Composition of analog components in feedback systems

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Outline

- Introduction to Analog Platform Based Design (APBD)
- Definition of composition for APBD
- Feedback composition with contracts
- Case study: LPF for a UWB receiver

APBD: Analog Platform Based Design

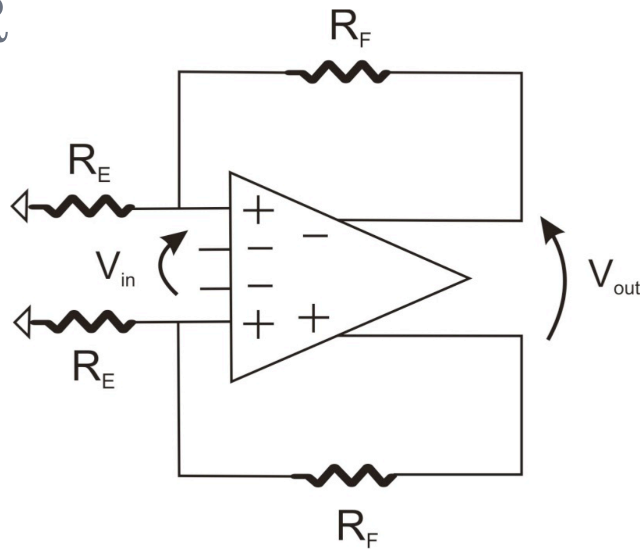
- GOAL: Extend the PBD methodology to the design of analog systems to:
  - Increase productivity
  - Foster design reuse
  - Ease the exploration of the design space

  (L. Carloni *et al.*, in *Proceedings of ESSCIRC*, pp. 25-36 (2002))

- CHALLENGE: Create a common semantic layer between system specifications and circuital implementation.
- HOW: each library component is described by
  - Behavioral Model
  - Performance Model

EXAMPLE: LINEAR AMPLIFIER

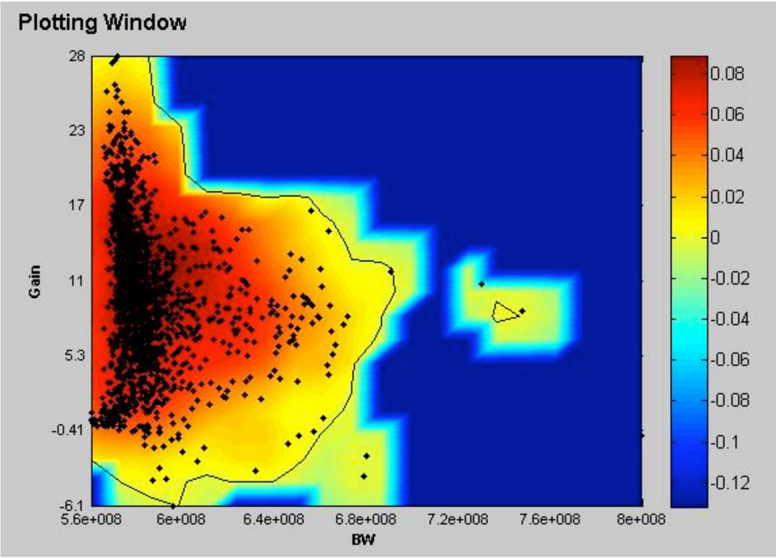
- Circuital implementation



- Behavioral Model

$$G = \begin{cases} 1 + \frac{R_F}{R_E}, & f < BW \\ 0, & f \geq BW \end{cases}$$

- Performance Model



Outline

- Introduction to Analog Platform Based Design (APBD)
- Definition of composition for APBD
  - Contracts
  - Mapping function
- Feedback composition with contracts
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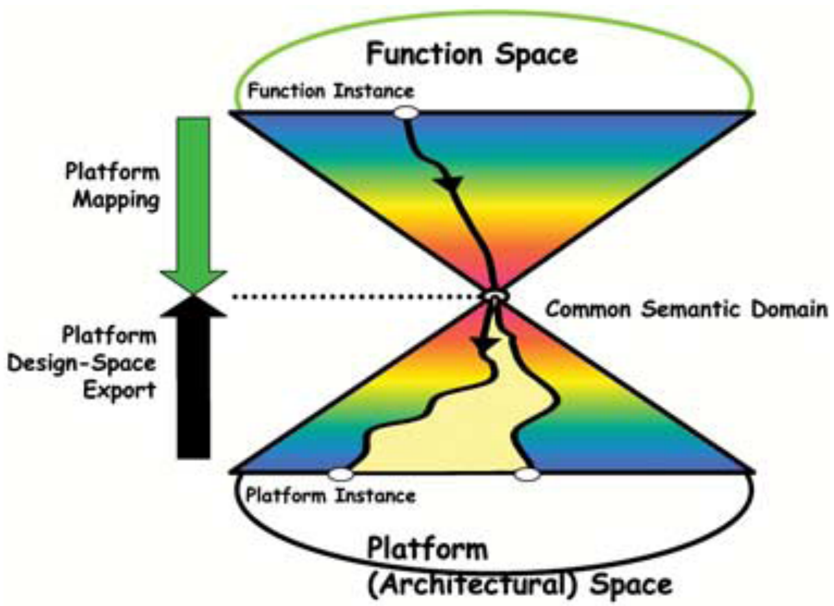
BLOCK COMPOSITION

- Fundamental step in system level exploration
- Given a set of library blocks to be composed, define:
  - A mapping function for the composition to propagate the system level requirements
  - A validity region over which the performance model holds to abstract away implementation details

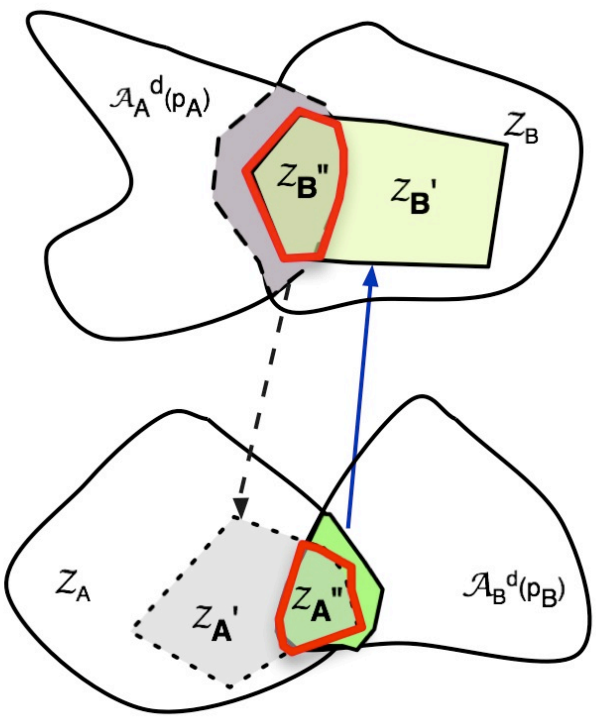


Block composition (2)

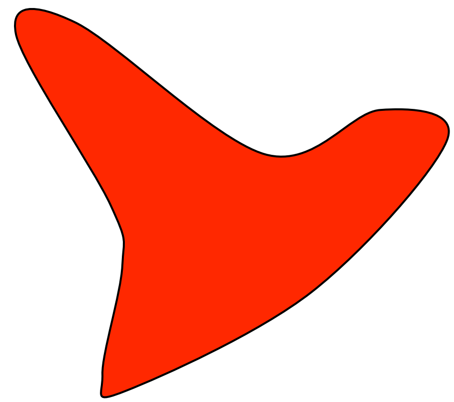
- Digital Domain
  - Very robust →"digital abstraction"
  - Very loose assumptions at the interfaces (delay)
- Analog Domain
  - High sensitivity to interface conditions
  - Communication Based Design: buffers to encapsulate blocks?
  - NO: power and area consuming
  - Complex and exhaustive model
  - NO: time consuming
  - SOLUTION: guarantee the ideal block performances just when a set of assumptions is satisfied

BLOCK COMPOSITION WITH CONTRACTS

SOLUTION: guarantee the ideal block performances just when a set of assumptions is satisfied



Simple Mapping function



Performance model of the composed block

X. Sun *et al.*, Proceedings of DAC 2009

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  - Contracts for feedback
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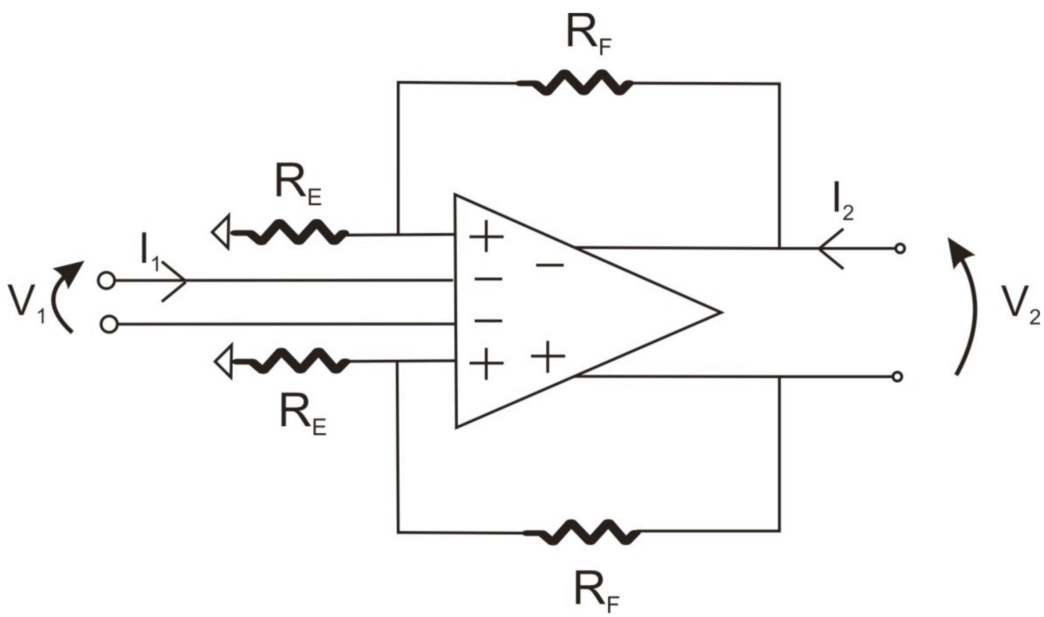
Contracts for feedback composition

- Project GOAL: extending the contract-based composition strategy to feedback composition
  - Feedback to synthesize system functionalities
  - Feedback to control parameter variations
- CHALLENGE:
  - Feedback composition results in a behavior that is not trivially related to the behavior of the composed blocks
  - Define regions of validity for simple models that capture the expected behavior of the system
- HOW:
  - Derive an exact way to characterize the performance space of the composed circuit
  - Define contracts on the obtained performance space to derive regions of validity for simplified mapping functions

Block characterization

- Define a set of circuit parameters $\mathcal{K}$ (Ws, Ls, Re, Rf…)
- Define a set of circuit performances $\mathcal{Y}$
  - Power, Area
  - Formal representation: two-port matrix (i.e. Z,G, H1, H2)
- Run a set of simulations while varying parameters k to find all feasible performances y

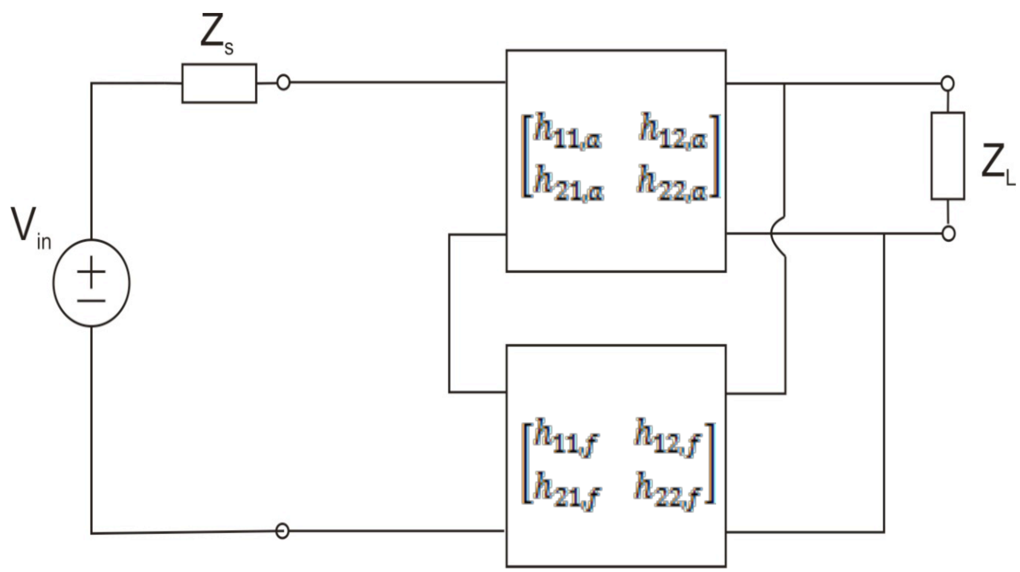
Two Port Representation: example



$$\begin{bmatrix} i_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ \left(1+\frac{R_F}{R_E}\right) * \left(\frac{1}{1+\frac{s}{BW}}\right) & 0 \end{bmatrix} \begin{bmatrix} v_1 \\ i_2 \end{bmatrix}$$

FEEDBACK COMPOSITION: EXTRACTION OF PERFORMANCES

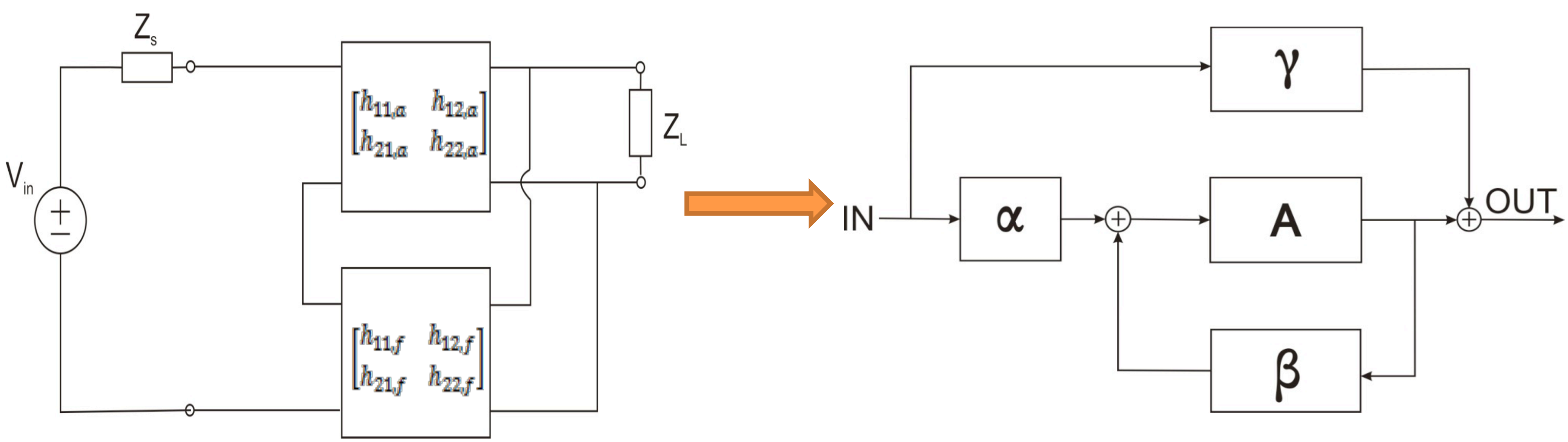
- Two two-port components can be composed in feedback just in 4 different ways:



Gray, Hurst, Lewis, Meyer,
"Analysis and Design of Analog Integrated Circuits"

FEEDBACK COMPOSITION: EXTRACTION OF PERFORMANCES (2)

- For any composition, the system can be represented as:



B. Pellegrini,
"Consideration on the feedback theory"

FEEDBACK COMPOSITION: EXTRACTION OF PERFORMANCES (3)

- H matrix of the composed block:

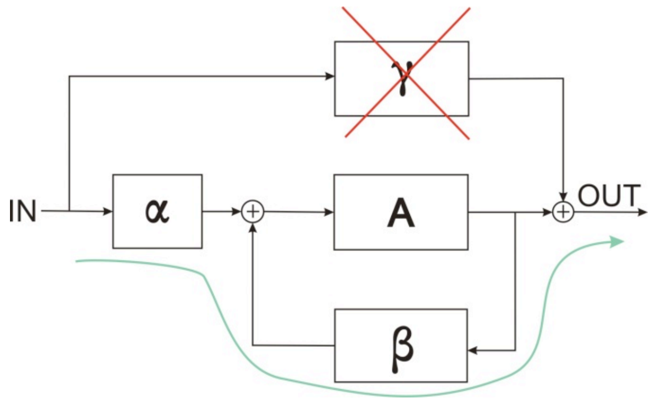
$$H_{composition} = \begin{bmatrix} h_{11,0} * \frac{1+G_{loop,0}}{1+G_{loop,\infty}} & \frac{\alpha_{12}A_{12}}{1-\beta_{12}A_{12}} + \gamma_{12} \\ \frac{\alpha_{21}A_{21}}{1-\beta_{21}A_{21}} + \gamma_{21} & h_{22,0} * \frac{1+G_{loop,0}}{1+G_{loop,\infty}} \end{bmatrix}$$

- $H_{composition}$ depends on:
  - Type of feedback
  - H matrixes of the two composing blocks
- Example:

$$A = \frac{h_{21,a} z_{IN}}{h_{12,a} h_{21,a} z_{IN} + h_{12,f} h_{21,f} h_{11,a} - h_{11,a} z_{IN} y_{OUT}} \qquad \beta = -\frac{h_{12,f} z_P}{z_{IN}} \qquad y_{OUT} = y_L + h_{22,f} + h_{22,a}$$

$$\gamma = \frac{h_{21,f} h_{11,a}}{h_{12,f} h_{21,f} h_{11,a} - h_{11,a} z_{IN} y_{OUT} + h_{21,a} h_{12,a} z_{IN}} \qquad \alpha = \frac{1 - h_{12,f}\gamma z_P}{z_{IN}} \qquad z_{IN} = z_S + z_P + h_{11,f}$$

CONTRACTS: MAPPING FUNCTION FOR NEGATIVE FEEDBACK



$$h_{21,composition}(s) = \frac{\alpha_{21} A_{21}}{1 - \beta_{21} A_{21}} + \gamma_{21}$$

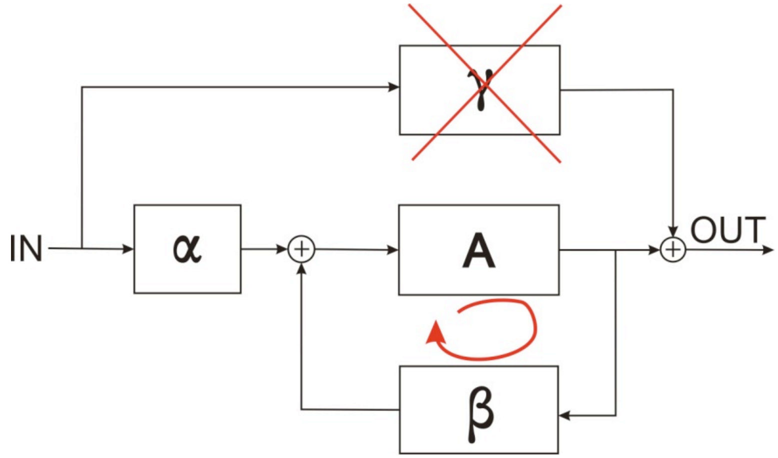
$$\Downarrow$$

$$h_{21,composition}(s) = -\frac{\alpha}{\beta}$$

- Contracts for negative feedback:
  1. $\left|\frac{\alpha A}{1 - \beta A}\right| \gg |\gamma|$
  2. $|\beta A| \gg 1$

  over the whole frequency range of interest

Contracts: Mapping function for Positive Feedback



$$h_{21,composition}(s) = \frac{\alpha_{21} A_{21}}{1 - \beta_{21} A_{21}} + \gamma_{21}$$

$$h_{21,composition}(s) = \frac{\alpha A}{1 - A\beta}$$

- Contracts for positive feedback:
  1. $\left|\frac{\alpha A}{1 - \beta A}\right| \gg |\gamma|$
  2. $|\beta A| < 1$

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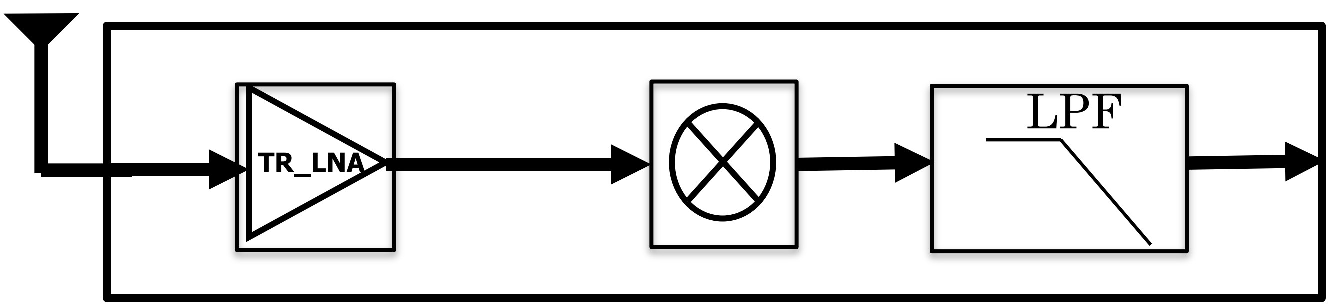
Case study: Low Pass Filter for a UWB receiver

- The top level system is a RX chain for an UWB link
  - S. Ergen, A. L. Sangiovanni-Vincentelli, X. Sun, R. Tebano, S. Alalusi, G. Audisio, M. Sabatini, "**The Tire as an Intelligent Sensor**", IEEE Transaction on Computer-Aided Design of Integrated Circuits and Systems

- LNA & Mixer were previously designed →LPF (suitable to study feedback)



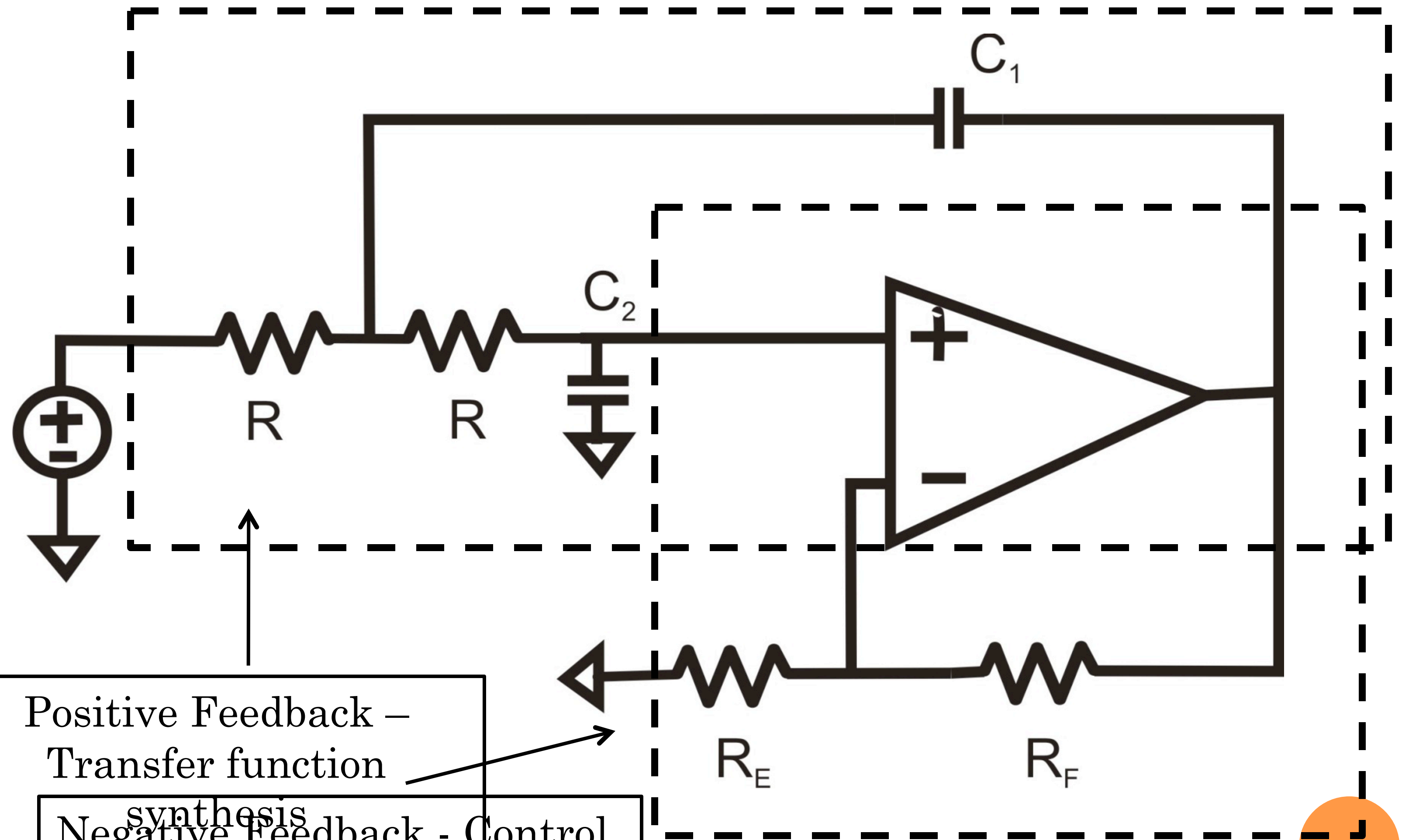
Biquadratic Cell

- Basic element of any filter
  - The desired transfer function is just the cascade of several biquads (ω_0=256MHz)
- Ideal transfer function

$$H(s) = \frac{K}{1 + s\frac{1}{Q\omega_0} + \frac{s^2}{\omega_0^2}}$$

- Sallen-Key biquad
  - Used in state-of-the-art RX for UWB systems
  - Representative of several "flavors" of feedback

The Sallen Key Cell

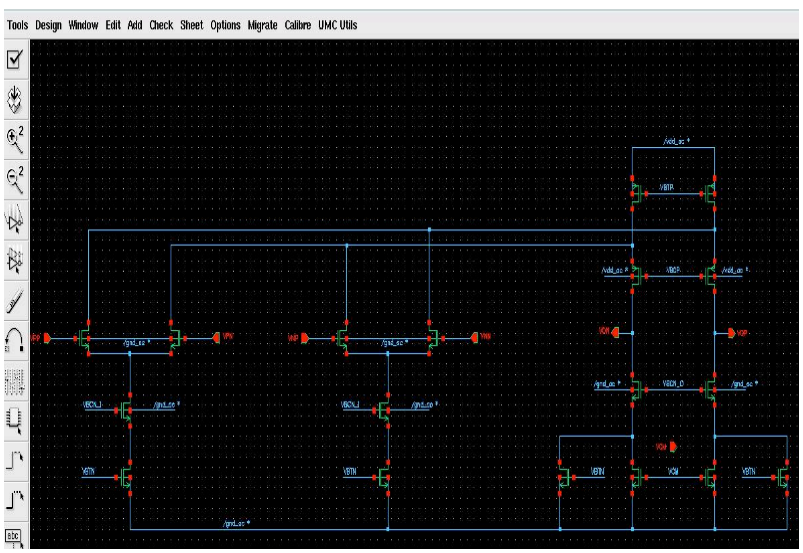


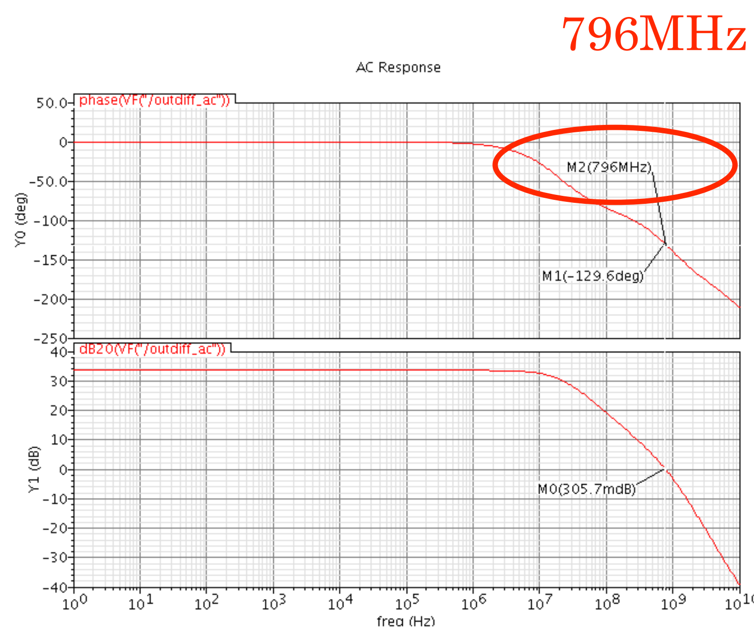
Positive Feedback – Transfer function synthesis

Negative Feedback - Control

STEP 1: CIRCUIT IMPLEMENTATION

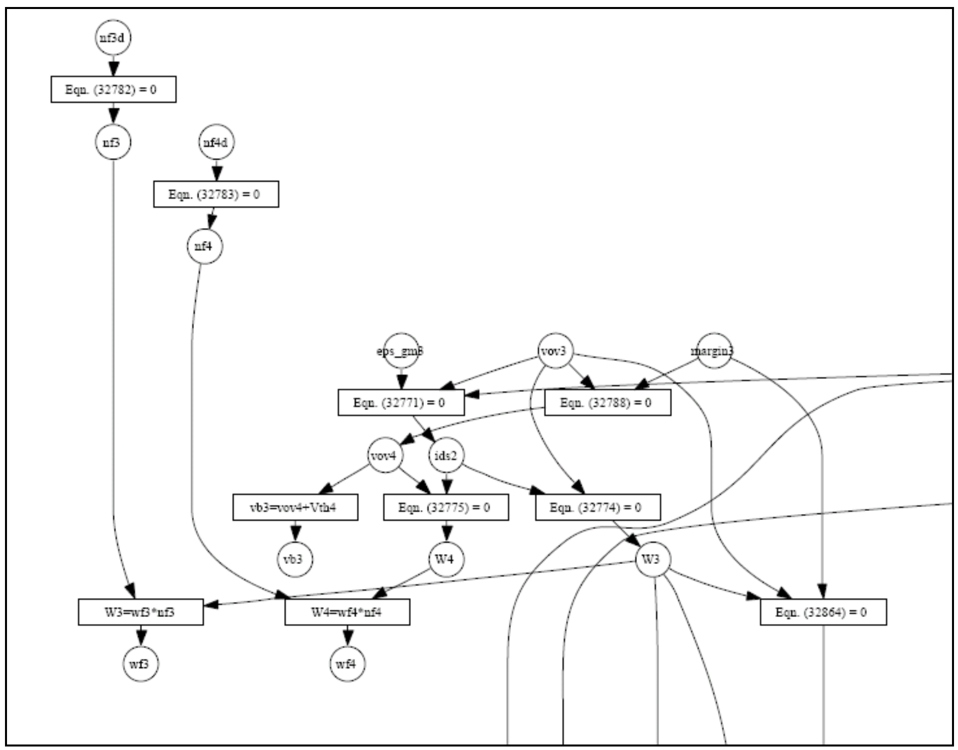
- Fully differential non inverting stage: Differential Difference Amplifier (DDA)
  - E. Sackinger *et al.*, IEEE JSSC (1988)





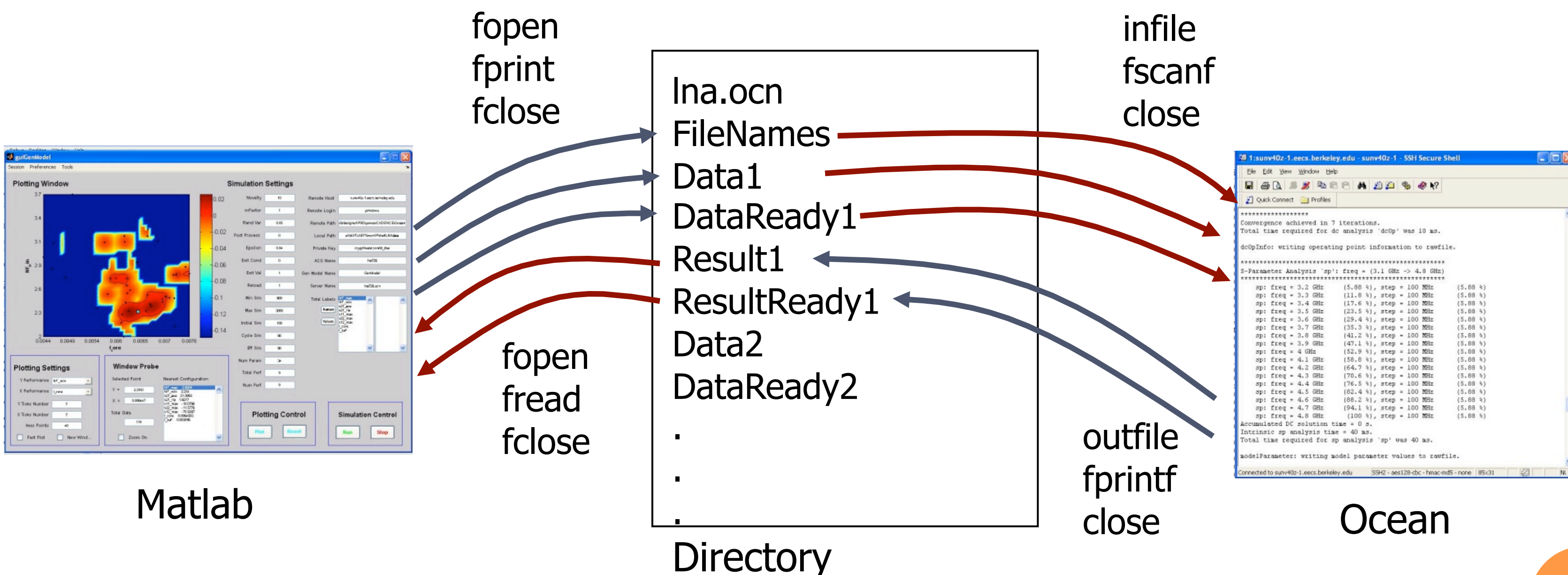
STEP 2: BLOCK CHARACTERIZATION

- IMPORTANT: capture the correlations among parameters k → Analog Constraint Graph
  - To avoid the "curse of dimensionality"



STEP 2: BLOCK CHARACTERIZATION (2)

- Automatic simulation run
  - To improve efficiency → Ocean



EXHAUSTIVE MODEL

$$A = \frac{K}{1 + s\tau_{DDA}} * \frac{R_s + z_p + R_2 + s(z_p + R_s)(C_{in} + C_2) + sC_1R_s(z_p + R_s)[1 + s z_p \| R_2(C_{in} + C_2)]}{R_s + z_p + R_2 + s(z_p + R_s)(C_{in} + C_2)}$$

$$\beta = \frac{sC_1 z_a}{1 + sC_1 z_a} * \frac{z_p}{z_p + R_2 + sR_2 z_p(C_{in} + C_2)}$$

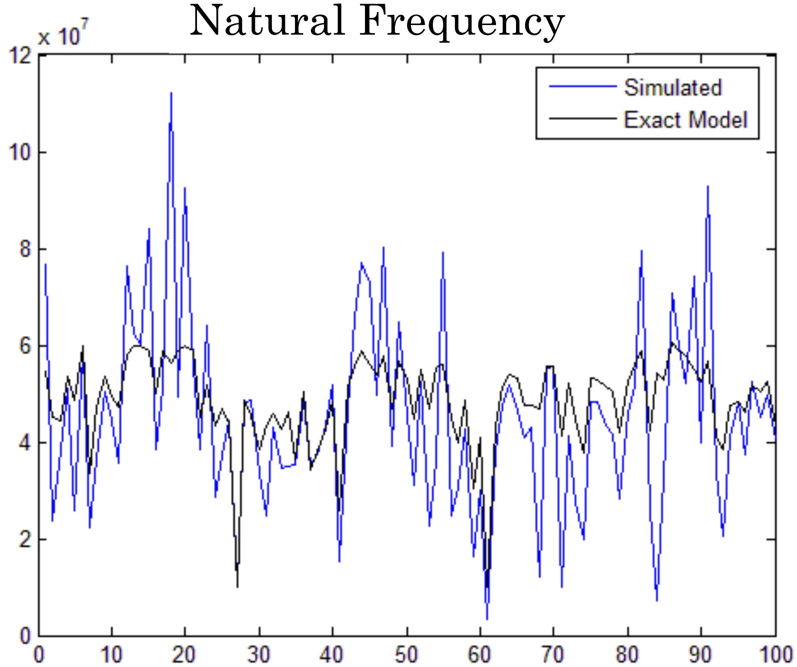
$$\gamma = \frac{z_b}{R_s + z_b} * \frac{sC_1R_0}{1 + sC_1R_0}$$

$$h_{21,composition}(s) = \frac{\alpha_{21}A_{21}}{1 - \beta_{21}A_{21}} + \gamma_{21}$$

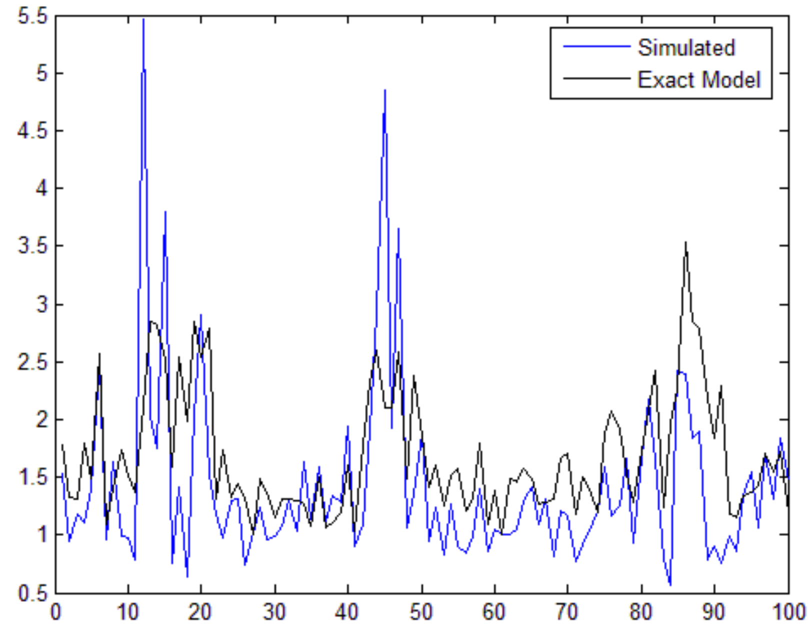
$$\alpha = \frac{z_b}{R_s + z_b} * \frac{z_p}{z_p + R_2 + sR_2 z_p(C_{in} + C_2)}$$

Results

Natural Frequency



Quality Factor



$$\frac{f_{modeled} - f_{simulated}}{f_{simulated}} = 7\%$$

$$\frac{Q_{modeled} - Q_{simulated}}{Q_{simulated}} = 4\%$$

Contracts and simplified model

$$\left|\frac{\alpha A}{1-\beta A}\right| \gg |\gamma|$$

$$|\beta A| < 1$$

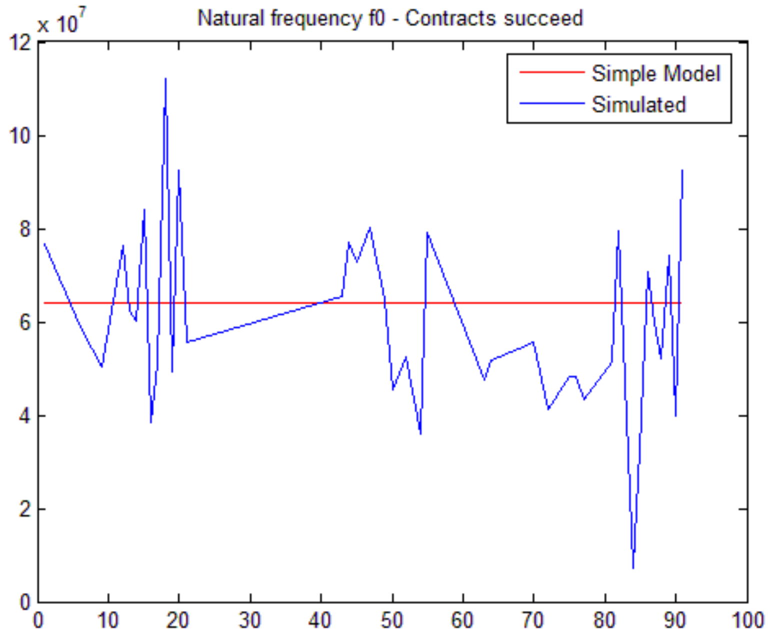
$$\begin{cases} Z_p \gg R_2 + R_s \\ C_{in} \ll C_2 \\ \dfrac{1}{2\pi C_1 R_0} \gg f_0 \end{cases}$$

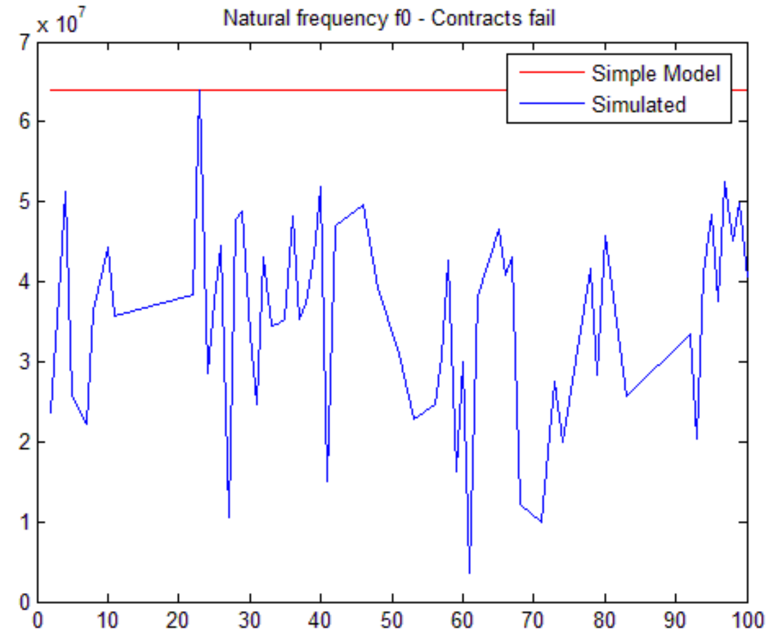
$$h_{21,composition}(s) = \frac{K}{1 + s\frac{1}{Q\omega_0} + \frac{s^2}{\omega_0^2}}$$

$$\omega_0 = \frac{1}{\sqrt{R_s R_2 C_1 C_2}}$$

$$Q = \frac{\sqrt{R_s R_2 C_1 C_2}}{(R_s + R_2)C_2 + R_s C_1(1-k)}$$

Results: Natural Frequency





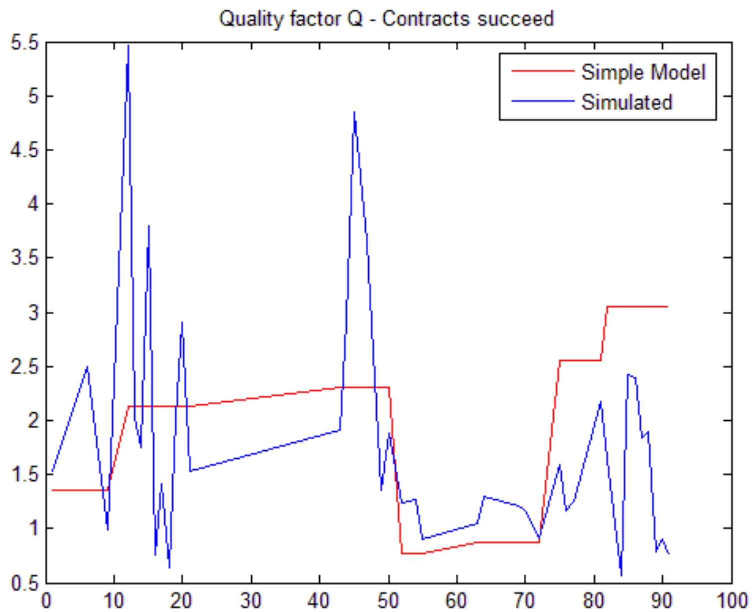
Contracts are respected

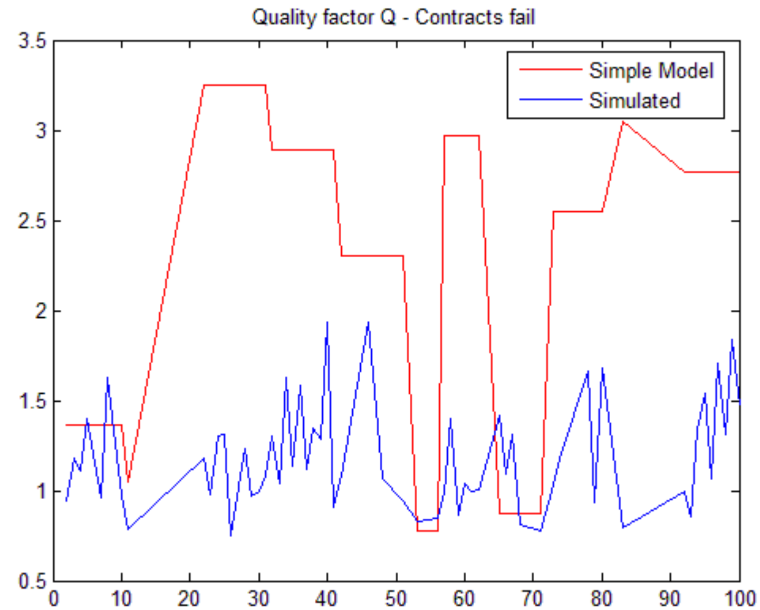
$$\frac{f_{simulated} - f_{Simple\ Model}}{f_{Simple\ Model}} = 8\%$$

Contracts are NOT respected

$$\frac{f_{simulated} - f_{Simple\ Model}}{f_{Simple\ Model}} = 32\%$$

RESULTS: QUALITY FACTOR





Contracts are respected

$$\frac{Q_{simulated} - Q_{Simple\ Model}}{Q_{Simple\ Model}} = 10\%$$

Contracts are NOT respected

$$\frac{Q_{simulated} - Q_{Simple\ Model}}{Q_{Simple\ Model}} = 50\%$$

SUMMARY

- Contracts: key to propagate feasible performances to higher level abstraction layers
- Extended the contract based strategy to the feedback composition
  - Exhaustive extraction of the performance space of the composed block
  - Contracts that define regions of the performance space in which the simple model holds
- Application of the methodology to the design of a LPF for UWB RX
  - Blocks characterization
  - Extraction of the performances of the composed block
  - Contract based definition of validity regions where the simplified model holds

Thank you for your attention