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Equalizing Gigabit-per-Second Signals on Copper Media

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1 Introduction

Equalization is a powerful method to extend transmission distance or data rate for gigabit-per-second (Gbps) NRZ data on lossy copper media. The use of analog or digital equalization techniques makes it practical to carry 2.5Gbps or 3.125Gbps data up to 50 inches on economical FR-4 PCB transmission lines, or up to 100 feet or more on coaxial cable. This technique provides a cost-effective alternative to very short reach (VSR) optics for 2.5Gbps to 10Gbps chassis-to-chassis applications, and enables the development of robust backplanes operating at Gbps rates.

This application note provides a brief overview and comparison of practical methods for equalization of NRZ telecom and datacom signals on lossy copper media. For specific examples of the capabilities of a state-of-the-art 3.2Gbps analog equalizer, please refer to Maxim Integrated Products' Design Note, HFDN10.0, Equalizing Gigabit Copper Cable Links with the MAX3800**.**

2 Why are Gigabit-per-Second Equalizers Needed?

Transmitting Gbps signals significant distances on copper media requires the use of controlled impedance transmission lines, typically $Z_0 = 50\Omega$ single-ended or 100Ω differential. In a printed circuit board (PCB) environment, such as across a board or backplane, these would typically be striplines; using FR-4 dielectric, if feasible, for cost reasons. In a chassis-to-chassis environment, this could be coaxial cable (coax) or shielded twisted pairs, depending on the distance to be spanned.

Unfortunately, at data rates above about 1Gbps, the frequency-dependent loss characteristic of the transmission line produces an unacceptable degree of eye closure at the destination with common NRZ signals and modest path lengths. This loss is predominantly due to dielectric loss with FR-4, and to skin effect with coaxial cable. On backplanes, signal impairments due to connectors and other impedance discontinuities also induce frequency-dependent losses. Figure 1 shows the eye closure for a 2.488Gbps NRZ signal, resulting from 50" of 6mil stripline and two inexpensive SMA connectors. The launched signal was a $1000mV_{p-p}$ SONET-type signal with very fast rise time. It is easy to see that there is virtually no eye opening in either horizontal (jitter) or vertical (amplitude) dimensions.

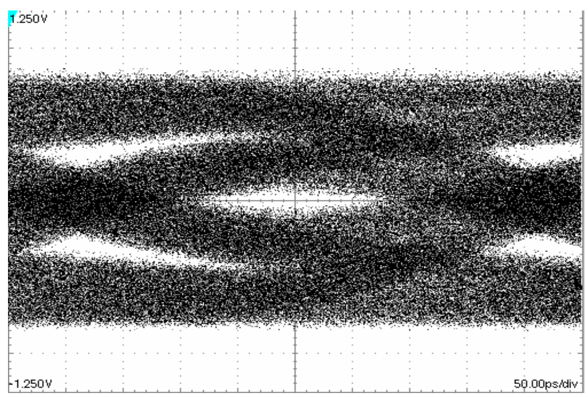

Figure 1. 1000mV, 2.488Gbps, PRBS7 eye diagram after 50" of FR-4

In PCB applications, the maximum effective transmission length can be increased by using low-loss microwave dielectric materials, but at a very significant cost premium. In coaxial cable applications, larger diameter coax or a proprietary cable technology, such as W. L. Gore's Eye-Opener™ cable can be used to provide improvement. In both cases, a more cost-effective solution is to employ equalization in the ICs at the transmit end, the receive end, or both.

3 Media Loss and Inter-Symbol Interference

A short sequence of the PRBS data from the signal of Figure 1 is plotted in Figure 2; where it is easy to see that the eye closure is caused by inter-symbol interference. In Figure 2, a single isolated bit following a short stretch of consecutive identical digits (CIDs) has much less swing than the same isolated bit following a transition. This is why 8B10B encoded data, with a shorter CID interval, creates lower ISI (deterministic jitter) for a given path than SONET PRBS-type data. Even when the path length can be kept short enough that the eye has sufficient signal amplitude (vertical eye opening) for the receiver to operate, the deterministic jitter (horizontal eye closure) is likely to exceed the receiver's jitter tolerance.

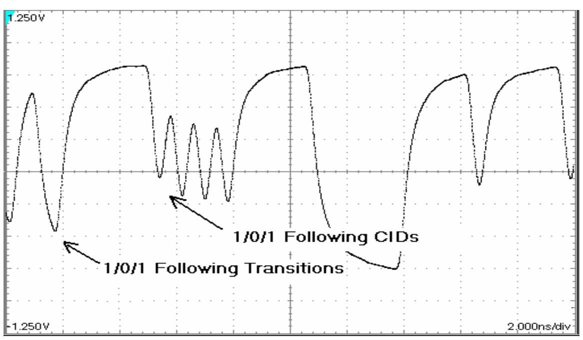

Figure 2. 2.488Gbps PRBS7 data stream – inter-symbol interference after CIDs

Inter-symbol interference is caused by frequency-dependent path loss, which has memory longer than the bit interval. Figure 3 shows the path loss (simulated, using SONNET Lite) for four typical lengths of 50Ω stripline, illustrating the relationship between path length, frequency and path loss. These simulations match very closely to responses measured in the lab on FR-4 stripline test structures.

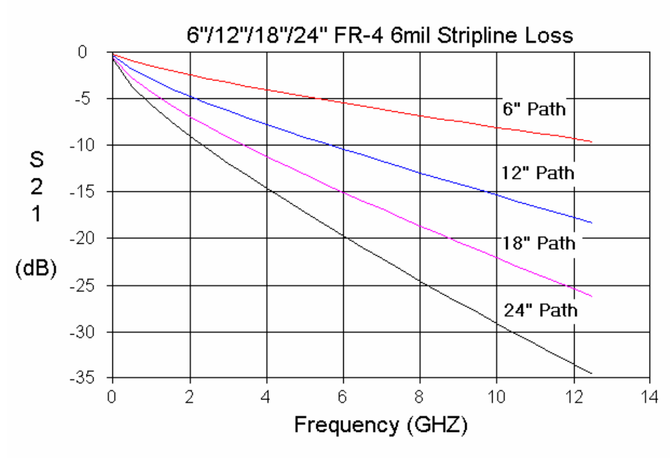

Figure 3. FR-4 stripline loss vs. path length

In FR-4, the key path losses are skin-effect loss, which has an $f^{-1/2}$ characteristic, and dielectric loss, which has an f^{-1} characteristic. Surface roughness can also be important in FR-4, increasing the DC path length. Figure 4 shows the relative contributions of skin effect and dielectric loss in a Z_0 = 50Ω, 6mil stripline; where it can be seen that above 2GHz, dielectric loss begins to dominate. Because of the relationship between trace width and dielectric thickness that determines Z_0 in PCB transmission lines, dielectric loss is set by the choice of Z_0 and the dielectric material characteristics (tan δ) alone; however, skin effect loss does vary with conductor trace width. In coaxial cable transmission lines, skin effect is the dominant loss mechanism, and it is determined by conductor (cable) diameter.

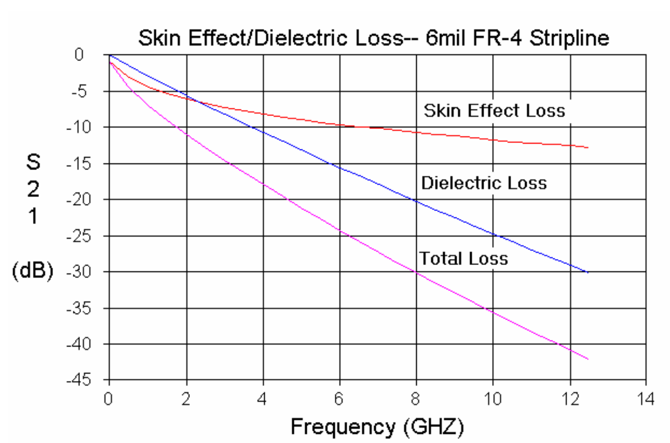

Figure 4. Relative path loss contributors in FR-4 stripline -- skin effect and dielectric loss

4 Gbps NRZ Data Equalization

The maximum reach (or rate for a given path length) can be significantly extended by employing an equalizer to counteract the frequency-dependent path loss, and thus restore the desired spectrum of the signal at the receive end. A number of equalization techniques are available to the signal path designer; the key ones are highlighted here.

4.1 Passive Equalizers

In circumstances with large signal swing at the transmitter and a sensitive receiver, passive equalization can provide the required signal restoration for a lossy signal path.

Passive constant-impedance RLC equalizer networks are a time-proven technique (Terman, 1943). The network can be placed anywhere in the signal path, and operates by attenuating the low frequencies in a manner complementary to path loss at high frequencies, so that the total signal path loss is essentially flat. Passive equalization can be built into data cables, where the amount of equalization can be matched to the cable length (e.g. InfiniBand cables).

Since these highpass networks operate by inducing additional compensating loss, passive equalizers require strong source drivers and sensitive receivers, and, in practice, are limited to around 9dB of path loss equalization. A Clock and Data Recovery (CDR) IC can also be used very effectively to eliminate deterministic jitter in cases where there is sufficient vertical eye opening at the end of the path. A number of high-sensitivity, high-jitter-tolerance, phase-locked-loop CDRs are available from Maxim; including the MAX3873 2.488Gbps CDR, with 50mVp-p input sensitivity and 0.55UIp-p of total high frequency jitter tolerance.

4.2 Active Transmit Equalizers

Transmit pre-emphasis is a widely used technique, because a finite impulse response (FIR) equalization filter at the signal source is amenable to a very simple and effective implementation when a synchronous clock is available (Feidler, 1997).

Figure 5 shows a functional diagram of a two-tap digital FIR transmit equalizer implemented in a system SERDES transceiver IC, where recovered clock and data are both present. The transfer function of this filter is $H(z) = 1 - az^{-1}$; the output is $y(n) = x(n) - ax(n-1)$. This filter has a highpass frequency response up to $f = 1/(2T_s)$, where the $\sin^2(x)/x^2$ power spectrum of an NRZ signal is down by 7.85dB.

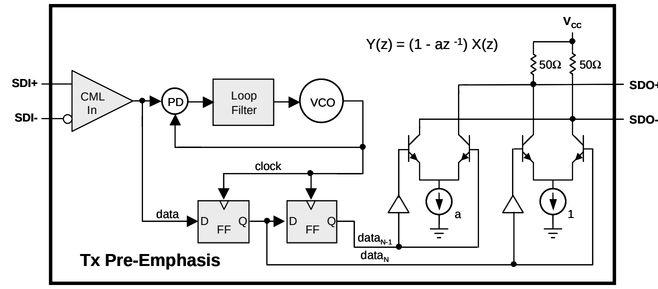

Figure 5. Transmit FIR Equalizer using Digital Delay

Figure 6 shows how this FIR equalizer operates on a short sequence of data; its effect is to boost the level of pulses following a transition.

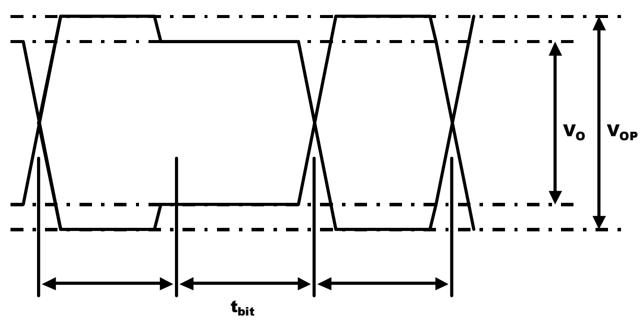

Figure 6. Data signal with transmit pre-emphasis

The table below relates the amount of boost in the CML output, the magnitude of the filter response in the frequency domain, and nominal equivalent path length in FR-4.

FIR Highpass Response vs. Tap Weight

a = **$(V_{OP} - V_O) / 2$**	**20 log $[H(1/2T_s)/H(0)]$**	**Equivalent Path Length @ 3Gbps (50Ω FR-4)**
0.175	3dB	6”
0.33	6dB	12”
0.475	9dB	18”

Adequate performance can be achieved with a single delay (two taps) as shown, but up to five taps may be appropriate for signal paths with complex frequency response characteristics. Of course, similar performance can also be achieved with an analog network; however, in either case, the amount of transmit equalization (digital or analog) is limited to around 9dB of maximum boost, because peaking results in large signal swings. Large swings are difficult to implement, consume power in the drivers, and often present an EMI challenge.

4.3 Active Receive Equalizers

When maximum performance (longest signal path) is required, active receive equalization provides the greatest practical boost. Effective analog receive equalizers can be produced in SiGe technology for 10Gbps telecom and datacom signals, with 21dB or more of boost (at 5GHz); even more for 2.5 or 3.125Gbps data. A boost of 21dB in a 10Gbps equalizer corresponds to a path length of 30 inches in 6mil FR-4 stripline or 25 feet in RG-316/U coax (although the optimal shape of the equalizer frequency response differs between coax and PCB).

The filter portion of an analog receive equalizer for 10Gbps is relatively straightforward circuitry in a low-noise, fast bipolar process such as SiGe or GaAs, although the implementation requires very careful engineering. Typically, a few filter stages are required in order to match (complement) the frequency response of the channel (Oshiro, 1998).

Adaptive receive equalization is frequently desirable in order to enable arbitrary user reconfiguration of the connections in backplane and cable interconnections. Adaptation enables the equalizer to automatically set the boost, based on information in the received signal, to match the path loss. It also helps the equalizer to tolerate path-loss frequency-response characteristics that vary from the design objectives. As with any integrated circuit, devising a robust active equalizer requires compromise among a number of competing objectives. In this case, the important objectives are IC complexity, flexibility to match arbitrary path loss, compatibility with a range of input and output levels, CID tolerance and tolerable level of residual output (deterministic and random) jitter.

A very effective approach, employed in Maxim's MAX3800 family of 3.2Gbps Si bipolar adaptive equalizers, is depicted in the functional diagram of Figure 7. Adaptation is embodied in a feedback loop that samples the power spectrum of the received signal (in two bands) and attempts to restore the $\sin^2(x)/x^2$ spectrum characteristic of NRZ signals. This approach is stable, converges quickly to the correct response and is amenable to a low power implementation.

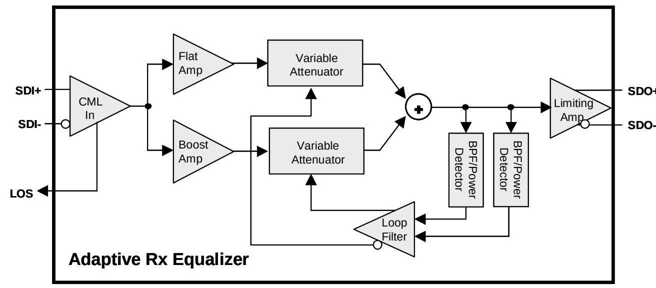

Figure 7. Adaptive analog receive equalizer

In the Maxim 3800 family, this architecture provides up to 30dB of compensation for 3.2Gbps data (at 1.6GHz) and robust adaptation to signal paths that includes coax, twinax, and FR-4 printed circuit board transmission lines. Please refer to Maxim design note HFDN10.0, for illustrations of MAX3800 operation in a variety of signal path environments.

Similar functionality can also be achieved with a digital receive equalizer. Normally, a digital receive equalizer is significantly more complex than its analog counterpart, but it can be less demanding of the IC technology, and thus feasible to implement in CMOS technology. Digital CMOS equalizers employ DSP techniques to accomplish the same objective as analog bipolar parts. In the end, what is important is how effectively the equalizer compensates for the channel response, as well as what amount of random and deterministic jitter the associated circuits (CML IO, limiting amplifier, etc.) in the equalizer chip add to the signal. A low-noise, high f_T, bipolar process such as SiGe is ideal for high-speed, low-noise equalization.

In applications where the signal path loss is engineered into the system design and doesn't change, a fixed settable equalizer can provide optimum equalization performance with greater signal flexibility. Because there is no feedback, a fixed equalizer can normally accommodate a wider range of signal characteristics such as data rate and spectrum. In applications, including rate-flexible line cards and long chip-to-chip connections on a PCB, system designers may value performance that is independent of signal format (e.g., PRBS vs. 8B10B) and/or supports a wider signal-rate range. In this case, a settable fixed equalizer would be preferable. Figure 8 shows a functional diagram of a non-adaptive version of the analog receive equalizer.

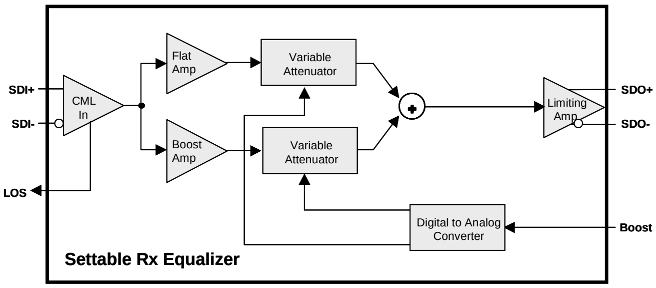

Figure 8. Fixed settable analog receive equalizer

4.4 Choosing Your Equalizer

Of course, many factors affect the specification and design of a signal path using equalization. Key among these are: shape and magnitude of the equalizer frequency response, ability to accommodate different path characteristics, residual jitter after equalization, compatibility with surrounding ICs, and performance in the presence of non-ideal signal-to-noise ratio. This last factor, which is often overlooked, can be critical because the purpose of the equalizer is to boost high-frequency signals, exactly where noise due to crosstalk is worst. Near-end crosstalk (NEXT) in a transceiver environment can sometimes be as large as 5%; which would cause a 1000mV_{p-p} transmitted signal to induce 50mV_{p-p} noise in an adjacent receiver.

5 Conclusions

As data rates exceeding 1Gbps become more common in datacom and telecom systems, equalization is becoming a critical tool for cable, backplane and chip-to-chip applications. Effective equalizer technology can enable system and signal-path designers to achieve maximum reach on copper media, and sometimes result in very significant cost savings compared to VSR optics.

Maxim produces a number of high-performance analog and digital equalizers, implemented in our low-noise, high f_T, Si bipolar and SiGe processes. For the latest information on Maxim's equalization technology, please refer to the Maxim Integrated Products web site, http://www.maxim-ic.com, or contact your Maxim applications engineer.

6 References

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