Versatile surrogate models for IC buffers

C. Diouf¹, M. Telescu¹, I. S. Stievano², F. C. Canavero², P. Cloastre¹, N. Tanguy¹

¹Université Européenne de Bretagne, Université de Brest ; CNRS, UMR 6285, Lab-STICC, France

²Dipartimento di Elettronica e Telecomunicazioni (DET), Politecnico di Torino, Italy

16/05/2012 - Sorrento
Outline

- Introduction
- New approach: theoretical framework
- Identification
- Recent developments
- Examples
- Conclusion
Introduction

- Assessing
  - EMC compatibility
  - Signal Integrity
- Reducing
  - Design Cost
  - Simulation time
  - Time to market
Introduction

- Nonlinear behavior of IC buffers
  - Fading memory
  - Highly nonlinear
    - Switching feature
    - Saturation
- Behavioral modeling techniques
  - IBIS
  - Mπlog
  - Neural networks, etc…
Introduction

- 2-piece model (Mπlog)
  - Black box modeling of buffers
  - Output buffer port modeled in respect to input state (ON or OFF)
  - Transitions between states modeled through weighting functions
  - Output port relations, two submodels scheme
Introduction

- $I_2 = f(v_2[k])$
- Transitions between states modeled through weighting functions
- Dynamic effect of $v_1$ not in the submodels
Introduction

- **SPI 2010** each submodel represented by SISO Volterra Series
- **SPI 2011** mathematical constraints on Volterra series, exact static behavior
New approach: theoretical framework
New approach: theoretical framework
New approach: theoretical framework

- I/O behavioral modeling method is:
  - **Versatile**
    - wide range of loads
    - working for a wide range of frequencies
  - **Surrogate**
    - Mathematical models
    - Based on very high order Volterra-Laguerre Series
New approach: theoretical framework

- I/O Relations, “admittance”, \( i_2[k] = f(v_2, v_1, [k]) \), “impedance” \( v_2[k] = f(i_2, v_1, [k]) \) =>

- Behavioral models: high order Volterra-Laguerre series

\[
Z \left\{ \phi_{n_l,i_l} [k] \right\}(z) = \sqrt{1 - a_{n_l}^2} \frac{z}{z - a_{n_l}} \left( \frac{1 - a_{n_l} z}{z - a_{n_l}} \right)^{i_l}
\]

\[
\bar{v}_{n_l,i_l} [k] = (v_{n_l} \ast \phi_{n_l,i_l}) [k], \quad n_l = 1,2
\]
New approach: theoretical framework

\[ i_2[k] = \sum_{i_1=0}^{I_1-1} C_{1,1,i_1} \bar{v}_{1,i_1}[k] + \sum_{i_1=0}^{I_1-1} C_{1,2,i_1} \bar{v}_{2,i_1}[k] \]

\[ + \sum_{i_1=0}^{I_2-1I_2-1} C_{2,1,1,i_1,i_2} \bar{v}_{1,i_1}[k] \bar{v}_{1,i_1}[k] + \sum_{i_1=0}^{I_2-1I_2-1} C_{2,1,2,i_1,i_2} \bar{v}_{1,i_1}[k] \bar{v}_{2,i_1}[k] \]

\[ + \sum_{i_1=0}^{I_2-1I_2-1} C_{2,2,1,i_1,i_2} \bar{v}_{2,i_1}[k] \bar{v}_{1,i_1}[k] + \sum_{i_1=0}^{I_2-1I_2-1} C_{2,2,2,i_1,i_2} \bar{v}_{2,i_1}[k] \bar{v}_{2,i_1}[k] \]

+ ...
Identification

- Apply a well-chosen identification sequence to the driver.
- Extract voltages \( (v_1, v_2) \) and output current \( (i_2) \)
- By least squares find \( C_m \) coefficients that satisfied best the Volterra-Laguerre relation

\[
i_2[k] = \sum_{m=1}^{M} \sum_{n_1=1}^{2} \cdots \sum_{n_m=1}^{2} \sum_{i_1=0}^{I_{m-1}} \cdots \sum_{i_m=0}^{I_{m-1}} C_{m,n_1,...,n_m,i_1,...,i_m} \prod_{l=1}^{m} \bar{v}_{n_l,i_l}[k]
\]
Identification
Variable identification load

- Allowing a good static exploration
- Dynamic exploration of \((i_2, v_2)\) trajectories resulting from interconnects reactive elements
Identification

\[
\begin{bmatrix}
\bar{\varphi}_{1,1,0}[k_0] & \bar{\varphi}_{1,1,1}[k_0] & \ldots & \bar{\varphi}_{m\ldots}[k_0] \\
\bar{\varphi}_{1,1,0}[k_1] & \bar{\varphi}_{1,1,1}[k_1] & \ldots & \bar{\varphi}_{m\ldots}[k_1] \\
\vdots & \vdots & \ddots & \vdots \\
\bar{\varphi}_{1,1,0}[k_I] & \bar{\varphi}_{1,1,1}[k_I] & \ldots & \bar{\varphi}_{m\ldots}[k_I] \\
\end{bmatrix}
\begin{bmatrix}
c_{1,1,0} \\
c_{1,1,1} \\
\vdots \\
c_{m\ldots} \\
\end{bmatrix}
= 
\begin{bmatrix}
i_2[k_0] \\
i_2[k_1] \\
\vdots \\
i_2[k_I] \\
\end{bmatrix}
\]
Recent developments

- Piece-wise approach, reduce computational cost, increase precision
- MISO submodels sharing the same internal state
- Submodel working area defined by $v_1, v_2, i_2$...
Recent developments

\[ i_2[k] = \sum_{i=1}^{I} W_i(v_1) i_{2,i}[k] \]
Example

- Test vehicle: tunable synthetic system mimicking single ended non-inverting driver

- $f(v_1, v)$ nonlinear current source

- Dynamic by reactive components
Example

- Input/Output static characteristic, different loads
**Example**

- System is identified through the described procedure
- Volterra Laguerre model is build up
  - 14th order
  - Total of 190 coefficients
- Implementation in spice simulator
  - Continuous representation
  - Ensuring compatibility, basic elements
    - Passive components, voltage controlled current sources
Example

- Validation
  - Input validation signal
  - On two load configurations

![Diagram of two load configurations with validation signals and parameters: Z₀=50 ohms, T₅=8e-12 s for one and Z₀=250 ohms, T₅=9e-11 s for the other.]
Example

- Input validation signal
Example

- First load, ~2sec,
Example

- Second load, non classic, ~2 sec
Example

- Cascaded drivers
Example

- System is identified through the described procedure
- Volterra Laguerre model is build up
  - 3 submodels
  - 5th order submodel
  - Total of 325 coefficients for each submodel
Example

- First Load, ~6 sec,
Example

- Second load, ~6 sec
Conclusion

- A new approach to IC buffer modeling seeking more general, versatile models
  - Based on MISO Volterra-Laguerre Series
  - Can easily take account of another input ex. \( V_{dd} \) supply voltage
- Optimization of spice structure, faster simulation
- Ongoing research on more complex, recent buffers
- Tuning the method on the needs of the industry