Challenges in Large-Scale Frequency Domain Circuit Simulation

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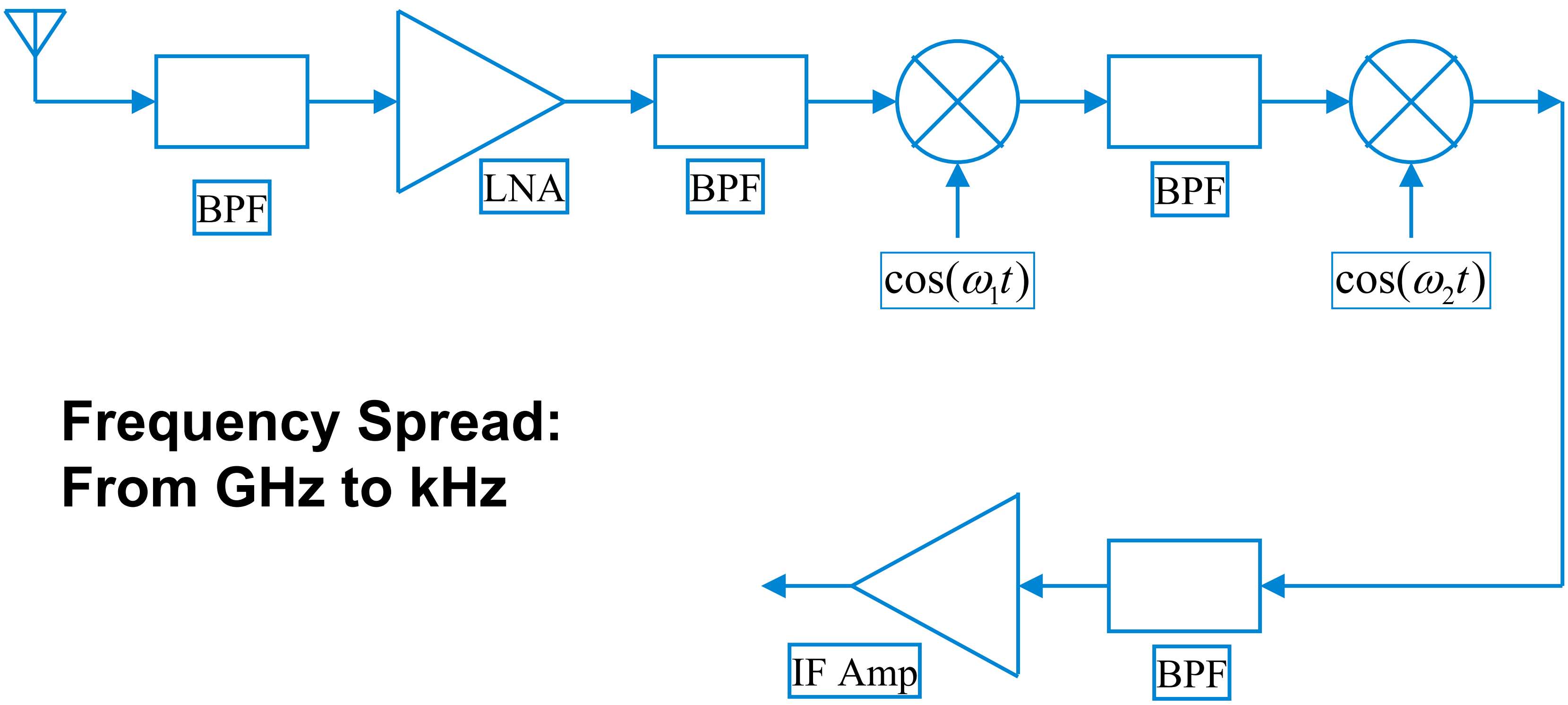
Agenda

- **Harmonic Balance – Introduction and Background**
- **Classes of Harmonic Balance Problems**
- **Limitations and Breakdown Mechanisms**
- **Examples**
- **Future Directions**

Why Frequency Domain?



Frequency Spread:
From GHz to kHz

Harmonic Balance

- Expands state variables as a Fourier series; solves for the Fourier coefficients
  - Insensitive to widely spaced spectral components
  - Excellent for dealing with complicated high-frequency passive (linear) components
  - Directly captures the large-signal quasi-periodic steady-state
  - For mildly nonlinear problems, exhibits good dynamic range

Harmonic Balance

Standard set of circuit equations:

$$g(x(t)) + \frac{d}{dt} q(x(t)) + \left(Y \otimes x\right)(t) = u(t)$$

$$x(t) = \sum_{h=-H}^{H} X_h \exp(j\omega_h t)$$

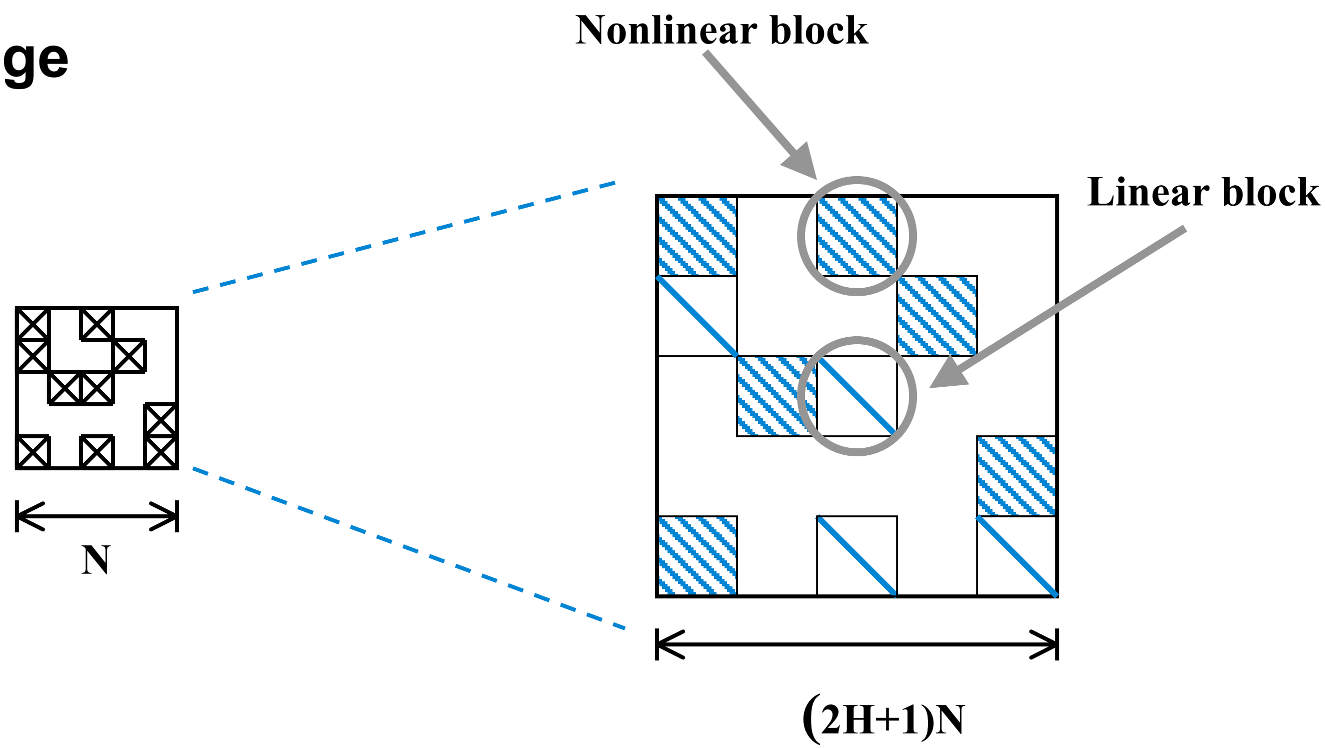
$$G(X) + \Omega Q(X) + YX = U$$

The Harmonic Balance Jacobian

Direct LU factorization:

$O(H^2)$ **storage**

$O(H^3)$ **time**



Historical Background

- Historically, Harmonic Balance was applied primarily to microwave circuits:
  - Small nonlinear device count
  - Large number of linear frequency-dependent elements
  - Long time constants
  - Late 80s: UC Berkeley Spectre simulator (Ken Kundert)
- In 1995, was extended to IC area by Melville/Feldmann/Long and by Brachtendorf
  - Krylov-subspace solvers
  - Matrix implicit multiplication via FFTs -- storage becomes O(H), comp. cost becomes O(H*log(H))

Classes of HB Problems

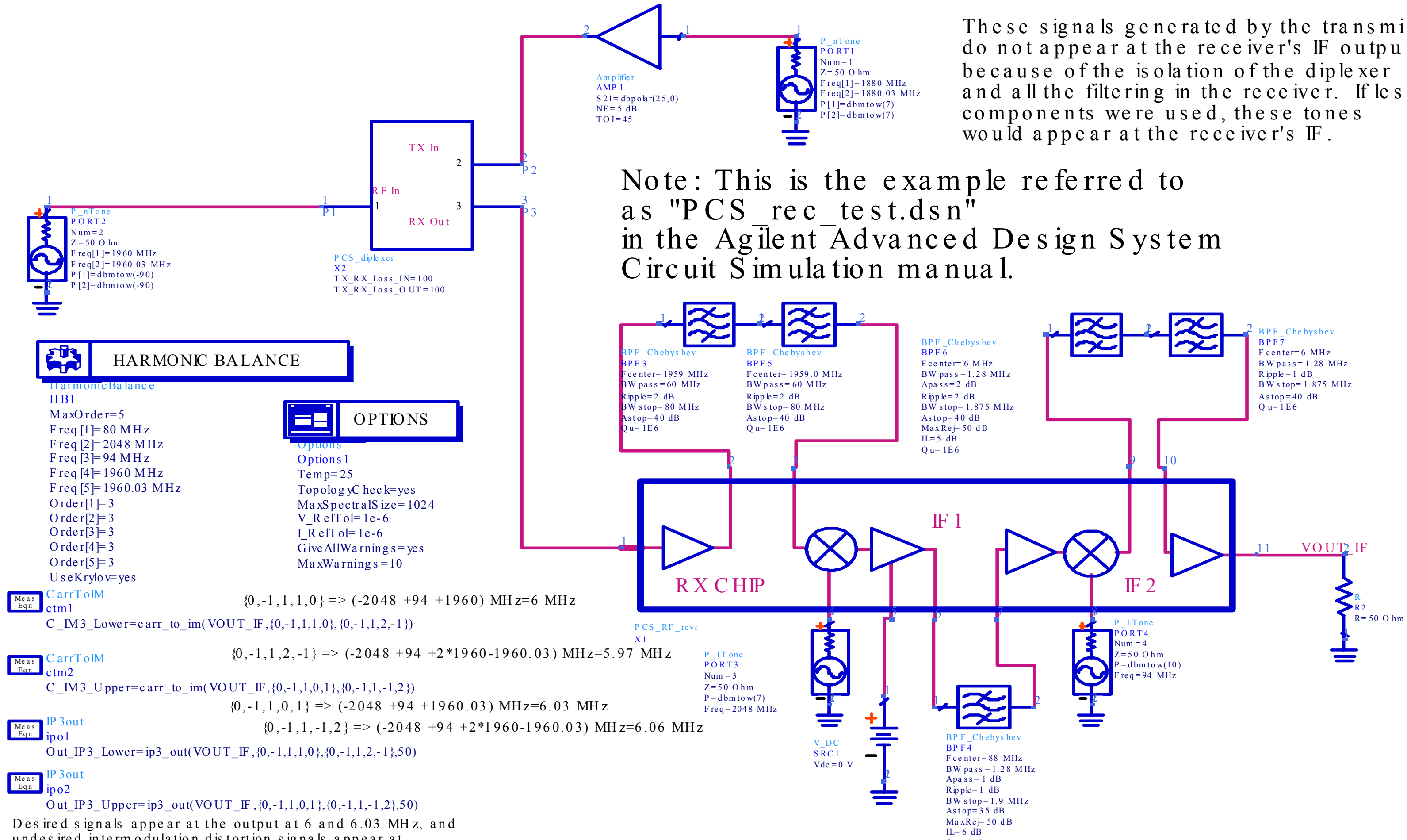
- 3 “axes of difficulty”: nonlinearity, device count, spectral content
- Microwave is ideal for HB -- low transistor count, lots of passives. Direct methods work well
- RFIC Area: Limited by degree of nonlinearity and number of nonlinear devices
- RF System Area: Limited by multi-tone FFT size

The “RF System” Class of Problems...

Receiver Third-Order Intercept Point and Carrier-to-Intermodulation Distortion Simulations

These signals generated by the transmi
do not appear at the receiver's IF outpu
because of the isolation of the diplexer
and all the filtering in the receiver. If les
components were used, these tones
would appear at the receiver's IF.

Note: This is the example referred to
as "PCS_rec_test.dsn"
in the Agilent Advanced Design System
Circuit Simulation manual.

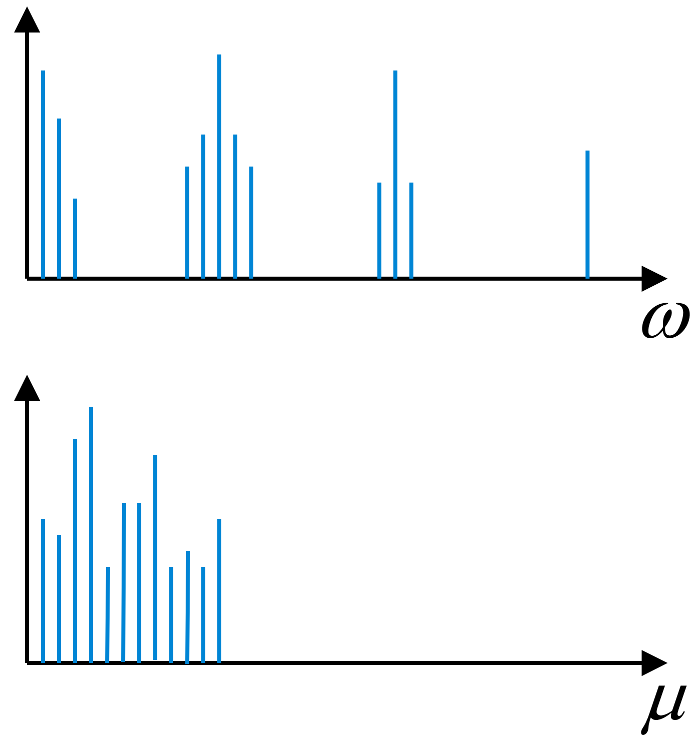


Desired signals appear at the output at 6 and 6.03 MHz, and
undesired intermodulation distortion signals appear at
5.97 and 6.06 MHz.

Multi-Tone Simulation / Frequency Remapping

$$\omega_h \in \{k_1\Omega_1 + k_2\Omega_2 + \ldots + k_M\Omega_M\}$$

$$\mu_h \in \{k_1\hat{\Omega}_1 + k_2\hat{\Omega}_2 + \ldots + k_M\hat{\Omega}_M\}$$



For multi-tone simulations with *M* > 2, the FFT size is generally much larger than the number of harmonics.

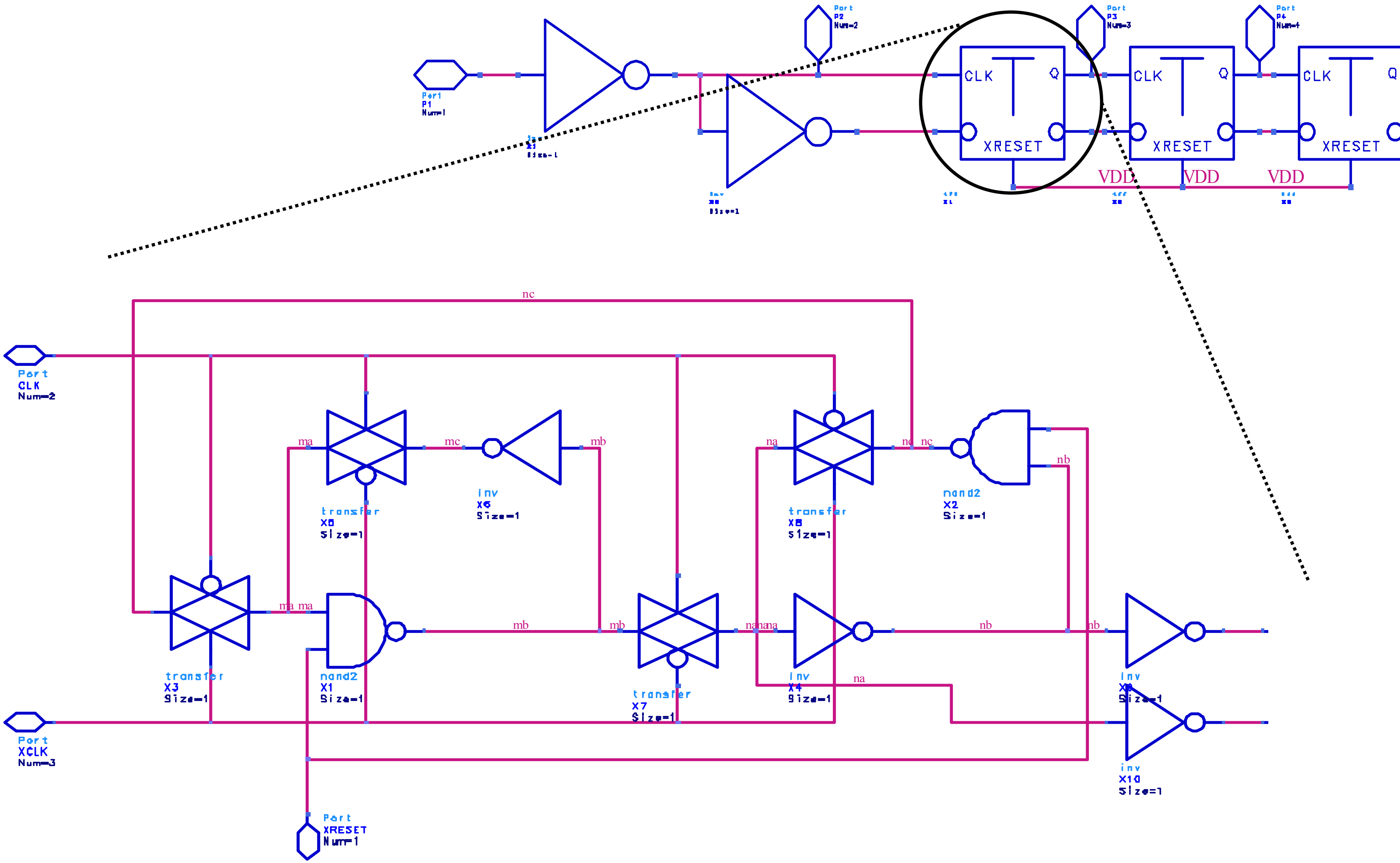
Spectral Packing/Compression and Remapping Schemes

- Different frequency remapping strategies can have a large impact on the FFT size
  - Algorithmic improvements have delivered impressive reductions in FFT size for multi-tone problems (e.g., 32X in size and 100X in speed for 8-tone problems)
  - The potentially increased aliasing effects need to be studied more closely
- Implicit Jacobian storage is a key bottleneck
  - “Lossless spectral packing” and “lossy spectral packing” (i.e., “compression”) can be used to reduce spectral storage by over 10X.
  - Speed penalty tends to be roughly 2X.

RFIC Problems

- Linear iterative solver breakdown (with standard preconditioners) can occur when some amplifiers are driven deep into compression
- "Digital" circuitry (e.g., frequency dividers/synthesizers, etc.) composed of latches/flip-flops is extremely problematic:
  - Arc-length continuation typically insufficient (need "transient assist")
  - Standard block-diagonal preconditioners typically fail

Example: a Small CMOS Div-By-8 Circuit...

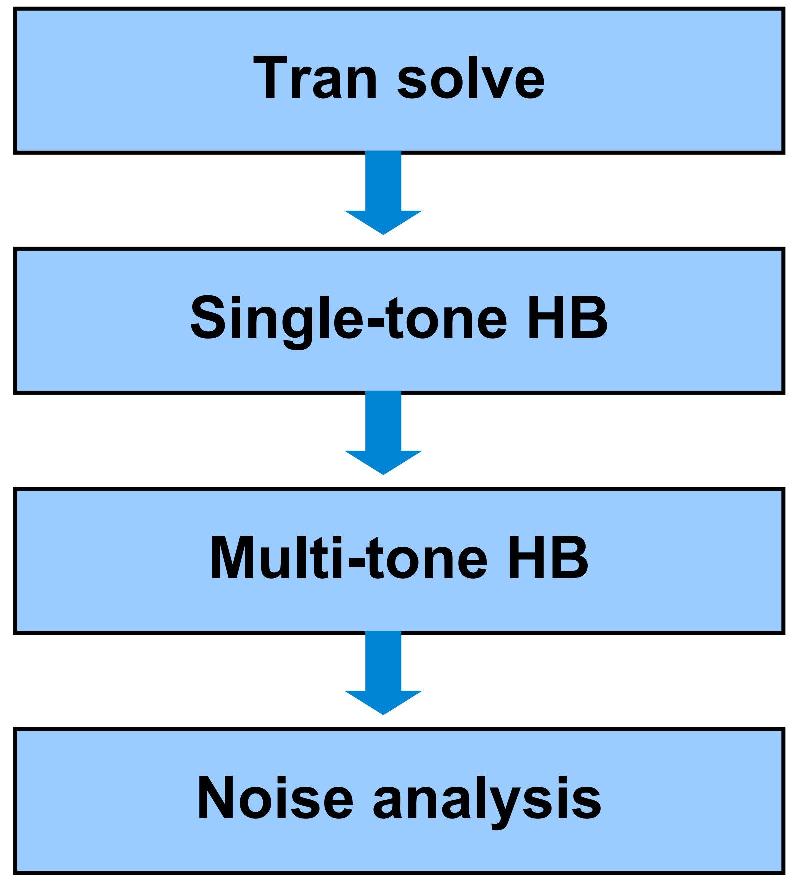


CMOS Frequency Divider

- 76 CMOS transistors, simulated at 256 harmonics
- Standard block-diagonal preconditioner converges, but "transient-assist" is necessary for initial starting point determination
- Run time is 96 sec for transient run (initial guess), 21 sec for subsequent HB analysis, 40 sec per phase noise point. (500 MHz Pentium III -- slow machine!)

Why Harmonic Balance In This Case?

- **Additional multi-tone excitations can be introduced after initial single-tone solve**
- **Continuation methods can then be employed with the single-tone solution as the starting point**



Linear Iterative Solver

Preconditioned linear solve without augmentation:

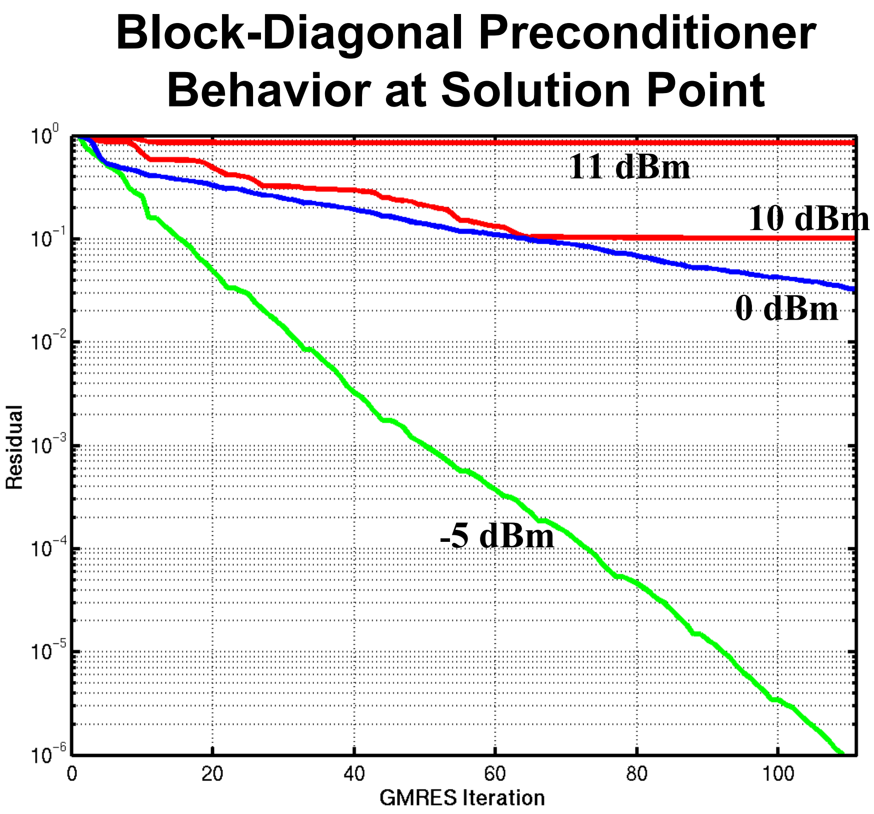
$$Jx = b \quad \Rightarrow \quad \left(JM^{-1}\right)Mx = b$$

Linear Iterative Solver Performance

- GMRES appears to be the most robust Krylov subspace method for the HB problem
- Convergence of the standard preconditioner is very good on most problems
- For very nonlinear RFIC problems, the standard preconditioner may break down
- For “behavioral-level” RF System problems, the standard preconditioner behaves superbly

Preconditioner Effectiveness

- **Power Amplifier:**
  700 BJTs
  280 Diodes
  6100 passives
- **Standard preconditioner begins to have problems at 0 dBm input power**
- **Solver fails outright at 10 dBm input power**

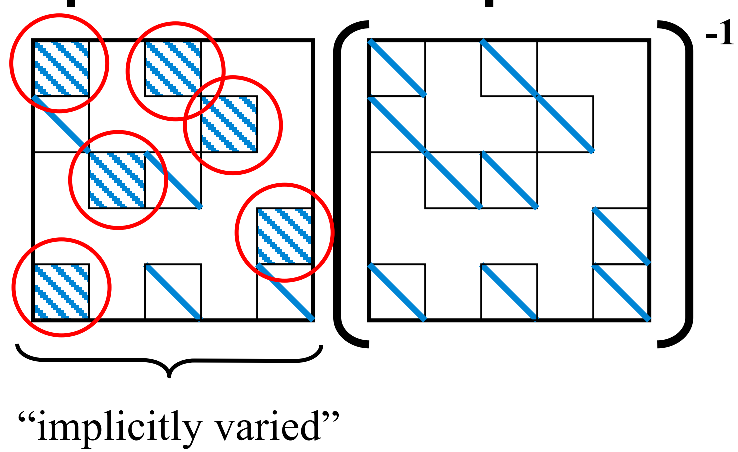


Augmenting the Standard Preconditioner

- **Two key problems:**
  - **Choosing which blocks must be augmented**
  - **Factoring the augmented system**
- **Both problems are more challenging than would appear at first glance...**

Block Selection

- Ideally, should be done on a single-tone variant of the problem if at all possible
- Straightforward heuristics can quickly limit the number of augmentation candidates to a manageable number
- Follow up with additional, more rigorous approach:
  - Far too expensive to re-select blocks and re-factor…
  - So, rank problematic blocks by using original block-diagonal preconditioner and "linearizing" candidate blocks in the implicit FFT multiplies

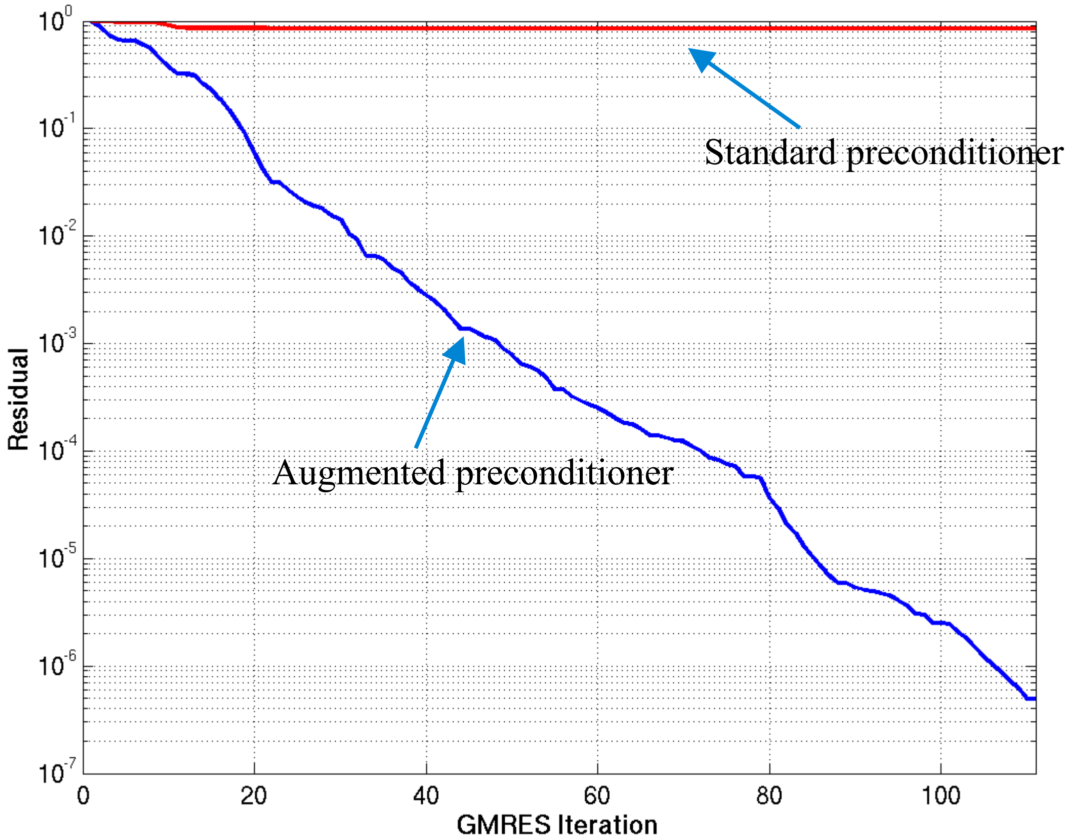


Factoring the Augmented Preconditioner

- “Brute force” factorization
  - Block-oriented sparse factorization algorithms
  - Good performance for H < 250 or so
- Column-oriented Schur Complement Preconditioner (Bell Labs)
- Exploitation of strong/weak split in two-tone problems
  - One such approach developed at Bell Labs
  - Another formulation will be presented later in this talk

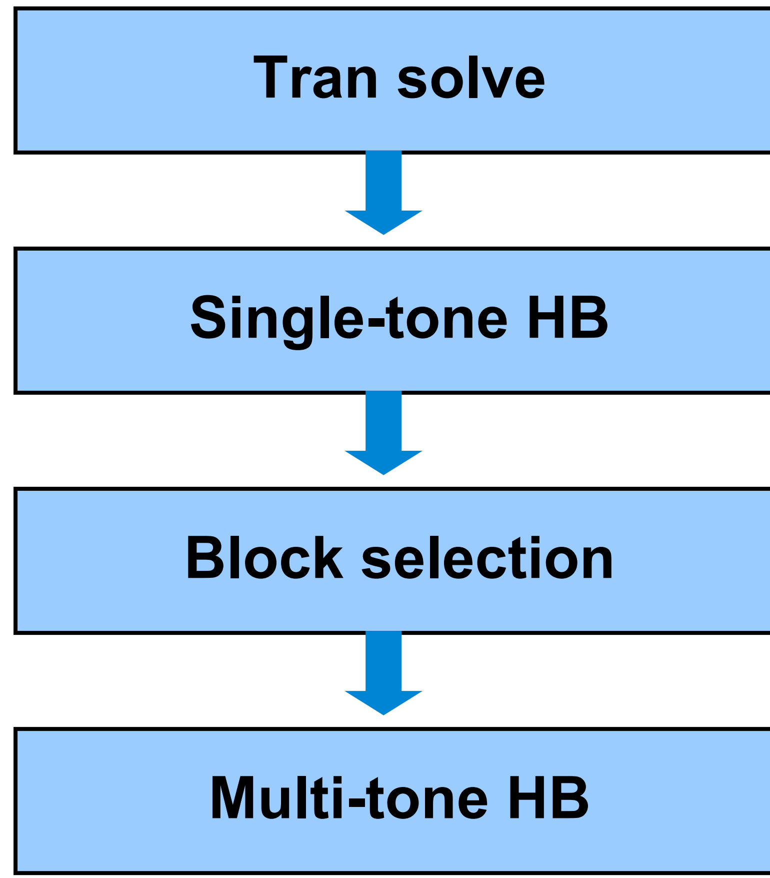
Power Amplifier Convergence with Augmented Preconditioner

- **H=64; 510,453 eqns**
- **Memory usage increases from 254MB to 313MB**
- **625 seconds on HP J6000 [550 MHz]**



A Challenging RFIC Problem...

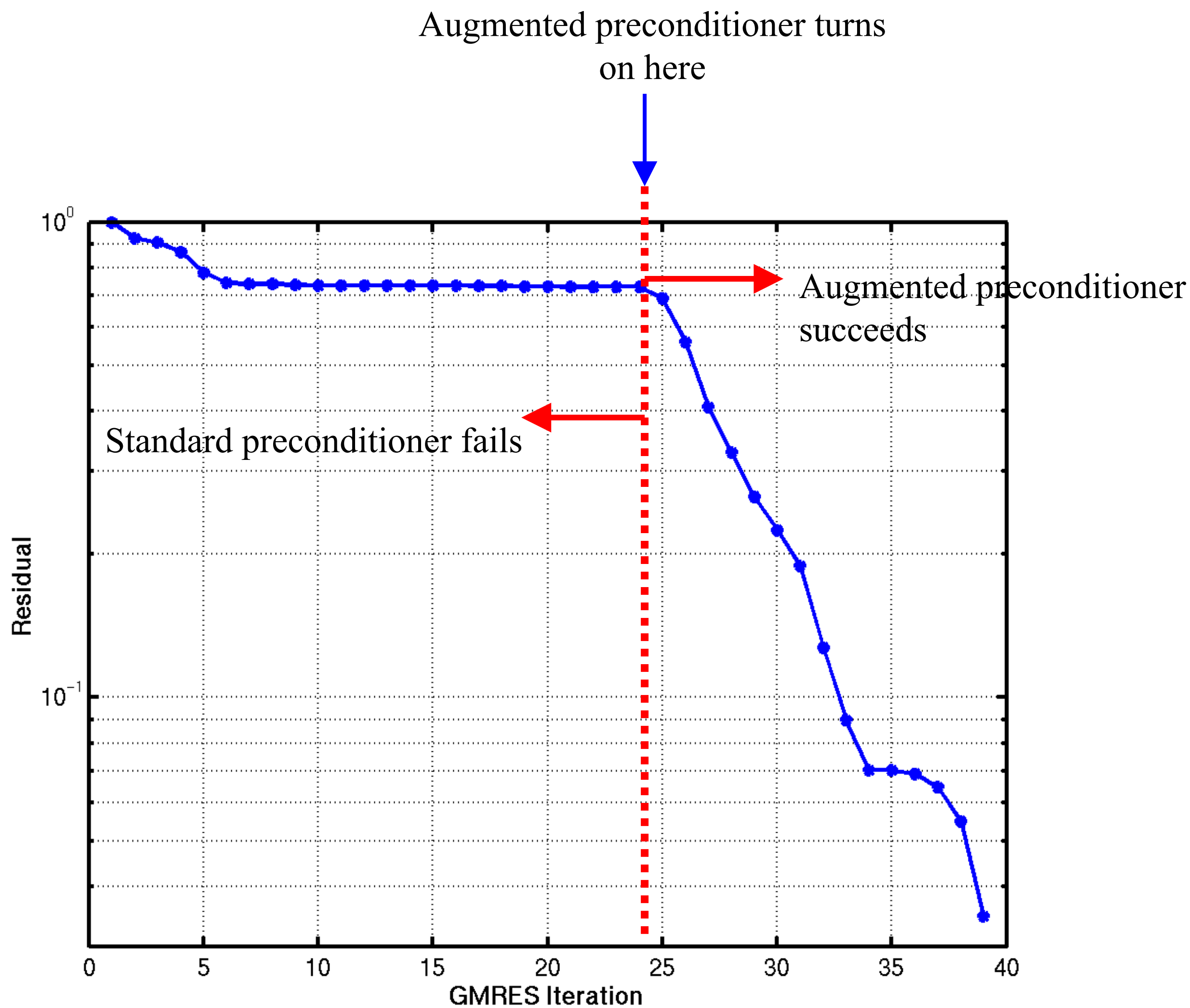
- BiCMOS chip: I/Q Mod, Freq Divider, Limiter, Mixer, AGC
- Over 1900 nonlinear devices, over 20,000 linear devices
- 120 harmonics; 1,057,026 eqns
- Both “transient assist” and Jacobian augmentation is necessary for convergence
- Frequency divider much more difficult to address than amplifier in terms of Jacobian augmentation



Convergence

4.4 hrs, 1.6GB
for six sweep points

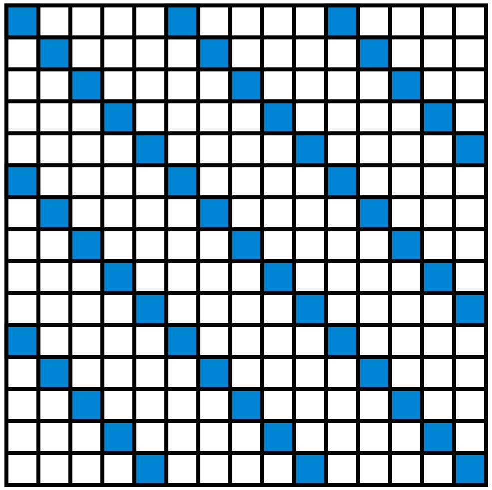
Augmentation:
16x16

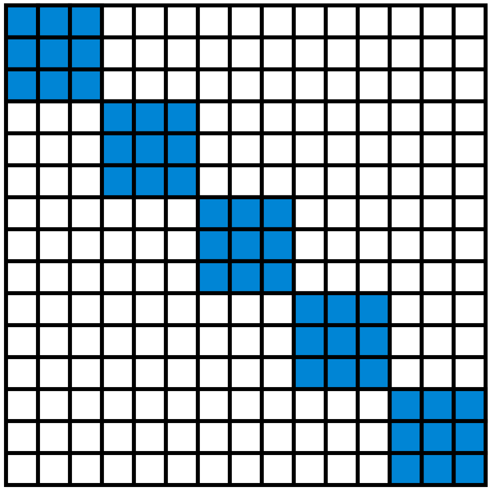


Some Comments...

- **Preconditioner breakdown in the case of amplifiers is often manageable, as only a relatively small number of augmented blocks is necessary for convergence**
- **“Digital”-type flip-flop circuitry is substantially more problematic, since the number of blocks that need augmentation can be quite large**
- **Augmentation algorithms cannot yet be viewed as being mature**

"Strong/weak" Decoupling





Flexible block-oriented sparse factorization codes can have certain blocks be diagonal, certain blocks be strong/weak permuted, and certain blocks full.

Summary and Future Directions...

- **Frequency remapping algorithms need to be pushed further for large multi-tone problems**
  - **Closed form techniques combined with optimal "search" techniques would be an interesting area to explore**
  - **The effect on aliasing needs to be studied as well**
- **Block selection algorithms must be pushed much further and be made more robust**
  - **Should be fast enough and reliable enough to work in full multi-tone mode**
  - **Much more rigor is necessary**

Summary and Future Directions (cont.)

- "Initial guess" algorithms for HB must be improved in view of the need to solve digital sub-blocks with multiple solns
  - Close coupling of tran/shooting/FDTD into HB solver
  - Advanced homotopy methods (?)
- Linear solvers must be made much more robust
  - Flexible strong/weak capability should be added, and pushed to multiple strong/weak tones if possible
  - Bell Labs SCP approach looks very promising
- Parallel solution methods should be pursued