Versatile surrogate models for IC buffers

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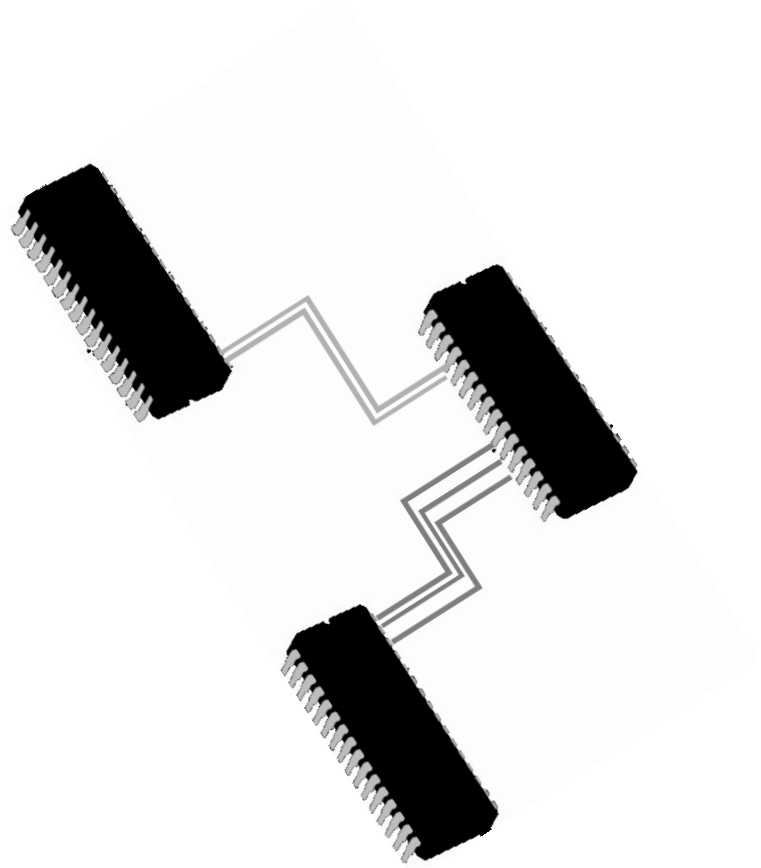
Outline

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

Introduction

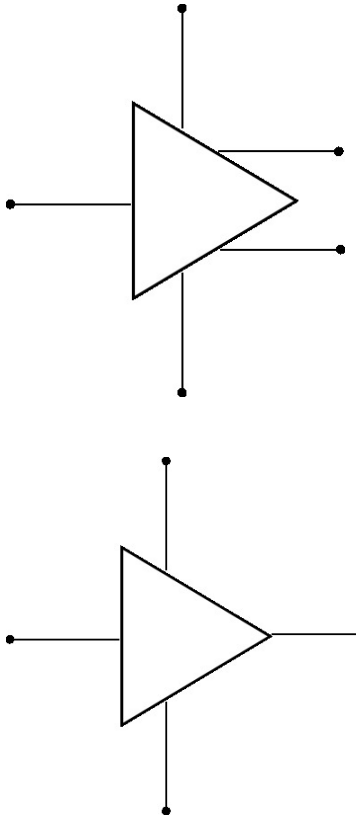
- Assessing
  - EMC compatibility
  - Signal Integrity
- Reducing
  - Design Cost
  - Simulation time
  - Time to market

……..



Introduction

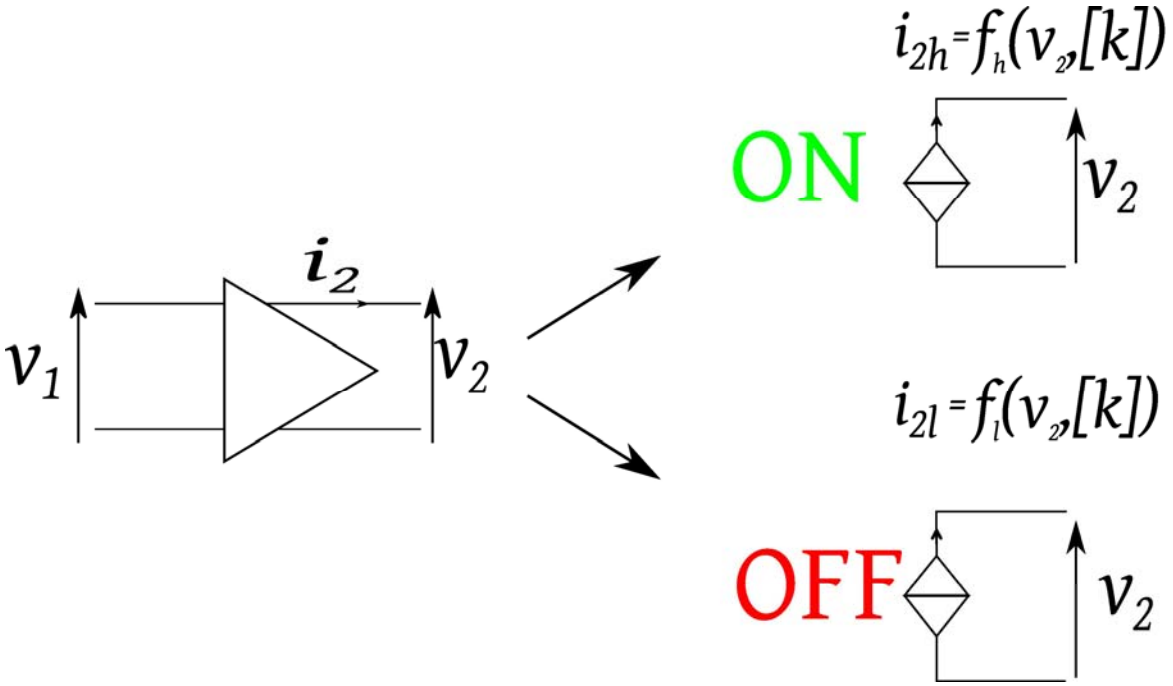
- Nonlinear behavior of IC buffers
  - Fading memory
  - Highly nonlinear
    - Switching feature
    - Saturation
- Behavioral modeling techniques
  - IBIS
  - Mπlog
  - Neural networks, etc…



Introduction

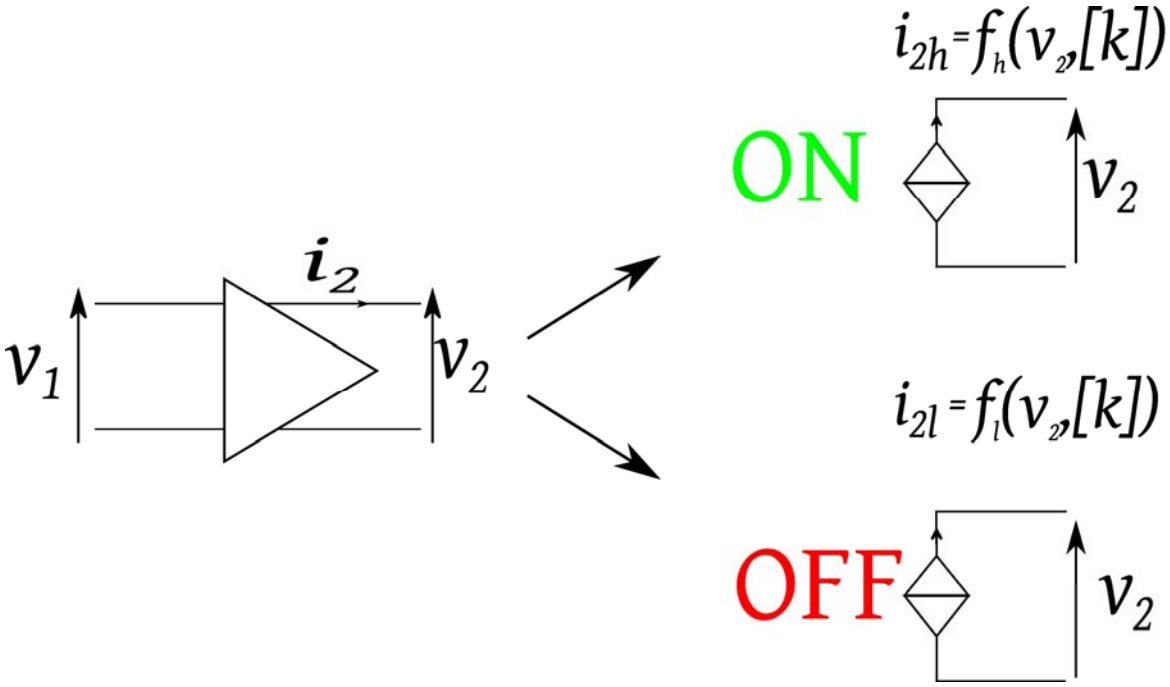
- 2-piece model (MπLog)
  - Black box modeling of buffers
  - Output buffer port modeled in respect to input state (ON or OFF)
  - Transitions between states modeled through weighting functions
  - Output port relations, two submodels scheme

Introduction



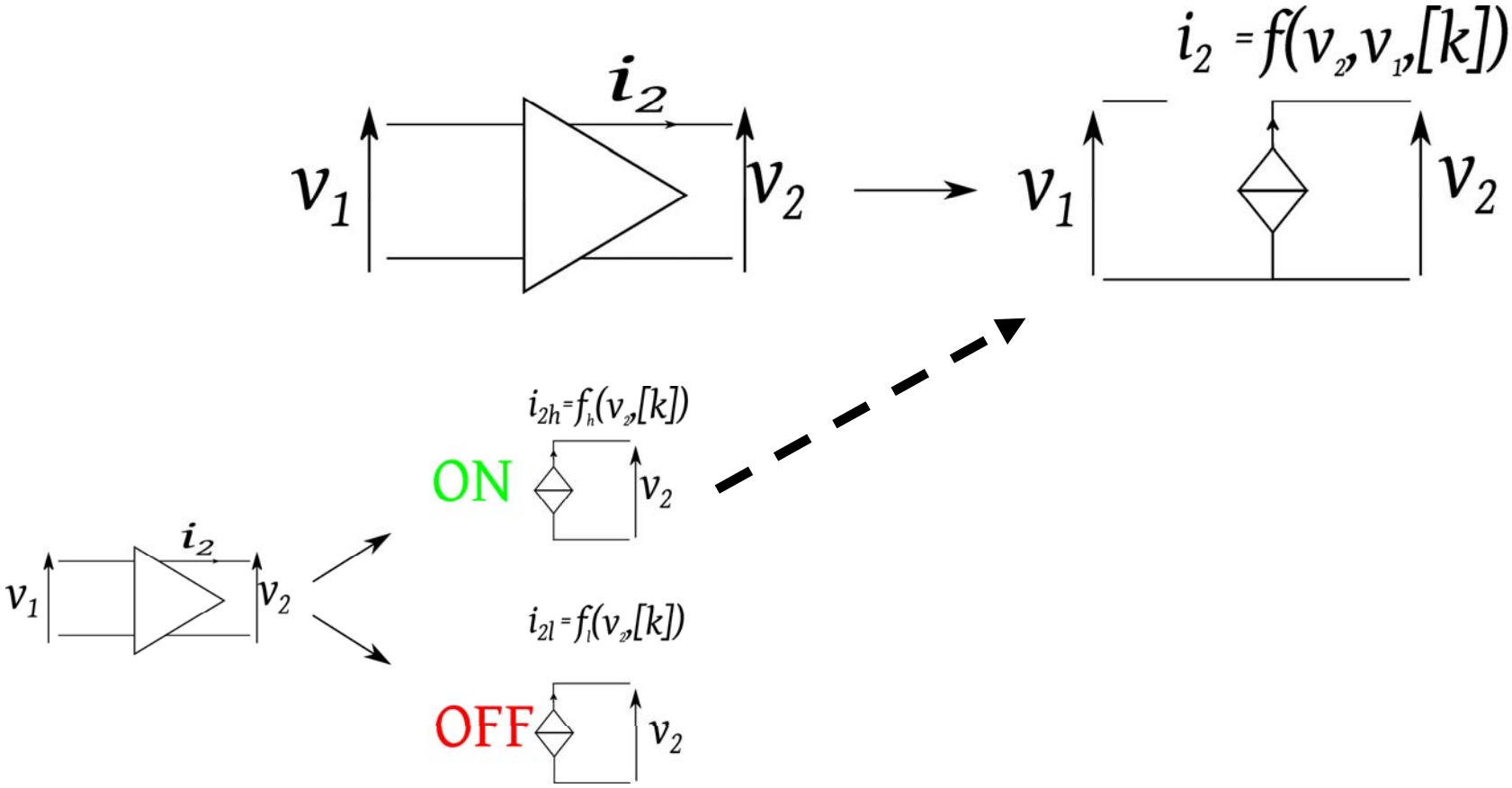
- $I_2 = f(v_2,[k])$
- Transitions between states modeled through weighting functions
- Dynamic effect of v_1 not in the submodels

Introduction

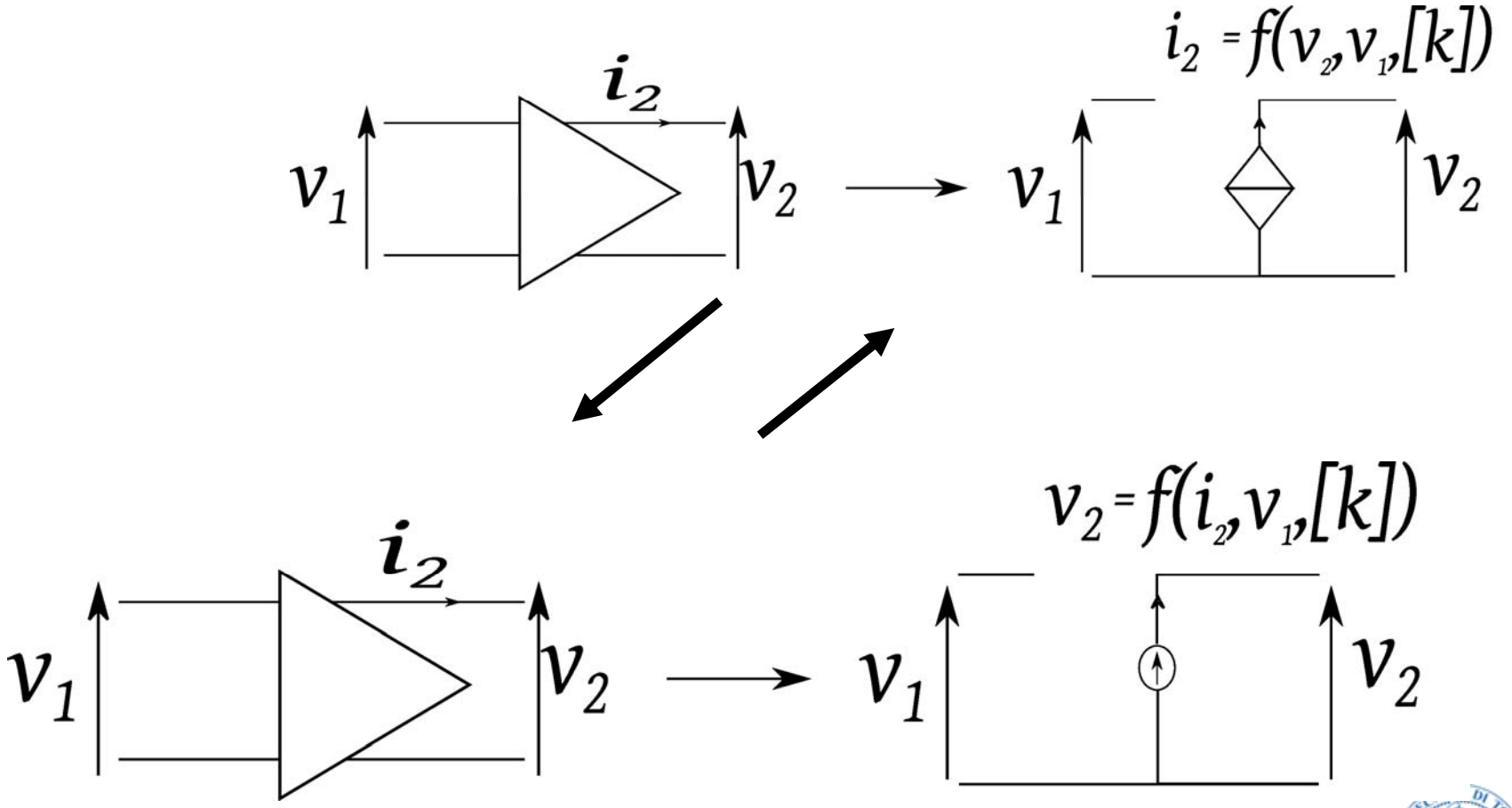


- **SPI 2010** each submodel represented by SISO Volterra Series
- **SPI 2011** mathematical constraints on Volterra series, exact static behavior

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

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

$$\bar{v}_{n_l, i_l}[k] = \left(v_{n_l} * \phi_{n_l, i_l}\right)[k], \qquad n_l = 1,2$$

New approach: theoretical framework

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

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

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

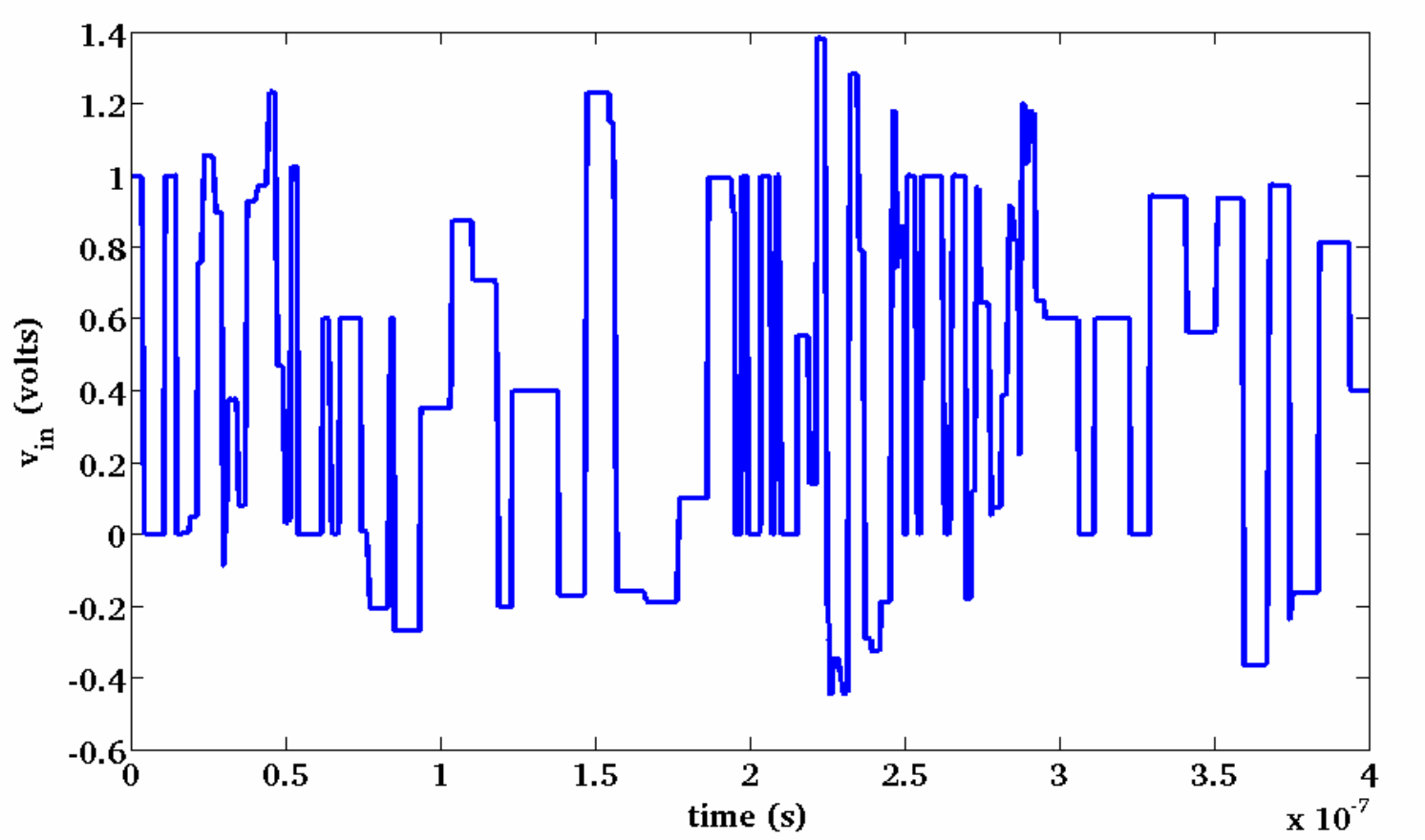
$$+ \ldots$$

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

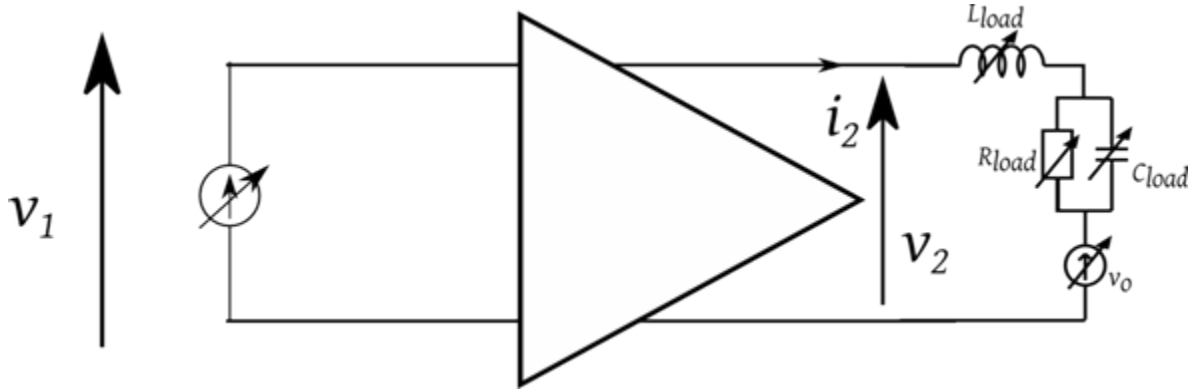
$$i_2[k] = \sum_{m=1}^{M} \sum_{n_1=1}^{2} \cdots \sum_{n_m=1}^{2} \sum_{i_1=0}^{I_m-1} \cdots \sum_{i_m=0}^{I_m-1} C_{m,n_1,\ldots,n_m,i_1,\ldots,i_m} \prod_{l=1}^{m} \bar{v}_{n_l,i_l}[k]$$

Identification



Identification

- Variable identification load
  - Allowing a good static exploration
  - Dynamic exploration of (i_2,v_2) trajectories resulting from interconnects reactive elements

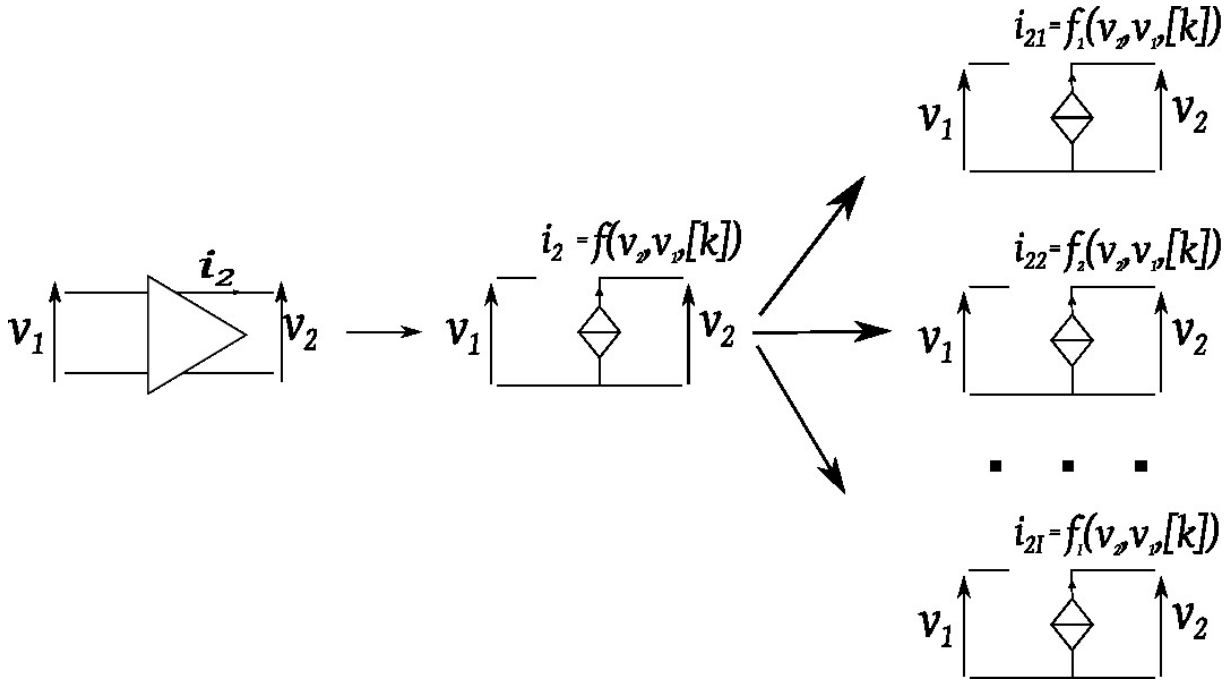


Identification

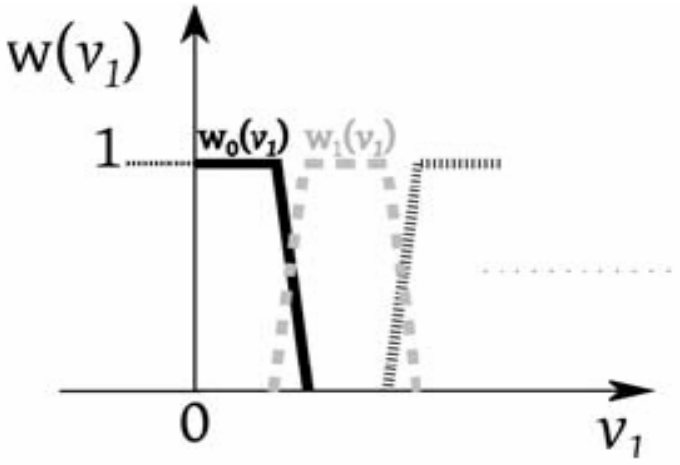
$$\begin{bmatrix} \overline{\varphi}_{1,1,0}[k_0] & \overline{\varphi}_{1,1,1}[k_0] & \dots & \overline{\varphi}_{m\dots}[k_0] \\ \overline{\varphi}_{1,1,0}[k_1] & \overline{\varphi}_{1,1,1}[k_1] & \dots & \overline{\varphi}_{m\dots}[k_1] \\ \dots & \dots & \dots & \dots \\ \overline{\varphi}_{1,1,0}[k_I] & \overline{\varphi}_{1,1,1}[k_I] & \dots & \overline{\varphi}_{m\dots}[k_I] \end{bmatrix} \begin{bmatrix} c_{1,1,0} \\ c_{1,1,1} \\ \dots \\ c_{m\dots} \end{bmatrix} = \begin{bmatrix} i_2[k_0] \\ i_2[k_1] \\ \dots \\ i_2[k_I] \end{bmatrix}$$

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…



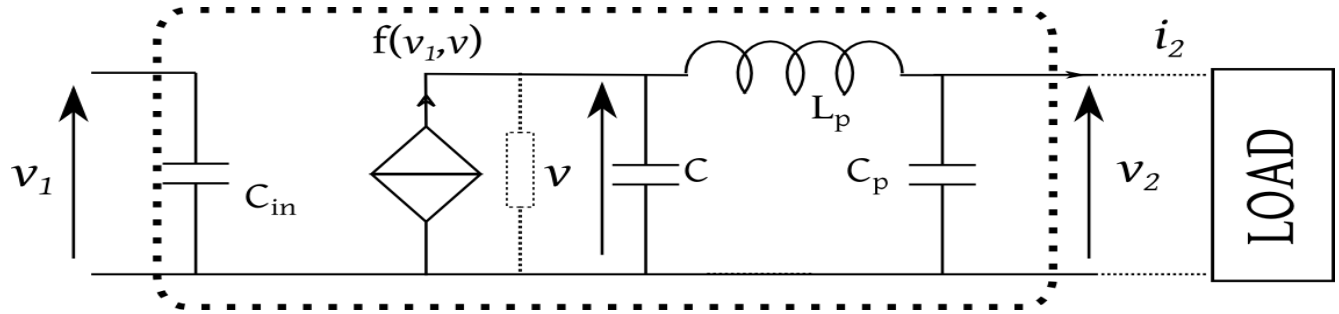
Recent developments



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

Example

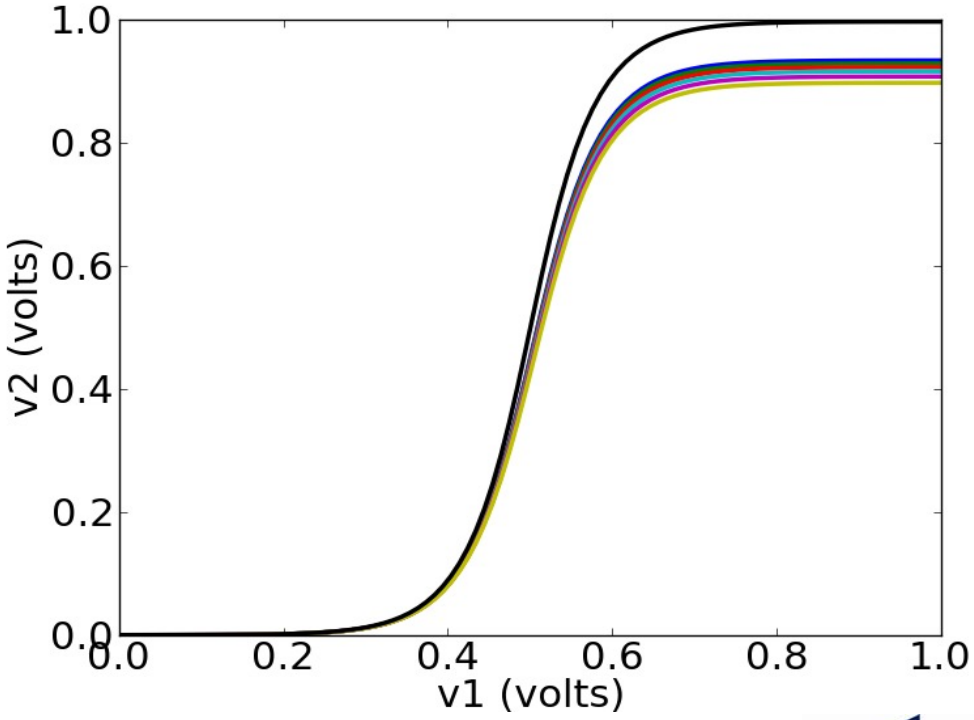
- Test vehicle: tunable synthetic system mimicking single ended non inverting driver



- $f(v_1,v)$ nonlinear current source
- Dynamic by reactive components

Example

- Input/Output static characteristic, different loads

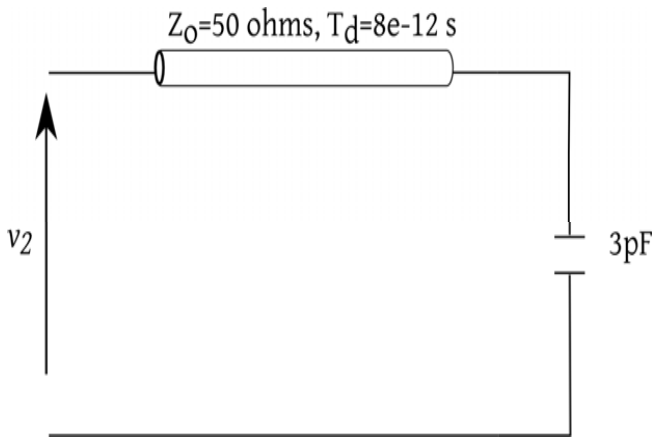


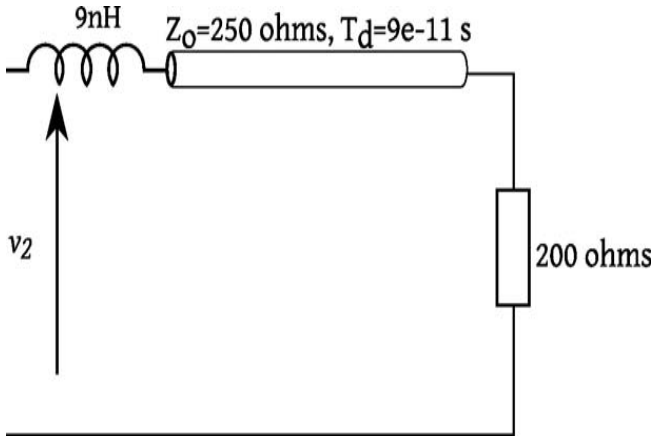
Example

- 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

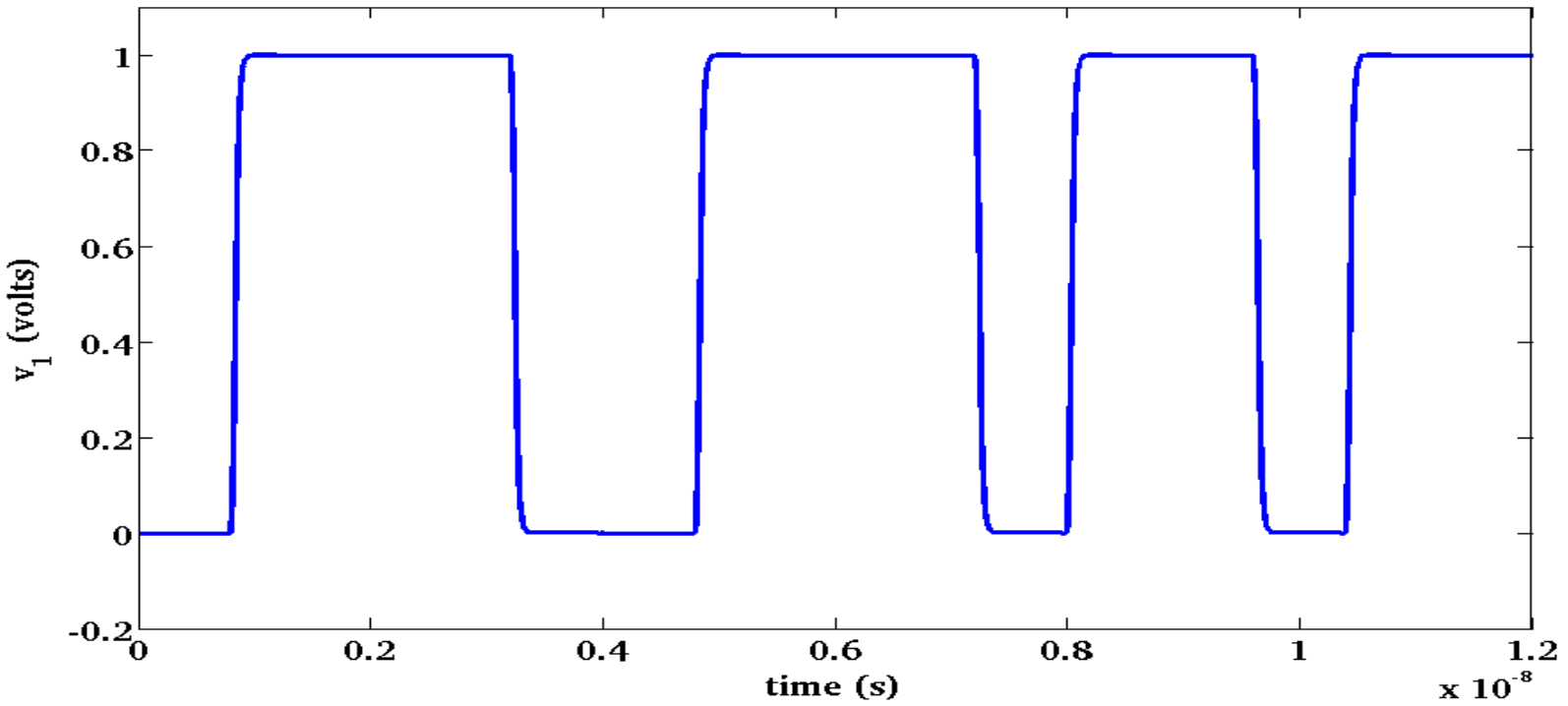
- Validation
  - Input validation signal
  - On two load configurations





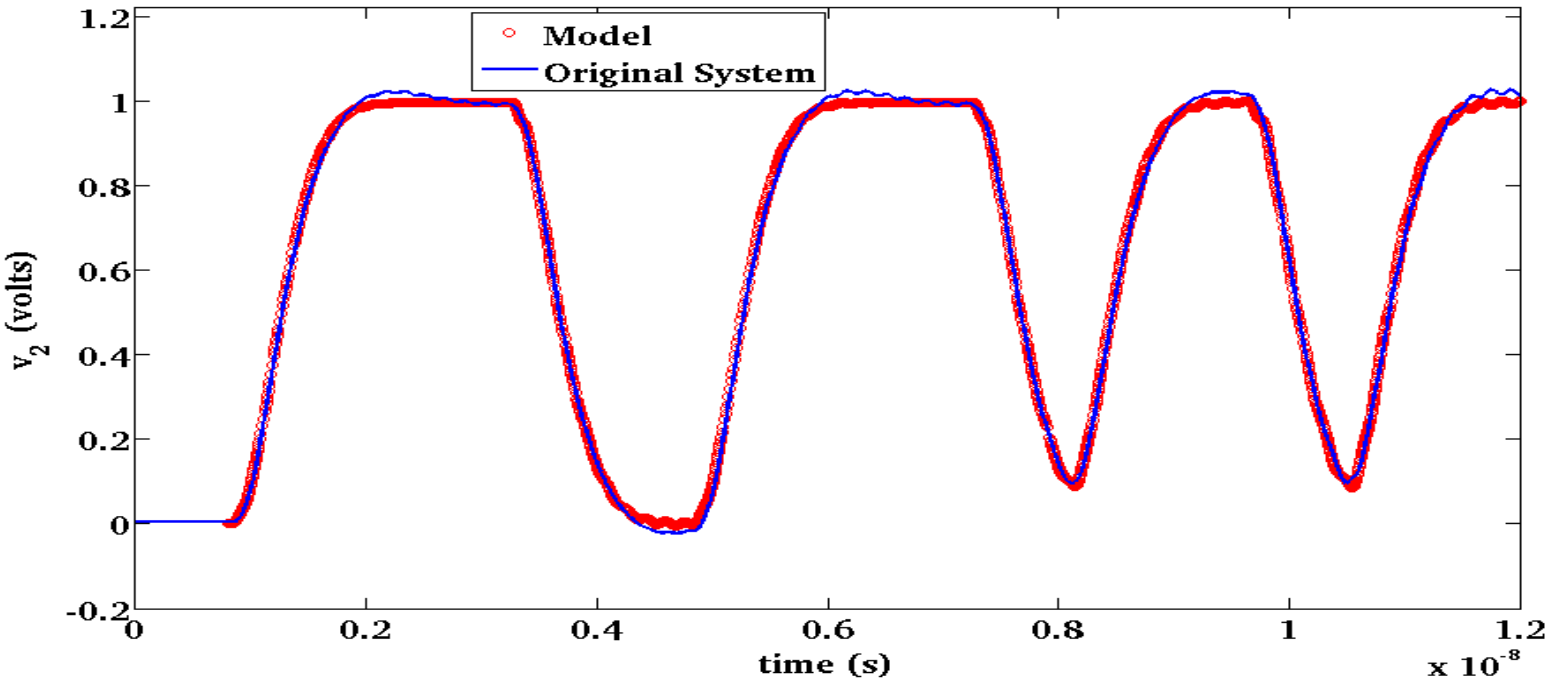
Example

- Input validation signal



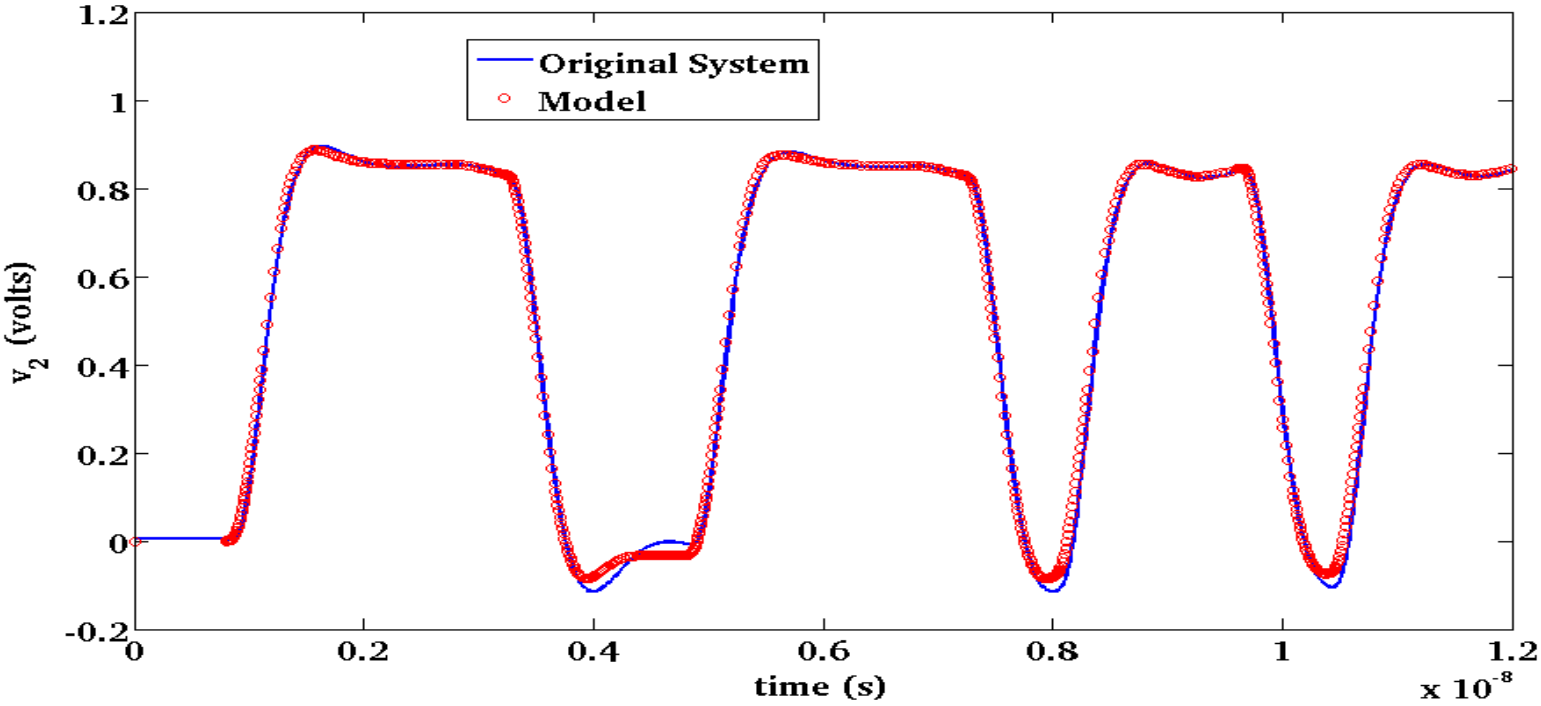
Example

- First load, ~2sec,



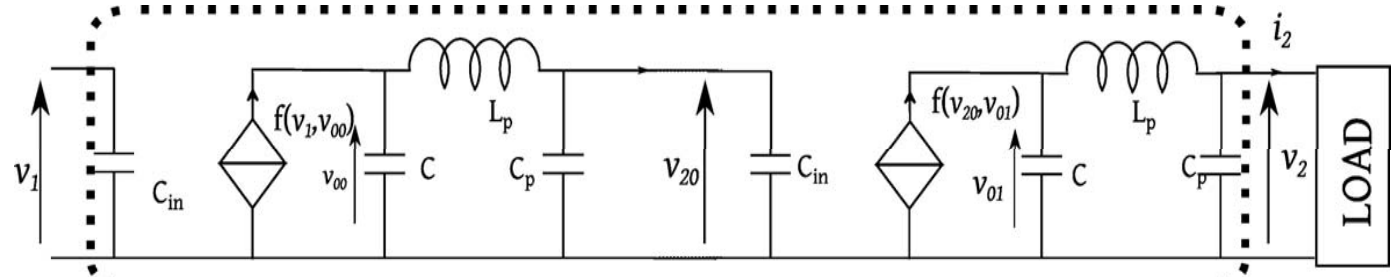
Example

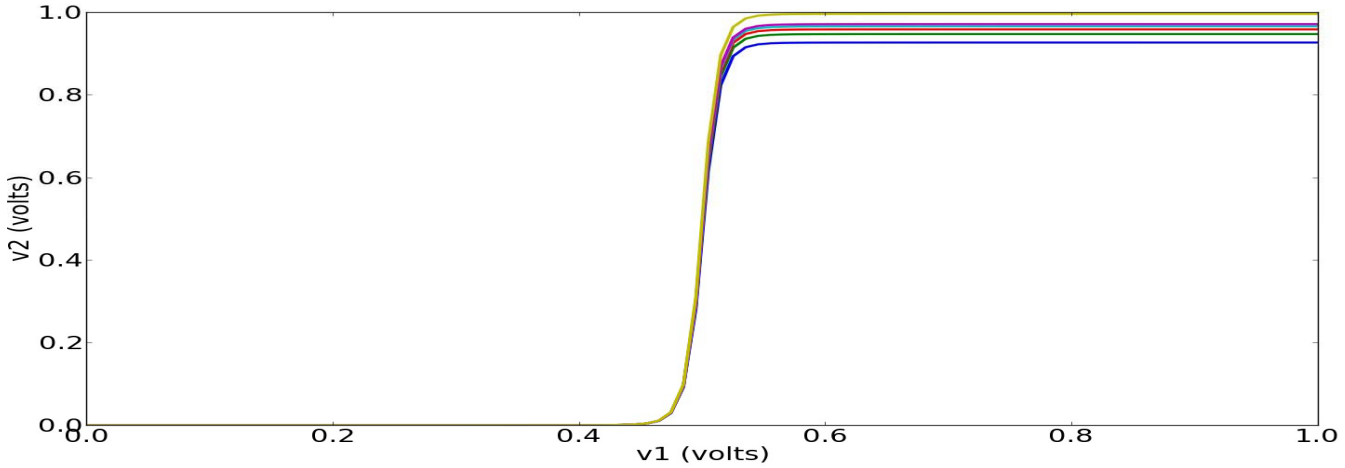
- Second load, non classic, ~2sec



Example

- Cascaded drivers



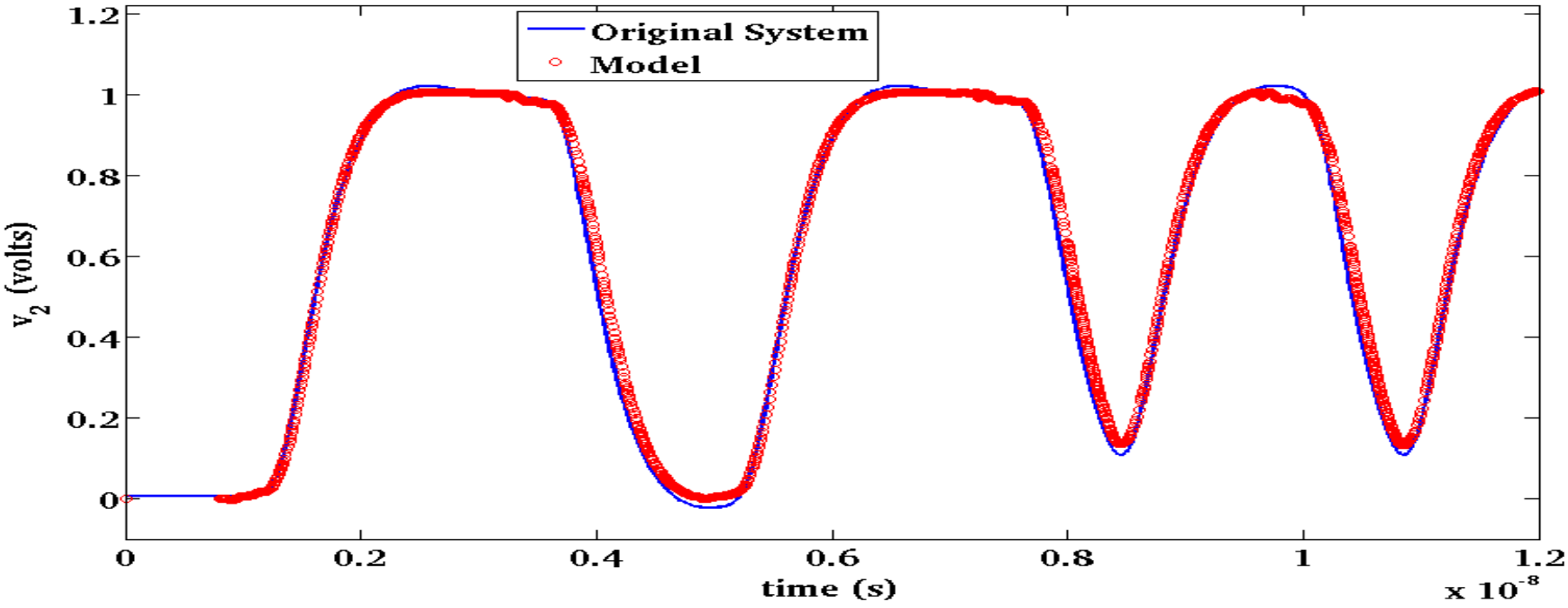


Example

- 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

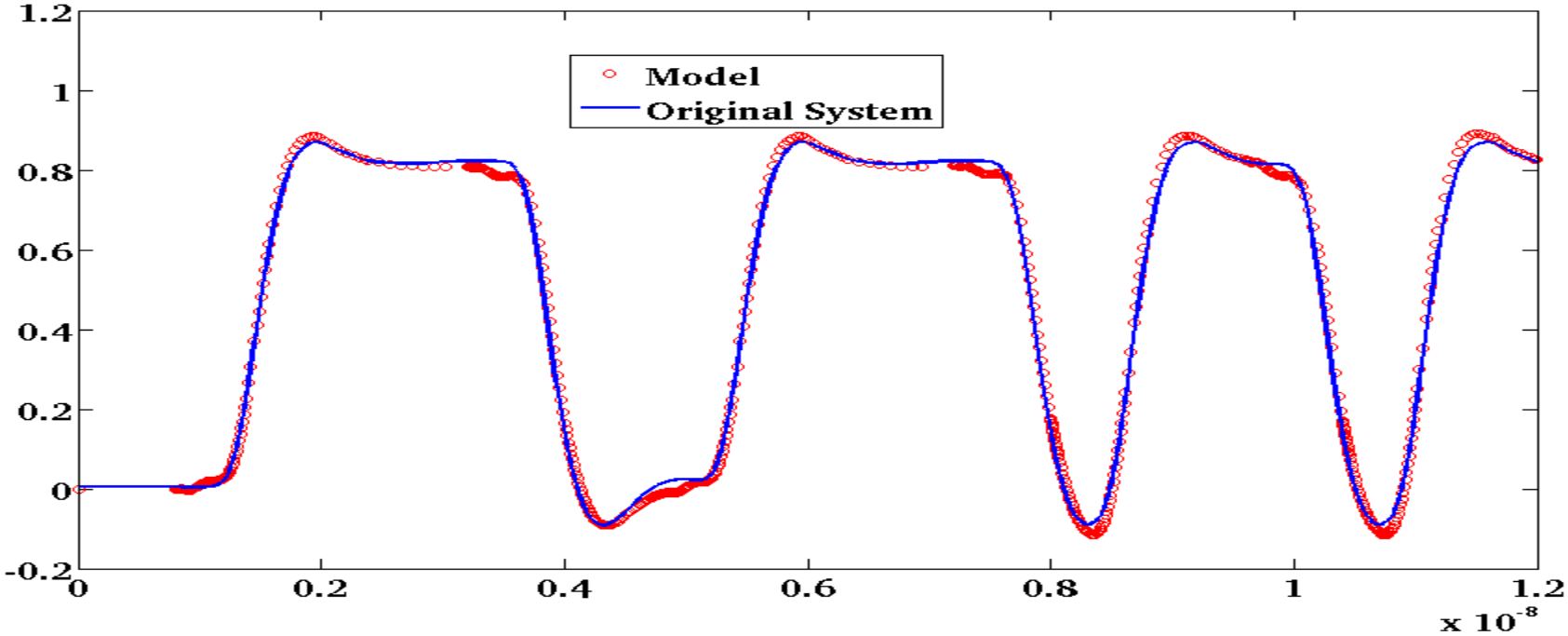
Example

- First Load, ~6sec,



Example

- Second load, ~6sec



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