Link Surroundings

- Links integrated onto 1V, 100A processors
  - Required $|Z_{supply}| < 1 \text{ m\ensuremath{\Omega}}$ for ~100mV supply noise

- Link supply (ground) often shared...

90nm Itanium

Measured Supply Noise
On-Chip Regulation

- Many links regulate supplies of critical blocks
  - Good/bad regulator design can make or break the link

Regulator Types

- Switching vs. linear
  - (“Easy” vs. “Not easy” to integrate)
- Linear: series vs. shunt
  - (Isolation vs. impedance)
Series Regulator Requirements

- Low drop-out voltage
  - Efficiency $\leq \frac{V_{\text{reg}}}{V_{\text{dd}}}$
  - Need to budget for $V_{\text{dd}}$ droops too

- High PSRR across a broad range of frequencies
  - Intrinsic supply rejection of load (e.g., ring oscillator) may be very low

Typical Low-Dropout Regulator
Compensation Techniques

- How do these two techniques achieve stability?
- What are the implications of that on PSRR?

Miller Compensation

RC Compensation

Dominant Pole: Amplifier vs. Output

[Graph showing supply sensitivity vs. frequency with Amplifier Dominant and Output Dominant regions indicated]
Optimizing Regulator PSRR

- For fixed amplifier GBW, find “best” PSRR by trading between gain and bandwidth

- Define PSRR as inverse of max. sensitivity

- Similar results if minimize $\sigma_{V_{\text{reg}}}/\sigma_{V_{\text{dd}}}$ with white noise on $V_{\text{dd}}$

Small Signal Model for Supply Noise

\[ V_{\text{reg}} - \frac{V_{\text{bp}}}{-V_{\text{ref}}} \]

\[ C_{\text{decap}} \quad \text{Load} \]

\[ f_{\text{load}} \quad V_{\text{dd}} \]

\[ g_{\text{out}} \quad C_{\text{bp}} \quad V_{\text{bp}} \]

\[ g_{\text{in}} \quad \Delta V_{\text{bp}} \quad V_{\text{reg}} \]
Small Signal Model for Supply Noise

Optimal Amplifier Design

- For clarity, normalize amplifier gain and bandwidth:
  - Amplifier bandwidth relative to output pole: \( \omega_a = \kappa \omega_o \)
  - Normalized gain-bandwidth: \( GBW = \kappa A_a \)

- If open loop gain \( (A_a A_o) \gg 1 \), optimal allocation is:
  \[
  \kappa = \sqrt{\frac{3}{2}} A_o GBW \\
  A_a = \sqrt{\frac{3}{2}} GBW \big/ A_a
  \]
What This Really Means

Implications

- With optimal allocation:
  \[ \text{PSRR} \propto \sqrt{\frac{1}{2}} A_o \cdot \text{GBW} \]

- To improve PSRR by 2x, both amplifier gain and bandwidth increase by 2x

- In other words, required gain-bandwidth scales with \( \text{PSRR}^2 \)
  - Tradeoff steep – any way to improve?
Towards an Improved Solution

• With $\omega_0 = 2\pi \cdot 100\text{MHz}$ and $A_o = 3$

<table>
<thead>
<tr>
<th>GBW</th>
<th>$\omega_a$</th>
<th>$A_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (100MHz)</td>
<td>$2\pi \cdot 212\text{MHz}$</td>
<td>0.47</td>
</tr>
<tr>
<td>10 (1GHz)</td>
<td>$2\pi \cdot 670\text{MHz}$</td>
<td>1.49</td>
</tr>
<tr>
<td>100 (10GHz)</td>
<td>$2\pi \cdot 2.1\text{GHz}$</td>
<td>4.71</td>
</tr>
</tbody>
</table>

• “Amplifier” in many cases is just acting like a (high-bandwidth) wire...

Source-Follower-Based Regulator
PSRR Comparison

“Practical” Issue #1
Practical Issue #2

Common-Source Has Issues Too...
Typical Design

Local Negative Feedback

- Local feedback efficiently trades gain for bandwidth
- Next lecture: use local f/b to drastically improve PSRR…