White Paper on Transmit Pre-Emphasis and Receive Equalization

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1. Introduction

This paper discusses the benefits of pre-emphasis and receive equalization at 3.125Gbps data rate and above across 30+ inches of backplane with connectors and 90 inches of trace board with standard FR-4 material. The causes of the signal degradations when high speed data traveling through a back plane are discussed and the principle of the pre-emphasis and equalization is explained. Experimental results are shown at the end of the paper to prove the effectiveness of both pre-emphasis and receive equalization.

2. The cause of the signal degradation when passing through a backplane

When a high speed signal traveling through a long PCB trace, the signal will be degraded due the electrical properties of the PCB traces[1,2, 3]. The higher the frequency and the longer the PCB trace, the higher the degradation is. This is caused by the bandwidth limitation of the PCB trace (we will refer as “the channel” in the following sections).

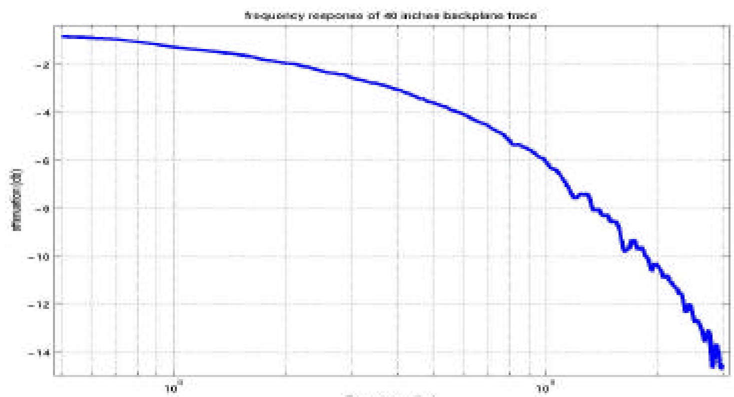

Figure 1 Measured frequency response of the 40inch PCB trace

When the data rate is higher than the bandwidth of the channel, the degradation of the signal will occur, as shown in Figure 2.

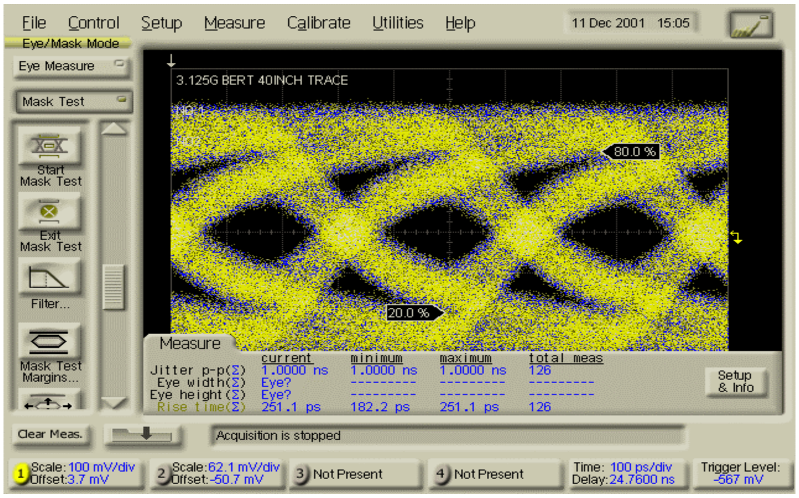

Figure 2 Eye Diagram and the Waveform after 40inch PCB trace

This frequency dependent loss curve are caused primarily by "skin effect". With the increase of the data rate, the currents tend to flow on the surface of the wire. The higher the date rate, the narrower the current path is. Therefore the higher the resistance of the trace is. This is known in physics as skin effect[2]. The skin depth is inversely proportional to the square root of frequency, making the effective series resistance of the line proportional to the square root of frequency, approaching the DC resistance at low frequencies. This phenomenon is usually described by the following relation[4],

$$\left.\frac{V_{out}}{V_{in}}\right|_{skin} = \exp\left[-\sqrt{\frac{f}{f_s}}\right] \qquad \textbf{Equation 1}$$

where $f_s = \left(2Z_o / R_s l\right)^2$, R_s is a parameter characterized by the line dimensions and conductor materials, l is the length of the trace and Zo is the intrinsic impedance of PCB trace.

If we could design circuits which can produce the reverse behavior of the channel' frequency response to compensate the effects, the signal will be restored. The pre-emphasis and equalization technique have been proven to be an effective way produce such effects and a correct design of a pre-emp/equalizer lie in the accuracy of the compensations.

3. Transmit Pre-Emphasis

The function of the pre-emphasis can be understood in both frequency domain and time domain. When the data rate is higher than the bandwidth of the channel, the binary data cannot complete transition within a symbol interval and it will spread into the adjacent symbols, know as ISI. Figure 3 shows the shape of a 200ps pulse before and after going through 40inch PCB trace. The long tail of the pulse spreads into several symbols.

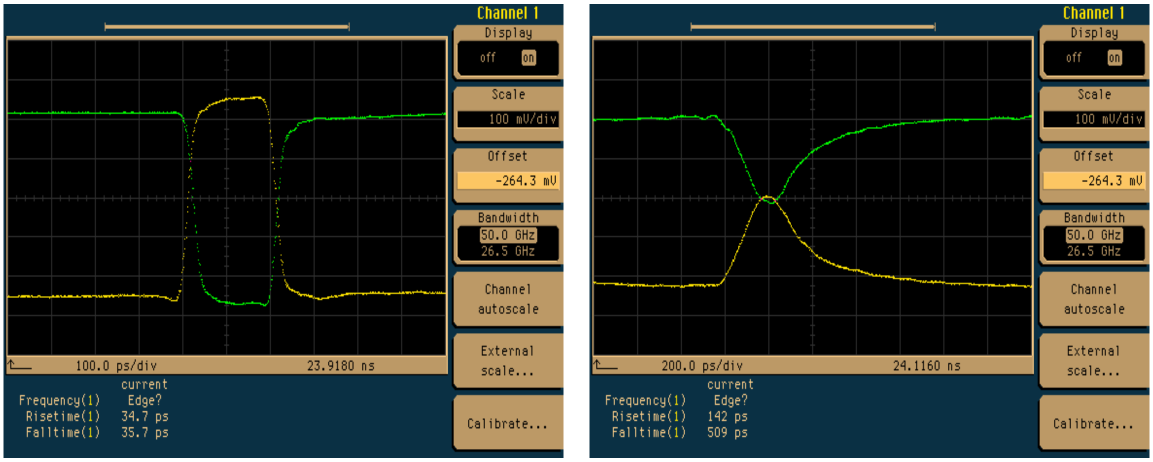

Figure 3 ISI in 40inch PCB trace

If we apply a delayed & reversed data to the channel at next cycle with proper amplitude, it will cancel the consequence of the previous data, as shown in Figure 4. This type of ISI mitigation is implemented at transmitter through “pre-emphasis”. When the inverted and delayed waveform is added to the original waveform, the resulting waveform looks as though its transition has been boosted, as shown in Figure 5. To achieve optimized pre-emphasis effects, more than one tap are required to further cancel the ISI. Our design practice showed that when the data rate is above 2.5Gbps, the best pre-emphasis effects are achieved by overcompensating the ISI with the first tap, and than using the second tap to cancel “the extra” compensation of the first tap. Figure 6 shows our testing results of pre-emphasis.

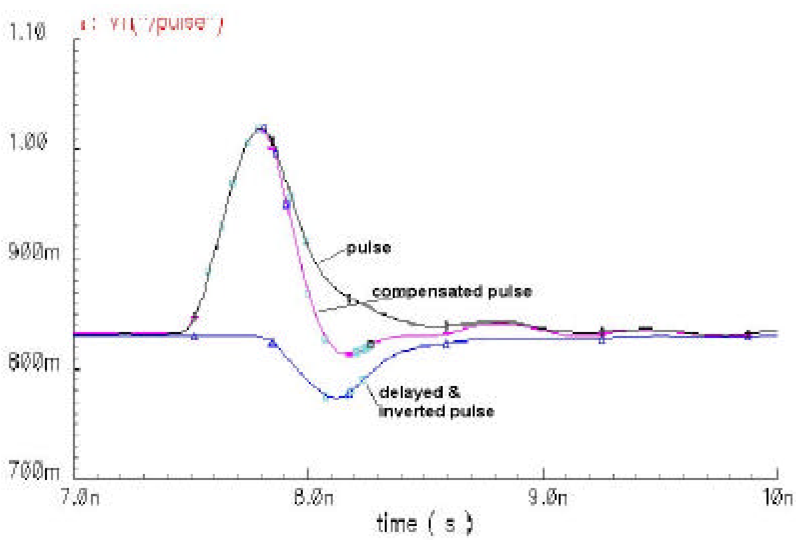

Figure 4 Using Pre-emphasis to cancel the tail of a pulse

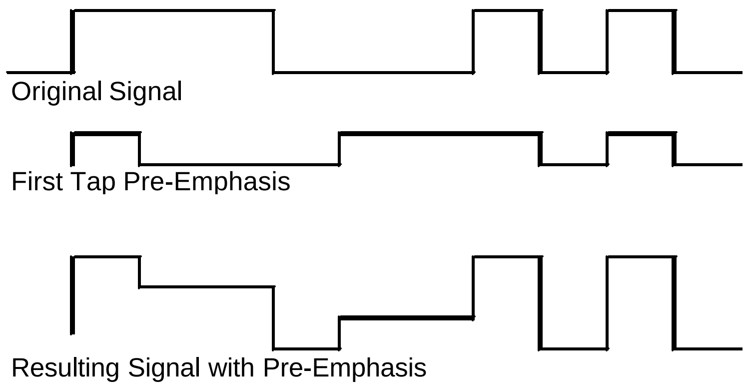

Figure 5 Data stream with pre-emphasis

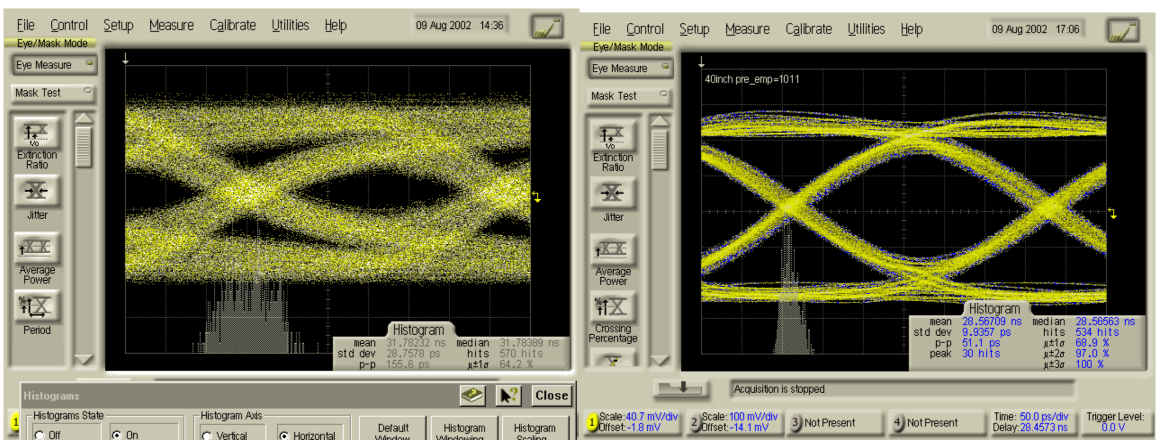

Figure 6 Signal after 40inch PCB trace with and without the pre-emphasis

The process of combining a delayed wave and a wave can be expressed as

$$F_{pre\text{-}emp}(t) = F(t) + a\ F(t)\,e^{jwT} = (\,1 + a\ e^{jwT}\,)\,F(t) \qquad \textbf{Equation 2}$$

The frequency response of the above equation is shown in Figure 7. It shows that the pre-emphasis can boost the high frequency and therefore compensates the loss from the channel. For pre-emphasis with one cycle delay, the peak of the frequency boost occurs at the data rate.

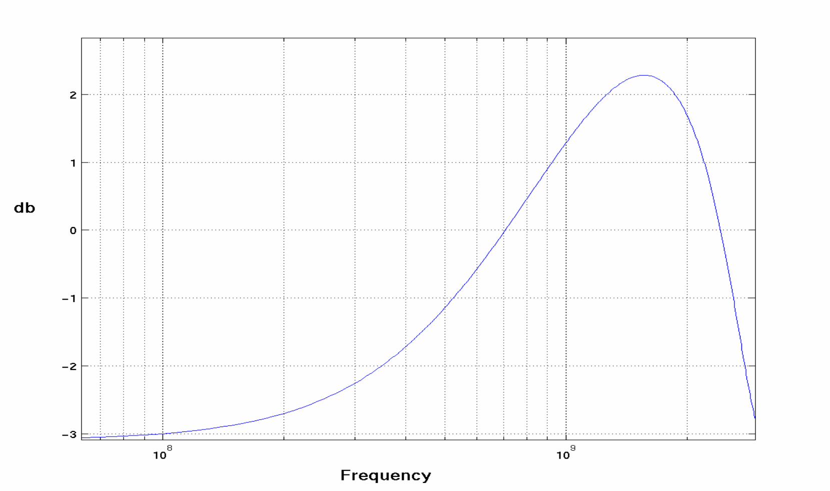

Figure 7 Illustration of the transfer function of the one tap pre-emphasis. a **= -0.3 in equation 2**

Pre-emphasis is preferred over receive equalization if cross-talk is not a factor in the transmission line. Otherwise, pre-emphasis will make cross-talk more pronounced by amplifying the transmit signals.

4. Receive Equalization

Receive equalization is a function applied at the receiver that counteracts the data degradation in the long transmission line. The equalizer could be either digital equalizer which is equivalent to applying the pre-emphasis techniques to the receiving end of the channel, or it could be the analog equalizer which employs RC filter to compensate the channel loss.

Receive equalization is preferred over pre-emphasis if signal to noise ratio (SNR) is not factor in the transmission line. Otherwise, receive equalization will amplify the noise transmitted across the transmission line at the receiver.

One of the advantages of receiver equalization over pre-emphasis is that the equalizer can be adaptive so that the equalization level can be selected automatically to achieve the proper fit, unlike adaptive pre-emphasis, which requires feedback from the receiver.

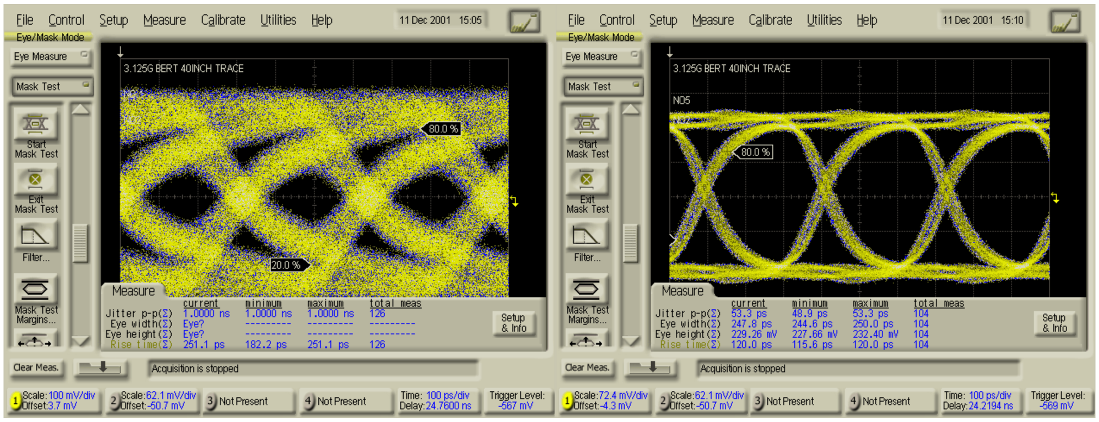

Figure 8 Before and after equalization for the data going through 40inch trace

5. Combination of Pre-emphasis and Equalization

Properly combined pre-emphasis and analog equalization technique have been proved to be the best method to combat the channel loss. In practice, we designed the analog equalization to compensate the loss at below 1GHz where the equalizer can be designed to compensate the channel loss accurately. The pre-emphasis can be best utilized to compensate the channel loss over giga hertz where the attenuation increases rapidly with the increase of the data rate. In our design practice, the general channel models are developed with the extensive experimental data so that our design can find broadest fits. In the case of custom design, we measure the custom system and extract the model accurately so that our transceiver can be fine tuned to achieve even better effects. Figure 9 shows the effects of the combination of the pre-emphasis and the equalization for an 80 inch trace board. The bandwidth of the system after compensation is extended significantly.

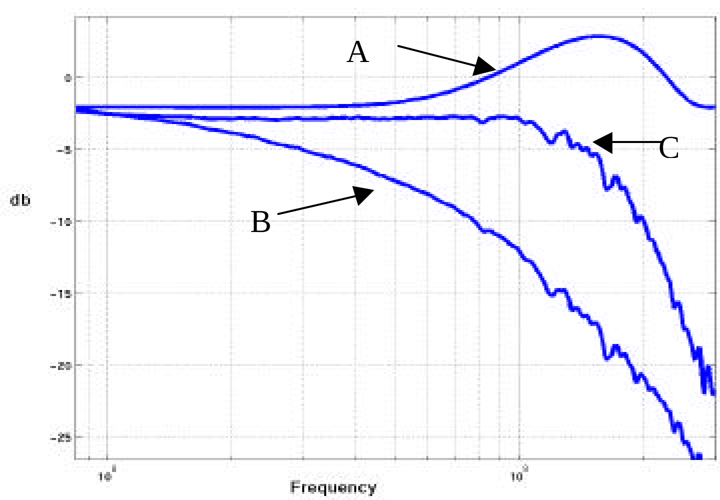

Figure 9 The transfer curve of the channel after applying both Pre-emphasis and Equalization.

(A) Frequency response of the pre-emphasis. (B) Frequency response of the 80 inch trace board. (C) Frequency response after compensation.

The achieved BER (Bit-Error-Ratio) over the 60 inches of backplane with 2 connectors 3.125Gbps was better than 10^{-12} with both pre-emphasis and equalization enabled.

The achieved BER (Bit-Error-Ratio) over the 80 inches of trace board with standard FR-4 material at 3.125Gbps was better than 10^{-14} with both pre-emphasis and equalization enabled.

The longest trace board achieved was 90 inches at 3.125Gbps with both pre-emphasis and equalization enabled, and BER was better than 10^{-12}.

References:

[1] H. B Bakoglu, "Circuits, Interconnections, and Packaging for VLSI", Addison-Wesley Publishing Company, 1990.
[2] Howard Johnson & Martin Graham, "High-Speed Digital Design, A Handbook of Black Magic", Prentice Hall, 1993.
[3] Moises Cases, M. & Doughlas M Quinn, "Transient Response of Uniformly Distributed RLC Transmission Line", IEEE Transactions on Circuits and System, Vol. CAS-27, No. 3 March 1990, p200-p207.
[4] Quint, D. & Bois, K., "The Digital Designer's Complete Lossy Transmission Line Model".