Texas A&M University  
Department of Electrical and Computer Engineering  

ECEN 720 – High-Speed Links  

Spring 2014  

Exam #2  

Instructor: Sam Palermo  

- Please write your name in the space provided below  
- Please verify that there are 9 pages in your exam  
- You may use one double-sided page of notes and equations for the exam  
- Good Luck!  

<table>
<thead>
<tr>
<th>Problem</th>
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<tr>
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Name: Sam Palermo  

UIN: ________________________________
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Problem 1 (25 points)
This problem involves the design of an active continuous-time linear equalizer (CTLE) for a 25Gb/s system. The CTLE should have a bandwidth of 17.5GHz, an ideal peaking at 12.5GHz that is 12dB higher than the low-frequency gain of -6dB. **Assuming the maximum zero frequency**, give the input transistor’s $g_m$ and the values for $R_D$, $R_S$, and $C_S$. You can neglect all of the transistor capacitors, i.e. only consider capacitors that are explicitly drawn in your analysis. Also assume that all transistors operate in the saturation region and have infinite output resistance.

$$H(s) = \frac{g_m}{C_P} \cdot \frac{s + \frac{1}{R_S C_S}}{(s + \frac{1}{R_S C_S} + \frac{g_m R_S}{R_S C_S})} \cdot \frac{1}{(s + \frac{1}{R_D C_P})}$$

$$\omega_p = 2\pi f_p = \frac{1}{R_D C_P} \Rightarrow R_D = \frac{1}{2\pi \omega_p C_P} = \frac{1}{2\pi (17.5 \text{GHz}) (10fF)} = 910\Omega$$

Ideal peaking:\n$$\frac{\omega_p}{\omega_2} = 12\text{dB} = 4 \Rightarrow \omega_2 = \frac{\omega_p}{4} = \frac{2\pi (12.5 \text{GHz})}{4} = 2\pi (3.125 \text{GHz})$$

Gain BW:\n$$A_{\omega} = A_C \cdot \frac{\omega_p}{\omega_2} = \left(\frac{1}{2}\right) \left(\frac{4}{2\pi (12.5 \text{GHz})}\right) = 2\pi (35 \text{GHz})$$

$$g_m = 2\pi (35 \text{GHz}) (10fF) = 2.2 \text{mA}$$

DC gain:\n$$\frac{g_m R_D}{1 + \frac{g_m R_S}{2}} = \frac{1}{2} \Rightarrow R_S = \frac{(g_m R_D - \frac{1}{2})4}{g_m} = \frac{6}{g_m} = 2.73 \Omega$$

$$\omega_2 = \frac{1}{R_S C_S} \Rightarrow C_S = \frac{1}{R_S \omega_2} = \frac{1}{(2.73 \Omega)(2\pi)(35 \text{GHz})}$$

$$g_{m1,2} = 2.2 \text{mA}$$
$$R_D = 910\Omega$$
$$R_S = 2.73\Omega$$
$$C_S = 18.7 fF$$
i. If I want to decrease the ideal peaking ratio to 6dB without changing the first pole, \( \omega_{p1} \), how should I change the CTLE?

\[
\text{ideal peaking ratio} = 1 + \frac{q_m R_s}{2} = 2
\]

\[
\Rightarrow \text{Change } R_s \text{ to } \frac{2}{q_m} = \frac{2}{2.2 \text{kHz}} = 910 \Omega
\]

However, this will have some impact on \( w_{p1} \), so need to tune \( C_s \) also.

\[
w_{p1} = \frac{1 + q_m R_s/2}{R_s C_s} \Rightarrow C_s = \frac{1 + q_m R_s/2}{R_s w_{p1}} = \frac{2}{(910)(2\pi)(12.56\text{kHz})}
\]

\[
R_s = 910 \Omega \\
C_s = 28.4 \mu F
\]

ii. If I want to move the zero frequency \( f_z \) to 1GHz without impacting the original ideal peaking ratio of 12dB, how should I change the CTLE?

\[
\text{Ideal peaking ratio} = \frac{w_{p1}}{w_2} = \left( \frac{1 + q_m R_z/2}{R_s C_s} \right)
\]

\[
= 1 + q_m R_z/2
\]

\[
w_2 = \frac{1}{R_s C_s} \Rightarrow \text{can tune } C_s \text{ w/o impacting peaking}
\]

\[
C_s = \frac{1}{R_s w_2} = \frac{1}{(2.73\text{kHz})(2\pi)(16\text{kHz})}
\]

\[
C_s = 58.3 \mu F
\]
Problem 2 (25 points)
This problem involves the voltage noise budgeting of a serial link system. Here we will conservatively assume that all distributions combine in a worst-case manner. The system consists of a transmitter with a 3-tap FIR filter which sends NRZ bits over a channel to a receiver modeled as a simple amplifier followed by a comparator. Each receiver block has a noise component which should be referred to the receiver input.

\[ \text{Attenuation} = 1 - \varepsilon_{\text{amp}} = 1 - 0.7 = 0.3 \]

\[ \sigma_{n,\text{amp}} = 1\text{mV} \quad \sigma_{n,\text{comp}} = 3\text{mV} \]

\[ \sigma_{RX} = \sqrt{\left(1^2 + \left|\frac{3}{2}\right|^2\right)} = 1.81\text{mV} \]

Complete the following noise budget table assuming a TX peak differential swing of 0.5V_{pp} and a target BER=10^{-15}. You can refer to the Q_{BER} table on page 2 if needed. (10 points)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(K_n)</th>
<th>RMS</th>
<th>Value (BER=10^{-15})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Differential Swing, (V_{\text{swing}})</td>
<td></td>
<td>0.5V</td>
<td></td>
</tr>
<tr>
<td>RX Offset + Sensitivity</td>
<td></td>
<td>5mV</td>
<td></td>
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<tr>
<td>Power Supply Noise</td>
<td></td>
<td>10mV</td>
<td></td>
</tr>
<tr>
<td>Residual ISI</td>
<td>0.05</td>
<td>= 25mV</td>
<td></td>
</tr>
<tr>
<td>Crosstalk</td>
<td>0.05</td>
<td>= 25mV</td>
<td></td>
</tr>
<tr>
<td>Random Noise</td>
<td></td>
<td>= 1.81mV</td>
<td>= 28.7mV</td>
</tr>
<tr>
<td>Attenuation (TX FIR)</td>
<td>= 0.3</td>
<td></td>
<td>= 150mV</td>
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<tr>
<td>Total Noise</td>
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<td>243.7mV</td>
<td></td>
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<tr>
<td>Differential Eye Height Margin</td>
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<td>256.3mV</td>
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</tbody>
</table>

What is the minimum peak differential swing, \(V_{\text{swing}}\), for a BER=10^{-15}, i.e. as the differential eye height margin goes to zero?

\[ V_{\text{swing}} \left(1 - \varepsilon_{ku}\right) \geq \frac{\text{Fixed Noise}}{1 - 0.4} = 72.8\text{mV} \]

What is the minimum peak differential swing, \(V_{\text{swing}}\), for a BER=10^{-12}, i.e. as the differential eye height margin goes to zero?

Fixed noise decreases due to consideration of less random noise.

\[ F_{\text{BER}} = 10^{-12} \Rightarrow RN = 14.069(1.81\text{mV}) = 25.5\text{mV} \]

\[ V_{\text{swing}} \geq \frac{40.5\text{mV}}{1 - 0.4} = 67.5\text{mV} \]
Problem 3 (25 points)
This problem involves the timing noise budgeting of serial link systems.
i. System jitter can be decomposed into the following random and deterministic jitter PDFs.
   Qualitatively sketch the total jitter PDF and give the total jitter at a $10^{-15}$ BER.

\[ TJ = D_{J, \text{ch}} + Q_{BER} \sigma_{J, \text{ch}} \]
\[ = 10_{\text{ps}} + 15.88 \cdot 2(\text{ps}) = 41.8\text{ps} \]
\[ TJ (\text{BER} = 10^{-15}) = 41.8\text{ps} \]

ii. Given the following jitter components from the TX, channel, and RX. What is the maximum RX random rms jitter, $\sigma_{J,RX}$, for a BER=$10^{-12}$ at a 25Gb/s data rate?

\[ BER = 10^{-12} \Rightarrow Q_{BER} = 14.069 \]
\[ D_{J, \text{ch}} + Q_{BER} \sigma_{J, \text{ch}} = \frac{1}{DR} \]
\[ \sigma_{J, \text{ch}} = \frac{1}{Q_{BER}} \cdot \frac{D_{J, \text{ch}} + Q_{BER} \sigma_{J, \text{ch}}}{14.069} = 1.71\text{ps} \]
\[ \sigma_{J, \text{ch}}^2 = 10^2 + \sigma_{J, \text{ch}}^2 \Rightarrow \sigma_{J, \text{ch}} = \sqrt{10^2 - \sigma_{J, \text{ch}}^2} = 14.71\text{ps} - (0.5\text{ps})^2 \]
\[ Max \sigma_{J,RX} (w/ DR=25\text{Gb/s}) = 1.64\text{ps} \]
Problem 4 (25 points)
This problem investigates two forwarded-clock 25Gb/s systems, a half-rate and a quarter-rate system, with a receiver de-skew circuitry consisting of an injection locked 4-stage ring oscillator (ILO). In order for the system to operate properly, a de-skew range of ±0.5UI is necessary.

a) **Half-Rate System.** What is the injection strength required for a maximum jitter tracking bandwidth of 500MHz? What is the minimum jitter tracking bandwidth over the required de-skew range?

**KEY EQUATIONS**

\[ \omega_p = \sqrt{\frac{K^2}{A^2} - \Delta \omega^2} \]

\[ \theta_{ss} = \sin^{-1} \left( \frac{A}{K} \Delta \omega \right) \]

\[ A = \frac{n}{2 \omega_{osc}} \sin \left( \frac{2\pi}{n} \right), \text{ where } n \text{ is the VCO stage number} \]

\[ \begin{align*}
\text{Max } &\text{ JTB } \implies \omega_p = \frac{K}{A} \\
k = A \omega_p = \frac{n \omega_p}{2 \omega_{osc}} = \frac{4(2\pi)(500 MHz)}{2(2\pi)(12.5 GHz)} = 0.08 \\
\text{For } \frac{1}{2} \text{ rate system } &\pm 0.5 \text{ UI } = \pm (0.5 \times 180^\circ) = \pm 90^\circ \\
A+ \theta_{ss} = 90^\circ &\implies \Delta \omega = \frac{K}{A} \sin \theta_{ss} = \frac{K}{A} \\
\omega_p = \sqrt{(\frac{K}{A})^2 - (\frac{K}{A})^2} = 0 \\
K (\text{max JTB } = 500 \text{MHz}) = 0.08 \\
\text{Min. JTB } & = 0
\end{align*} \]
b) **Quarter-Rate System.** What is the injection strength required for a maximum jitter tracking bandwidth of 500MHz? What is the minimum jitter tracking bandwidth over the required de-skew range?

\[
K = \frac{A \omega_p}{2 \omega_{sc}} = \frac{4 \pi (2\pi) (500 \text{MHz})}{2 \pi (2\pi) (6, 25 \text{GHz})} = 0.16
\]

For \( \frac{1}{4} \) rate system:

\[
\pm 0.5 \text{ UI} = \pm 0.5 \times (90^\circ) = \pm 45^\circ
\]

\[
A + \Theta_{ss} = 45^\circ \implies \Delta \omega = \frac{K}{A} \sin(45^\circ) = \frac{K}{A^{1/2}}
\]

\[
\omega_{J} = \sqrt{\left(\frac{K}{A}\right)^2 - \left(\frac{K}{A^{1/2}}\right)^2} = \frac{K}{A^{1/2}} = \frac{2\pi (500 \text{MHz})}{2}
\]

\[
K \text{ (max JTB = 500MHz)} = 0.16
\]

\[
\text{Min. JTB = 354MHz}
\]
Scratch Paper