Extend Your Reach

RocketIO transceivers included in the Virtex-4 FPGA family incorporate highly flexible equalization circuits that significantly extend the range and performance of high-speed serial links.

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Every multigigabit backplane, trace, and cable distorts the signals passing through it. This degradation may be slight or devastating, depending on the conductor geometry, materials, length, and type of connectors used.

Because they spend their lives working with sine waves, communications engineers like to characterize this distortion in the frequency domain. Figure 1 shows the channel gain, also called the frequency response, of a perfectly terminated typical 50 ohm stripline (or 100 ohm differential stripline). This stripline acts like a low-pass filter, attenuating high-frequency sine waves more than lower frequency waves.

Figure 2 illustrates the degradation inherent to a digital signal passing through 20 inches (.5 meters) of FR-4 stripline. The dielectric and skin-effect losses in the trace reduce the amplitude of the incident pulse and disperse its rising and falling edges. We like to call the received pulse, much smaller than normal, a "runt pulse." In a binary communication system, any runt pulse that fails to cross the receiver threshold by a sufficient margin causes a bit error.

For the purposes of this discussion, three things degrade the amplitude of the runt pulse in a high-speed serial link: losses in the traces or cables, reflections due to connectors and other signal transitions, and the limited bandwidth of the driver and receiver.

A classic test of dispersion appears in Figure 3. This particular waveform – adjusted so that the long flat portions of the test signal represent the worst-case, longest runs of ones or zeros available in your data code – displays the runt-pulse amplitude. In the absence of reflections, crosstalk, or other noise, this single waveform (as measured at the receiver) represents a worst-case test of channel dispersion. Longer traces introduce progressively more dispersion, eventually causing receiver failure at (in this example) a length of 1.5 meters.

One measure of signal quality at the receiver is voltage margin. This number equals the minimum distance (in volts) between the signal amplitude and the receiver threshold at the instant sampling occurs. In a system with zero reflections, crosstalk, or other noise you could theoretically operate with a very small voltage margin and still expect the system to operate perfectly.

In a practical system, however, you must maintain a healthy noise margin sufficient to soak up the maximum amplitude of all reflections, crosstalk, and other noise in the system, while still keeping the received signal sufficiently above the threshold to account for the limited bandwidth and noise inherent to the receiver.

Following the example in Figure 4, a runt-pulse amplitude equal to 85% of the nominal low-frequency signal amplitude exceeds the receiver threshold by only 35%, instead of the nominal 50%. A smaller runt pulse with amplitude 75% of the normal size would reduce the voltage margin by half – a huge hit to your noise budget, but still workable. For generic binary communication using no equalization, we would like to see the runt pulse arrive with amplitude never smaller than 70% of the low-frequency pulse amplitude.

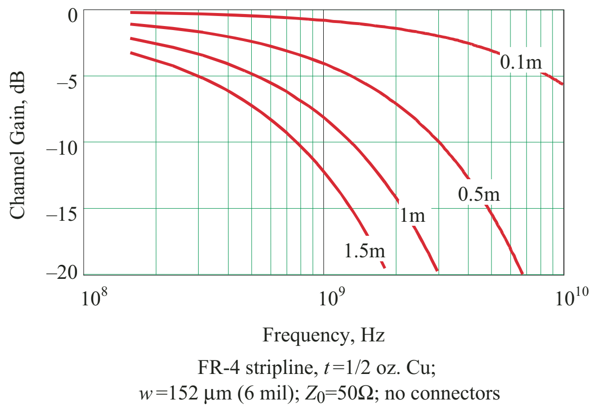

Figure 1 – The effective channel gain associated with a long PCB trace depends on the trace width, dielectric materials, length, and type of connectors used.

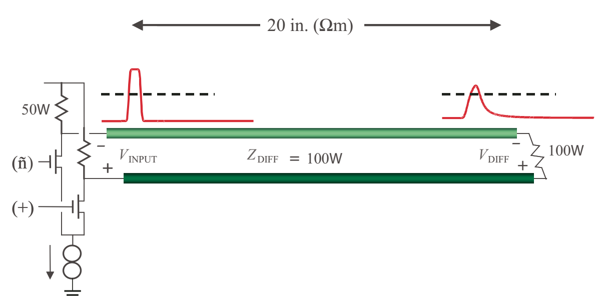

Figure 2 – Long traces reduce the amplitude of the input pulse and disperse its rising and falling edges.

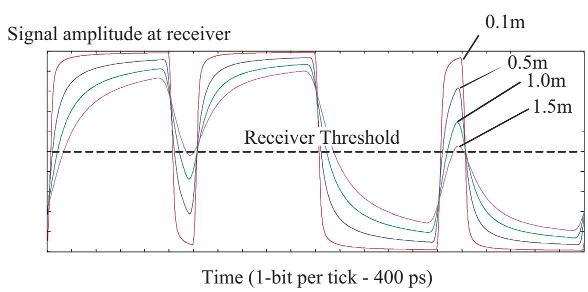

Figure 3 – This test waveform displays the worst-case runt-pulse amplitude.

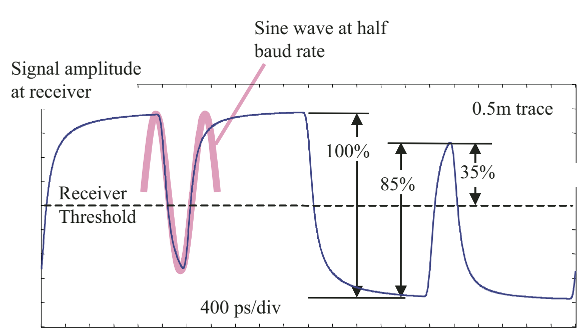

Figure 4 – A runt-pulse amplitude equal to 85% of the nominal low-frequency signal amplitude reduces the voltage margin above the threshold to only 35%, instead of the nominal 50%.

Runt-Pulse Degradation

On the left side of Figure 4 is a sine wave with a period of two baud. To the extent that the runt-pulse pattern (101) looks somewhat like this sine wave, you should be able to infer the runt-pulse amplitude from a frequency-domain plot of channel attenuation. Let's try it.

In Figure 4, the data waveform has a baud rate of 2.5 Gbps. One half this frequency (the equivalent sine wave frequency) equals 1.25 GHz. According to Figure 5, the half-meter curve gives you 4.5 dB of attenuation at 1.25 GHz. The same curve also shows 1.5 dB of attenuation at 1/10th this frequency, corresponding roughly to the lowest frequency of interest in an 8B10B coded data transmission system. The difference between these two numbers (-3 dB) approximates the ratio of runt-pulse amplitude to low-frequency signal amplitude at the receiver. With only -3dB degradation, the system satisfies our 70% frequency-domain criterion for solid link performance – precisely explaining why time-domain waveforms look so good at a half-meter.

Looking closely at Figure 4, the actual runt-pulse amplitude in the time domain is 85%, not quite as bad as the -3dB predicted by our quick frequency-domain approximation. This discrepancy arises partly from the harmonic construction of a square wave, where the fundamental amplitude exceeds the amplitude of the square wave signal from which it is extracted, and partly from the natural fuzziness inherent to any quick rule-of-thumb translation between the time and frequency domains. The simple frequency-domain criteria conservatively estimates these factors.

If your data code permits longer runs of zeros or ones than 8B10B coding, then you must use a correspondingly lower frequency as your "lowest frequency of interest." In the time domain, you will see the

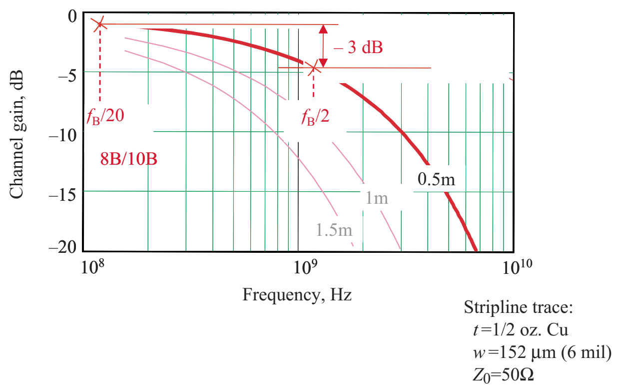

Figure 5 – The difference between high-frequency and low-frequency channel gain in this 2.5 Gbps system equals 3 dB.

received signal creep closer to the floor (or ceiling) of its maximum range before the runt pulse occurs, making it even more difficult for the worst-case runt pulse to cross the threshold.

As a rule of thumb, we look at the difference between the channel attenuation at the highest frequency of operation (the 101010 pattern) and the lowest frequency of operation (determined by your data coding run length) to quickly estimate the degree of runt-pulse amplitude degradation at the receiver. This simple frequency-domain method only crudely estimates link performance. It cannot substitute for rigorous time-domain simulation, but it can greatly improve your understanding of link behavior.

A channel with less than 1 dB of runt-pulse degradation works great with just about any ordinary CMOS logic family, assuming that you solve the clock skew problem either with low-skew clock distribution or by using a clock recovery unit at the receiver. A channel with as much as 3 dB degradation requires nothing more sophisticated than a good differential architecture with tightly placed well-controlled receiver thresholds. A channel with 6 dB of degradation requires equalization.

Transmit Pre-Emphasis

The Xilinx® Virtex™-4 RocketIO™ transceiver incorporates three forms of equalization that extend your reach on deeply degraded channels. The first is transmit pre-emphasis.

Figure 6 illustrates a simple binary waveform x[n] and the related first-difference waveform x[n]-x[n-1]. If you are familiar with calculus, you can think of the first-difference waveform as a kind of derivative operation. On every edge, the difference waveform creates a big kick. The transmit pre-emphasis circuit adds together a certain proportion of the main signal and the first difference waveform to superimpose the big kick at the beginning of every transition. As viewed by the receiver, each kick boosts the amplitude of the runt pulses without enlarging low-frequency portions of your signal, which are already too big.

The first-difference idea helps you see how pre-emphasis works, but that is not how it is built. The actual circuit sums not two but three delayed terms, called the pre-cursor, cursor, and post-cursor. This architecture gives you the capacity to realize both first and second differences by adjusting the coefficients associated with these three terms. Programmable 5-bit multiplying DACs control the three coefficients. The first and third amplitudes are always inverted with respect to the main center term, a trick that is accomplished by using the NOT-Q outputs of the first and third flip-flops. As an example, Figure 7 plots the frequency response corresponding to the particular coefficient set [-0.056, 0.716, -0.228].

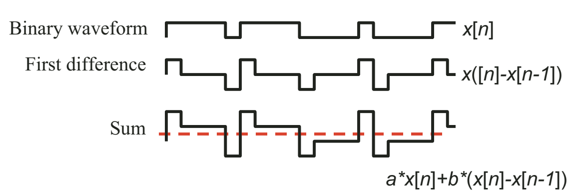

Figure 6 – The transmit pre-emphasis circuit creates a big kick at the beginning of every transition.

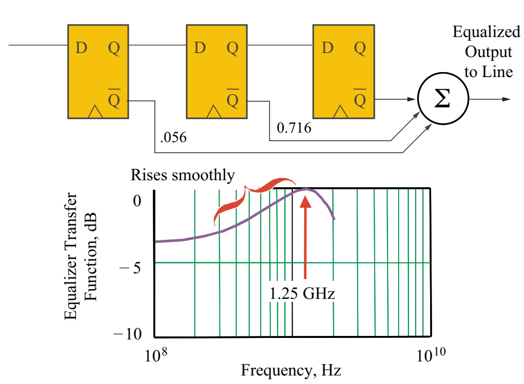

Figure 7 – Over the critical range from DC to 1.25 GHz, the pre-emphasis response rises smoothly.

Over the critical range from DC to 1.25 GHz, the pre-emphasis response rises smoothly – just the opposite of the plummeting curves drawn in Figure 5. The response peaks at 1.25 GHz. If you clock this pre-emphasis circuit at a higher data rate, the peak shifts correspondingly higher, always appearing just where you want it at a frequency equal to half the data rate.

Figure 8 overlays the pre-emphasis response with the channel response at 1 meter, showing a composite result (the equalized channel) that appears much flatter than either curve alone. In very simplistic terms, a flatter composite channel response should make a better-looking signal in the time domain.

The time-domain benefits of pre-emphasis appear in Figure 9. At shorter distances the signal appears over-equalized. The overshoot at each transition works fine in a binary system, assuming that the receiver has ample headroom to avoid saturation with the maximum-sized signal. At 1 meter, the signal looks quite nice, with very little runt-pulse degradation visible and (if you look closely) very little jitter. The 1.5 meter waveform now just meets the 70% criteria for runt-pulse success.

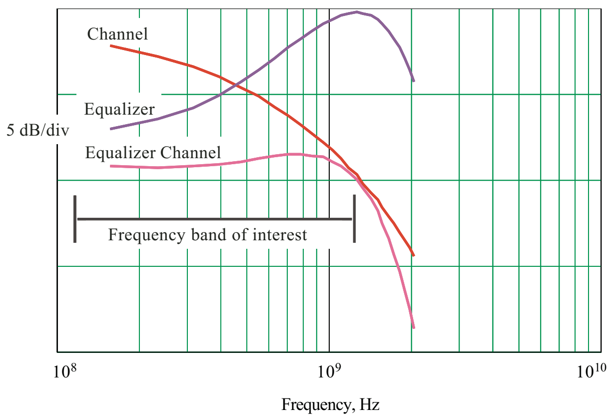

Figure 8 – Composing the pre-emphasis circuit with the channel produces an overall response much flatter than either curve alone.

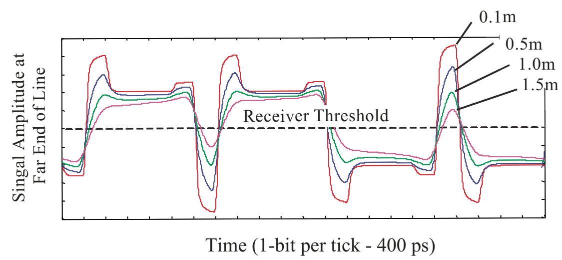

Figure 9 – A pre-emphasis circuit at least doubles the length of channel over which you may safely operate.

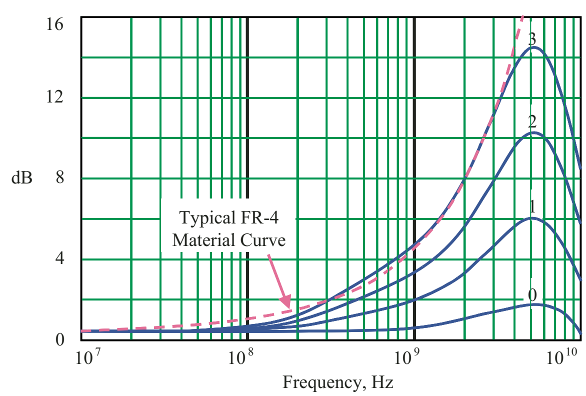

Figure 10 – The linear equalizer in the receiver may be set to one of four distinct response curves preprogrammed to match the response of various lengths of FR-4 PCB trace.

Compared to a simple differential architecture, the pre-emphasis circuit has at least doubled the length of channel over which you may safely operate.

Linear Receive Equalizer

In addition to the pre-emphasis circuit, the RocketIO transceiver also incorporates a sophisticated 6-zero, 9-pole receive-based linear equalizer. This circuit precedes the data slicer. It comprises three cascaded stages of active analog equalization that may be individually enabled, turning on zero, one, two, or all three stages in succession.

Figure 10 presents the set of four possible frequency-response curves attainable with this receiver-equalization architecture. Each section of the equalizer is tuned to approximate the channel response of a typical PCB channel with an attenuation of about 3 dB at 2.5 GHz. With all stages on, you get a little more than 9 dB of boost at 2.5 GHz. Because the response keeps rising all the way to 5 GHz, this equalizer is useful for data rates up to and beyond 10 Gbps.

When setting up the equalizer, first select the number of sections of the RX linear equalizer that best match your overall channel response. Then fine-tune the overall pulse response using the 5-bit programmable coefficients in the transmit pre-emphasis circuit to obtain the lowest ISI, the lowest jitter, or a combination of both. After building the circuit, a clock phase adjustment internal to the receiver helps you map out bit error rate (BER) bathtub curves, so you can corroborate the correctness of your equalizer settings.

The flexibility provided by these two forms of equalization lets you interoperate with an amazing array of serial-link standards, meeting exact transmitted signal specifications and at the same time adding receiver-based equalization to keep your system working at the peak of performance.

Decision-Feedback Equalizer

As a last defense against the slings and arrows of uncertain channel performance, the RocketIO transceiver includes a manually adjustable six-tap decision-feedback equalizer (DFE). This device is integrated into the slicer circuit at the receiver. The DFE is particularly useful with poor-quality legacy channels not initially designed to handle high serial data rates. It has the remarkable property of accentuating the incoming signal without exacerbating crosstalk.

Those of you familiar with signal processing will recognize that a DFE inserts poles into the equalization network, while a TX pre-emphasis circuit creates zeros. (A very accessible book about digital equalization, including DFE circuits, is John A.C. Bingham's "The Theory and Practice of Modem Design.")

Working together, the DFE, TX-pre-emphasis, and RX linear equalizer provide an incredibly rich array of possible adjustments.

Conclusion

For any channel with as much as 6 dB of runt-pulse degradation, a simple pre-emphasis adjustment easily doubles the length at which your link operates.

If you anticipate more than 6 dB of runt-pulse degradation, we strongly suggest that you simulate your system in detail before making the final equalizer adjustments. Contact your local Xilinx customer support office or visit the Xilinx website to obtain the necessary RocketIO models and associated design kits for modeling your channel. The modeling effort is well worth it, as equalization can substantially extend the reach of your circuits.

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Figures 1, 3, 4, and 9 are adapted with permission from Johnson and Graham, *High-Speed Signal Propagation: Advanced Black Magic*, Prentice-Hall, 2003.