Analog and Mixed-Signal Verification for Communications

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U of Minn ECE Dept

- $\sim$ 44 faculty, several areas of activity
  - Communications: Alouini, Giannakis, Kaveh, Tewfik
  - Comp. Arch.: Lilja, Kinney
  - Signal Proc./DSP: Ebbini, Moon, Parhi
  - Devices/Nano: Campbell, Cohen, Kiehl, Nathan, Jacobs
  - Optics/MEMS: Gopinath, Leger, Talgadher
  - Controls/Imag Proc.: Georgiou, Sapiro

U of Minn ECE Dept

- CAD, Analog Design
  - Bazargan: FPGAs, reconfigurable computing, physical design
  - Harjani: RF and mixed-signal design
  - Sapatnekar: Physical design, timing, delay, crosstalk
  - Roychowdhury: Analog and system verification

Analog System Verification Group

- 5 PhD students, 1 MS student
- Undergraduate members
- Projects
  - Automated nonlinear macromodelling
  - Digital-to-analog substrate noise prediction
  - Oscillator, PLL macromodelling/simulation
  - Multi-time methods, robust envelope techniques
  - Fast fiber simulation
  - Prototying infrastructure
- Funding and collaborations: NSF, SRC, DARPA, Fujitsu, Sandia, IBM, TI, Agilent, BDA

Analog System Verification Group

- More information: http://laoo.dtc.umn.edu/~jr/

Market and Circuit Trends

Market Trend: Portable Devices

- Proliferation of small, cheap, ubiquitous devices
  - ☛ cellphones, PDAs, wireless LANs, Bluetooth
  - ☛ already: two-way paging, SMS, 802.11g/a, 2.5G networks
  - ☛ next: 3G, UMTS

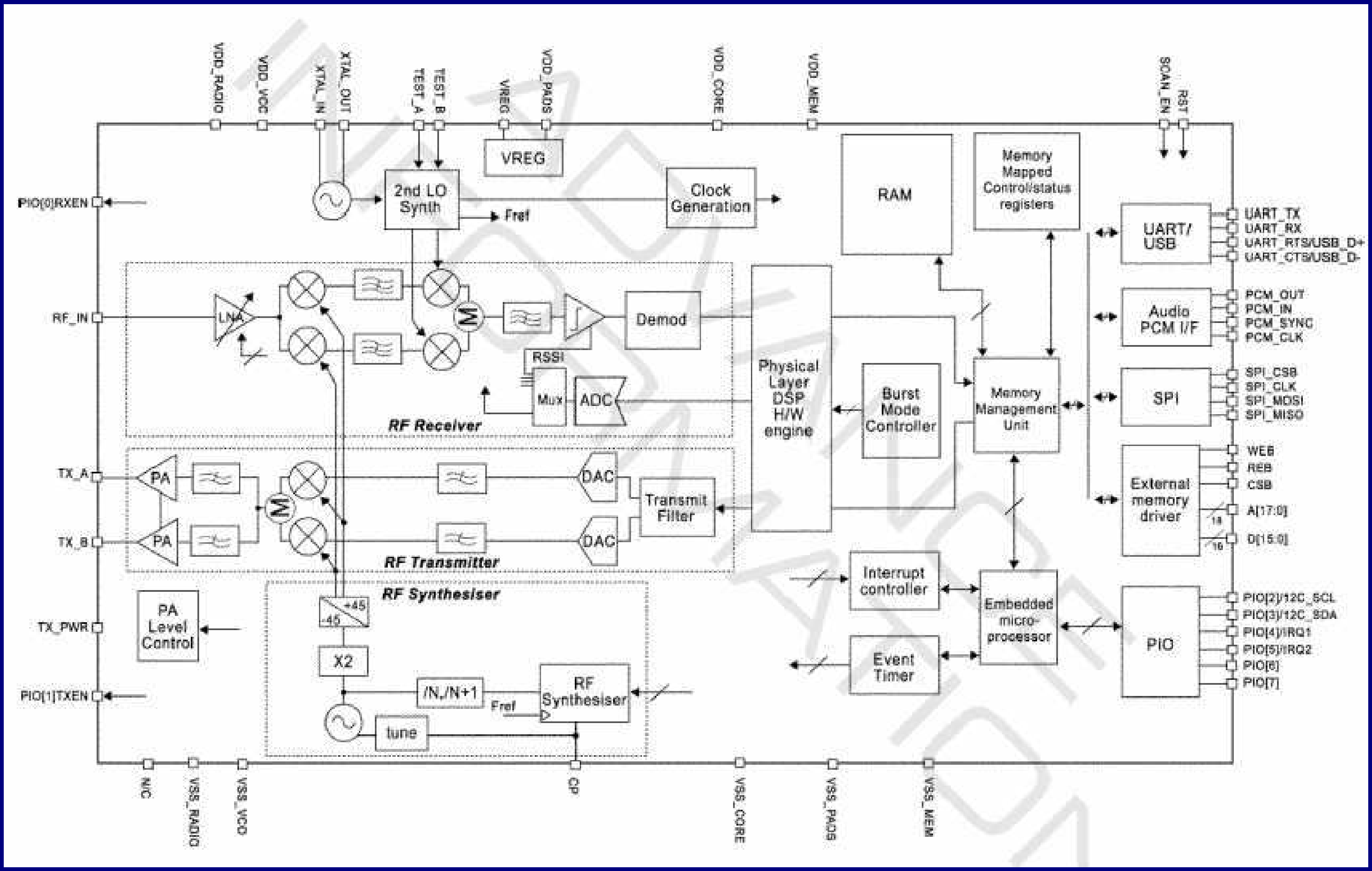
Demand for Portable Commns.

- 2 billion users worldwide by 2007
  - ☛ Maximum growth: SE Asia and China
  - ☛ India: 28M users (Dec 2003); 100M projected, 2005
- US: Tenfold growth by 2005 (200x?)
  - ☛ \$22–\$140b (IDC, Merrill-Lynch)
  - ☛ exceed PC growth over last decade: Intel

Drivers for Demand

- Price
  - ☛ India: 2.1M new subscribers, Dec 2003
    - ☛ *"driven by some of the lowest tariffs in the world"*
- Time to market
  - ☛ competitive pressures
- Design challenge: mixed-signal/RF blocks
  - ☛ the *main* design bottleneck

Integrated Bluetooth Transceiver



Important Mixed-Signal Blocks

- VCOs, mixers, phase detectors, frequency dividers
- **PLLs**: synchronization, clock recovery, frequency synthesis
- LNAs, power amps: rcvr/xmit
- ADCs, ΣΔs, DACs
- z-domain switched-capacitor ckts: baseband filtering
- System focus: deliver everything working together

Simulation Challenges

Mixed-Signal Simulation Challenges

- Larger systems
  - more and bigger blocks: traditional SPICE simulation slow
  - analog/digital proximity: substrate coupling
- Tighter system specs for portable
  - lower power, lower V_{DD}; stringent channel interference specs
  - Noise a greater concern
- New complex design styles, architectures
  - Intimate mix of digital and analog/RF: Viterbi PLLs
  - Marriage of disparate design styles: IC and microwave
  - Highly nonlinear meets widely separated time scales: simulation slow

RF Integration

- High volumes, low cost, low power $\Rightarrow$ integration
  - ☛ skilled one-of-a-kind *vs* fast low-cost mass production
  - ☛ today: $>$ 10 shuttles for RF subsystems
  - ☛ CAD tools for RF are key
- Traditional tools from μW and analog IC inadequate
  - ☛ RFICs: marriage of microwave and analog IC design styles
  - ☛ *e.g.*, switching mixer
  - ☛ size, nonlinearity, high frequencies, disparate time scales
- Need new RF CAD tools
  - ☛ traditional μW or IC tools cannot handle the combination

Mixed-Signal Simulation Needs

- Correct, speedy noise simulation
  - mixers, oscillators, PLLs
  - issues: nonlinearity, cyclostationarity
- Automated macromodelling techniques
  - enabler for effective hierarchical system verification
  - issues: nonlinearity; oscillators/PLL dynamics
- Faster basic time- and frequency-domain simulation
  - VCOs, PLLs, mixers, ...
  - issues: fast-slow dynamics, strong nonlinearities
- Research to production tool: “Time-to-market”
  - need effective transition path
  - issue: traditionally extremely slow

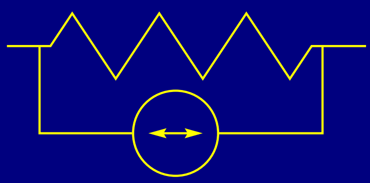
Noise Simulation

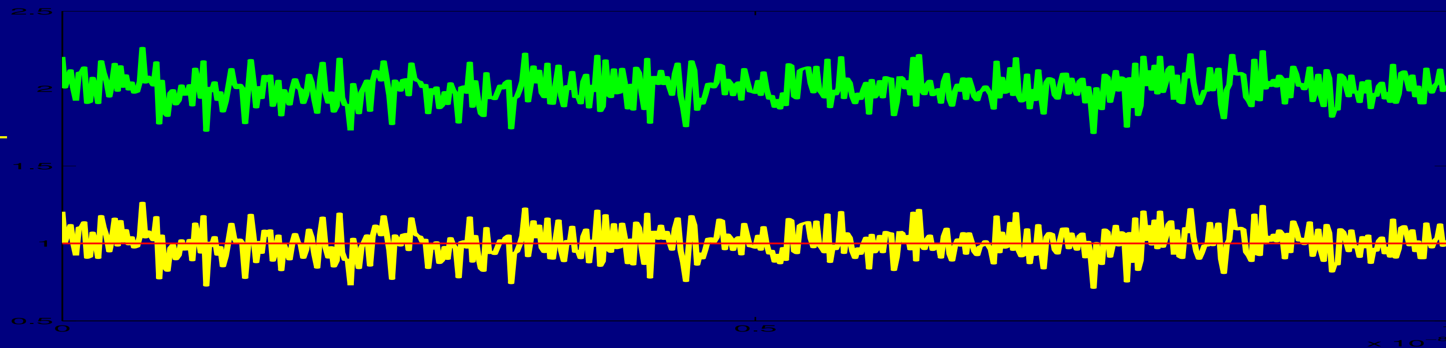
Circuit Noise

- Random variations corrupting circuit voltages and currents
  - sources: thermal, shot, flicker noise in devices
  - impact: S/N ratio, BER degradation
- Different generation and propagation mechanisms
  - Stationary noise (LNAs)
  - Mixing noise (mixers, sampling circuits)
  - Phase noise/jitter (oscillators, PLLs)
  - Digital interference “noise” (substrate coupling)

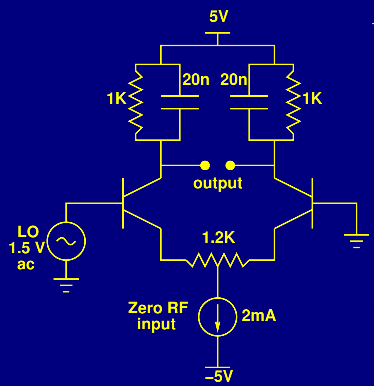
Stationary, Mixing and Phase Noise

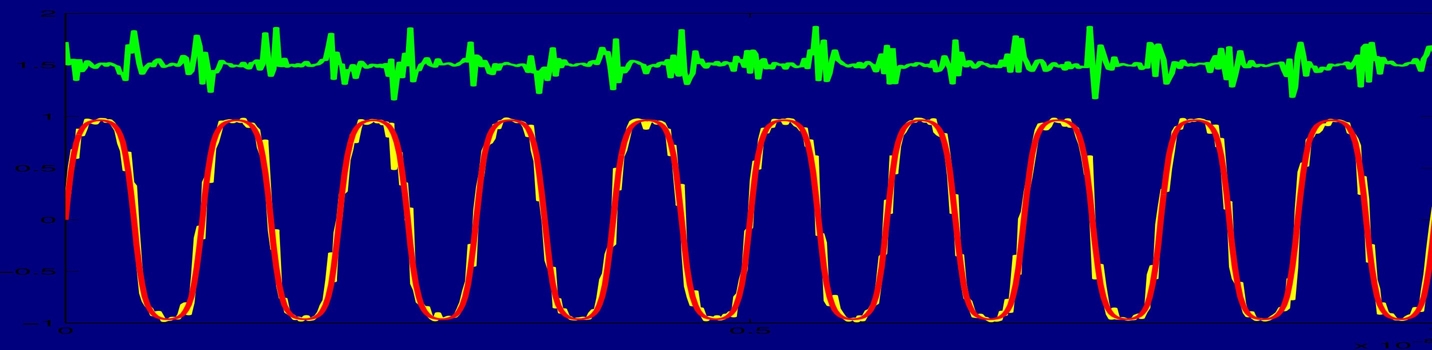
stationary noise: "linear" circuits



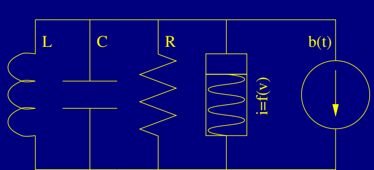


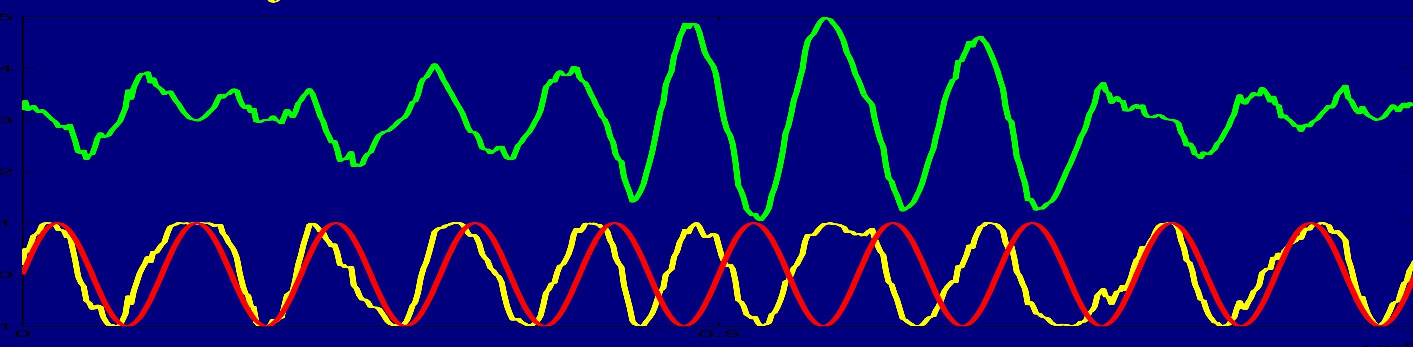
mixing noise: mixers, switching ckts, large signal swings





phase noise/jitter: oscillators

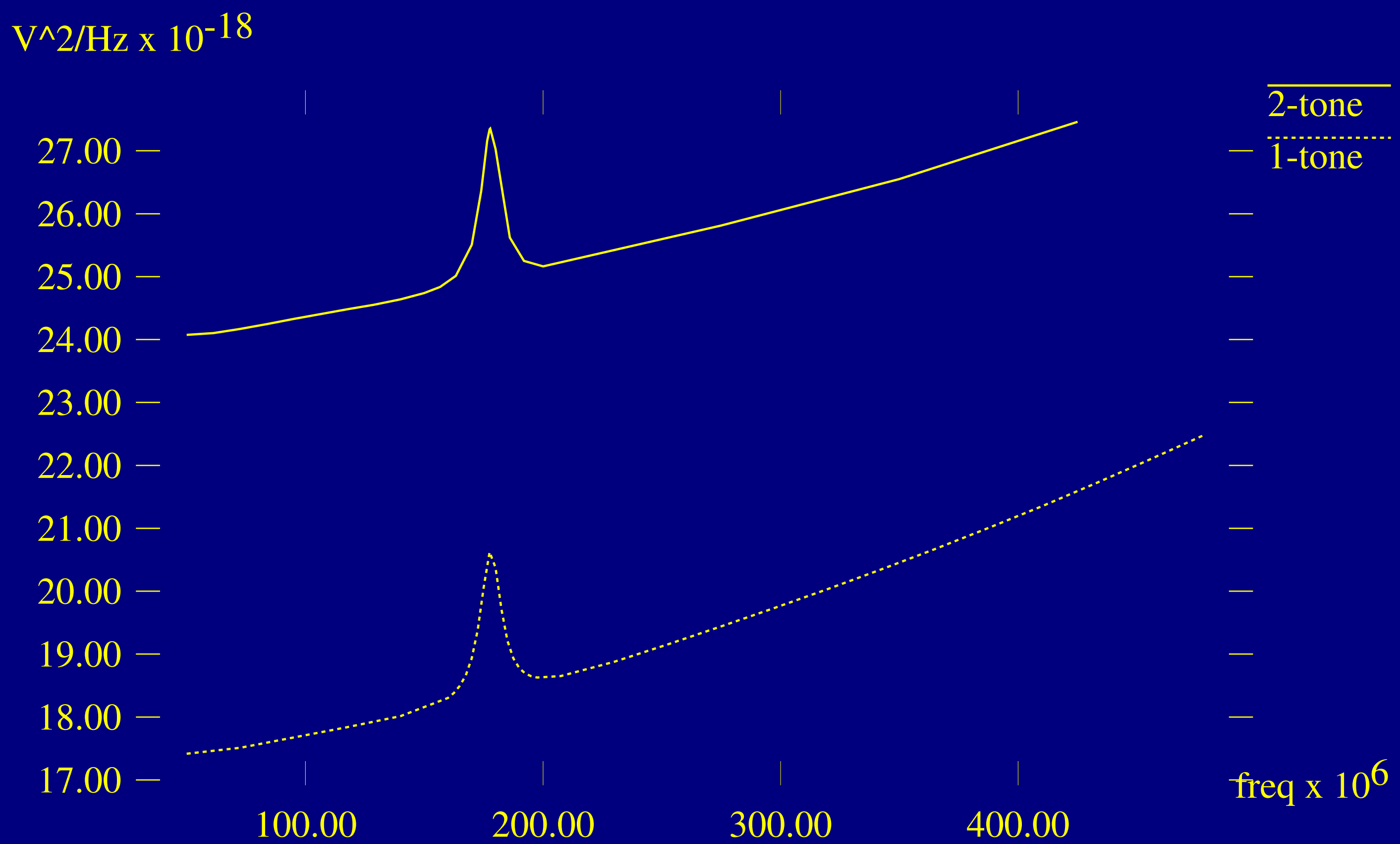




Predicting Noise

- Stationary: LTI propagation
  - LTI theory: $S_{\text{out}}(f) = |H(f)|^2 S_{\text{in}}(f)$
  - computation $\sim$ system size
- Mixing noise (cyclostationary): LTV propagation
  - LPTV Toeplitz matrix relation: $\mathcal{S}_{\text{out}}(f) = \mathcal{H}^*(f)\mathcal{S}_{\text{in}}(f)\mathcal{H}(f)$
  - computation $\sim$ system size $\times N \log N$ (w fast methods)
- Phase noise/jitter: nonlinear analysis, almost LPTV
  - Lorenzian (single pole lowpass) spectrum: finite PSDs
  - underlying LPTV calculations; nonlinear SDE solution
  - computation $\sim$ system size $\times N \log N$ (w fast methods)

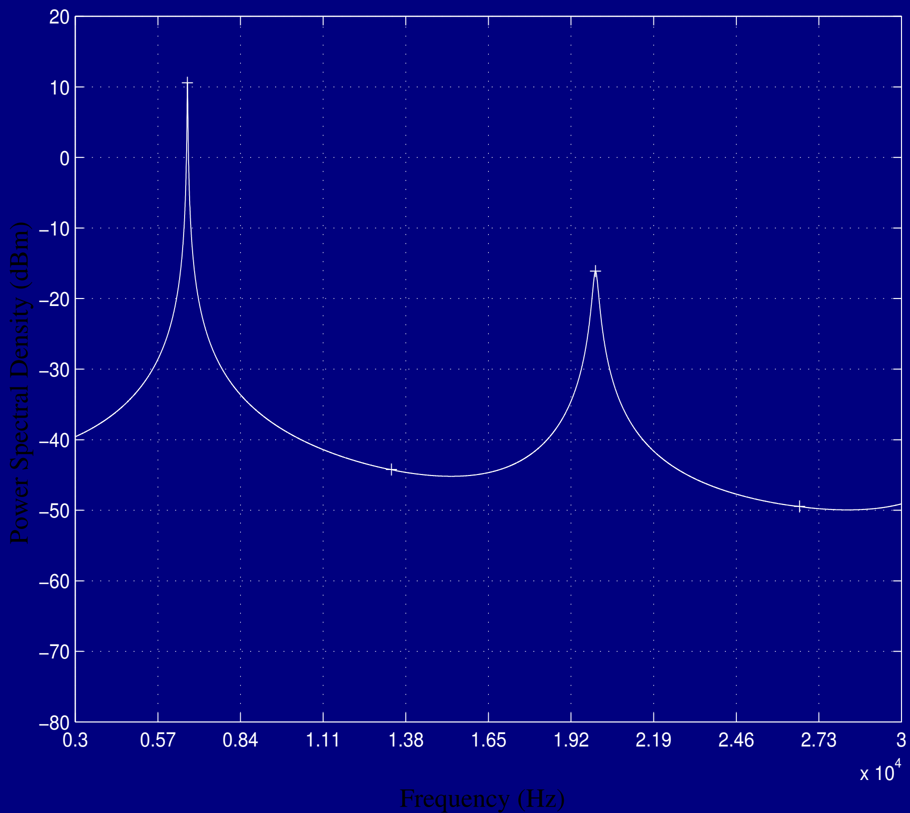
Mixing Noise: Lucent W2013 Noise

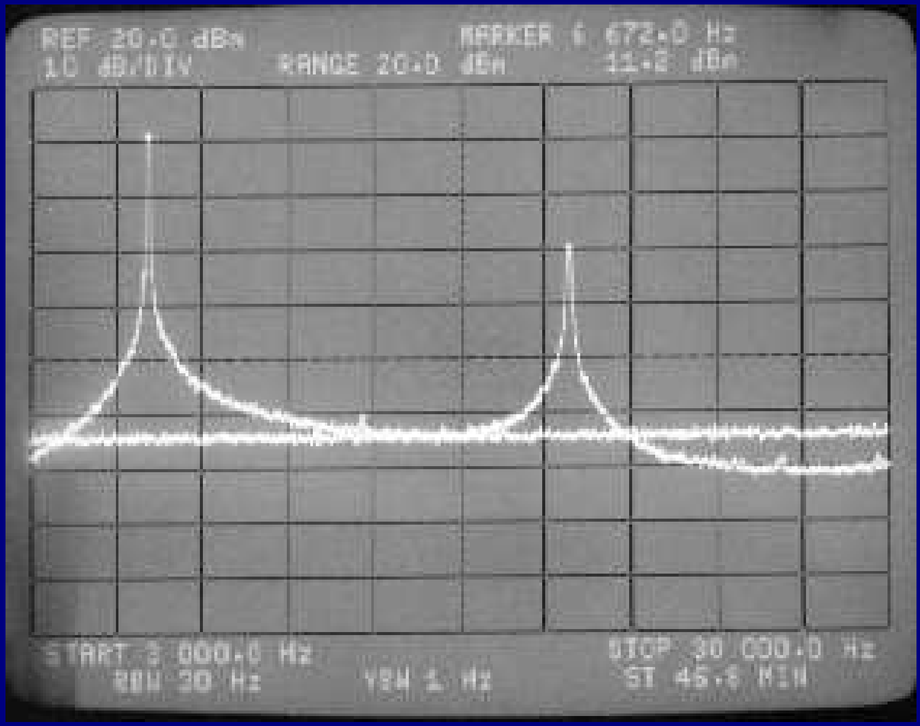


- $\sim$ 500 MOSFETs; LO+blocker+noise; $\sim$ 10 minutes
- baseband noise upconversion
- strong RF tone increases noise through folding

Oscillator Phase Noise Spectrum

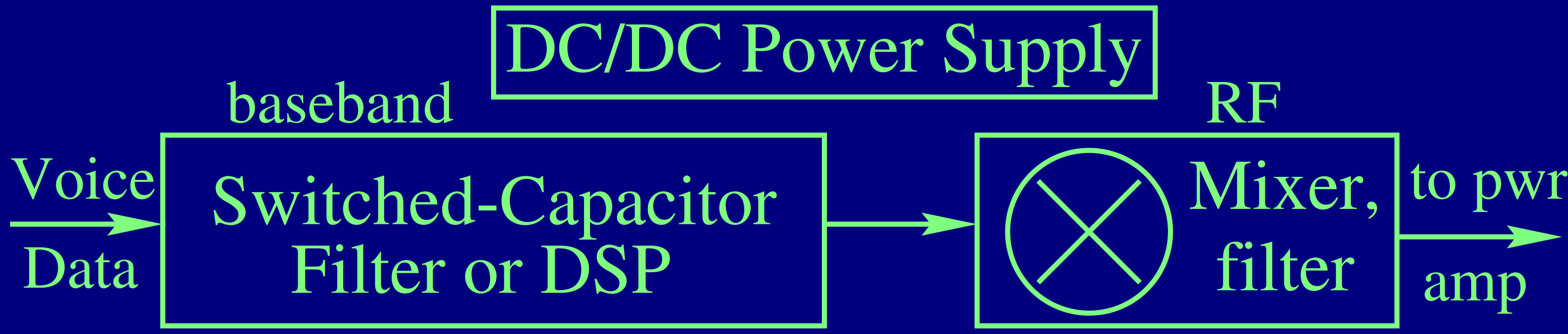
Tow-Thomas oscillator (Toth et al, IEEE TCAS-I, 1998)





Automated Macromodel Generation

Macromodelling Mixed-Signal Blocks



- Substitute big block by small
  - preserve I/O relationship
- Speed system verification
  - simulate connection of macromodels
- <u>Automated</u> macromodel generation
  - Input: (large) SPICE deck
  - Output: (small) SPICE/Matlab macromodel
  - <u>Fast/convenient</u>: "Computers made of iron, let them work"[a]
  - Applicable to <u>*general classes*</u> of circuits

[a] Vladimir Rokhlin, ~1997

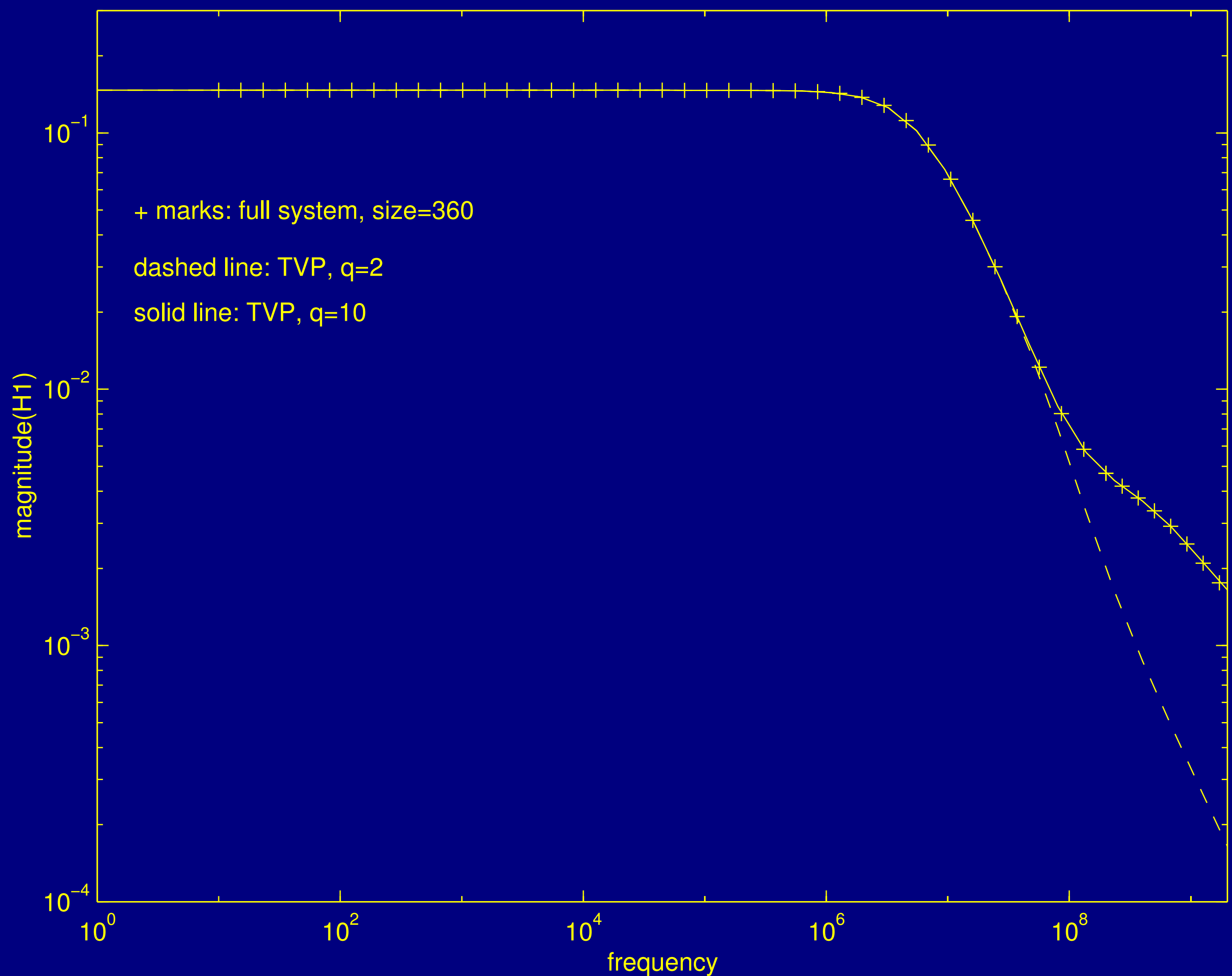
Types of Algorithmic Macromodelling

- Linear Time Invariant (LTI) macromodelling
  - ☛ application: interconnect networks (delay, crosstalk)
  - ☛ AWE, PVL, PRIMA, TBR
- Linear Time Varying (LTV) macromodelling
  - ☛ mixers, sampling/switching circuits
  - ☛ TVP (Time-Varying Padé)
- Weakly nonlinear macromodelling
  - ☛ companding circuits, amplifier/mixer gain compression
  - ☛ Low-order polynomial-based reduction
- Strongly nonlinear macromodelling
  - ☛ Piecewise polynomial (PWP): comparators, switching
  - ☛ Other: oscillators, PLLs, ...

Application to RF mixer block

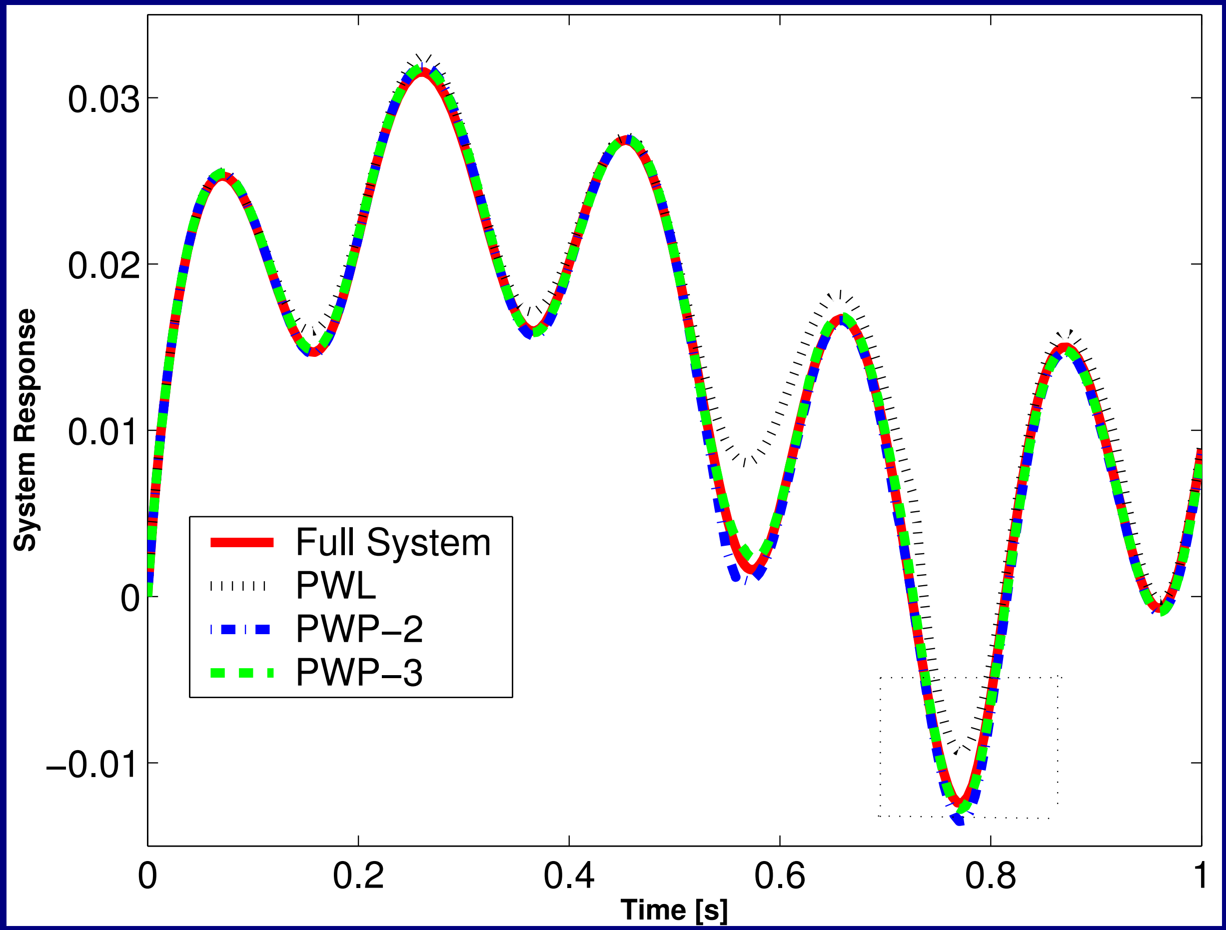
- I-channel mixer and buffer block (Lucent ME W2013 RFIC)
  - 360 nodes, RF≈80kHz, LO=178MHz
  - Steady-state: Harmonic Balance with 10 LO harmonics, zero RF input
- TVP: Lanczos process on frequency-domain Jacobian
  - $q = 2$: provides reasonable macromodel
  - $q = 10$: matches xfer fn upto twice LO frequency
  - size reduction: 30–100; macromodel evaluation speedup: > 500

W2013 mixer: upconversion transfer function, +ve frequencies



Nonlinear transmission line macromodelling using PWP

Transient Simulation



Full system size: 100

Reduced size: 10

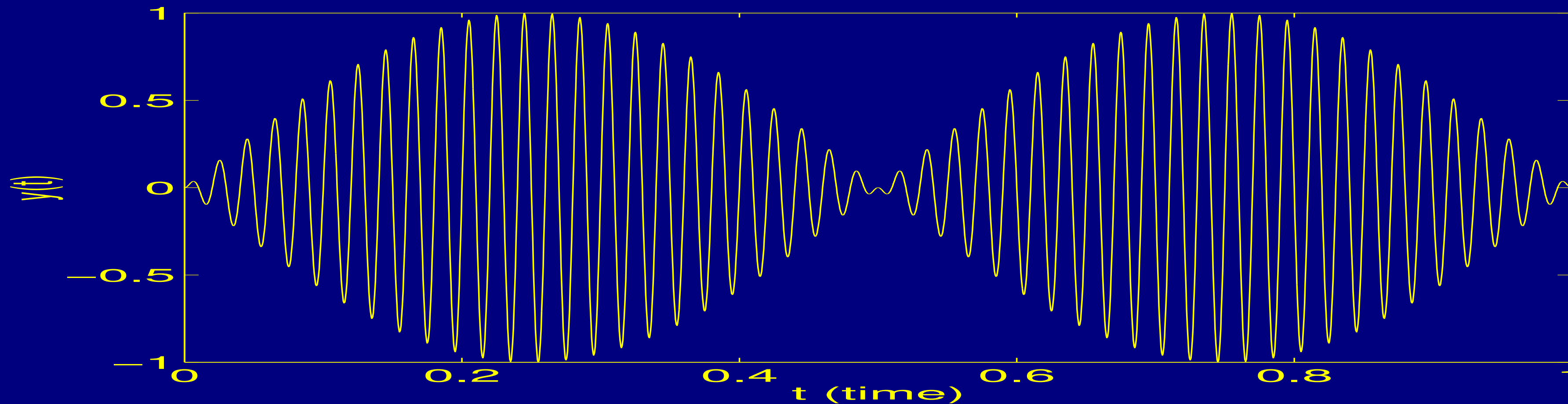
Multi-time methods for Fast Simulation

Information Modulation: Features

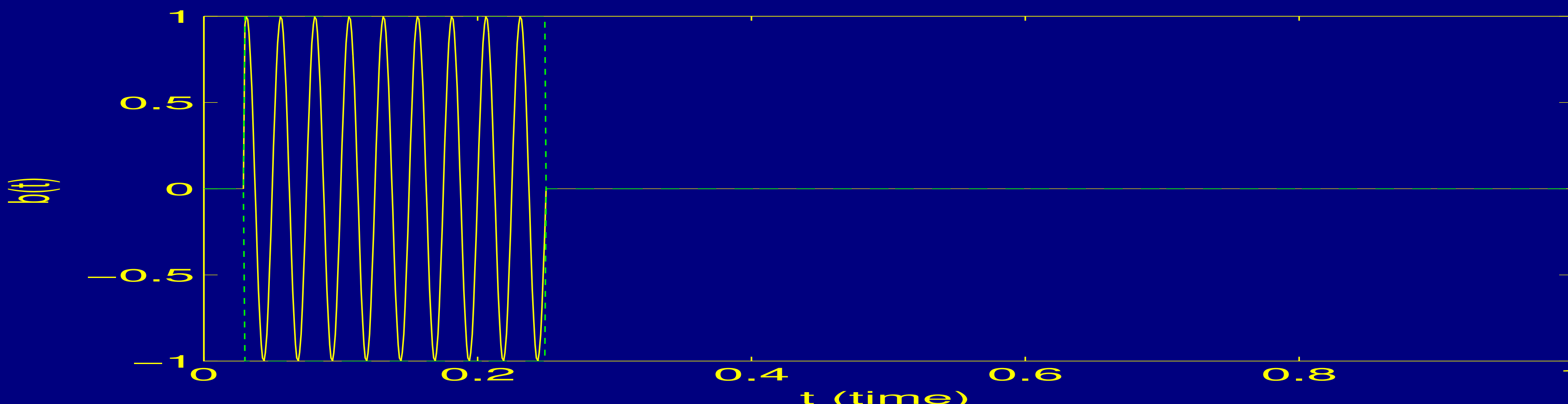
- Mixers, switched-capacitor filters, oscillators, PLLs, DC-DC converters...
- Multiple tones (aka quasiperiodic signals)
  - ☛ eg, AM: $\sin(2\pi 1000t)\sin(2\pi 10^9 t)$
  - ☛ or: $\sin(2\pi 1000t)\mathrm{pulse}(10^9 t)$
- Slow envelopes
  - ☛ eg, $e^{-\frac{t}{1000}}\sin(2\pi 10^9 t)$

Representing "multi-rate" signals

$\boxed{b(t) = \sin(2\pi 1 t)\sin(2\pi 10^9 t)}$ TD: 10^{10} samples; FD: 2 harmonics

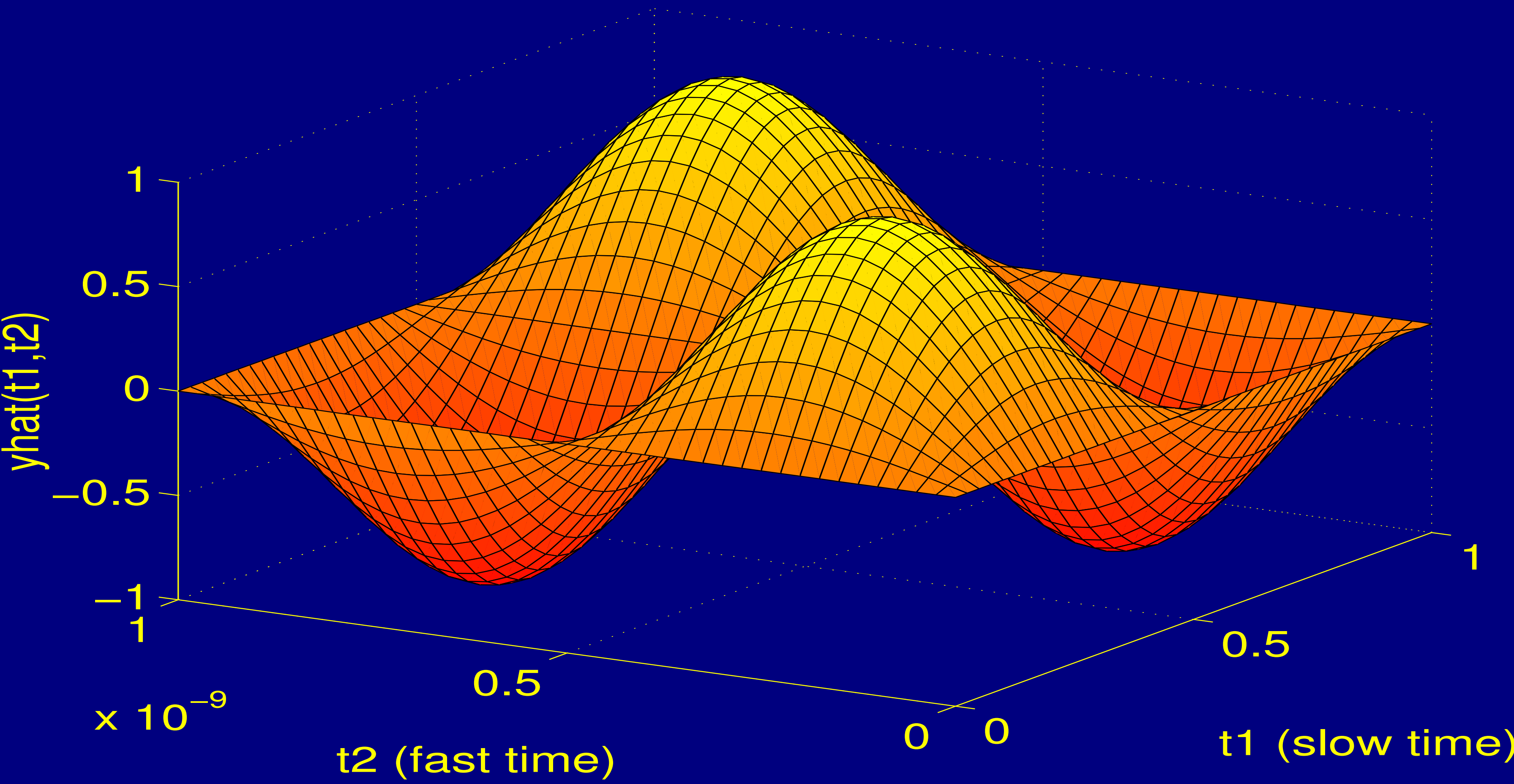


$\boxed{b(t) = \text{pulse}(1t)\sin(2\pi 10^9 t)}$ TD: 10^{10} samples; FD: 10^n harmonics



Two Artificial Time Scales

- Two time variables separate time scales



$$\hat{x}(t_1, t_2) = \sin(2\pi 1 t_1)\sin(2\pi 10^9 t_2) \qquad x(t) = \hat{x}(t, t)$$

The Multitime Partial Differential Equation (MPDE)

- Re-write DAE using multi-time variables

DAE

$$\dot{q}(x) + f(x) = b(t)$$

$\rightsquigarrow$

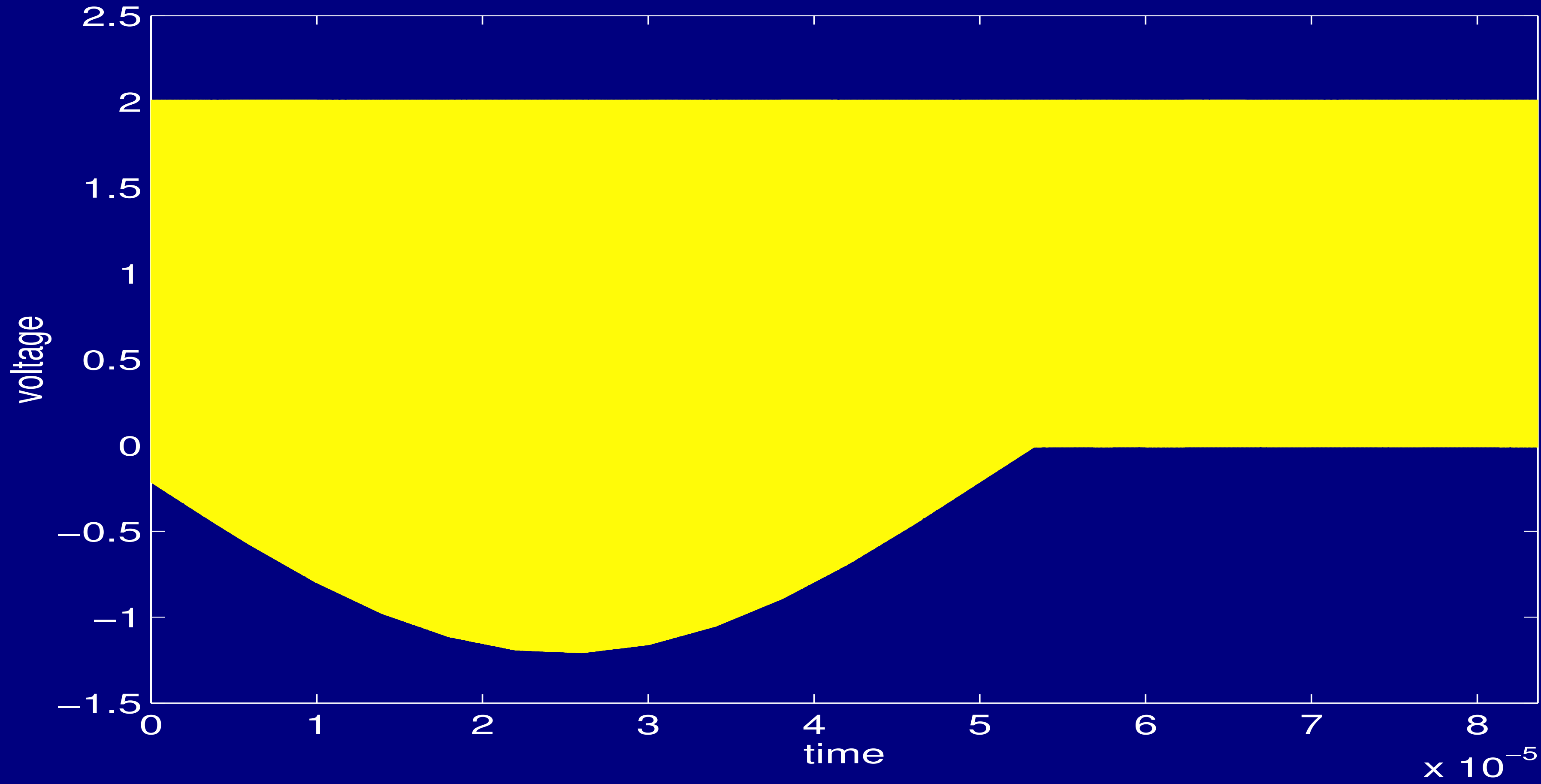
MPDE

$$\left(\frac{\partial}{\partial t_1} + \frac{\partial}{\partial t_2}\right) q(\hat{x}) + f(\hat{x}) = \hat{b}(t_1, t_2)$$

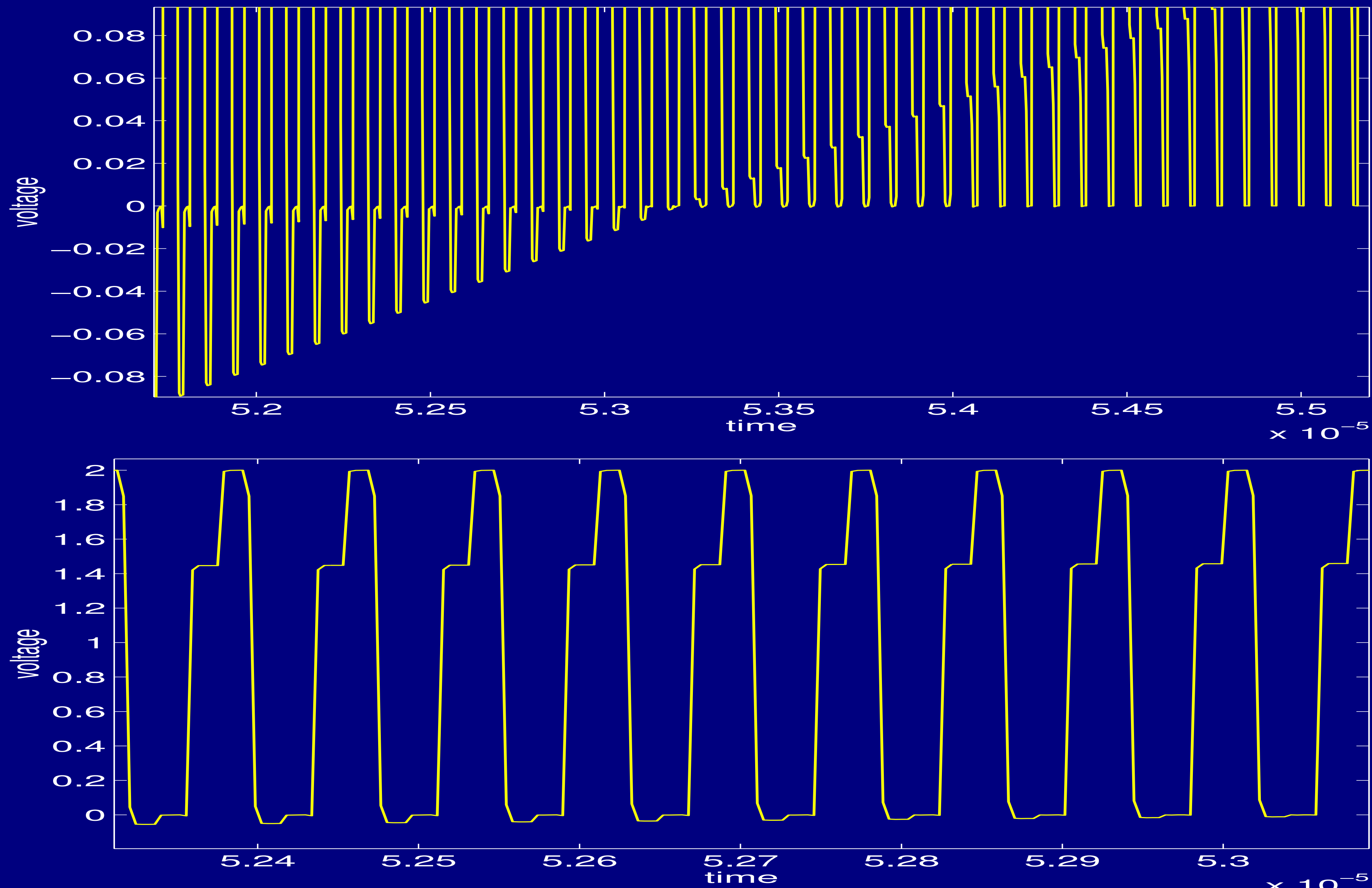
- $\hat{x}(t_1, t_2)$: vector of *multivariate* unknowns
- $\hat{b}(t_1, t_2)$: multivariate form of inputs
- Key: solve for multivariate forms *directly*
- More general forms: WaMPDE (oscillators): $\omega(t_2)$

Switched-Capacitor Integrator

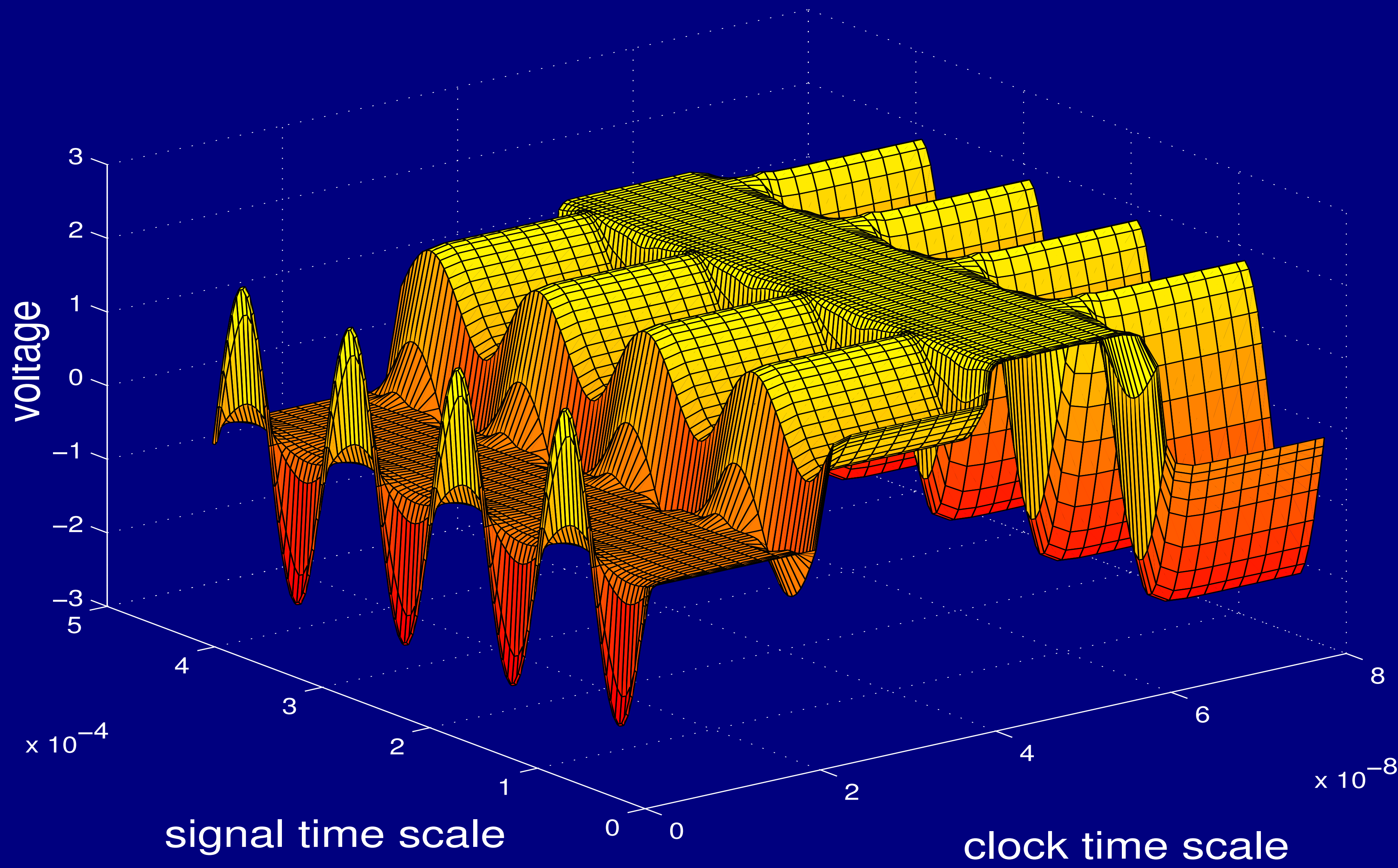
- Lossy balanced design; 350 MOSFETs
- clock: 12.8 MHz; test signal: 10 kHz



SC Integrator: transient detail



SC Integrator: Multi-Time Simulation



Open Source for Effective Prototyping

Why Open Source for Analog?

- **Open simulation infrastructure**
  - **device models**
  - base algorithms: **robust nonlinear solution**, transient, HB/TD steady-state, Krylov-subspace implementations, parsing, output, $\cdots$
  - Avoid **huge** (waste of) effort of re-development
- **Coalesces scattered resources**
  - Co-operative efforts
  - Motivation: recognition, empowerment
  - Many-eyes effect: high quality

Our approach: MATLAB-centered

- **Dramatically reduces** development time/pain
  - Numerical methods: sparse matrices, LU, iterative linear methods, ODE solution, FFTs, ...
  - Short, simple, intuitive
  - Interfaces to C/C++/Fortran
  - Push-button C-code generation
  - Strong system-level functionalities
- Cleanly separated devices, numerics, algorithms, I/O
- HB implemented and debugged in **15 person-hours**

Conclusion

- Mixed-signal simulation: need for new algorithms and tools beyond SPICE
  - automated macromodelling
  - noise
  - faster simulation
  - collaborative infrastructure
- More information: http://laoo.dtc.umn.edu/~jr/