The Mixed-Level Circuit and Device Simulator LinzFrame for Modeling of RF Circuits and Devices

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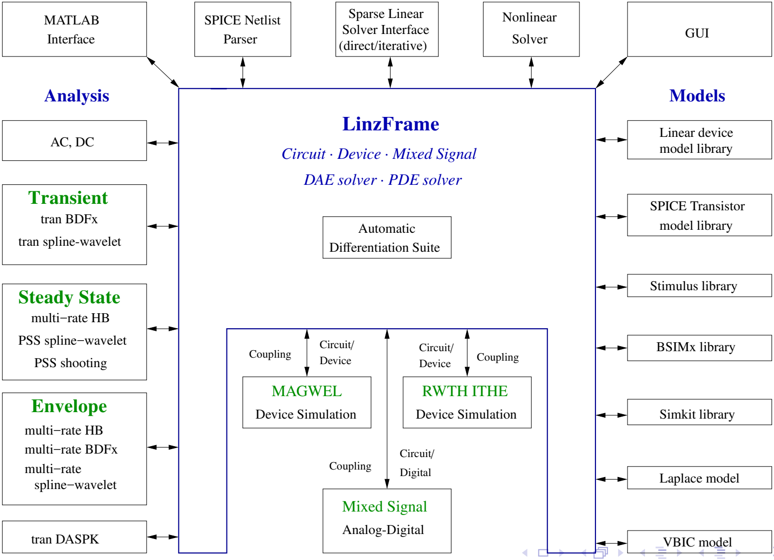
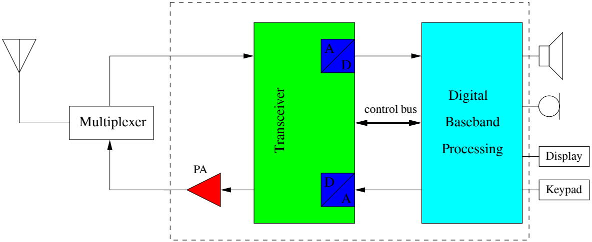
The Mixed-Level Simulator LinzFrame

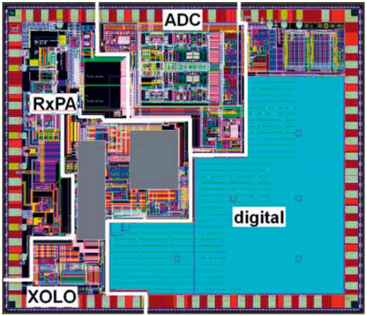


Transceiver · Crosstalk Analog-Digital

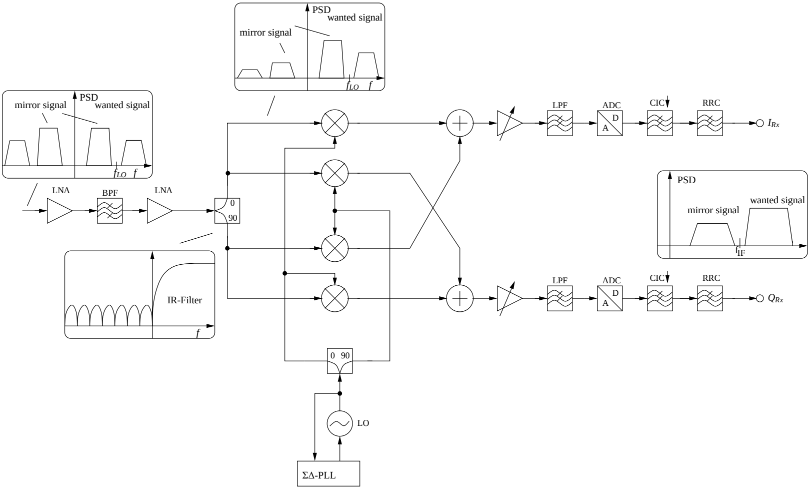
Analog front-end and DSP



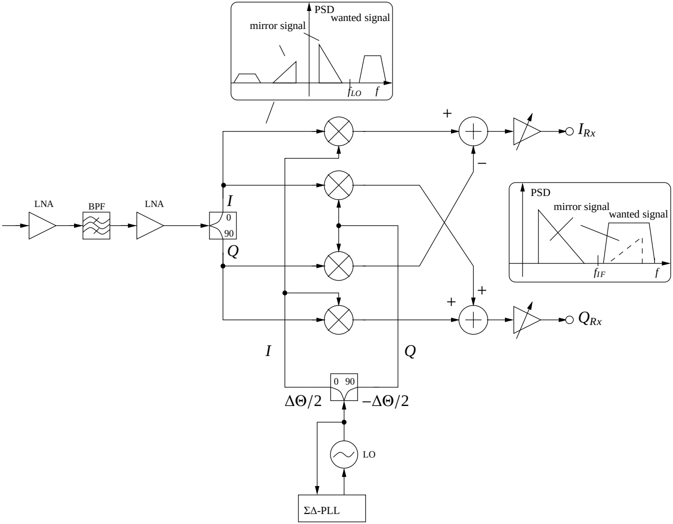
Analog and DSP on the same die



Mismatches · Crosstalk



Design requirements · Mirror signals



Simulation Perspective

- Baseband (envelope) and RF signals occur simultaneously · sampling theorem bottleneck
- Nonlinearities of the devices to be taken into account
- Lumped and distributed devices on the same die
- Modeling of nonlinear RF devices from measurements (e.g. X-params)

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Simulation Challenges · Solutions

- Sampling theorem bottleneck · Multi-rate methods
- Nonlinearities of the devices · Multi-rate methods for nonlinear differential equations
- Lumped and distributed devices · Mixed-level circuit and electromagnetic field simulation
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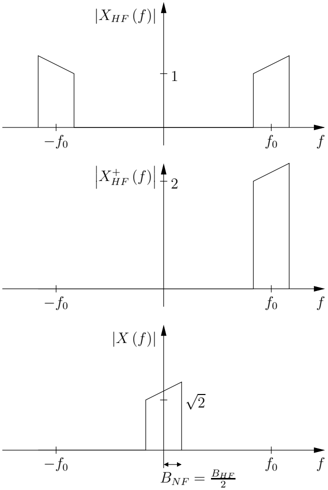
State of the Art · Equivalent Complex Baseband Method (ECB)



- Unified theoretical treatment of baseband and bandpass communication (i. e. GMSK, OFDM)
- Simulation of bandpass systems independent of the carrier frequency
- Circumventing the bottleneck of Shannon's sampling theorem
- Method is restricted to LTI systems

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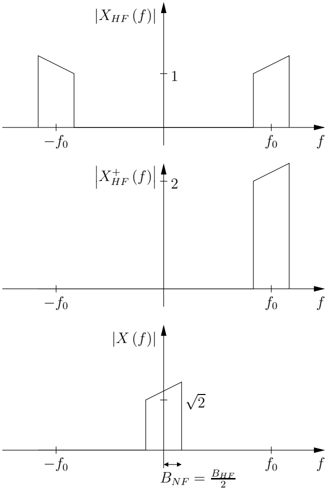

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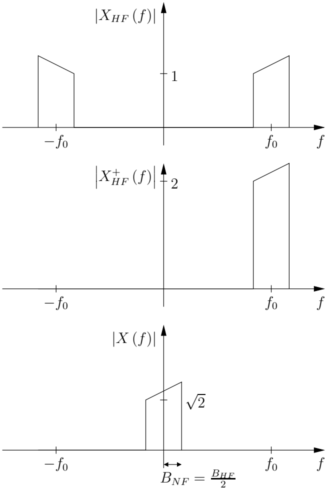

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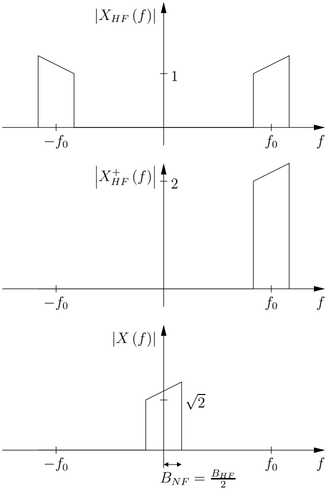

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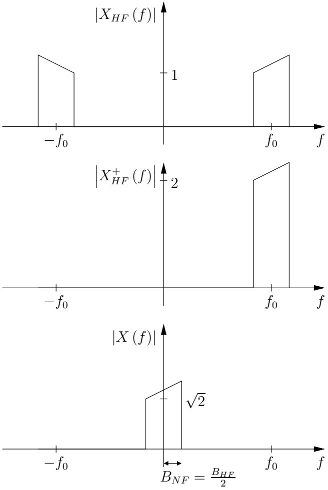

- Generation of the analytical signals by filtering of the bandpass signals

$$X^+_{HF}(f) = \begin{cases} 2X_{HF}(f), & f \geq 0 \\ 0, & f < 0 \end{cases}$$

- Modulation (frequency shift) of the analytical signal

$$X(f) = \frac{1}{\sqrt{2}} X^+_{HF}(f + f_0)$$

- Baseband signal is complex valued in general

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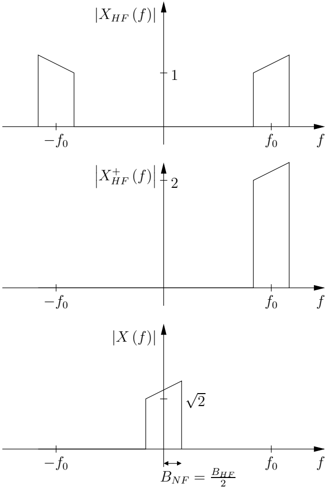

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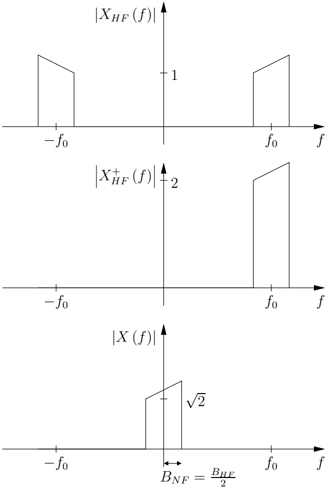

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Multi-rate signals · Goals

- Avoiding the bottleneck of Shannon's sampling theorem by decoupling the baseband (envelope) signal from the carrier signal
- Generalizing the ECB method for nonlinear systems and nonlinear differential equations from electronic circuits
- Method shall be compatible with standard circuit simulators (i.e. SPICE) employing the Modified Nodal Analysis (MNA)
- State of the art device models (BSIM, MEXTRAM etc.) including Jacobians
- Therefore perturbation methods such as Volterra series are out of scope since they require higher order derivatives

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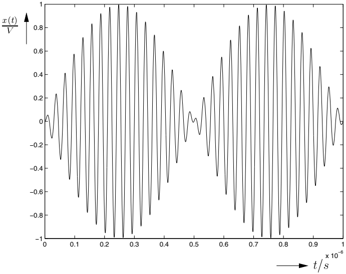
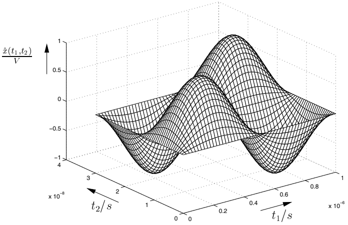
Multi-rate signals · bottleneck





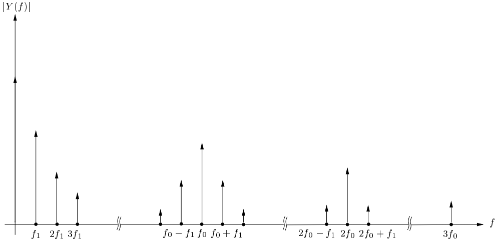
Assumptions: $f_c \gg B_{NF}$;
The sampling rate is a factor of $5-10$ larger than the Nyquist rate;
Simulation over interval of length $T > \frac{1}{B_{NF}}$

$$\rightsquigarrow \text{Number of samples: } K \gg 10 \cdot \frac{f_c}{B_{NF}}$$

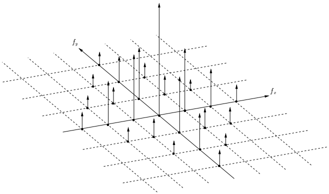
Separation of scales: Introducing a slow time scale t_1, a fast time scale t_2 and a multirate waveform $\hat{x}(t_1, t_2)$:
$\rightsquigarrow$ $K = 10^2$ in the domain (t_1, t_2) at the same accuracy independent of the frequencies with periodic boundary conditions

Intermodulation distortion · Spectra

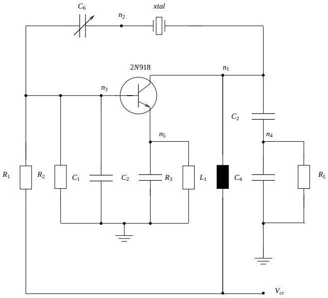
Sparse one dimensional spectrum $X(f)$



Dense two dimensional spectrum of the multirate waveform $\hat{X}(f_1, f_2)$



Quartz crystal oscillators · Transients



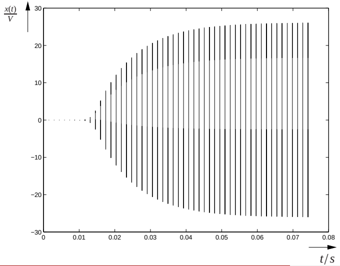
Highly stiff systems with oscillatory behavior such as quartz crystal oscillators etc.

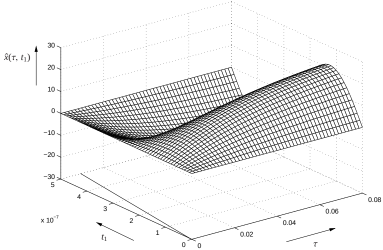
e.g. Pierce oscillator: $f_{LO} = 2$ MHz

settling time $T_r \approx 50 ms$

$\rightsquigarrow$ Number of sampling points:

$K \approx 10 \cdot T_r \cdot f_{LO} = 10^6$





Nonlinear Multi-rate · The multi-rate PDE

- Circuit equations (MNA): $\frac{d}{dt}q\big(x(t)\big) + i\big(x(t)\big) = s(t), \quad x(0) = x_0$
- **Multirate formulation:** partial DAE

$$\frac{\partial}{\partial\tau}q\big(\hat{x}(\tau,t)\big) + \omega(\tau)\frac{\partial}{\partial t}q\big(\hat{x}(\tau,t)\big) + i\big(\hat{x}(\tau,t)\big) = \hat{s}\big(\tau,t\big)$$

- $x_\theta(t) = \hat{x}\big(t,\Omega_\theta(t)\big), \qquad \Omega_\theta(t) = \theta + \int_0^t \omega(s)\,ds$

  solves

$$\frac{d}{dt}q\big(x(t)\big) + i\big(x(t)\big) = \hat{s}\big(t,\Omega_\theta(t)\big)$$

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The multi-rate PDE · Further requirements

- Periodicity: $\hat{x}(\tau,t)=\hat{x}(\tau,t+P)$ $\hat{s}(\tau,t)=\hat{s}(\tau,t+P)$
- e.g. $P=1$, $P=2\pi$ or $P=T_2$ (period of carrier)
- Initial values $\hat{x}(0,t)=X_0(t)$, $X_0(0)=x_0$
- Additional unknown $\omega(\tau)$
- For any $\omega_1(\tau)$ and $\omega_2(\tau)$ and corresponding solutions $\hat{x}_1(\tau,t)$ and $\hat{x}_2(\tau,t)$ there is an $S(\tau)$ with

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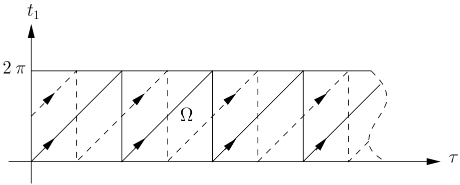
The multi-rate PDE · Characteristic curve

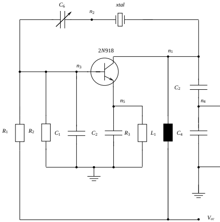


Solution of ordinary DAE along characteristic curve

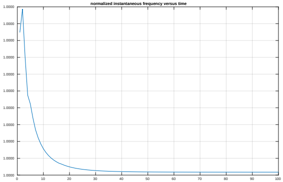
$$\big(t, \Omega_\theta(t)\big)$$

for a family of initial conditions;
specifically $\theta = 0$ for the solution of the initial value problem $X(0) = x_0$

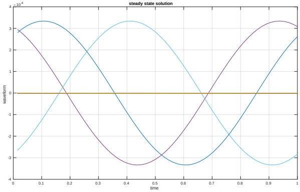
2 MHz Pierce quartz crystal oscillator



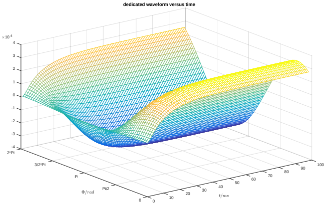
Circuit schematic



Instantaneous frequency

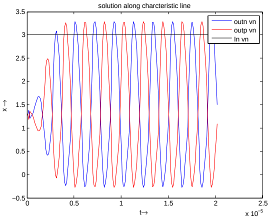


Steady state solution

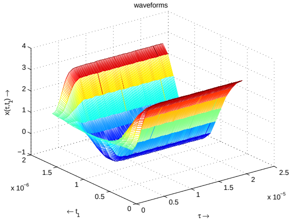


Partial DAE solution

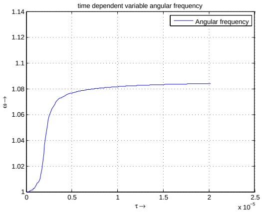
Voltage Controlled Oscillators (VCO)



time domain solution

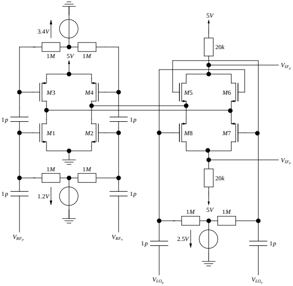


partial DAE solution

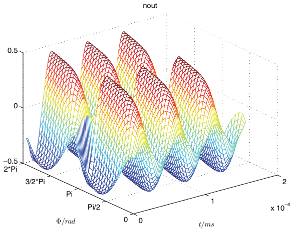


instantaneous frequency

Folded Mixer



circuit schematic



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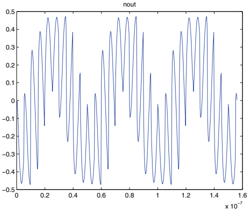
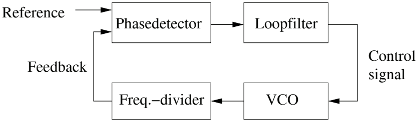
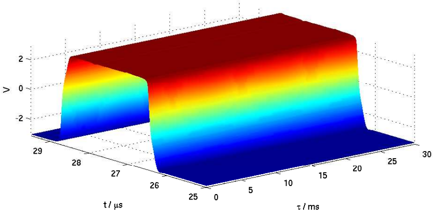


time domain solution

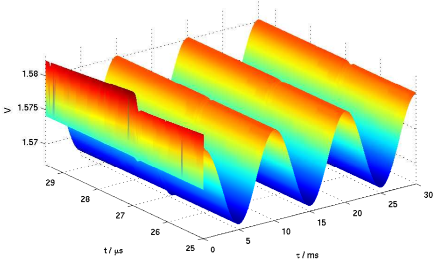
PLL $s(t) = \sin\left(2\pi f_1 t + \frac{\Delta_f}{f_2}\sin(2\pi f_2 t)\right)$



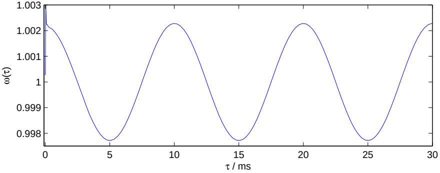
Block diagram



Feedback

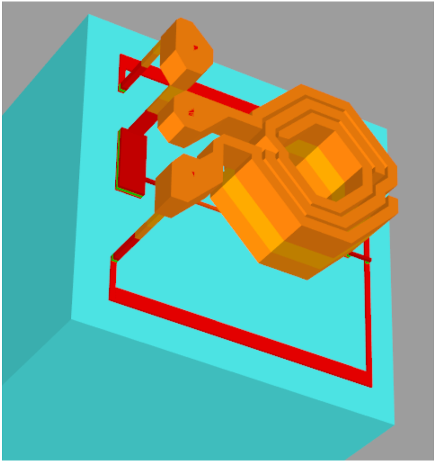


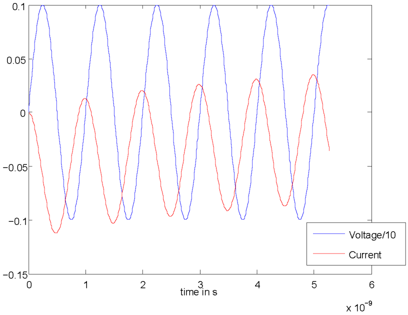
Control



$\omega(\tau)$

fp7 nanoCOPS · On-chip Inductor





Simulation perspective

- Distributed devices: 3D electromagnetic field simulation
- Distributed and (approximately) lumped devices in the same circuit
- Standard approach: characterization of distributed devices by S-params in the frequency domain.
- Either by measurements or 3D electromagnetic field simulation
- New approach: Mixed-level circuit and field simulation employing Magwel's field simulator devEM

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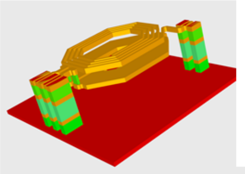
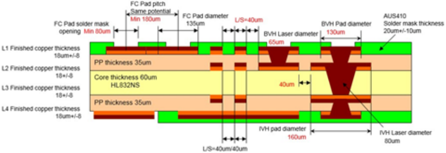
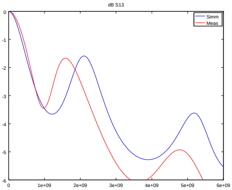
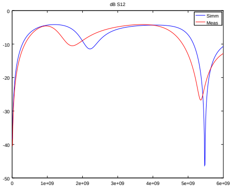
Coupled simulation: π phase shifter balun



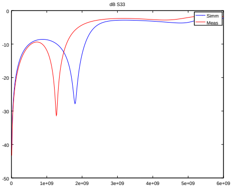




S_{13} dB

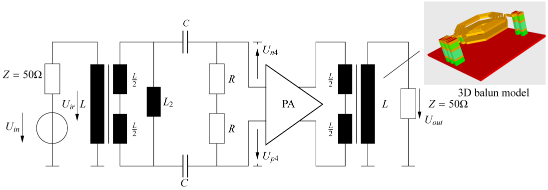


S_{12} dB

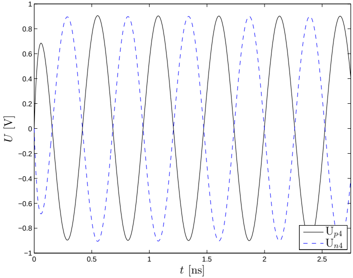


S_{33} dB

Balun with power stage

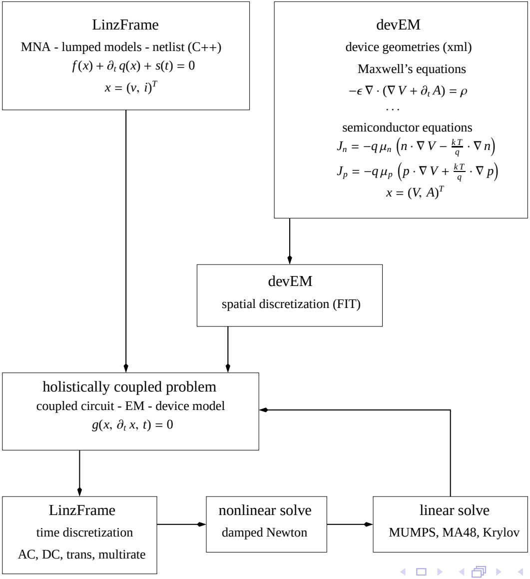


Power stage with single/differential wiring

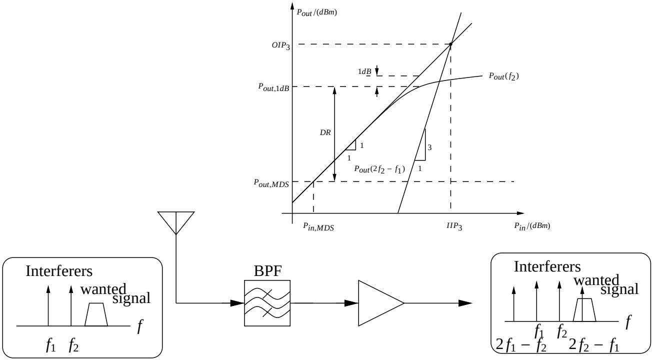


Differential output

The Coupled Simulator · Master-Slave



InterReg – InterOP · Nonlinearities · IP3



- Continuous wave interferers at frequencies f_1 and f_2
- Nonlinear intermodulation distortion at frequencies $2f_1 - f_2$ and $2f_2 - f_1$ falling inband
- Sophisticated filter techniques required

Modeling Perspective

- IP3 is basically a Taylor series expansion of 3rd order
- Dynamical effects (memory) is not taken into account
- Frequency domain: generalizations of S-params: X-params
- X-params: measurement equipment and behavioral modeling tools available
- Behavioral modeling techniques do not fit measurements well

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Current and future work

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- Floquet theory approach resulting theory of dynamical systems
- Volterra series
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The circuit simulator LinzFrame