Today’s Assignment

- Term Project
  - checkpoint 2 due on Wednesday 11/25
- Reading
  - Sections 5.3 and 5.4
A Quick Overview

• The Power-Distribution Problem
  – DC supply voltage with small tolerance
  – AC current, large di/dt
  – Inductive and resistive supply components

• Inductive Power Supply Noise
  – L supplies low-frequency current, C supplies high frequency
  – ripple due to current variation within each cycle
  – transient at start/stop of load current

• Bypass Capacitors
  – parasitic L and R in capacitors make them effective only below a certain frequency

• Local Regulation
  – series and parallel (shunt)
  – clip voltage ripple
  – ‘subtract’ AC current
  – distribute at a more convenient voltage

The Power Distribution Problem

• Modern digital systems operate at small DC voltages
  – 1.5 to 3.3V
  – must be held to within ±10% (or less)

• and draw large AC currents
  – 10A or more per chip, 100A per board, KA in a system
  – may go from 0 to full current in less than one clock cycle

• over a supply network with parasitic elements
  – Inductance of bus bars, PC boards, packages, and bond wires
  – Resistance of on-chip wires
A Typical Power Supply Network

- Actually a tree with branching at each level
- Parasitic inductance (off-chip) and resistance (on-chip)
- Power and ground networks are usually symmetric
- Capacitance added to give a tapered frequency response

Typical Load Current

- For a given clock domain, load is usually periodic with the clock
- May stop or start in a single clock cycle
- With multiple clock domains, they may drift into phase reinforcing one another
- Load is often resistive, varying linearly with supply voltage
- Some loads are high impedance, constant independent of supply voltage
Local Loads and Signal Loads

- Logic loads connect a point in the power network to a corresponding point in the ground network
  - current can be supplied from a nearby bypass capacitor
- Signal loads connect a point in the power network to a distant point in the ground network
  - usually due to unbalanced signaling
  - current must return over a long path
  - bypass capacitors are not effective

Inductive Supply Noise

- Each section of the supply network is an LC circuit
  - has a resonant frequency, $\omega_{LC} = (LC)^{1/2}$
  - inductor carries DC current ($\ll \omega_{LC}$)
  - capacitor supplies AC current ($\gg \omega_{LC}$)
- Size capacitor to
  - supply cycle to cycle AC current with acceptable ripple
  - handle inductor start/stop transient
Response of an LC Section to Typical Supply Current

Magnitude of Ripple within a Cycle

- Over a clock cycle, inductor current is essentially constant, \( I_{avg} \).
- Load current varies considerably.
- Capacitor current is the difference.
- Capacitor voltage ripples due to this AC current.

\[
\Delta V = \frac{k_l I_{avg} f_{ck}}{C_B}
\]

\[
C_B > \frac{k_l I_{avg} f_{ck}}{\Delta V_{max}}
\]
Starting and Stopping on a Dime

- When circuit is off, inductor current is 0.
- During startup, the capacitor must supply current to the load while the inductor current ramps up.
- Similarly, when the circuit shuts down, the capacitor must absorb the inductor current while it ramps down.
- In either case, the situation is that of a step current into an LC circuit.
- Response is a sine-wave

\[ \Delta V = I_{avg} \frac{L}{C} \sin(\omega_c t) \]

\[ \Delta V_{\text{max}} = I_{avg} \sqrt{\frac{L}{C}} \]

Bypass Capacitor to Handle Start/Stop Transient

\[ \Delta V_{\text{max}} = I_{avg} \sqrt{\frac{L}{C_B}} \]

\[ C_B > \left( \frac{I_{avg}}{\Delta V_{\text{peak}}} \right)^2 L \]
Sizing Bypass Capacitors

- Bypass capacitor must be sized to handle both types of inductive power supply noise
  - ripple due to non-uniform current within a clock cycle
  - start/stop transients
  - maximum ripple can happen at peak or trough of transient
- Approximate capacitance requirement by summing the independent requirements

\[
\Delta V_{\text{max}} = I_{\text{avg}} \sqrt{\frac{L}{C_B}} + \frac{k_i I_{\text{avg}} t_{\text{ck}}}{C_B}
\]

\[
C_B > \left( \frac{I_{\text{avg}}}{\Delta V_{\text{max}}} \right)^2 L + \frac{k_i I_{\text{avg}} t_{\text{ck}}}{\Delta V_{\text{max}}}
\]

\[
C_B > \left( \frac{I_{\text{avg}}}{\Delta V_{\text{max}}} \right) \left( k_i t_{\text{ck}} + \frac{I_{\text{avg}}}{\Delta V_{\text{max}}} L \right)
\]

The Truth about Bypass Capacitors

- Most capacitors are only capacitors at low frequencies
- Capacitors have parasitic series resistance and inductance
- Every pico-Farad has its very own nano-Henry
- Two key breakpoints
  - LC frequency
  - RC frequency
- Capacitors are ineffective at bypassing currents above \textit{either} of these frequencies
Impedance vs. Frequency for some Typical Capacitors

![Impedance vs. Frequency graphs for different capacitors](image)

Capacitor Properties

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<tr>
<th>Type</th>
<th>C</th>
<th>R</th>
<th>L</th>
<th>f&lt;sub&gt;RC&lt;/sub&gt;</th>
<th>f&lt;sub&gt;LC&lt;/sub&gt;</th>
<th>f&lt;sub&gt;LR&lt;/sub&gt;</th>
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<tr>
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<tr>
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<tr>
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<tr>
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<td>3KHz</td>
<td>800KHz</td>
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</table>

- High frequency is only achieved with small capacitors
- Many capacitors can be used in parallel to increase capacitance without reducing frequency
Local Power Supply Regulation

- Can put a regulator in series or parallel with the power supply
- Parallel or *shunt* regulators control current
  - add a current to the AC load current to make it look more like a DC current
- Series regulators control voltage
  - clip off the top of the voltage ripple and transient response
  - distribute power at a higher voltage (or AC voltage)

Shunt Regulators and Clamps

- Shunt regulators maintain a steady current draw from the distribution network
  - Measure the load current, $I_L$
  - Generate a shunt current $I_R = I_{max} - I_L$
  - Current is now DC
    - but large
- A clamp handles the turn-off transient to avoid overvoltage
  - measure the load voltage, $V_C$
  - draw current when $V_C$ exceeds a threshold
Series Linear Regulators

- Think of the regulator as a variable series resistor
  - drop distribution voltage (e.g., 3.3V) down to a load voltage (e.g., 2.5V)
- Can *clip* off the top of the voltage ripple by resistively dropping it
- Limited by
  - frequency response of the regulator (can’t track fast transients)
  - series nature of regulator, can’t divert transient inductor current

Switching Regulators

- A *switching* regulator uses a reactive element (usually a transformer or inductor) to convert the supply from one voltage to another with only a small loss in power
- Distributing power at a high voltage improves things quadratically
  - less current to distribute
  - more voltage to tolerate ripple
- Often advantageous to make this distribution voltage AC (at 0.1kHz to 1MHz)

\[
V_D = kV_P \\
I_D = \frac{I_P}{k} \\
\frac{\Delta V_D}{V_D} = \frac{Z_D I_D}{V_D} = \frac{Z_D I_P}{k^2 V_P}
\]
Next Time

- On-Chip Power Distribution