High-Level Simulation for RF Systems

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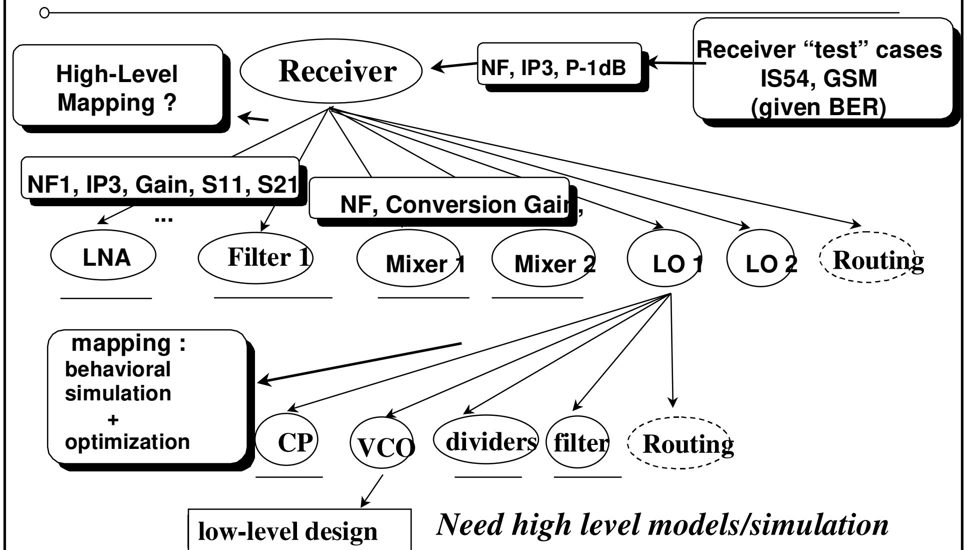
Motivation: RF System High-Level Decomposition



Need high level models/simulation techniques

RF Systems: High-Level Design Approaches

- Use "spreadsheet" with cascade formulas:

$$NF_{TOTAL} = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \ldots + \frac{NF_N - 1}{G_1 G_2 \ldots G_{N-1}}$$

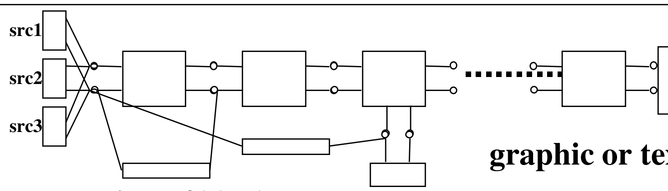
$$\frac{1}{IP_{3_{TOTAL}}} = \frac{1}{IP_{3_1}} + \frac{G_1}{IP_{3_2}} + \frac{G_1 \cdot G_2}{IP_{3_3}} + \ldots + \frac{G_1 \cdot G_2 \cdots G_{N-1}}{IP_{3_N}}$$

- approximation
- Some effects ignored (feedback, phase cancellation,coupling etc..)
- Over-design (Example: IM3 cancellation)
- Need more efficient technique: from RF models and system specifications get total SNDR

RF High-Level Simulation: Possible Solutions

- Transient simulation using Macro-models
  - \+ do not depend on # of harmonics
  - \+ can be implemented with current simulators
  - – depend on implementation
  - – complicated modeling of frequency-dependent non-linearities
  - – may have convergence problems
- Harmonic Balance
  - need differential equation model
  - exponential complexity w/ # harmonics
- Volterra I/O map for N-ports with harmonic balance

Simulator I/O Description



graphic or text interface

- •Interconnection of blocks
- •Description of "block" parameters - frequency domain
  - •gain
  - • 2nd, 3rd order distortion, compression
  - •filtering characteristics
  - •noise spectrum
- •Harmonic sources
- •Blocks: n-ports (R, Mixers, Amplifiers)
- •Other files with frequency domain models
- •Block parameters: From specs or low level simulation

•freq. domain spectrum (all nodes)
•noise spectrum
•overall noise, disto, SNDR

Volterra Series Approach (Frequency Domain)

- Basic Idea: Volterra series extended to n-ports (D. Wiener 76)
  - Assuming: N ports, K input harmonics, M-th order non-linearities, $x_1 \ldots x_n$ inputs $y_1 \ldots y_n$ outputs:
  - output: infinite sum of high order interactions given by high-order "kernels"

$$\overline{\mathbf{x(t)}} = \sum_{q=1}^{K} \overline{\mathbf{x_k}} \cdot e^{j2\pi fkt}, \ \overline{\mathbf{x_k}} = [x_{1_k,\ldots}x_{N_k}]^T$$

$$y_n(t) = \sum_{m=1}^{M} y_n^{(m)}(t),$$

$$y_n^{(m)}(t) = \sum_{\substack{n_1,\ldots n_m \\ k_1,\ldots,k_m}} H^{(m)}_{nn_{1\ldots}n_m}(f_{k1},\ldots,f_{km}) \cdot x_{n1}(f_{k1})\cdot\ldots\cdot x_{nm}(f_{km}) \cdot e^{j2\pi(fk1+\ldots+fkm)t}$$

Strong Non-linearities

- Assuming periodically-driven strong non-linearities "side-band" transfer functions can be used
  - Periodically-driven with frequency LO, harmonic input:

LTV system: $$y(t) = \int_{-\infty}^{\infty} h_1(t;\tau_1) \cdot x(\tau_1)\, d\tau_1$$

assuming h(t) periodical (mixers - periodical excitation)
Fourier transform- harmonic input $x_f\, e^{j2\pi f}$

frequency domain: $$y(t) = \sum_{l=-\infty}^{\infty} H^l(f) \cdot x_f\, e^{j2\pi(f+l\cdot f_{LO})t}$$

➡can also be applied to strong non-linearities due to large input assuming periodic signals

Strong Non-linearities (cont.)

- Expand to Volterra: weakly non-linear, periodically time-varying system (mixer w/ distortion)

$$y(t) = \int_{-\infty}^{\infty} h_1(t;\tau_1) \cdot x(\tau_1) d\tau_1 + \ldots + \int_{-\infty}^{\infty} \ldots \int_{-\infty}^{\infty} h_n(t;\tau_1,\ldots,\tau_n) \cdot x(\tau_1)\ldots x(\tau_n) d\tau_1 \ldots d\tau_n$$

(Flake 63, Rice 73, Swerdlow 78)

Harmonic inputs - multiple Fourier transform

Few non-zero

$$y_n^{(m)}(t) = \sum_{n1=1}^{N} \ldots \sum_{nm=1}^{N} \sum_{k1=1}^{K} \ldots \sum_{km=1}^{K} \sum_{l=-L}^{L} \boxed{H_{nn_1\ldots n_m}^{(m),l}(f_{k1},\ldots,f_{km}) \cdot} \; x_{n1}(f_{k1}) \ldots x_{nm}(f_{km}) \cdot e^{j2\pi(fk1+\ldots+fkm+l\cdot f_{LO})t}$$

RF High-Level Models

✓Sum of complex sources, impedences, Volterra kernels
✓Defined at given frequency points only (I/O look-up table)

Mixer Specifications
- Conversion Gain (f)
- IP_3 , P_{-1dB} , IP_2
- Noise Figure
- Image Rejection

OR

ckt simulation results

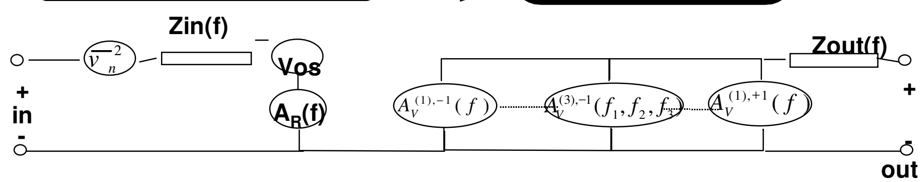
Mixer Model

$A_V^{(1),-1}(f)$

$A_V^{(3),-1}(f_1, f_2, f_3)$

$\overline{v}_n^2$

$A_V^{(1),+1}(f)$



High-Level Simulation Approach

- Determine output harmonics:

$$f_j = \sum_{i=1}^{K} m_i \cdot f_i + \sum_{i=1}^{L} l_i \cdot f_{LOi}, \quad \forall m_i,\ l_i : \quad \sum_{i=1}^{K} \left|m_i\right| \le M_{\max}, \quad \sum_{i=1}^{L} \left|l_i\right| \le L_{\max},$$

  - f_i: weak inputs, f_{LOi}: strong nonlinearities
- Formulate network equations:
  - (2b+n) x J equations and unknowns

$\forall f_j$:

KCL: $\mathbf{A} \cdot \overline{\mathbf{i}(f_j)} = \mathbf{0}$

KVL: $\overline{\mathbf{v}(f_j)} - \mathbf{A}^T \cdot \overline{\mathbf{e}(f_j)} = \mathbf{0}$

$$\sum_{i,l:\, f_i + q_l f_{LO_l} = f_j} \mathbf{K}_I^{(1)q_l f_{LO_l}}(f_i) \cdot \mathbf{i}(f_i) + \sum_{i,l:\, f_i + q_l f_{LO_l} = f_j} \mathbf{K}_V^{(1)q_l f_{LO_l}}(f_i) \cdot \mathbf{v}(f_i) + \ldots \sum_{\substack{i1,i2,i3,l: \\ f_{i1}+f_{i2}+f_{i3}+q_l f_{LO_l} = f_j}} \mathbf{K}_V^{(3)q_l f_{LO_l}}(f_{i1}, f_{i2}, f_{i3}) \cdot \mathbf{v}(f_{i1}) \otimes \mathbf{v}(f_{i2}) \otimes \mathbf{v}(f_{i3}) = \mathbf{S}(f_j)$$

Generalized branch equations for every harmonic

High-Level Simulation Approach (cont.)

- Formulate "harmonic balance" nonlinear system of equations:

$$\mathbf{Q}^{(1)} \cdot \mathbf{x} + \mathbf{Q}^{(2)} \cdot \mathbf{x} \otimes \mathbf{x} + \mathbf{Q}^{(3)} \cdot \mathbf{x} \otimes \mathbf{x} \otimes \mathbf{x} = \mathbf{S}$$

$$\text{where } \mathbf{x} = \begin{bmatrix} \mathbf{i}(f_1) \\ \cdots\cdot \\ \mathbf{i}(f_J) \\ \mathbf{v}(f_1) \\ \cdots \\ \mathbf{v}(f_1) \\ \mathbf{e}(f_1) \\ \cdots \\ \mathbf{e}(f_1) \end{bmatrix} \quad \text{and } \mathbf{Q}^{(i)} \text{ are assembled from } K_{V,I}^{(m),1}$$

Very Sparse !

•similar approach: VIOMAP(Verbeyst 94)
- •only for weakly nonlinear
- •cascade

- ◆ Solve non-linear system using Newton-Raphson
- ◆ Problem: exponential complexity
  - ▲OK for small RF behavioral systems

Results

- Behavioral description
  - 10 blocks, 2 LOs, 3 RF inputs
  - 10 nodes, 20 branches
- Solution
  - 16,000 possible output frequencies
  - 217 useful output frequencies
  - 11,000x11,000 complex system of equations
  - Jacobian 0.02% sparse
- 8 CPU sec on 600MHz DEC Alpha
- Working on simulating full receiver example
  - SpectreRF for blocks, behavioral for system

Noise Simulation - Cyclo-stationary

- Input: $R_{ss}(t,\tau) = \sum_{i=-\infty}^{\infty} R_{x_i}(\tau) \cdot e^{ji2\pi f_o t}$
- LTV system: $h(t,\tau) = \sum_{m=1}^{L} \sum_{i=-\infty}^{\infty} h^{m,i}(\tau) \cdot e^{ji2\pi f_m t}$
- Output spectrum:

$$S_{xx_0}(-\omega) = \sum_{\omega_{j1}} \sum_{\omega_{j2}} \sum_{i=1}^{N} \sum_{k=1}^{N} H_{xu_i}^{\omega_{j1}}(\omega - \omega_{j1}) \cdot \mathrm{S}_{u_i u_k}^{\omega_{j2}}(-\omega + \omega_{j1}) \cdot H_{xu_k}^{\omega_l - \omega_{j1} - \omega_{j2}}(-\omega + \omega_{j1} + \omega_{j2})$$

- Need to compute all the sideband transfer functions from all ports to X , where $H_{xu_i}^{\omega_{j1}}(\omega) = H_{xu_i}^{m,j}(\omega - \omega_{j1}) : \omega_{j1} = j \cdot \omega_m$
- Use unity sources, KCL, KVL, branch equations to compute $H_{xu_i}^{\omega_{j1}}(\omega - \omega_j), \forall \omega_j$

Status

- Simulator: under testing
- Test it for pager system design
- Build more accurate noise models