Lecture 8.
Introduction to RF Simulation

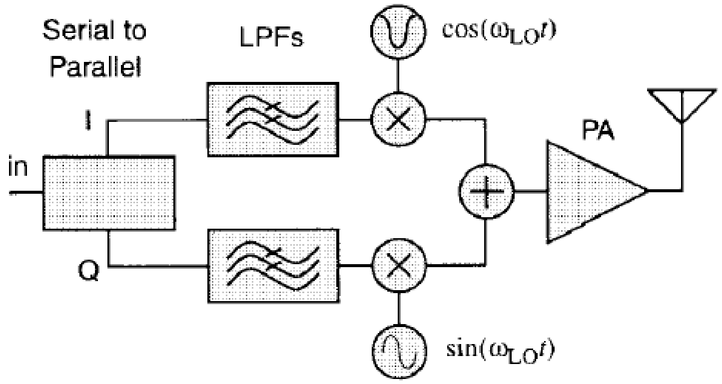
Jaeha Kim
Mixed-Signal IC and System Group (MICS)
Seoul National University
jaeha@ieee.org

Overview

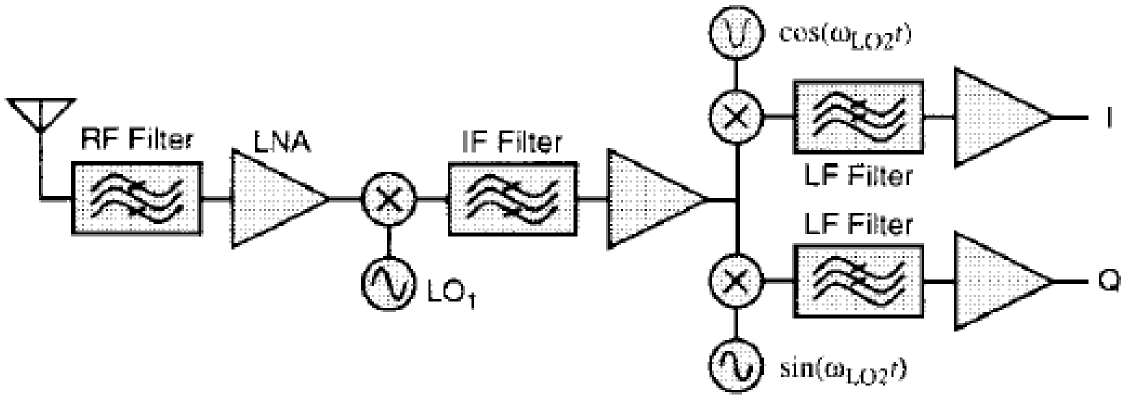
- Readings:
  - K. Kundert, “Introduction to RF Simulation and Its Application,” JSSC, Sept. 1999.
  - L. Zadeh, “Frequency Analysis of Variable Networks,” Proc. I.R.E., Mar. 1950, pp. 291-299.
- Background:
  - This lecture introduces advanced class of simulation algorithms that perform linear, periodically time-varying (LPTV) analyses on circuits. These simulations are commonly referred to as “RF simulations”, but once you understand the underlying principles, there are a myriad of ways to utilize them for broad classes of circuits beyond RF.

RF Transceiver

Direct Conversion Transmitter



Super-Heterodyne Receiver



- Identify the key circuit blocks and their purposes
  - Filters, LNA, LO, mixers, PA, …
- Which ones would have difficulties in characterizing their functionalities/performances using conventional SPICE?

SPICE Analysis Modes: TRAN

- TRAN: time-domain analysis
  - Most versatile way of simulating a circuit – measures the output time-waveforms for given inputs' time-waveforms
  - Note: when digital folks say "simulation", they always mean this transient analysis (e.g. Verilog only runs in time-domain)

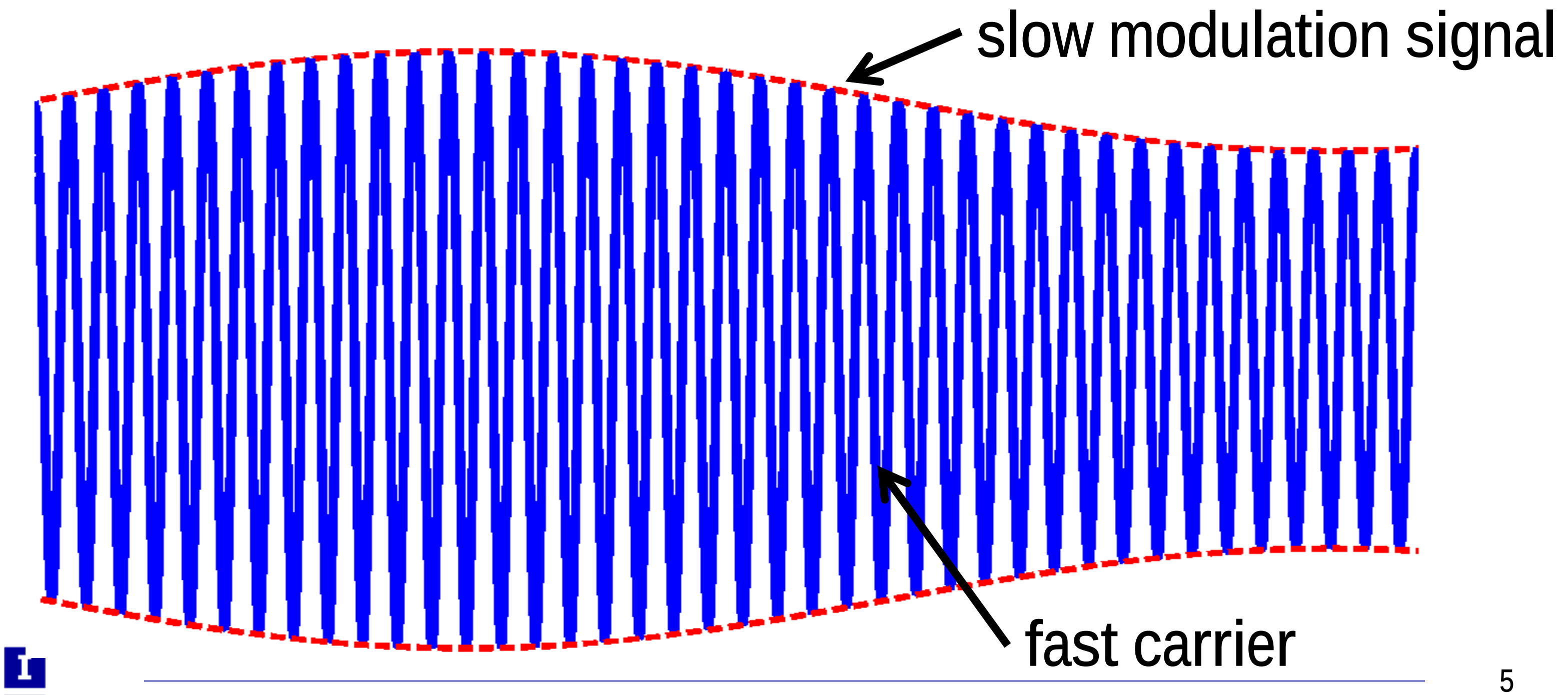
- Which blocks can you verify/characterize with TRAN?
  - Check each of filter, LNA, LO, mixer, PA, …
  - Yes, you can simulate any circuits with TRAN but you can never *<u>completely verify</u>* the circuit with it
  - This is why digital people ask for "formal verification tools"

RF Characteristics I: Narrowband Signals

- RF signals are expressed as *modulated carriers*, e.g.,

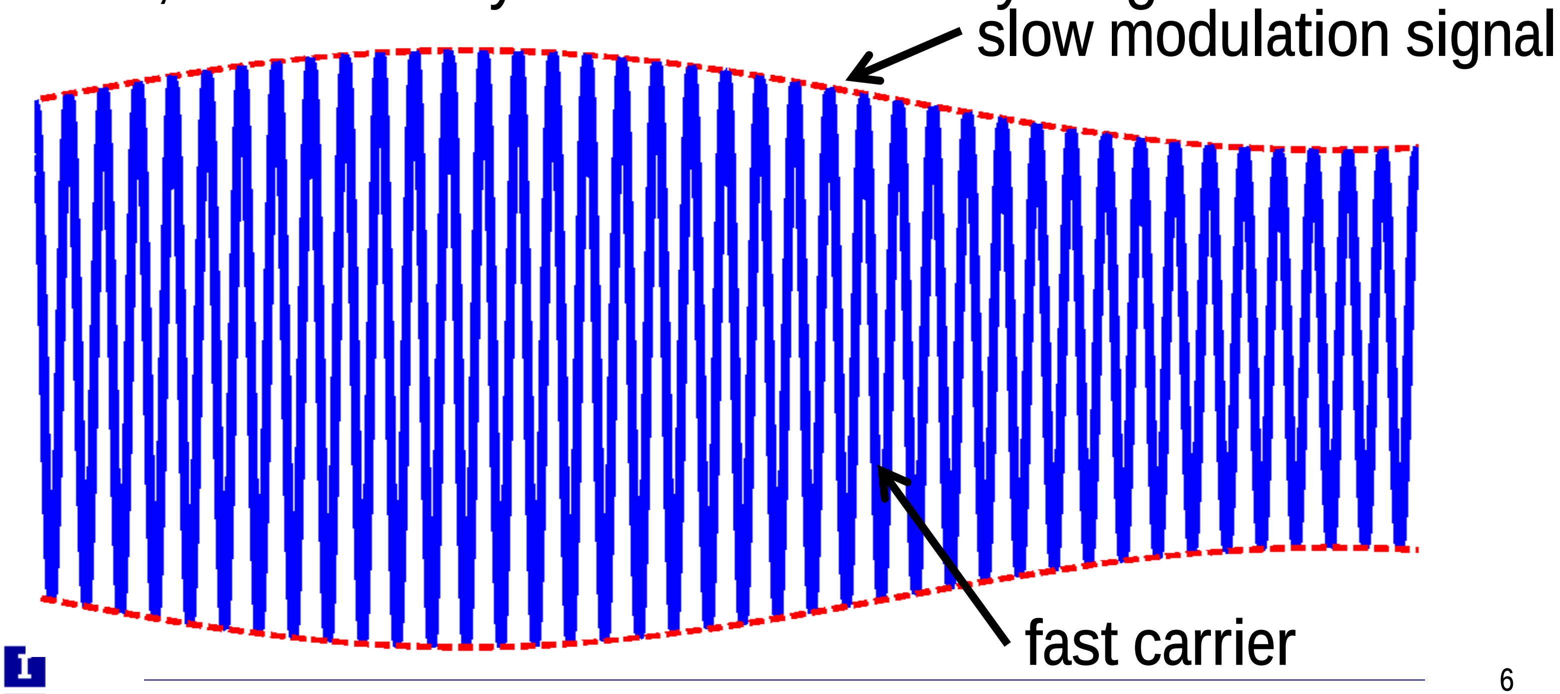
$$y(t) = m(t) \times A_c \cdot cos(\omega_c t)$$

  - Amplitude, phase, or frequency can be modulated



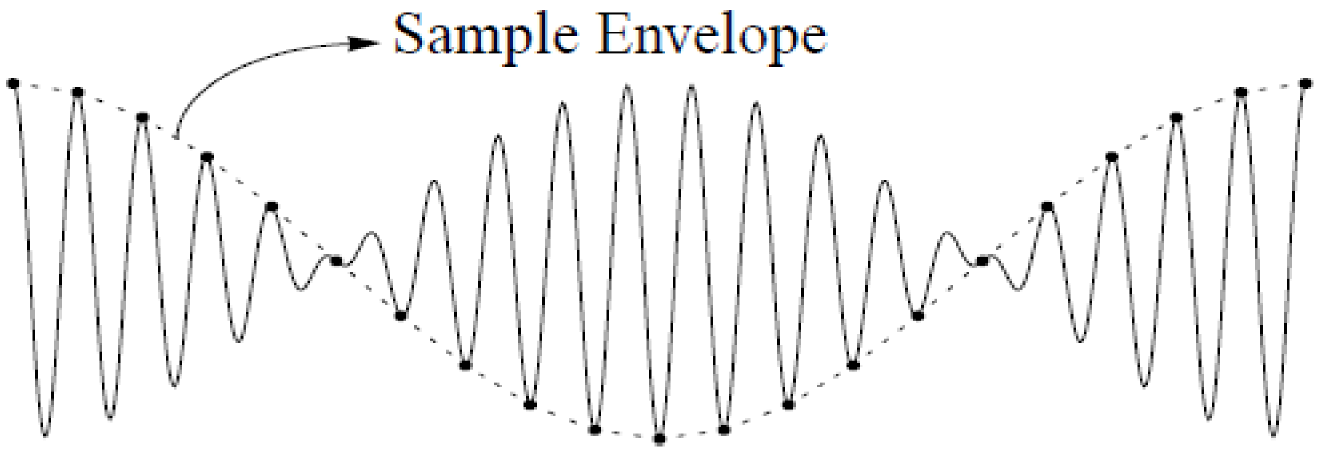
RF Characteristics I: Narrowband Signals

- To measure RF circuit responses with TRAN analysis
  - We need fine time steps due to the high-frequency carrier
  - Also, long time span due to the low-frequency signal
- Hence, TRAN analysis can take a very long time



RF Analysis Modes: Envelope-Following

- Accelerates transient simulation assuming that the response is a slowly-modulated periodic waveform
  - Once the periodic waveform (i.e. the carrier) is found, only the small changes between the cycles are computed
  - e.g. for simulating initial transients of phase-locked loops



SPICE Basics

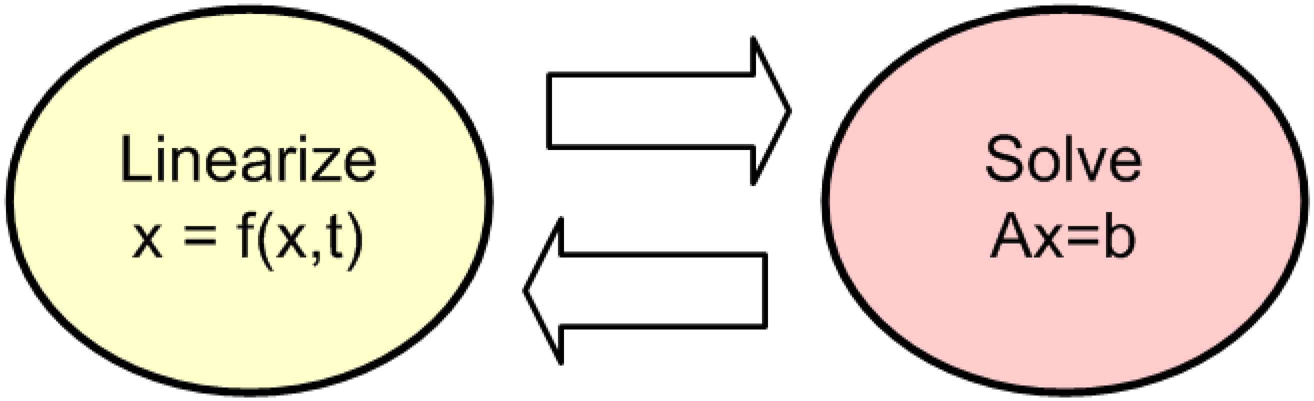
- SPICE is basically a nonlinear ODE solver, which formulates an arbitrary circuit into:

KCL: $$f(v(t),t) = \underbrace{i(v(t))}_{\text{nonlinear conductors}} + \underbrace{\frac{dq(v(t))}{dt}}_{\text{nonlinear capacitors}} + \underbrace{u(t)}_{\text{current sources}} = 0$$

- One reason for SPICE's success was its reliable equation formulation algorithm
  - called modified nodal analysis (MNA)

SPICE Basics (2)

- Once the equation is formed, its solution is found by iterating between linearization and solving
  - Linearize the nonlinear ODE around its temporary solution
  - Solve the linear ODE
  - Repeat until the solution converges



Linearize
$x = f(x,t)$

Solve
$Ax=b$

SPICE Analysis Modes: DC, AC

- SPICE offers two kinds of steady-state analysis
- DC: finds the DC steady-state response of a circuit
  - Assuming the circuit reaches a DC state at t=∞, solve:

$$f(v(t=\infty), t=\infty) = i(v_{DC}) + u_{DC} = 0$$

  - Solving this eq is actually the most difficult task in SPICE!
  - Note: it finds “a” solution but not all the solutions…
- AC: calculates the steady-state response to a small-signal, sinusoidal perturbation
  - Linearizes the system and use phasor analysis to compute the transfer functions
  - Extremely efficient computation – the fastest in SPICE!

Characterization with DC/AC Analyses

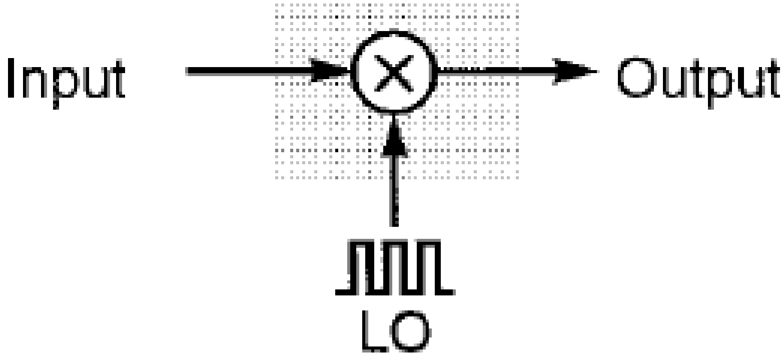
- Which blocks can you verify/characterize with DC/AC?
  - Your choices: filter, LNA, LO, mixer, PA, …

- The ones with linear, time-invariant (LTI) behaviors
  - Filters (LPF, BPF), LNA, and PA fall into this category
  - A frequency-domain transfer function completely describes their functional behavior (filtering, narrow-band amplification)

- But what about others?
  - Mixers and oscillators – are they just nonlinear?

RF Characteristics II: Linear Time-Varying

- Mixers, just like other RF circuits, are designed to be as linear as possible *from its input to output* while minimizing distortion/nonlinearities
- Mixer circuit itself exhibits strong nonlinearity and typically driven by a large-signal LO clock:

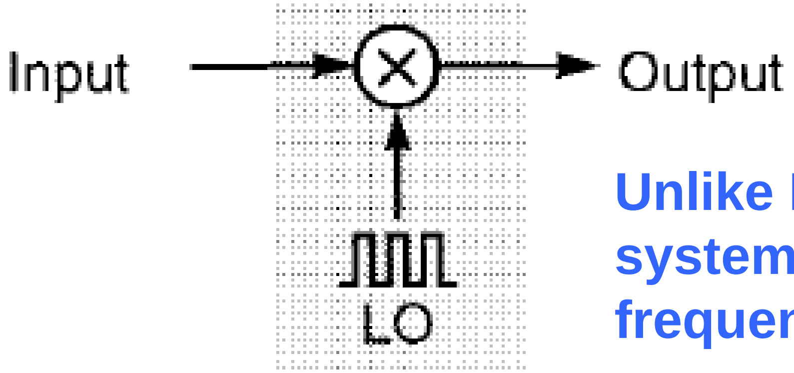


RF Characteristics II: Linear Time-Varying

- However, the LO clock does not bear any information
  - It is more like part of the circuit (i.e. the circuit wouldn't function correctly – frequency translation – without it)
- Then mixer+clock can be perceived as a LPTV system:

$$v_{in}(t) = m(t) \cdot cos(\omega_c t)$$

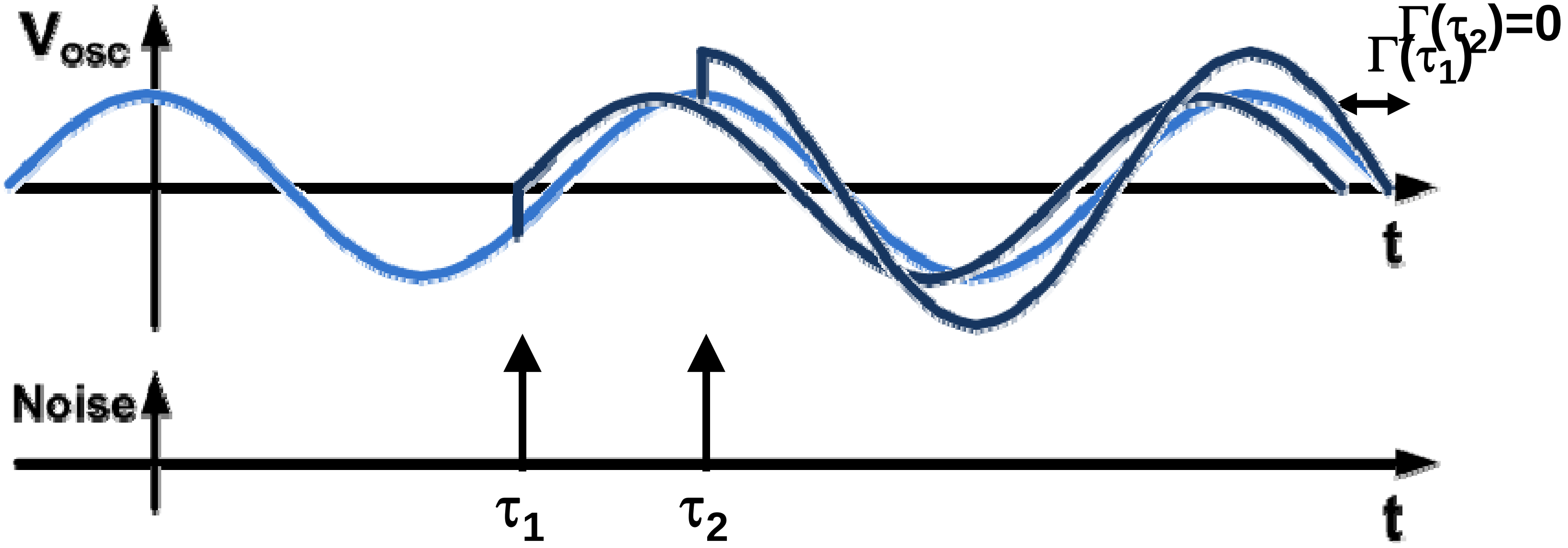
$$v_{out}(t) = LPF\{cos(\omega_{LO} t) \cdot v_{in}(t)\} = m(t) \cdot cos((\omega_c - \omega_{LO})t)$$



Unlike LTI systems, LPTV systems can translate frequencies!

RF Characteristics II: Linear Time-Varying

- Oscillators are time-varying systems since:
  - Its steady-state is a time-varying waveform (periodic)
  - Its response to external noises varies with time



* A. Hajimiri and T. H. Lee, "A General Theory of Phase Noise in Electrical Oscillators," IEEE JSSC, Feb. 1998.

Periodic Steady-State (PSS) Analysis

- Finds a steady-state response of a periodic circuit
  - The circuit may be driven by periodic, large-signal excitations
  - The resulting response is a large-signal one, but must be periodic
  - e.g. output of a mixer with DC input, oscillator output clock
- PSS is an extension of DC analysis to periodic circuits
  - Finds the final waveforms after infinite period of time
  - Useful for:
    - Measuring the steady-state frequency of a VCO
    - Measuring the steady-state phase-offset of a locked PLL
  - However, as with DC, PSS is the most difficult analysis
    - Can have convergence issues if care is not taken

PSS Method 1: Harmonic Balance

- Harmonic balance directly finds the PSS solution in frequency domain
  - Assuming that the PSS solution is T-periodic, it can be expressed in a Fourier series:

$$f(v(t),t) \rightarrow \sum_{k=-\infty}^{\infty} F_k(V) \cdot e^{j2\pi kt/T} = 0$$

$$F_k(V) = I_k(V) + \frac{j2\pi k}{T} Q_k(V) + U_k = 0$$

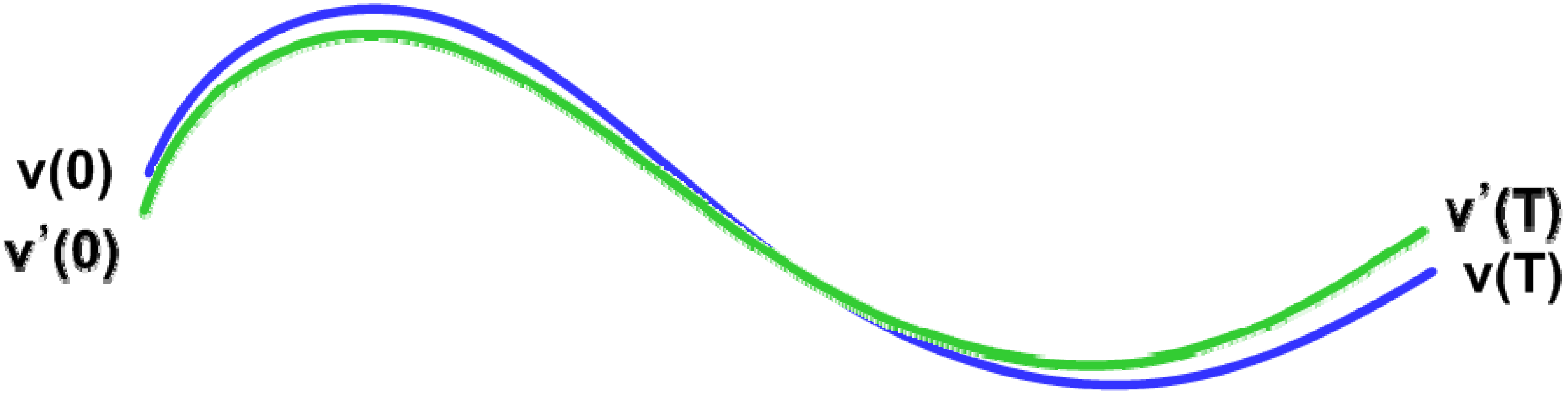
  - Solve a system of equations for k=0, ±1, …, ± K
  - Accuracy/speed depends on the choice of K

PSS Method 2: Shooting Newton

- Shooting solves a boundary value problem to find a T-periodic solution:

$$v(T) - v(0) = 0$$

  - In other words, find a circuit state v(0) that makes the state after T identical to v(0)
  - Requires to calculate the sensitivity of v(T) w.r.t. v(0)



Harmonic Balance vs. Shooting

- Harmonic Balance (e.g. Agilent ADS)
  - A frequency-domain method
  - Easily handles frequency-domain models (e.g. S-parameters)
  - Its accuracy is limited by the number of harmonics used – not suitable for simulating strongly nonlinear responses
- Shooting (e.g. Cadence SpectreRF)
  - A time-domain method
  - Need not choose the number of harmonics – however, the time step should be fine enough to simulate the max frequency AC response
  - Can't handle frequency-domain models directly

SpectreRF Syntax for PSS

- To find its full description (in fact, it works on any Spectre commands):

```
unix> spectre –h pss
```

- For example:

```
PSS_Shooting  pss fund=1G tstab=100n
+ errpreset=conservative

PSS_HB  pss fund=1G harms=10 harmonicbalance=yes
+ errpreset=conservative
```

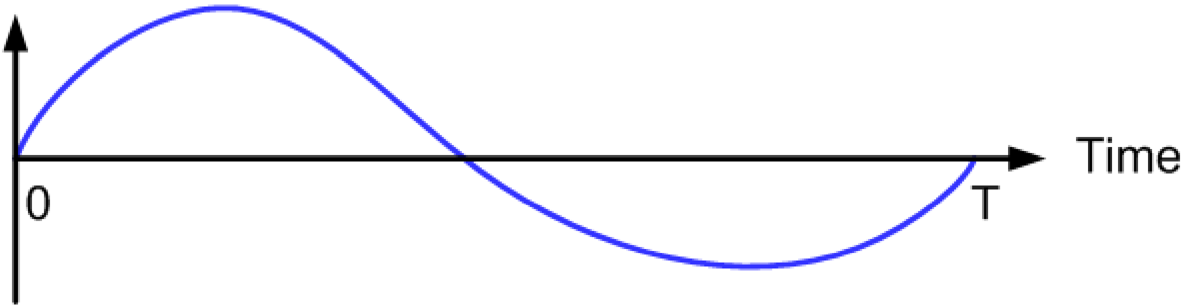
- Tip: use ‘`simulator lang=spice`’ and ‘`simulator lang=spectre`’ to switch the languages within a deck

Dealing with PSS Convergence Issues

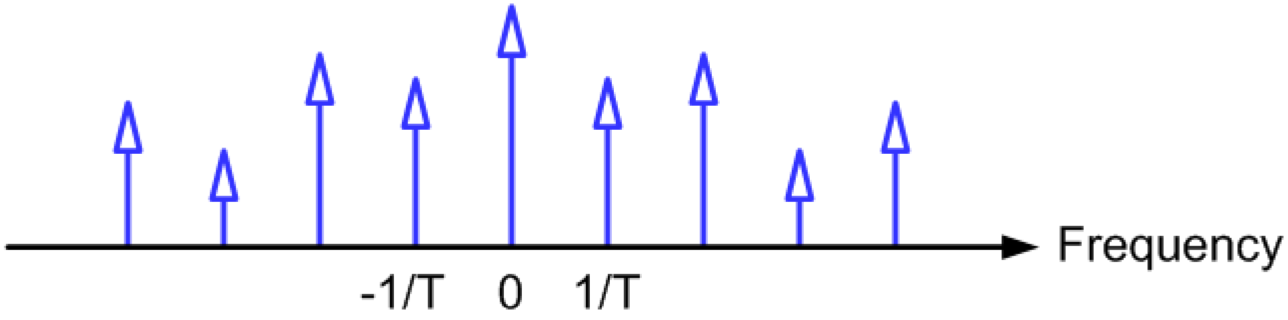
- Before SPICE became mature enough, circuit designers used to encounter “DC convergence failure” error a lot
  - These days, you may get the equivalent messages with PSS
- However, convergence problems are usually the designers’ faults – the circuit isn’t really periodic!
  - Remember, the *entire* circuit must be *perfectly periodic* at the prescribed fundamental frequency
  - Common pitfalls (e.g. for a PLL)
    - Some part of the circuit has longer periods (e.g. divider, prbs)
    - The PD has hysteresis or deadzone near the locked point and the PLL doesn’t lock to a single point

Output of PSS Analysis

- A unit-period time-domain waveform



- A collection of Fourier series component



Quasi Periodic Steady State (QPSS)

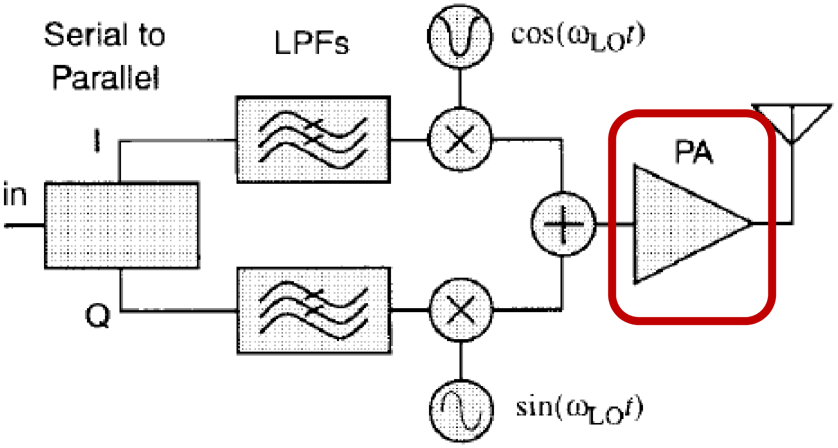
- A circuit driven by two large-signal excitations may have two fundamental tones:

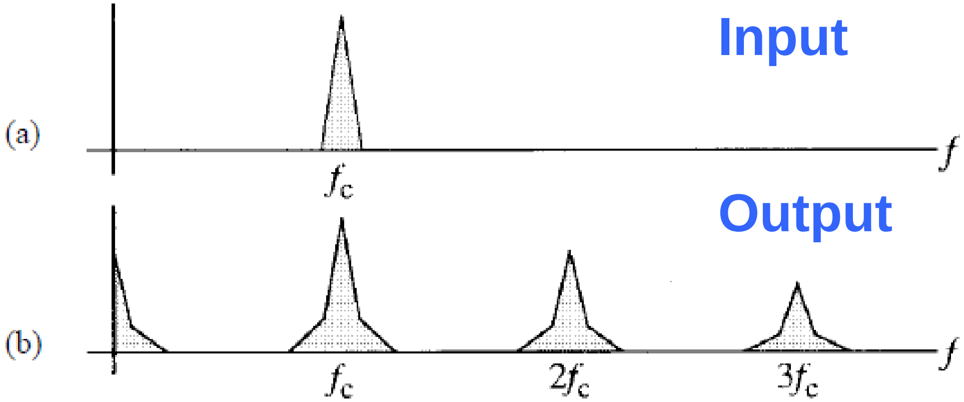
$$x(t) = \sum_{k=-\infty}^{\infty} \sum_{l=-\infty}^{\infty} X_{kl} \cdot e^{j2\pi(kf_1+lf_2)t}$$

- Its steady-state response (i.e., a periodically modulated periodic signal) can be found either by harmonic balance or by shooting

PSS vs. DISTO

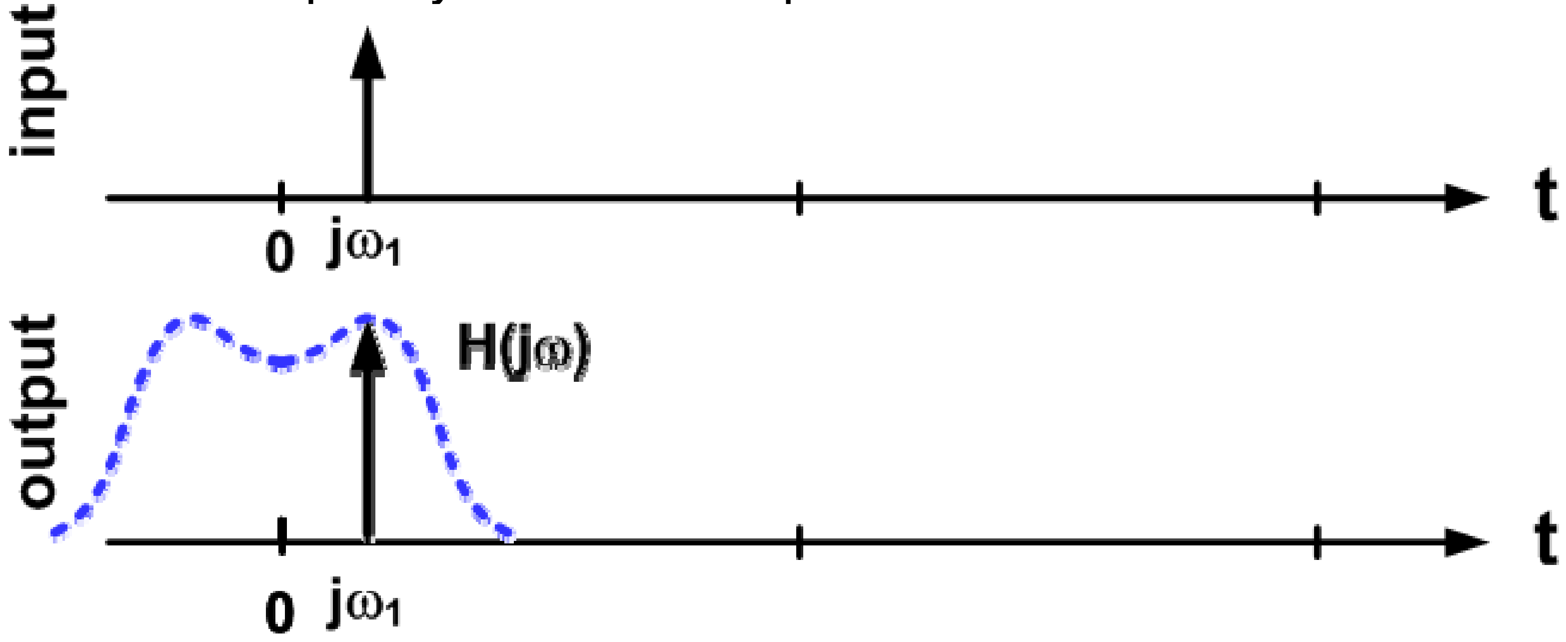
- Consider a PA driven by a large, periodic signal at f_c
  - The PSS output waveform may have spectrums at $k \cdot f_c$ due to the PA's nonlinearities (i.e. harmonic distortion)
- Comparison with SPICE's distortion analysis (DISTO)
  - DISTO computes the harmonic distortions due to "small-signal" inputs while PSS does for "large-signal" inputs





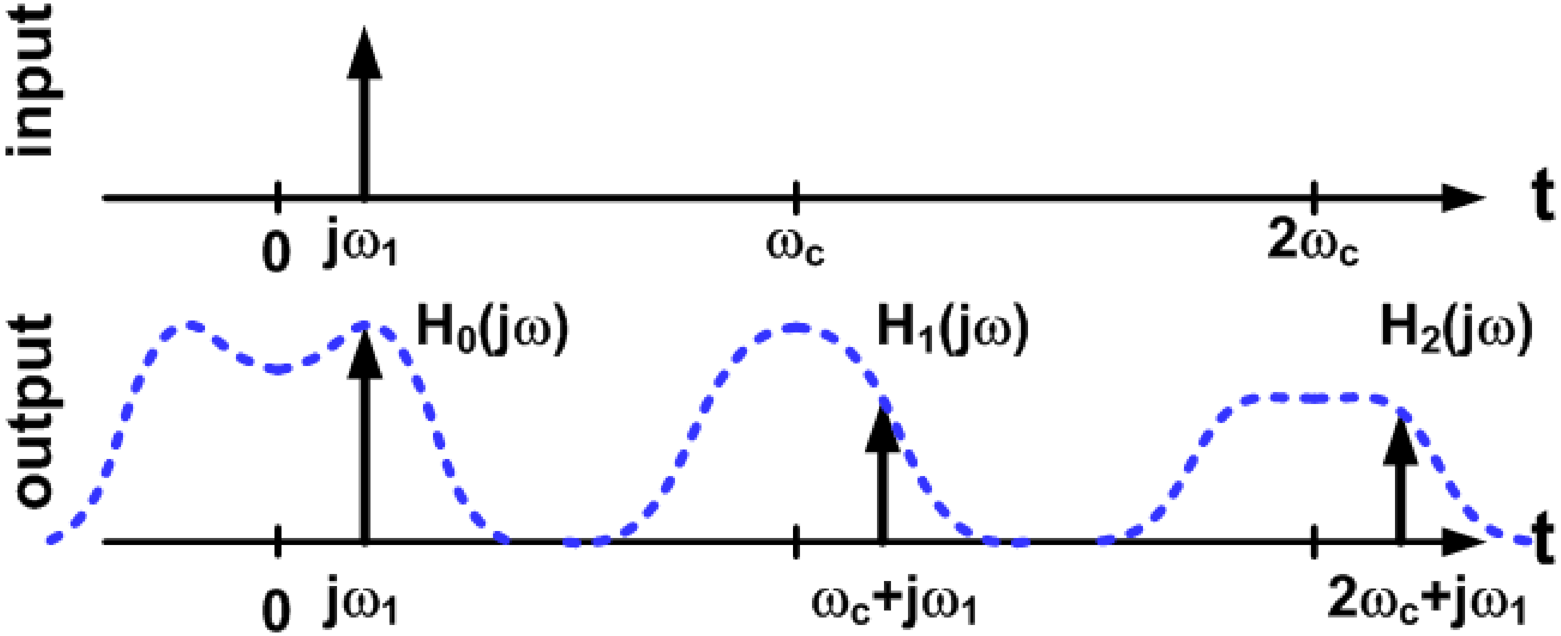
RF Analysis Modes: Periodic AC (PAC)

- Computes the steady-state response to a small-signal sinusoid excitation of a circuit about its PSS
- For LTI systems, AC analysis returns $X(j\omega_1)\cdot H(j\omega_1)$
  - No frequency translation is possible



RF Analysis Modes: Periodic AC (PAC)

- For LPTV systems, a sinusoid input at ω_1 can excite the output at multiple frequencies of $\omega_1+m\cdot\omega_c$
  - $H_m(\omega_c)$ is the transfer function mapping to the m-th sideband
  - In PAC, you specify which $H_m(\omega_c)$ to be reported



Linear Time-Varying System Basics

- Time-varying impulse response h(t,τ):

$$y(t) = \int_{-\infty}^{t} h(t,\tau) \cdot x(\tau) d\tau$$

- Time-varying transfer function H(jω;t):

$$Y(j\omega)e^{j\omega t} = H(j\omega;t) \cdot X(j\omega)e^{j\omega t}$$

- Relationship between h(t,τ) and H(jω;t):

$$H(j\omega;t) = \int_{-\infty}^{\infty} h(t,\tau) \cdot exp(-j\omega(t-\tau)) d\tau$$

- For LPTV system H(jω;t) = H(jω;t+T):

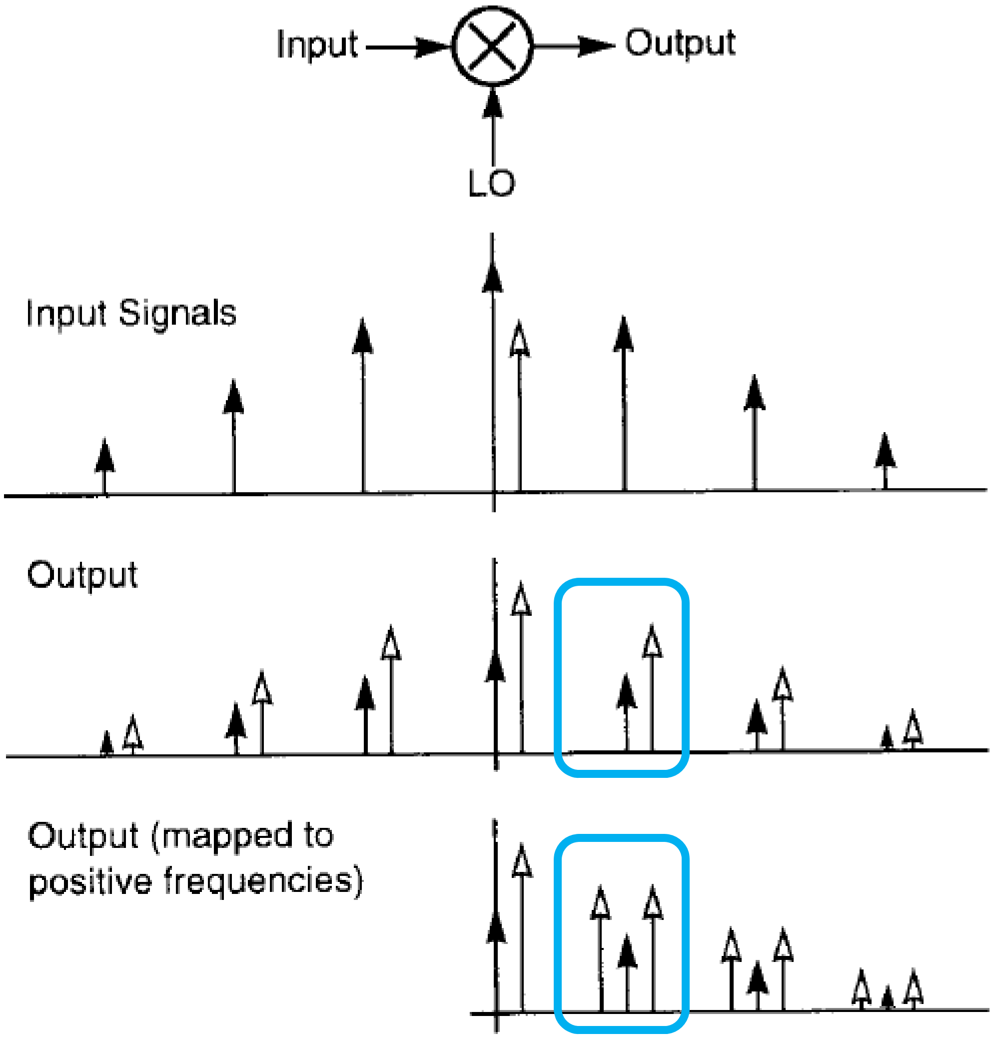
$$H(j\omega;t) = \sum_{m=-\infty}^{\infty} H_m(j\omega) \cdot e^{jm\omega_c t}$$

---

* L. Zadeh, "Frequency Analysis of Variable Networks," Proc. I.R.E. Mar. 1950.

A Mixer Example

- Consider a up-conversion mixer
- TF to which sideband would you be interested in?
- That TF describes the conversion gain, bandwidth, etc.

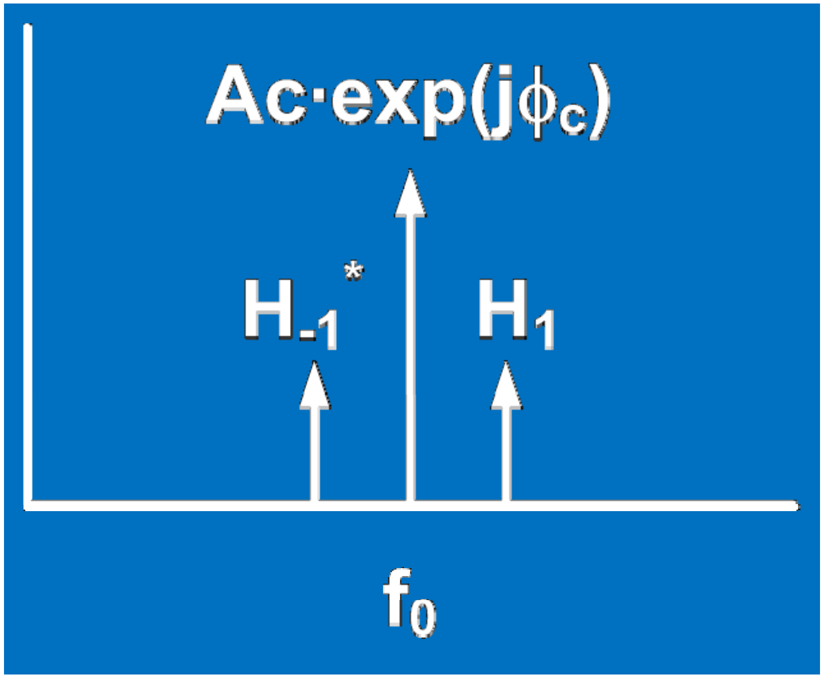


PM vs. AM

- Based on narrowband angle modulation approximation, one can derive whether the input perturbation modulates the phase or the amplitude of the carrier:

$$PM = \frac{j}{A_c} \cdot (H_{-1}e^{j\phi_c} - H_1 e^{-j\phi_c})$$

$$AM = \frac{1}{A_c} \cdot (H_{-1}e^{j\phi_c} + H_1 e^{-j\phi_c})$$



SpectreRF Syntax for PAC

- First, you need a PAC stimulus:

```
Vin   ( in gnd )  vsource dc=0 pacmag=1 pacphase=0
```

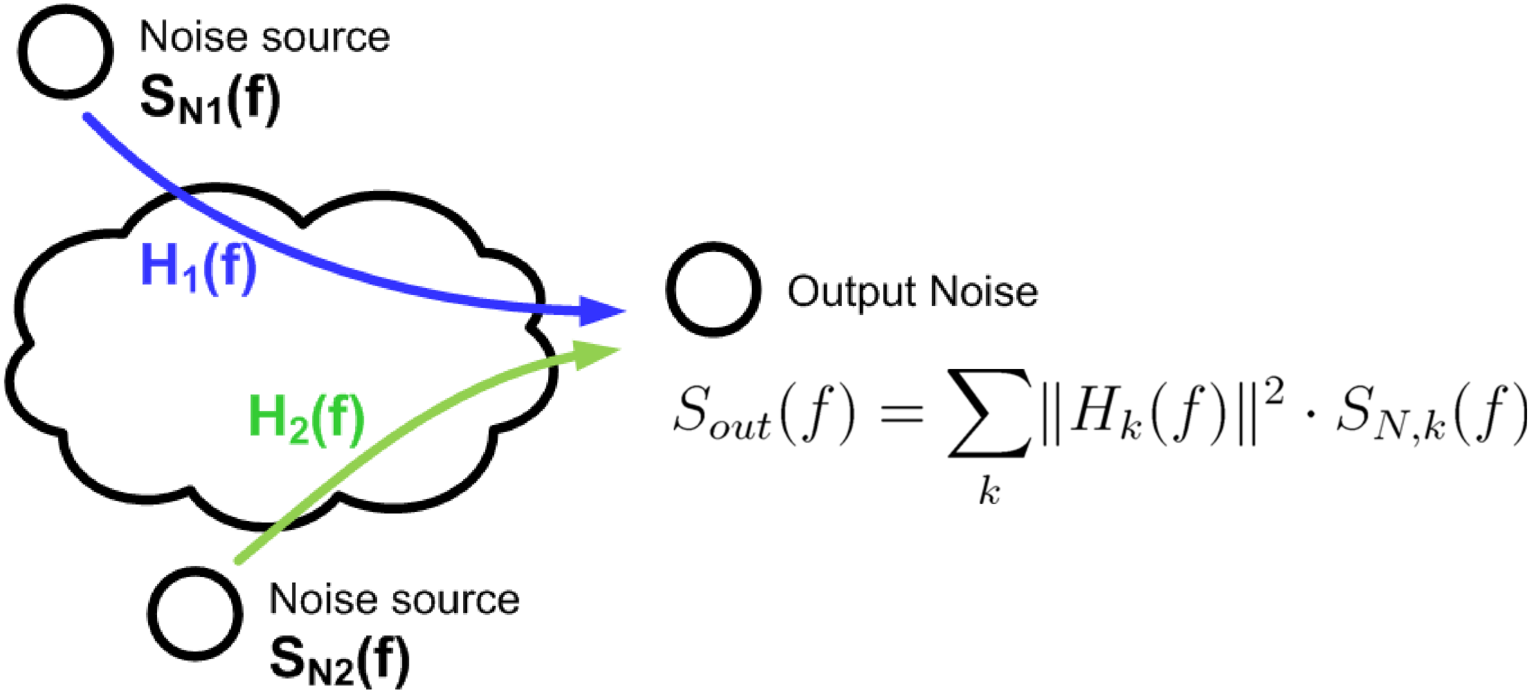
- Then the analysis statement:

```
sim_PAC pac start=1k stop=.1G dec=10 maxsideband=10
freqaxis=in
```

  - **sidebands:** array of relevant sidebands for the analysis.
  - **maxsideband:** equivalent to sidebands = [-maxsideband ... 0 ... +maxsideband
  - **freqaxis:** specifies whether the results should be output versus the input frequency (in), the output frequency (out), or the absolute value of the output frequency (absout)

SPICE Analysis Modes: NOISE

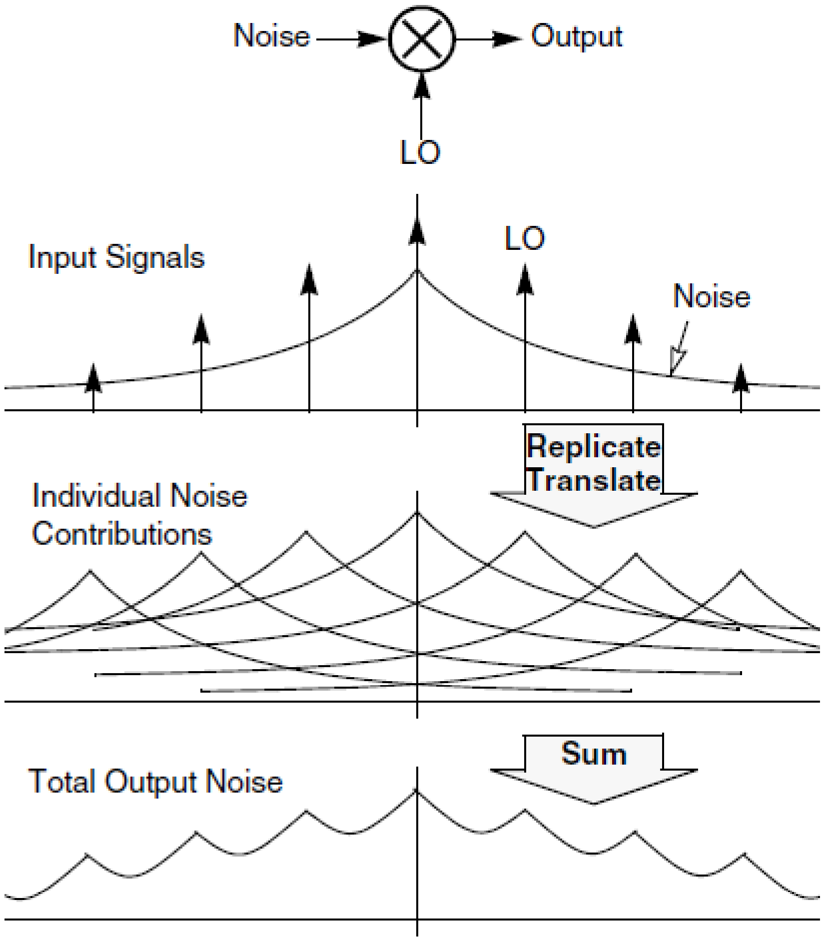
- Computes output noise PSD contributed by multiple noise sources
- Based on the TFs obtained by small-signal AC analysis



$$S_{out}(f) = \sum_k \|H_k(f)\|^2 \cdot S_{N,k}(f)$$

RF Analysis Modes: Periodic Noise

- Since in LPTV systems a single-frequency input can give rise to outputs at multiple frequencies, noise folding may occur
- The resulting noise is in general cyclostationary



SpectreRF Syntax for PNOISE

- Reporting time-averaged PSD of the output noise

```
sim_PNOISE ( outp outn ) pnoise
+       start=1 stop=0.5G dec=20
+       maxsideband=50 noisetype=sources
```

  - maxsideband specifies the # of sidebands in the noise TF to be considered

- Reporting the output noise PSD at specific time (hence, cyclostationary noise):

```
sim_PNOISE ( outp outn ) pnoise
+       start=1 stop=0.5G dec=20
+       maxsideband=50 noisetype=timedomain
+       noisetimepoints=[0.5n] numberofpoints=1
```