer function of the parallel RC circuit as a function of voltage is:

$$H(s,V) = \frac{1}{R(V)} + sC(V) = \frac{1 + sC(V)R(V)}{R(V)}$$

(This works in HSPICE up to a few dependent terms).
Proving that it works

Laplace element coefficients as a function of voltage
*****************************************************
.TRAN 1.0e-12 15.0e-9
.OPTIONS ACCT POST=1
*****************************************************
.param Rval = 200
.param Cval = 10.0pF
*****************************************************
.IC V(RC1) = 1
R1  RC1  0  R=Rval
C1  RC1  0  C=Cval
*
.IC V(RC2) = 1
Rd2  RC2  0  R=1e+6
G2  RC2  0  LAPLACE RC2 0
+ 1 'Rval*Cval' / Rval
*
.IC V(RC3) = 1
R3  RC3  0  R='Rval*(1/V(RC3))'
C3  RC3  0  C=Cval
*
.IC V(RC4) = 1
Rd4  RC4  0  R=1e+6
G4  RC4  0  LAPLACE RC4 0
+ 1 'Rval*(1/V(RC4))*Cval' / 'Rval*(1/V(RC4))'
*****************************************************
.END
*****************************************************
Revisiting complex algebra

\[ Z_{\text{measured}} - Z_{\text{DC}} = Z_{\text{AC}} \]

Since \( Z_{\text{DC}} \) (IV curve) is a real number, it does not have an imaginary part, and
\[ \text{Im}(Z_{\text{AC}}) = \text{Im}(Z_{\text{measured}}). \]

Also, because \( Z_{\text{DC}} \) is a frequency independent number (i.e. constant),
\[ \text{Re}(Z_{\text{AC}}) = \text{Re}(Z_{\text{measured}}) - k \]
(which is a simple shift)
Medium complexity example with Mathcad

Two parallel RCs in series

\[ R_1 := 10 \quad C_1 := 1.0 \cdot 10^{-12} \]
\[ R_2 := 90 \quad C_2 := 9.0 \cdot 10^{-12} \]

\[ f := 0, 1 \cdot 10^6 \ldots 2 \cdot 10^9 \]
\[ \omega (f) := 2 \pi \cdot f \]
\[ s(f) := 0 + i \cdot \omega (f) \]

\[ H(f) := \frac{1}{ \frac{1}{R_1} + \frac{1}{R_2} + \frac{s(f) \cdot C_1}{1 + s(f) \cdot C_1} + \frac{s(f) \cdot C_2}{1 + s(f) \cdot C_2} } \]

or

\[ H(f) := \frac{1 + s(f) \cdot (C_1 \cdot R_1 + C_2 \cdot R_2) + s(f)^2 \cdot C_1 \cdot R_1 \cdot C_2 \cdot R_2}{R_1 \cdot R_2 + s(f) \cdot (R_1 \cdot C_2 \cdot R_2 + C_1 \cdot R_1 \cdot R_2)} \]

if

\[ H_{dc}(f) := \frac{1}{R_1 + R_2} \]

then

\[ H_{ac}(f) := H(f) - H_{dc}(f) \]

\[ H_{ac}(f) := \frac{\left( C_1 \cdot R_1^2 \cdot C_2 \cdot R_2 + C_1 \cdot R_1 \cdot C_2 \cdot R_2^2 \right) \cdot s(f)^2 + \left( C_1 \cdot R_1^2 + C_2 \cdot R_2^2 \right) \cdot s(f)}{\left( R_1^2 \cdot C_2 \cdot R_2 + R_1 \cdot C_2 \cdot R_2^2 + C_1 \cdot R_1^2 \cdot R_2 + C_1 \cdot R_1 \cdot R_2^2 \right) \cdot s(f) + R_1^2 + 2 \cdot R_1 \cdot R_2 + R_2^2} \]

\[ n_0 := 0 \]
\[ n_1 := C_1 \cdot R_1^2 + C_2 \cdot R_2^2 \]
\[ n_2 := C_1 \cdot R_1^2 \cdot C_2 \cdot R_2 + C_1 \cdot R_1 \cdot C_2 \cdot R_2^2 \]
\[ d_0 := R_1^2 + 2 \cdot R_1 \cdot R_2 + R_2^2 \]
\[ d_1 := R_1^2 \cdot C_2 \cdot R_2 + R_1 \cdot C_2 \cdot R_2^2 + C_1 \cdot R_1^2 \cdot R_2 + C_1 \cdot R_1 \cdot R_2^2 \]
\[ d_2 := 0 \]

n0 = 0
n1 = 7.3 \cdot 10^{-8}
n2 = 8.1 \cdot 10^{-19}
d0 = 1 \cdot 10^4
d1 = 9 \cdot 10^{-7}
d2 = 0
Real and Imaginary part plots from Mathcad

Total response
DC response
AC response
HSPICE netlist segment for Mathcad example

**********************************************************************
.param Bias= 0.0
.param C1 = 1.0pF
.param C2 = 9.0pF
.param R1 = 10
.param R2 = 90
*
.param n0 = 0
.param n1 = 'C1*pow(R1,2)+C2*pow(R2,2)'
.param n2 = 'C1*pow(R1,2)*C2*R2+C1*R1*C2*pow(R2,2)'
.param d0 = 'pow(R1,2)+2*R1*R2+pow(R2,2)'
.param d1 = 'pow(R1,2)*C2*R2+R1*C2*pow(R2,2)+C1*pow(R1,2)*R2+C1*R1*pow(R2,2)'
.param d2 = 1e-21
 $ 1e-21 to keep HSPICE happy
**********************************************************************

Vac1  RC1  0 AC= 1 DC= Bias
*
R1a   RC1  RC1a R= R1
C1a   RC1  RC1a C= C1
R1b   RC1a 0 R= R2
C1b   RC1a 0 C= C2

**********************************************************************
Vac2  RC2  0 AC= 1 DC= Bias
G2a   RC2  0 CUR=’V(RC2)/100’ $ Parallel R
*
**********************************************************************
G2b   RC2  0 LAPLACE RC2 0 $ Two || RCs in series minus DC + n0 n1 n2 / d0 d1 d2

**********************************************************************
.END
**********************************************************************
Frequency domain response with HSPICE

Behavioral matches real model perfectly
Behavioral matches real model perfectly
HSPICE netlist segment of real buffer model

**********************************************************************
Vac2  RC2  0  AC=Vac  DC= Bias
X2a   RC2  0  FET_IV

G2b   0  RC2  LAPLACE  RC2  0

+ '-4.6156E-02 \ 
   +2.1192E-02*V(RC2) \ 
   +9.2658E-04*pow(V(RC2),2) \ 
   -1.1509E-03*pow(V(RC2),3) \ 
   +2.1795E-06*pow(V(RC2),4) \ 
   +1.8981E-05*pow(V(RC2),5) '

+ '-8.6576E-12 \ 
   -2.4567E-11*V(RC2) \ 
   +2.7304E-11*pow(V(RC2),2) \ 
   -1.0631E-11*pow(V(RC2),3) \ 
   +1.8243E-12*pow(V(RC2),4) \ 
   -1.1699E-13*pow(V(RC2),5) '

+ '-1.9814E-22 \ 
   -8.1507E-22*V(RC2) \ 
   +6.4066E-22*pow(V(RC2),2) \ 
   -2.6783E-22*pow(V(RC2),3) \ 
   +5.5096E-23*pow(V(RC2),4) \ 
   -4.3215E-24*pow(V(RC2),5) '/

+ 1

+ '+1.5954E-10 \ 
   +6.5574E-10*V(RC2) \ 
   -4.8825E-10*pow(V(RC2),2) \ 
   +1.8850E-10*pow(V(RC2),3) \ 
   -3.6452E-11*pow(V(RC2),4) \ 
   +2.6923E-12*pow(V(RC2),5) '

+ '+7.8650E-23 \ 
   +3.2570E-22*V(RC2) \ 
   -2.5402E-22*pow(V(RC2),2) \ 
   +1.0774E-22*pow(V(RC2),3) \ 
   -2.2593E-23*pow(V(RC2),4) \ 
   +1.8119E-24*pow(V(RC2),5) '

**********************************************************************
Frequency response of a real buffer with HSPICE
dV/dI and dR/dV

In .AC analysis SPICE uses the slope of the IV curves for transistors, diodes and PWL sources. However, an IV curve implemented as a voltage controlled resistor (VCR) will produce delta R in a .AC sweep.

For this reason we need to use PWL sources to implement IV curves (in SPICE) for behavioral models.

$$R_1 = \frac{V_1}{I_1}$$
$$R_2 = \frac{V_2}{I_2}$$

but

$$\frac{V_2 - V_1}{I_2 - I_1} \neq R_2 - R_1$$

or

$$\frac{dV}{dl} \neq \frac{dR}{dV}$$
AC sweep of FET, I-V and R-V models

The real part of the RV model at DC is incorrect!

The real part of the IV model at DC is correct.

The AC component at higher bias voltages is incorrect as explained before.
Issues / work in progress

- TRAN mode simulations of real buffer is still in progress
- Numerical issues make it difficult to achieve a working model
  - the accuracy of these experiments was limited by the order of curve fitting function (due to the available space in the HSPICE Laplace element)
  - not may tools can curve fit to a complex number data table
    - HSPICE optimization doesn’t converge well
- second curve fitting for voltage dependency
  - could be more accurate if done in a single process as a multi dimensional problem
- H(s) and table format for Laplace element did not converge in .TRAN yet for a real buffer behavioral model
  - could be due to numerical stability issues (denominator must be higher order than numerator), or the range of exponents is too wide for HSPICE
  - rearranging transfer function to have higher order denominator may get this to work
- could try pole-zero format
- these problems may not be an issue if a tool was designed to do this
- Transient behavior of AC components need to be studied more
  - extending the concept to multi dimensional transfer functions (time variant, voltage dependent) could account for transients
  - could possibly use the V-t curves or similar information to control transient behavior of the AC components of the model, but more research is needed to understand this
Conclusions

• We need to consider only one additional element for the IBIS-X specification to achieve a highly accurate FD/TD behavioral model
  • this element would replace the existing C_comp parameter
  • this element needs to interpret some sort of a transfer function
  • various formats could be supported, table driven, transfer function (equation) driven, or pole-zero driven
  • various types of data could be supported, Z, Y, S-parameters, and/or voltage and current (each of which is complex)

• Complex number capability is needed to make this work
• The concept shown here using a one-port circuit can be extended to a special multi terminal port representing all nodes of the buffer
  • need at least two terminals for the power and ground rails
  • need one or two terminals for single ended or differential buffers
  • the complex impedance as a function of output and supply voltage, time, temperature, process, etc. between each of these terminals can be described according to the concept shown here