Understanding the Pre-Emphasis and Linear Equalization Features in Stratix IV GX Devices

AN-602-1.0 | Application Note

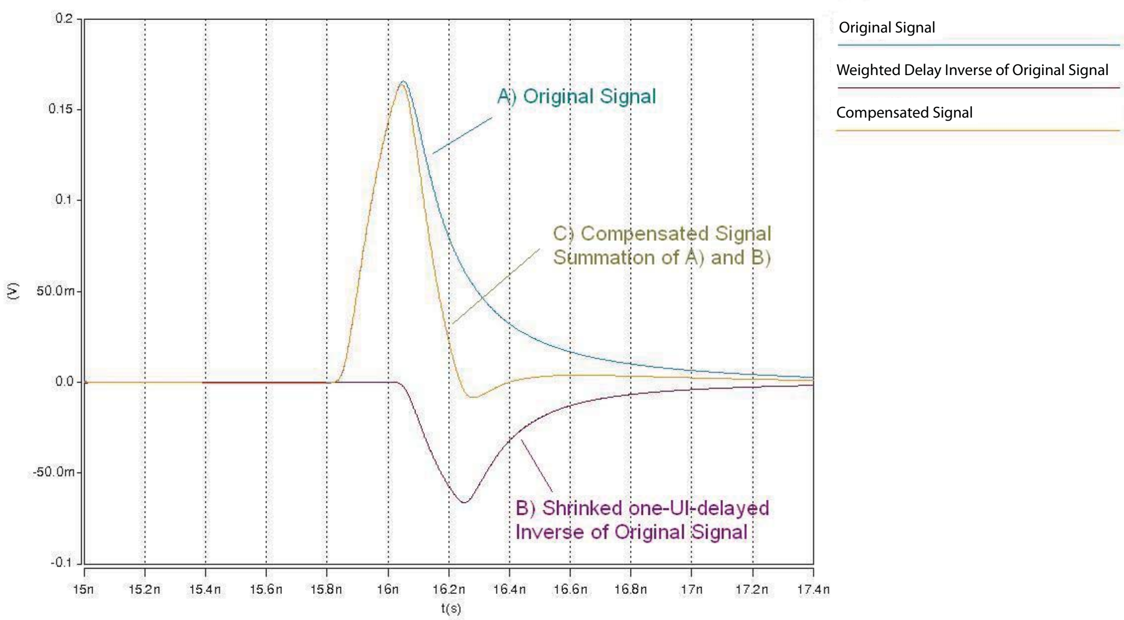
A high-speed signal travelling through a backplane is subject to high-frequency losses, primarily skin effect and dielectric losses. These losses can severely degrade and attenuate the high-frequency content of the signal, making it difficult for the receiver to interpret the signal. Stratix® IV GX devices offer pre-emphasis and linear equalization to address this problem and improve the high-speed signal quality.

This application note provides information about the transmitter pre-emphasis and receiver equalization behavior of Stratix IV GX devices. Specific examples demonstrate how an impacted signal is improved by these two features, on a time domain, a frequency domain, or both.

Transmitter Pre-Emphasis in Stratix IV GX Devices

An ideal signal for a receiver completes the transition within a symbol interval. However, when the signal travels through a lossy backplane, the transition expands to adjacent intervals. This effect is referred to as inter-symbol interference (ISI). The purpose of pre-emphasis is to apply delay and inversion to the signal and add it back to the original signal with the proper weight, thereby compensating for the "expansion" or ISI from the nearby data symbol. Figure 1 shows an example of delay-inverse-weight compensation.

Figure 1. ISI Compensation with Pre-Emphasis



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Depending on the channel characteristics, one simple delay, inversion, and weight process may not be enough to achieve your target compensation. For example, the compensation shown in Figure 1 only reduces the expansion after the main cursor (the main pulse) but not the expansions before the cursor. Shrinking and inverting a signal ahead of the current cursor can address the pre-cursor ISI.

To achieve the optimal channel loss compensation, you can combine different delays, weights, and polarity in one pre-emphasis setup. Therefore, a real pre-emphasis implementation generally works like a finite impulse response (FIR) filter with different “taps,” which refer to signals after different unit delays.

In the frequency domain, pre-emphasis boosts the high-frequency energy on every transition in the data stream.

Pre-Emphasis Features in Stratix IV GX Devices

A Stratix IV GX transmitter contains four programmable drivers. One is the main driver, V_{OD}, which controls the base amplitude with or without pre-emphasis. The other three are pre-emphasis taps: pre-tap, 1st post-tap, and 2nd post-tap. A polarity setting is also available for the pre-tap and 2nd post-tap. Multiple programmable pre-emphasis taps and polarity flexibility can address a large number of backplanes with different channel characteristics. Figure 2 shows a Stratix IV GX pre-emphasis digital filter with V_{OD} and three pre-emphasis taps.

Figure 2. Pre-Emphasis Digital Filter

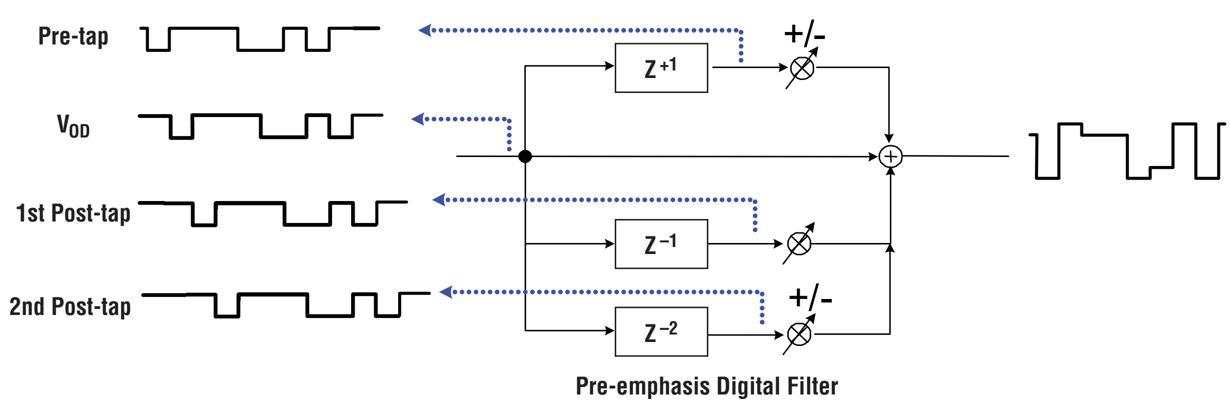
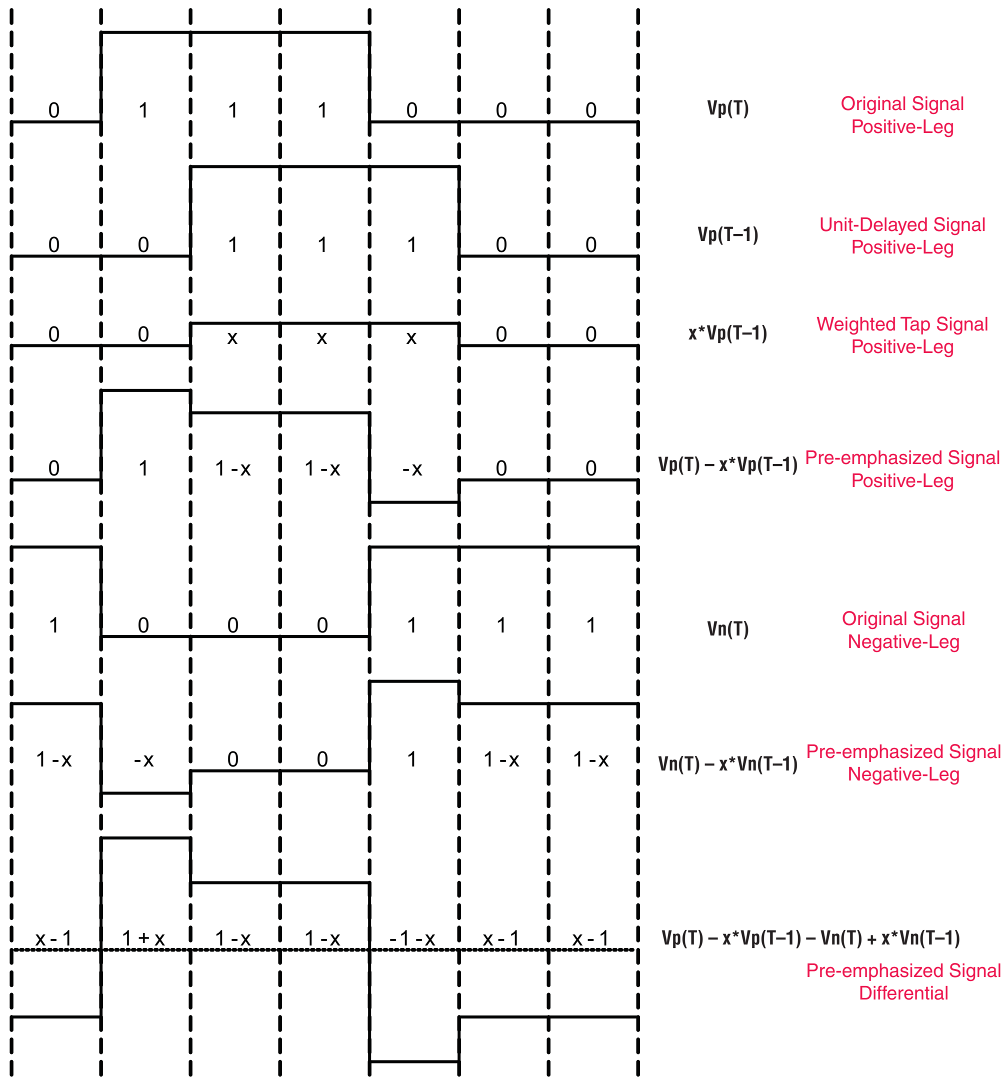


Figure 3 shows how a differential pre-emphasis signal is generated with the 1st post-tap. The original positive-leg signal Vp(T) is compared with the unit-delayed positive-leg signal Vp(T-1). Assuming the pre-emphasis weight is x ($0<x<1$), the difference between the Vp(T) signal and the weighted x*Vp(T-1) signal is the emphasized signal (positive-leg). The negative-leg of the emphasized signal is similarly generated. The pre-emphasized differential signal is differentiated from the positive-leg and negative-leg signals.

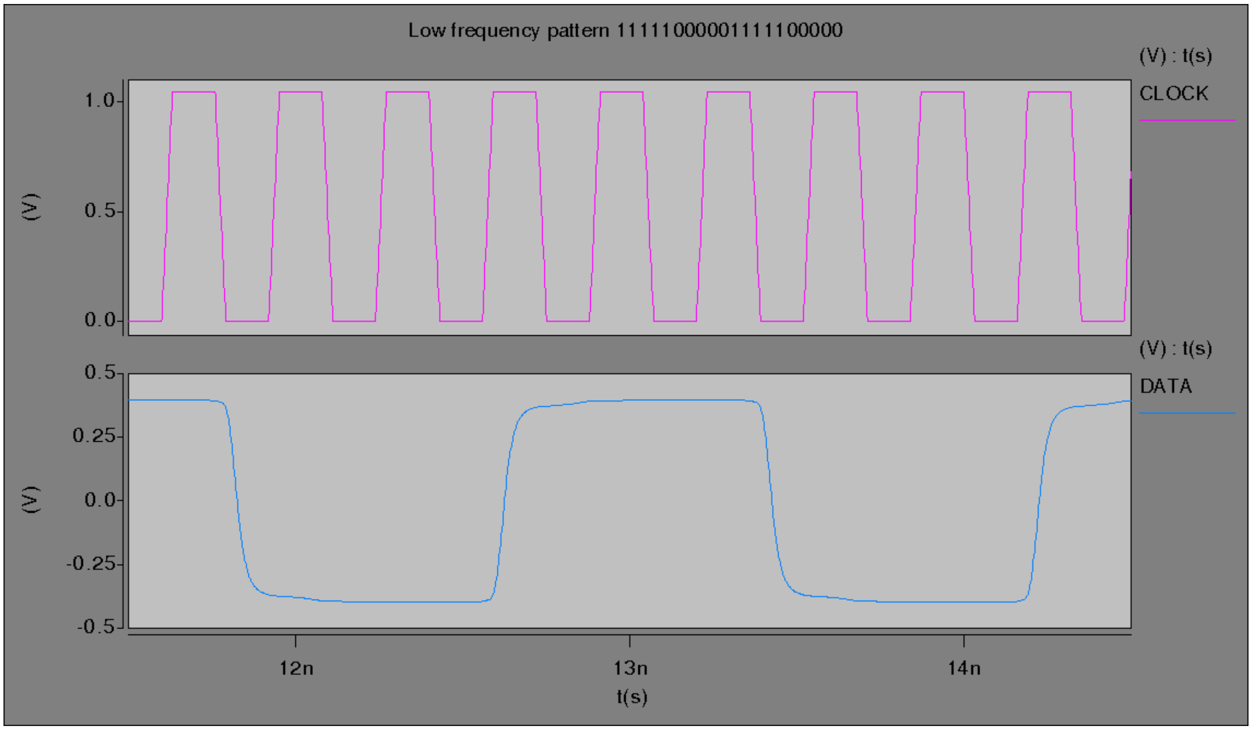
Figure 3. Pre-Emphasis Signal Generation



Effects of Each Pre-Emphasis Tap

The following analysis demonstrates the effects of each tap with ideal and simulation waveforms. A pattern with long 1s and long 0s is used for this purpose. Figure 4 shows a sample data pattern with long 1s and 0s. A 1010 high-frequency pattern is not suitable in this study because the pre-emphasis effect on the consecutive bits is not visible with such a pattern. A pseudo-random binary sequence (PRBS) is not suitable because the random transitions combine and complicate the effects of different taps.

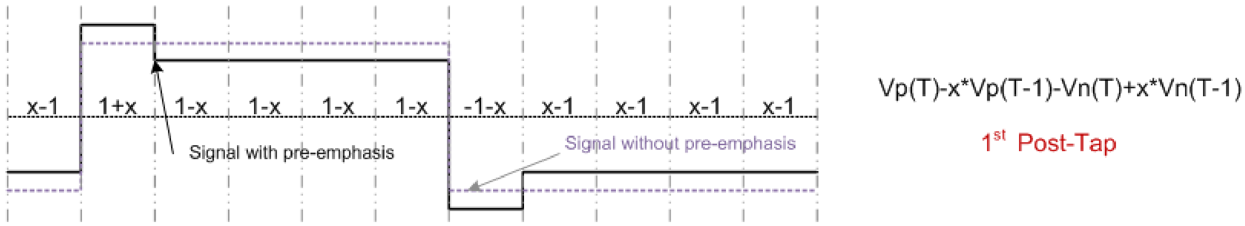
Figure 4. Sample Data Pattern with Long 1s and 0s



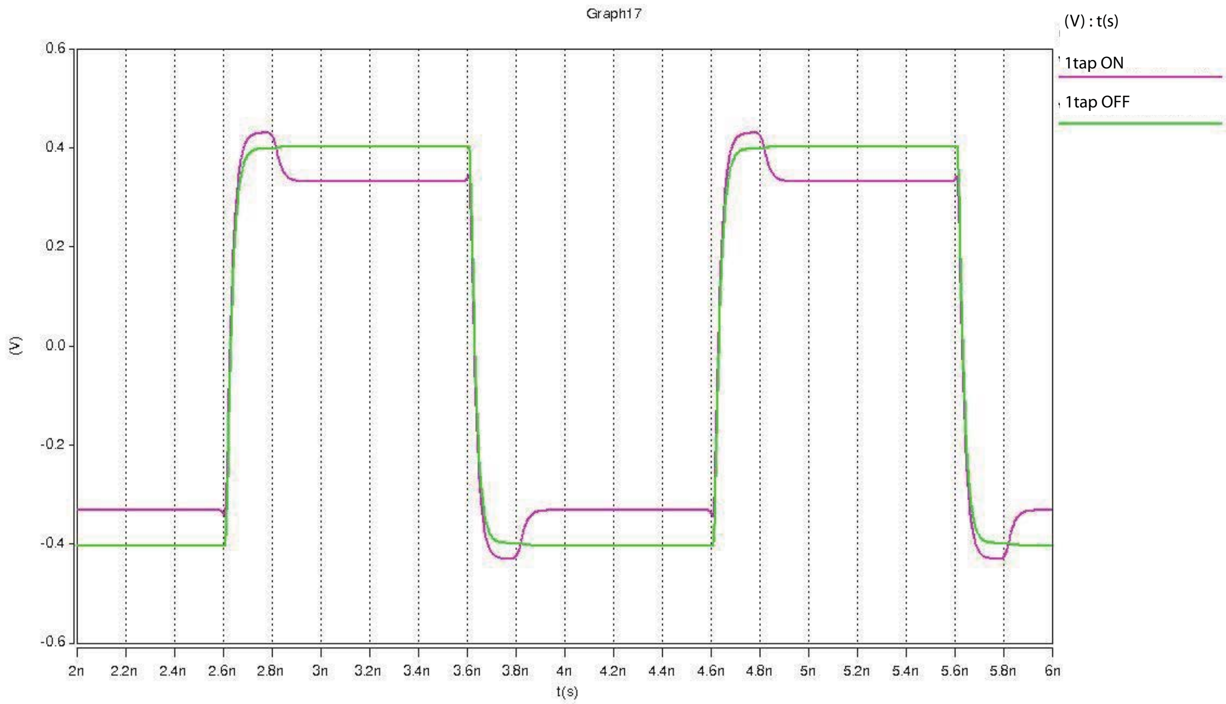
The simulation is running at 5 Gbps on a Stratix IV GX HSSI Verilog-A buffer model without package, with V_{OD}=8 mA and a 100-Ω internal termination. The following simulation waveforms are probed at the differential buffer output. The green waveforms represent a signal without pre-emphasis. The purple waveforms are signals with pre-emphasis. The brown waveforms for 2nd post-tap and pre-tap are also signals with pre-emphasis but with different polarity.

The 1st post-tap is usually the most effective tap. It emphasizes the bit period immediately after the transition and de-emphasizes the remaining bits (Figure 5). Because of the nonlinear saturation effect when combining the 1st post-tap and V_{OD}, the emphasizing above V_{OD} is not as significant as de-emphasizing below V_{OD}.

Figure 5. Effect of the 1st Post-Tap



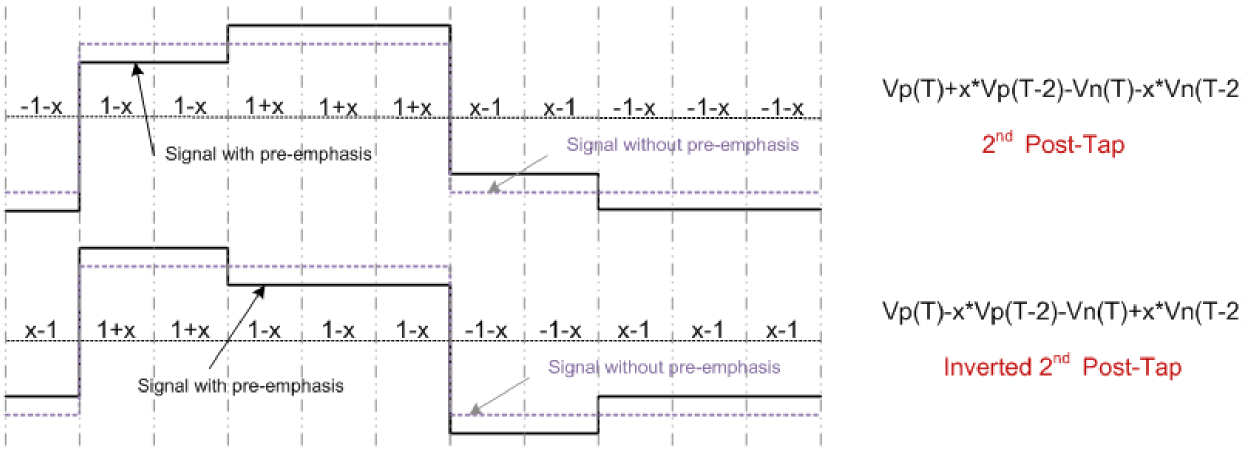
a) Ideal 1st post-tap effect (assuming V_{OD}=1 and x is the tap weight)



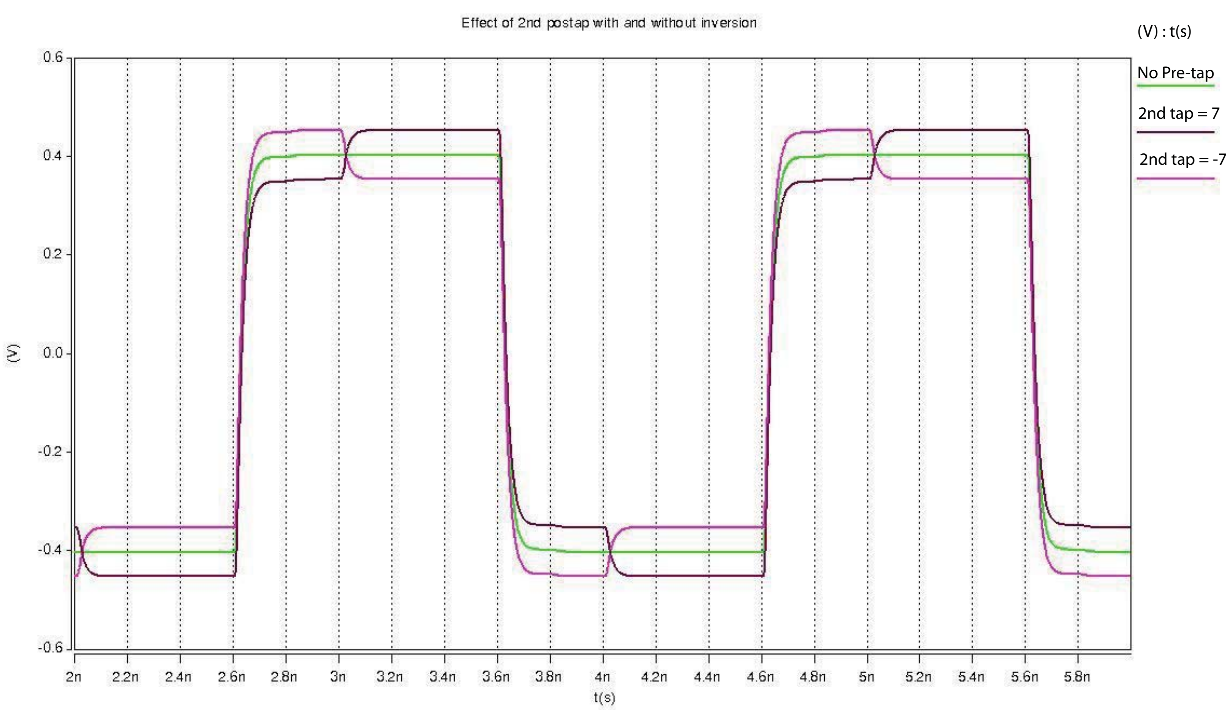
b) Stratix IV GX 1st post-tap simulation

The 2nd post-tap de-emphasizes the first two bits after the transition and emphasizes the remaining bits. A different polarity on the 2nd post-tap does the opposite (Figure 6).

Figure 6. Effect of the 2nd Post-Tap



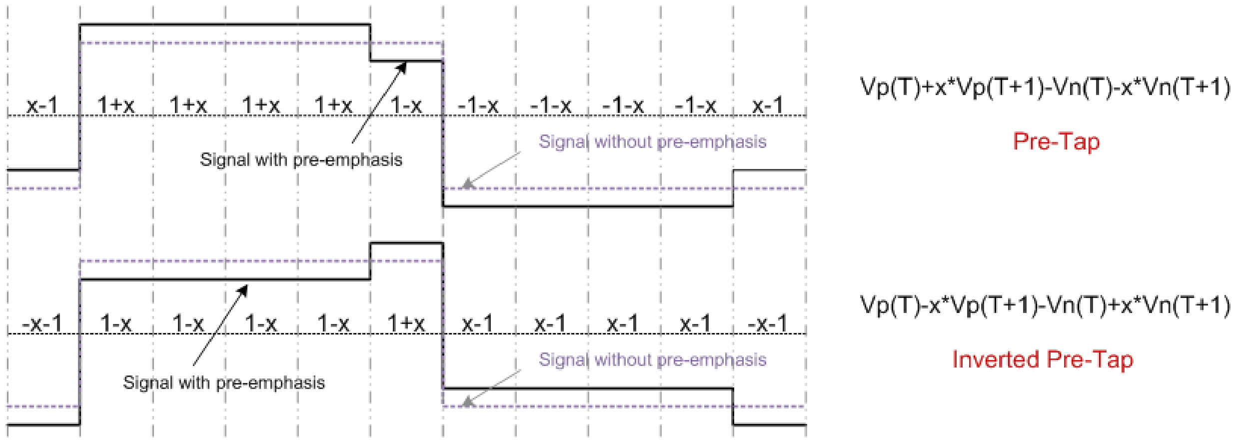
a) Ideal 2nd post-tap effect (assuming V_{OD}=1 and x is the tap weight)



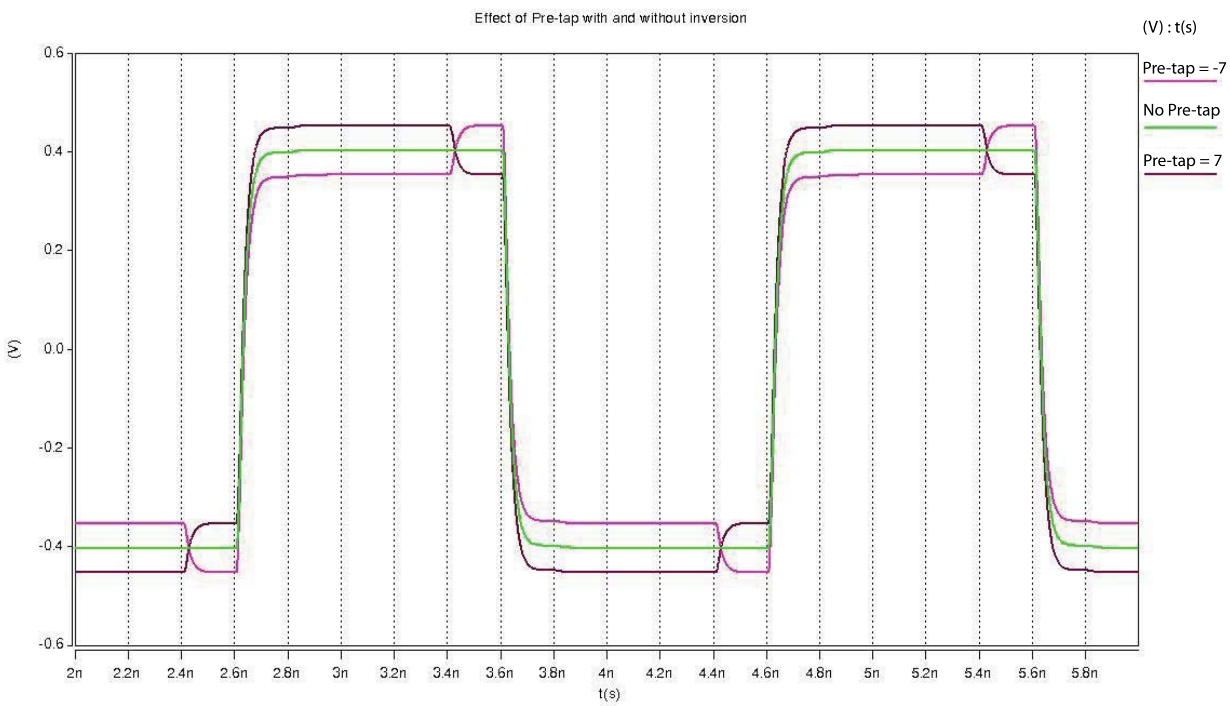
b) Stratix IV GX 2nd post-tap simulation

The pre-tap de-emphasizes the bit before the transition and emphasizes the remaining bits. A different polarity on pre-tap does the opposite (Figure 7). In a system that features DFE in the receiver, pre-tap is important. Because DFE can only address the post-cursor ISI, pre-tap in a Stratix IV GX device can reduce the pre-cursor ISI effect.

Figure 7. Effect of the Pre-Tap



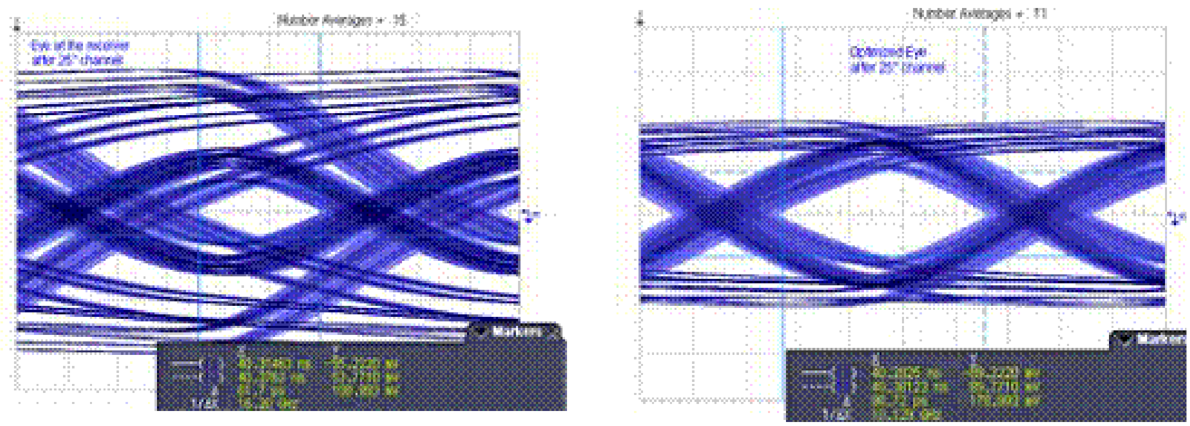
a) Ideal pre-tap effect (assuming V_{OD}=1 and x is the tap weight)



b) Stratix IV GX pre-tap simulation

Figure 8 shows the eye diagram of a PRBS-7 pattern after a lossy channel without pre-emphasis (shown on the left) and with certain pre-emphasis taps on (shown on the right). The significant difference between the two eyes demonstrates how pre-emphasis can improve signal integrity through the lossy channel.

Figure 8. Eye Diagram of Data Pattern without Taps and with Taps *(Note 1)*



Note to Figure 8:

(1) Comparing the marker readings of the two cases, the eye width increased from 61.7 ps to approximately 98.72 ps, a gain of 37 ps or 60%. Similarly, the eye height increased from 108.9 mV to approximately 178.9 mV, a gain of 70 mV or 64.3%.

Amount of Pre-Emphasis Change

Pre-emphasis is often quantified with the percentage obtained through the pre-emphasis taps. You can calculate the percentage from the amplitudes of the emphasized signal (V_1) and the de-emphasized signal (V_2), as shown in Equation 1.

Equation 1.

$$\begin{aligned}\%\ \text{Voltage change} &= [(V_1 - V_2)/V_2] \times 100 \\ \text{dB increase} &= 20\log(V_1/V_2)\end{aligned}$$

Assume V_{OD} is set to V and the pre-emphasis tap weight is x. The emphasized signal amplitude is $V_1=V+x$ and the de-emphasized signal amplitude is $V_2=V-x$. Replacing V_1 and V_2 in Equation 1 leads to Equation 2.

Equation 2.

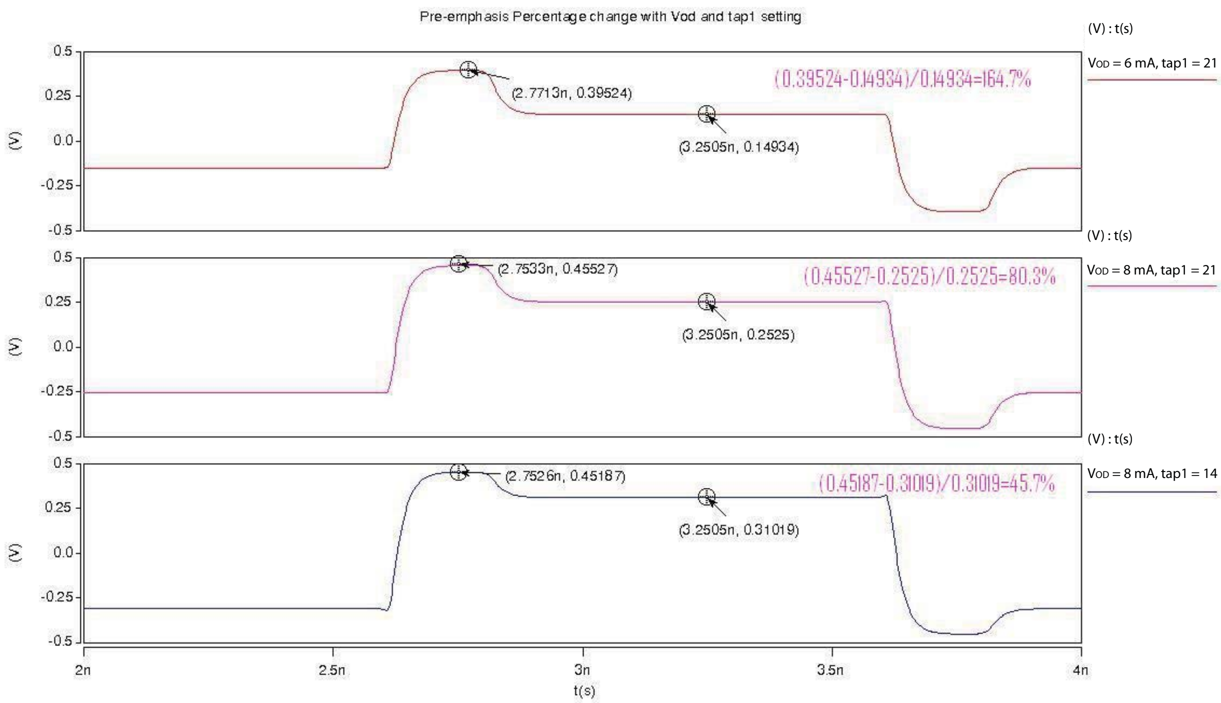
$$\begin{aligned}\%\ \text{Voltage change} &= [2x/(V - x)] \times 100 \\ \text{dB increase} &= 20\log[(V + x)/(V - x)]\end{aligned}$$

Equation 2 shows how the pre-emphasis tap setting and V_{OD} setting impact the percentage achieved by the pre-emphasis tap:

- The bigger the pre-emphasis tap, the more the percentage changes
- The bigger the V_{OD}, the less the percentage changes

Figure 9 shows an example of the percentage changes achieved with different V_{OD} and 1st post-tap settings. The top waveform has V_{OD} = 6 mA and tap1 = 21. The percentage is quantified at 165%. The middle waveform increases V_{OD} to 8 mA and uses the same tap1 setting. The percentage is reduced to 80.3%. The bottom waveform uses the same V_{OD} as the middle waveform but reduces the tap1 setting to 14. The percentage is reduced to 45.7%.

Figure 9. Percentage Change Variation with V_{OD} and Pre-Emphasis Tap Setting



Altera's transmitter implements both pre-emphasis and de-emphasis. It increases the high-frequency components and decreases the low-frequency components. The total amount of emphasis is the difference between pre-emphasis and de-emphasis. The advantage of this implementation is that it dissipates less power than the traditional pre-emphasis and achieves the same amount of emphasis.

Limitations of Pre-Emphasis

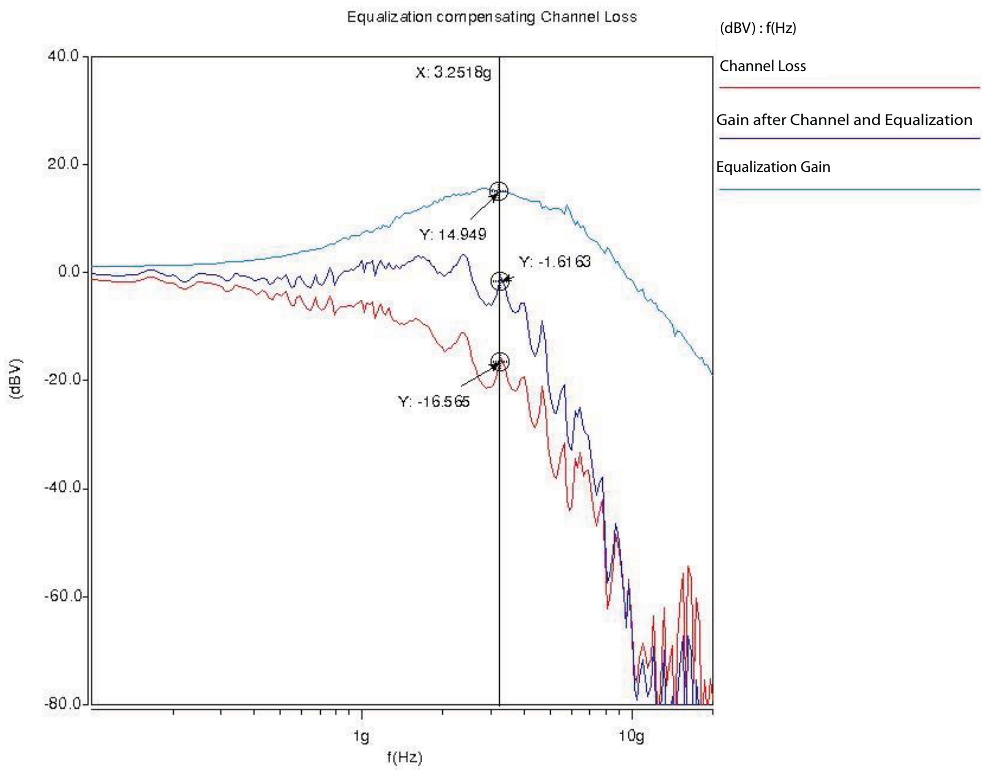
Pre-emphasis increases the signal edge rate, which increases the crosstalk on the neighboring channels. Meanwhile, because pre-emphasis emphasizes the transition bits and de-emphasizes the remaining bits, if there is any discontinuity along the channel, the reflection at the discontinuity is more complicated than without pre-emphasis. Because the impact of pre-emphasis on crosstalk and channel discontinuity is highly case-dependent, simulation is required to ensure the impact is minimal.

The pre-emphasis selection is also a key to the signal integrity at the receiver. Over-emphasis tends to degrade rather than help the receiver signal quality. Stratix IV GX devices offer multiple toolkits to determine or simulate the best pre-emphasis setting for a given backplane.

Linear Equalization in Stratix IV GX Receivers

Receiver equalization is another signal conditioning feature to overcome high-frequency losses through a transmission channel. An equalizer acts as a band pass filter, which boosts the contents inside a band of frequencies and attenuates both the high and low frequency contents outside. Figure 10 shows an example of equalization compensating channel loss. The channel loss at 3.25 GHz is approximately –16.5 dB. The equalization boosts the gain by 14.9 dB at 3.25 GHz, thus bringing the end gain up to –1.6 dB.

Figure 10. Equalization Compensating Channel Loss

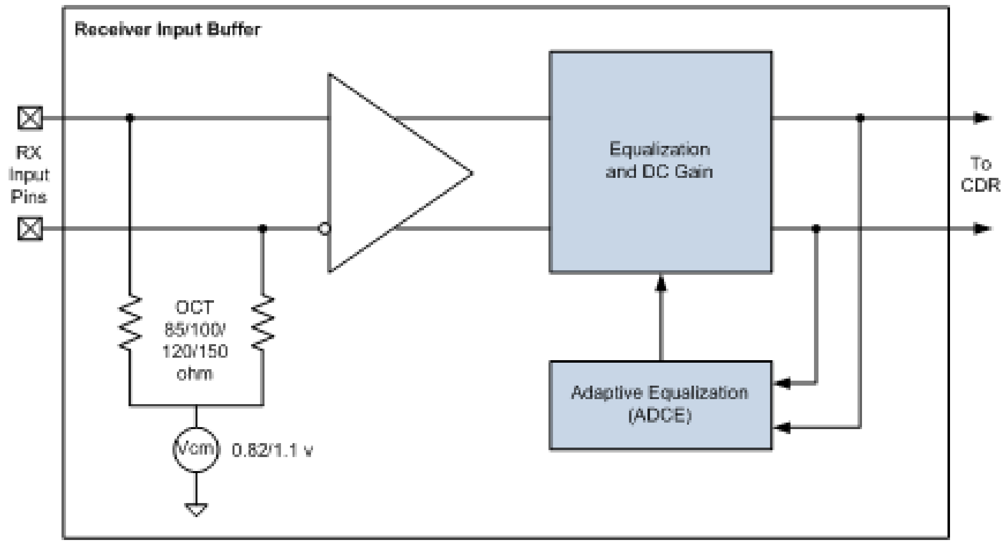


Programmable Linear Equalization in Stratix IV GX Devices

The Stratix IV GX receiver supports programmable common mode voltage (RX Vcm), equalization, DC gain, and on-chip termination (OCT) settings. A Stratix IV GX receiver may also support an optional adaptive equalization, ADCE.

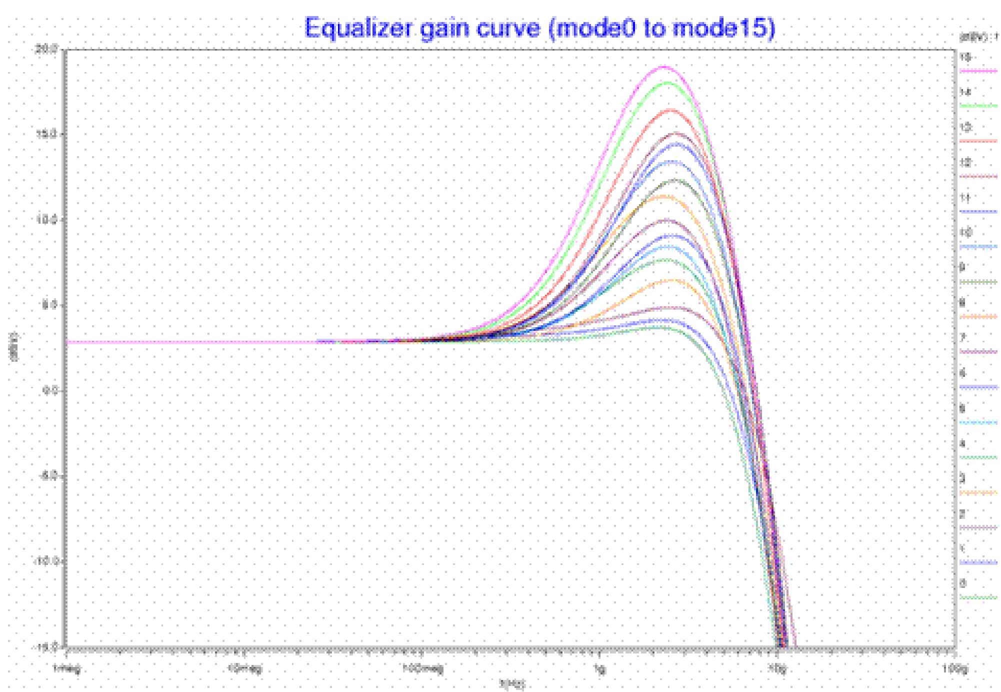
Figure 11 shows the Stratix IV GX receiver input buffer.

Figure 11. Receiver Input Buffer



The programmable linear equalization is optimized at 6.5 Gbps. There are 16 equalization modes that boost the high-frequency content from 2.6 dB (Mode 0) to 17.8 dB (Mode 15). Figure 12 shows the equalizer gain curves of the different equalization modes offered in the Stratix IV GX receiver.

Figure 12. Linear Equalizer Gain Curves

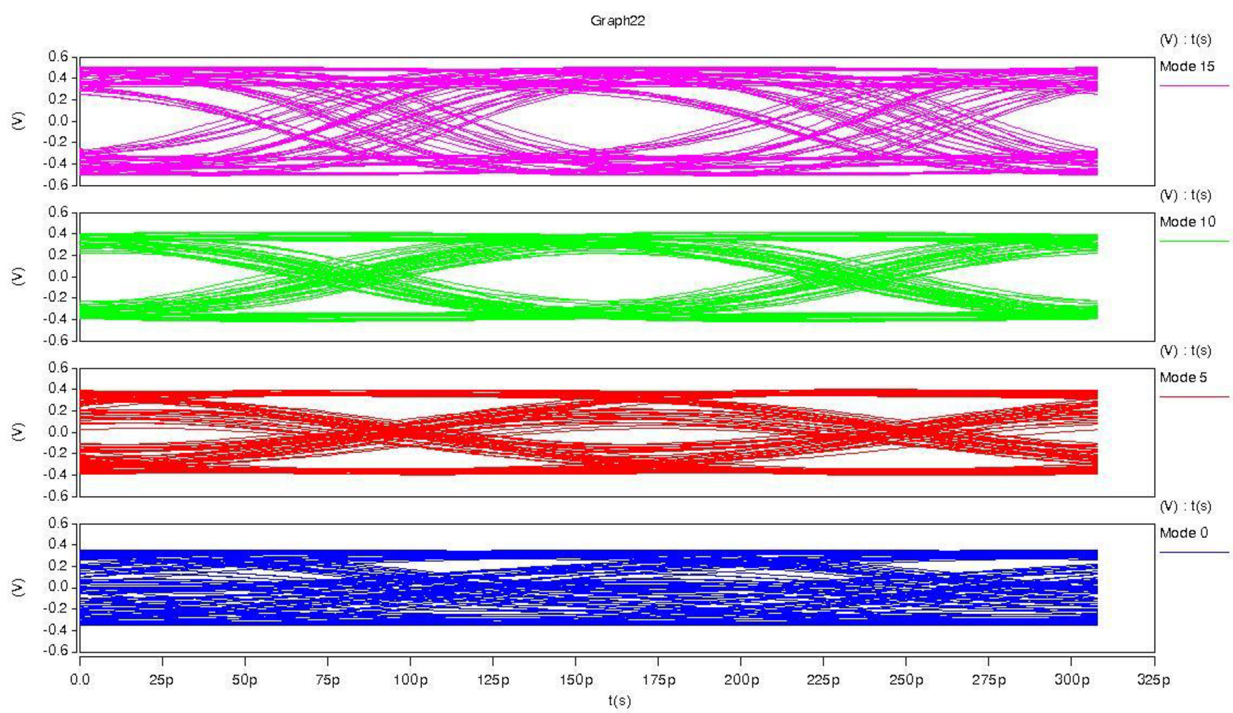


Signal Quality with Linear Equalization in a Stratix IV GX Receiver

Figure 13 shows an example of equalization compensation on a lossy channel. Four equalization modes—Mode 0, Mode 5, Mode 10, and Mode 15—are applied to the data stream out of the channel. All the eye diagrams are differential signals probed at equalizer output.

- Mode 0 provides very little high-frequency boost. The eye is completely closed because of the channel loss.
- Mode 5 achieves limited eye opening from a high-frequency boost.
- Mode 10 provides much more high-frequency boost and the eye is wide open with a 400 mV eye height.
- Mode 15 has the most high-frequency boost but the eye is not as clean as Mode 10. This behavior is called over-equalization.

Figure 13. Eye Diagrams of Equalization Outputs



Frequency Dependency of the Linear Equalizer

The linear equalizer is frequency dependent. The boost at the optimal frequency and the boost at the other frequencies can vary significantly. You can see this behavior by studying the equalization output with sinusoidal inputs at different data rates.

In Figure 14, a 6.5 Gbps sinusoidal input (magenta) is sent into the equalizer. The equalizer outputs (green, brown, purple, and blue waveforms) are amplified by up to 550 mV. However, with a sinusoidal input at 650 Mbps (Figure 15), the equalization will only amplify 87 mV, even at the highest equalization setting. The key is the peak frequency of the equalizer gain. A 6.5 Gbps input data is running at the peak frequency while a 650 Mbps input is running at only 10% of the peak frequency. As seen in Figure 12, the closer the input data frequency is to the peak frequency, the more equalization gain the equalizer provides.

Figure 14. Receiver Equalizer Response to 6.5 Gbps Sinusoidal Input

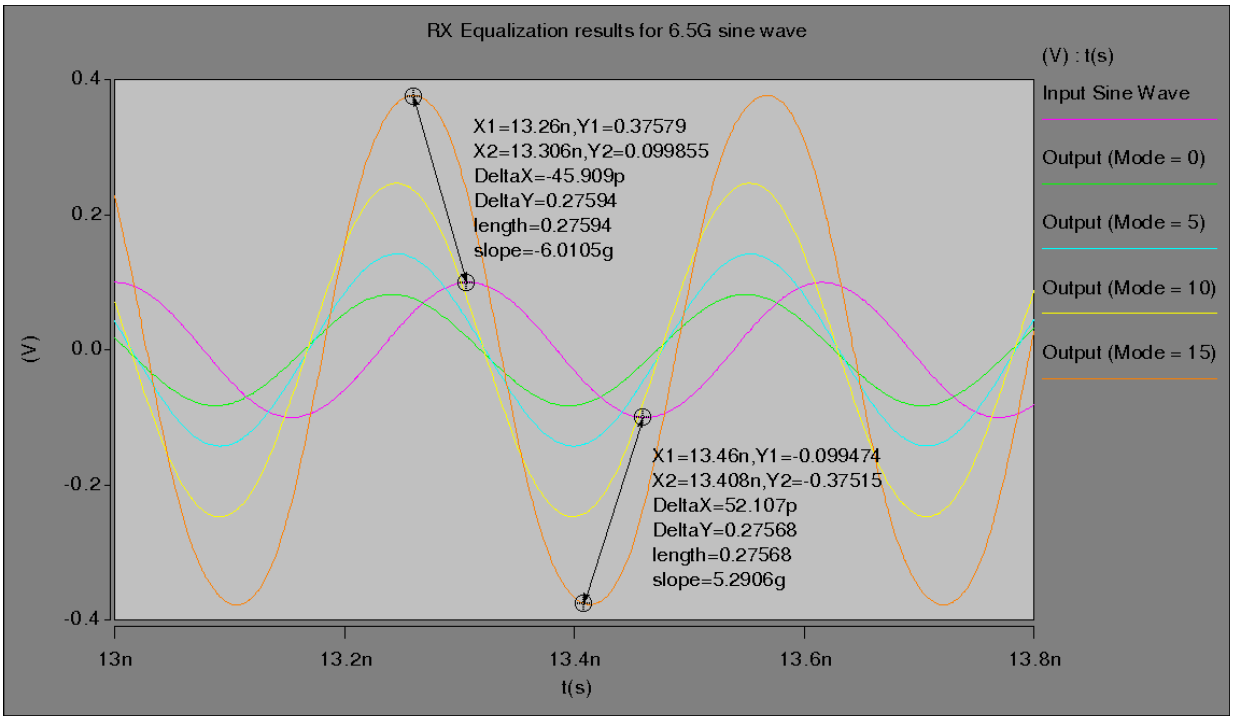
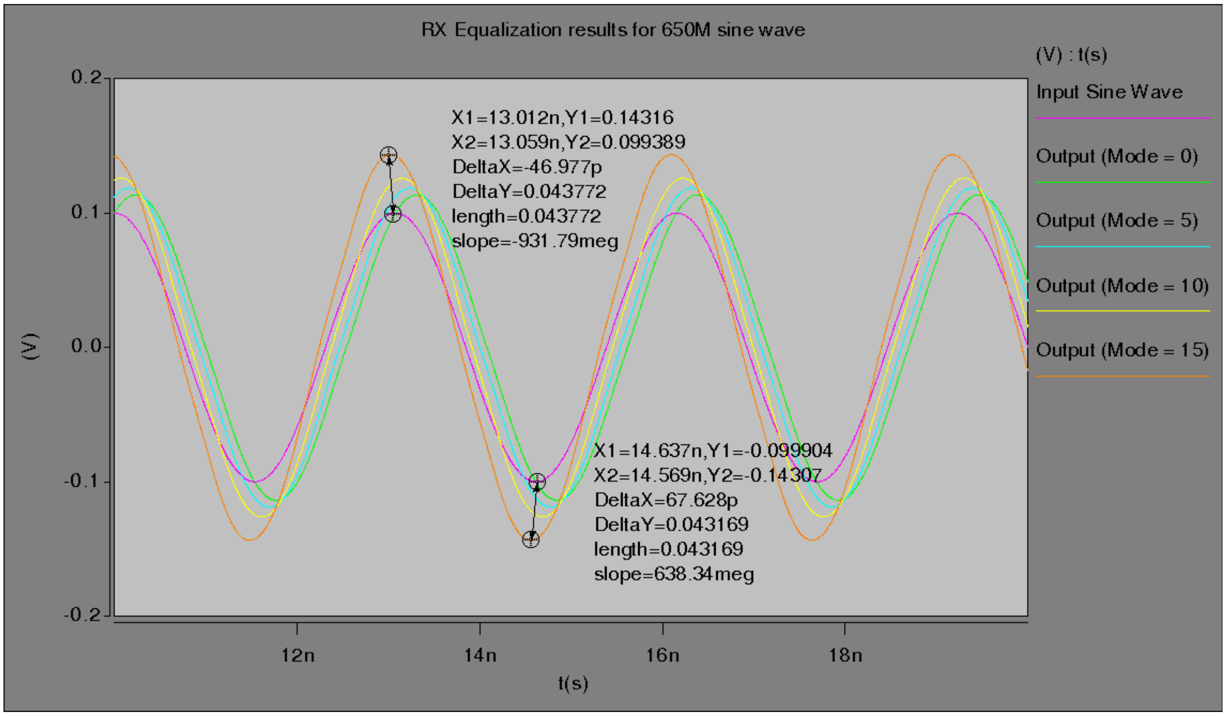


Figure 15. Receiver Equalizer Response to 650 Mbps Sinusoidal Input



Limitations of Linear Equalization

Linear equalization boosts the high-frequency component of the input stream, regardless of data signal or noise. If the noise introduced in the channel is in the optimal frequency range of the equalization, the noise component is boosted and negatively impacts the correct sampling of the data stream and clock data recovery (CDR).

Similar to pre-emphasis, equalization selection is also a key to the signal integrity of the equalizer output. Over-equalization degrades the signal quality instead of improving it. Stratix IV GX devices offer multiple toolkits to determine and simulate the best receiver equalization setting in a given backplane.

Conclusion

This application note describes how pre-emphasis and linear equalization compensate for high-frequency losses. Pre-emphasis inverts, shifts, and shrinks the adjacent symbols to boost the bit transition. Linear equalizer amplifies the gain in certain frequency ranges.

Stratix IV GX devices offer programmable pre-emphasis and linear equalization. Pre-emphasis in a Stratix IV GX transmitter has one pre-tap and two post-taps with programmable weight and polarity. Linear equalization in a Stratix IV GX receiver is optimized at 6.5 Gbps and has 16 different modes that provide a high-frequency boost from 2.6 dB to 17.8 dB.

Pre-emphasis and linear equalization can work together to compensate for the high-frequency channel loss. The setting selection is also critical for pre-emphasis and linear equalization to achieve optimal compensation. Stratix IV GX devices offer multiple toolkits to determine or simulate the optimal setting.

Document Revision History

Table 1 lists the revision history for this application note.

Table 1. Document Revision History

Date	Version	Changes
November 2010	1.0	Initial release.