Green-box testing: A method for optimizing high-speed serial links

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Introduction

If you have ever worked with communications, data centers, or enterprise networking equipment—routers, switches, server chassis—you probably have heard the term green-box test. A green-box (GB) test applies to multi-gigabit serial links and is a procedure that seeks to identify the optimum transmitter equalization settings by sweeping these parameters and measuring a corresponding figure of merit (FoM). For systems with hundreds or thousands of high-speed channels, GB testing is often the most reliable way to pinpoint the transmitter settings which enable the system to meet the required bit error rate (BER). This article describes the GB test methodology and its applications.

Why do we need green-box (GB) tests?

Before explaining how a GB test is performed, it is important to first understand why GB testing is necessary. Today's high-speed serial links run at speeds of 28+ Gbps and operate over channels with insertion loss in excess of 35 dB at 14 GHz. To ensure successful data transmission over a variety of channel media (printed circuit boards, copper cables, backplane connectors, and so on), complex equalization circuits are utilized in the serializer/deserializer (SerDes) transmitter (TX) and in the SerDes receiver (RX). The task of equalizing a channel is shared between these two components.

Receivers typically implement a continuous-time linear equalizer (CTLE) and a decision-feedback equalizer (DFE) that automatically adapt to equalize the incoming signal. Transmitters often utilize a finite-impulse-response (FIR) filter with one pre-cursor and one post-cursor tap to help compensate for pre-cursor and post-cursor intersymbol interference (ISI) in a transmission channel. Figure 1 illustrates a serial interface consisting of a TX, a channel, and a RX.

Transmitter FIR filter coefficients are not self-adaptive because the transmitter does not have a priori knowledge of the channel into which it is transmitting, so it does not know how much equalization to apply to satisfy the receiver and meet the system BER. This is why using GB testing to identify the optimum transmit FIR settings is necessary.

Figure 1. Example of TX FIR settings impacting final eye opening

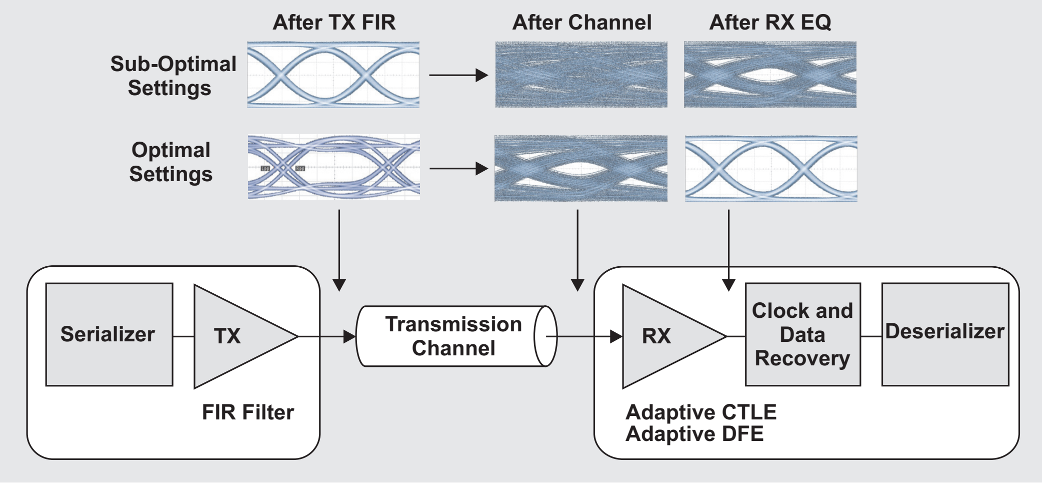
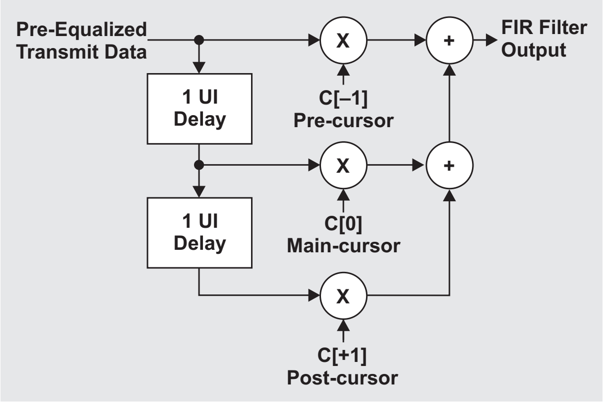


Figure 2. FIR equalizer block diagram



Transmit FIR equalizer

A transmit FIR filter is classically implemented as shown in Figure 2, with one pre-cursor, one main-cursor, and one post-cursor tap. When the pre- and post-cursor coefficients have a sign that is the opposite of the main-cursor, the resulting waveform has a high-pass characteristic, whereby low-frequency portions of the signal are de-emphasized and high-frequency portions are not. This pre-distorts the waveform before it is launched into the channel so that, by the time it reaches the end of the channel, the resulting waveform is more equalized.

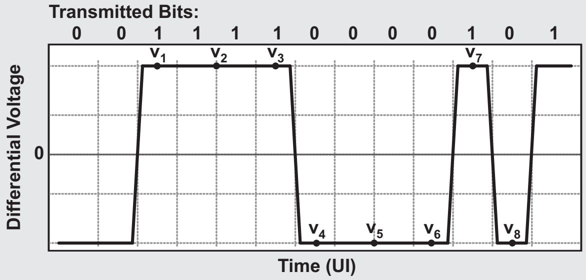
The most common way of configuring an FIR filter is to accentuate the transitions and de-emphasize the non-transitions. The bit before a transition is accentuated via the pre-cursor tap, and the bit after the transition is accentuated via the post-cursor tap. This is referred to as "negative" pre- and post-cursor because the sign of these taps is negative when the sign of the main-cursor tap is positive (Figures 3 and 4).

A less common approach is to use a positive sign for pre- and post-cursor with a positive sign for main-cursor to produce a waveform with low-pass characteristics (Figure 5). With this combination of coefficient signs, transitions are de-emphasized and non-transitions are accentuated.

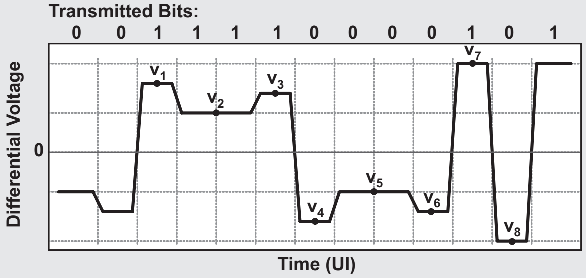
The following characteristics can be derived from the example waveforms in Figures 3 through 5.

1. Peak-to-peak output differential voltage, $VOD_{PK\text{-}PK} = v_7 - v_8$
2. Low-frequency output differential voltage, $VOD_{Low\text{-}frequency} = v_2 - v_5$
3. Pre-cursor de-emphasis, $Rpre_{DB} = 20 \times \log_{10}(v_3/v_2)$
4. Post-cursor de-emphasis, $Rpst_{DB} = 20 \times \log_{10}(v_1/v_2)$

Figure 3. Example FIR waveforms #1

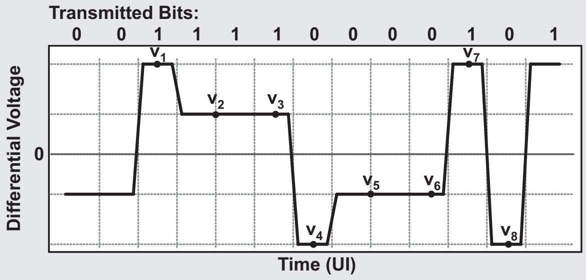


(a) No pre-cursor or post-cursor

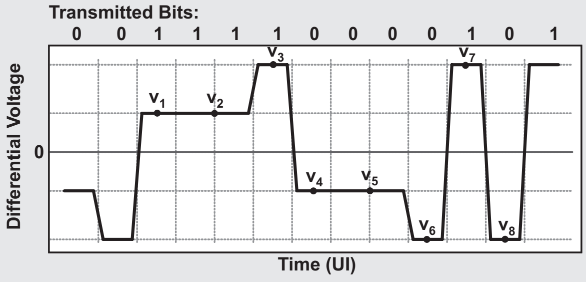


(b) Negative pre-cursor and post-cursor

Figure 4. Example FIR waveforms #2

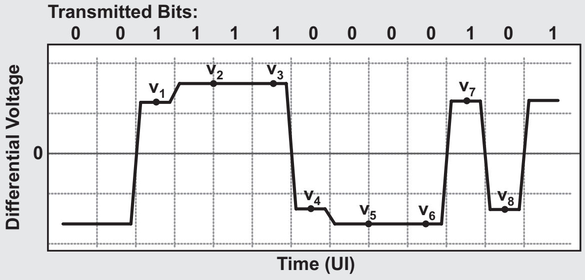


(a) Negative post-cursor

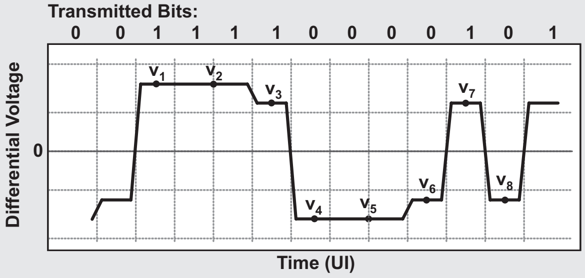


(b) Negative pre-cursor

Figure 5. Example FIR waveforms #3



(a) Positive post-cursor



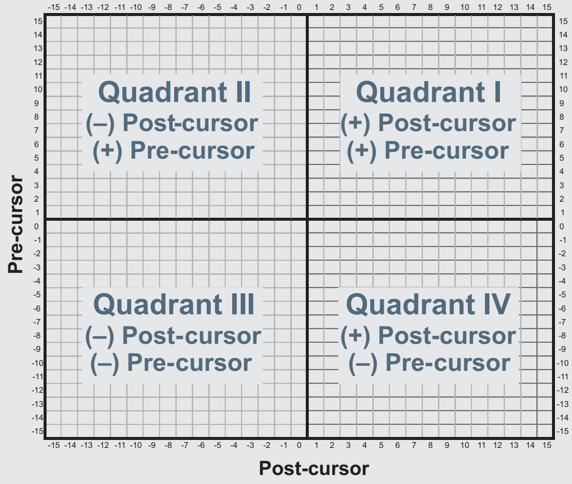
(b) Positive pre-cursor

How to run a GB test

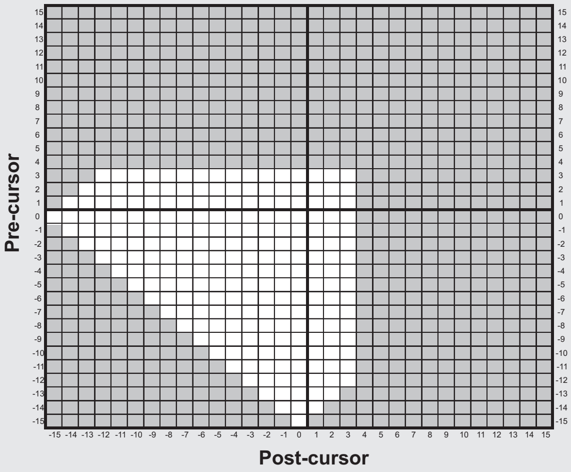
This is the basic procedure for running a GB test:

1. Define the two-dimensional space of transmit pre- and post-cursor settings to sweep over (Figure 6a). This space typically consists of all valid non-positive pre- and post-cursor settings, with the main-cursor fixed to a positive value. This “(–)pre/(–)post” quadrant, quadrant III, produces a high-pass characteristic on the transmitted waveform that helps to equalize the output channel. Many transmitters have rules that limit the valid coefficient space based on the absolute sum of the coefficients (pre, main, and post). It is important to follow these rules when defining the sweep space. Some transmitters implement positive (low-pass) in addition to negative (high-pass) pre- and post-cursor coefficients. If the transmitter has this capability, consider including a few settings in quadrants I, II, and IV, as this gives a better overall picture of the system performance. Figure 6b shows an example sweep space for a transmitter that requires $|pre| + |main| + |post| \le 31$ and $|main| > |pre| + |post|$.
2. Enable the TX PRBS generator, selecting a test pattern that is representative of actual system data traffic (for example, PRBS31 for 64b/66b-encoded data).
3. Initialize the TX to a setting inside the sweep space.
4. After the TX is configured, initialize the corresponding RX, giving it ample time to re-adapt its CTLE and DFE to the new TX settings.

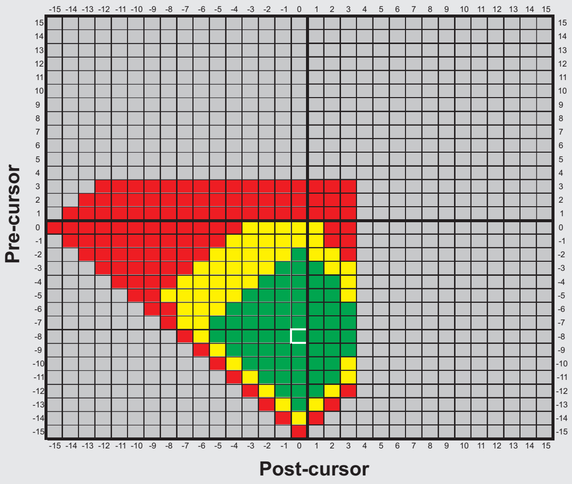
Figure 6. Green box (GB) test example



(a) Definition of transmit FIR quadrants



(b) Example sweep space



(c) Example GB test result

5. After the RX adaptation is complete, perform a short BER test and record the error count reported by the RX. For example, running a BER test at 25.78125 Gbps for 12 seconds will give a high level of confidence in a BER of 1E–11 or better. The factor of 3 in Equation 1 is used so that a zero error result gives a 95% confidence level that the true BER is better than or equal to the target BER.

$$\text{Test\_time\_per\_setting} = \frac{3}{\text{Data\_Rate} \times \text{Target\_BER}} \tag{1}$$

   The application may require a lower BER like 1E–12, 1E–15, or even 1E–17. Such low BERs may not be practical to measure. Therefore, the procedure recommended here is to run the test using a practical BER target (such as 1E–11) and to extrapolate these results for the purposes of selecting an optimal setting.
6. Repeat steps 3 through 5 for all TX settings in the sweep space. Figure 6c shows an example result. Settings with zero errors are colored green. Settings with greater than zero errors, but less than the maximum number that the RX can record, are colored yellow. Settings with maximum errors are colored red. To reduce test time, you can read the RX error counter shortly after each test begins. If the error counter is saturated, record this data point as having maximum errors and move on. There is no need to wait the full test time at points which quickly yield maximum errors.
7. The optimum TX setting is usually the setting in the center of the green region. Note that sometimes the green region will extend to the edge of the sweep space, so the true boundary of the green region is not discernible from the results. In such cases, judgment must be applied in selecting the optimum TX setting, knowing that the green region could extend beyond the region that was tested. Figure 6c shows an example result, highlighting the optimum TX setting based on the center of the green region.

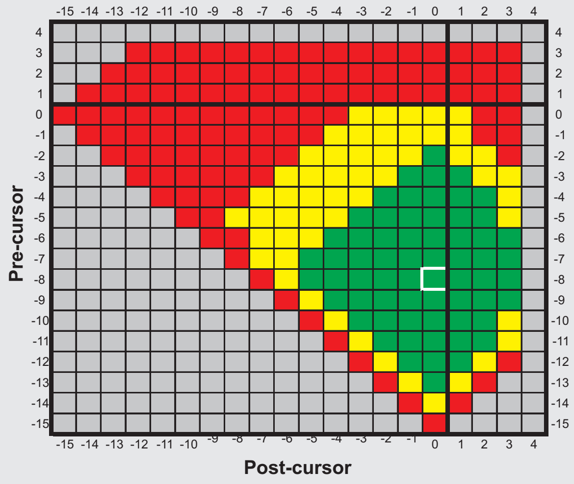
How to interpret the results

The key results to extract from a GB test are:

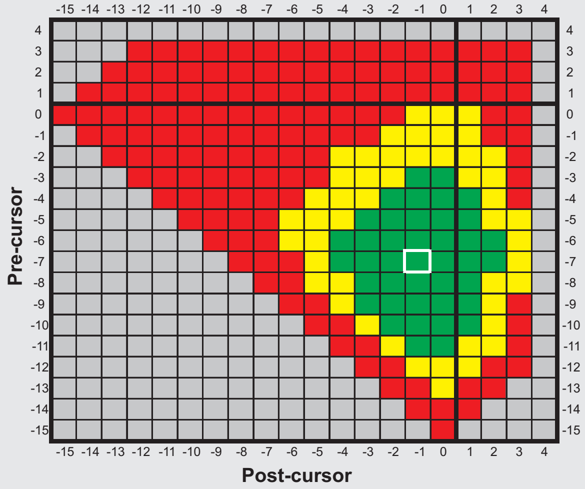
1. The size of the largest contiguous green region
2. The center point of the largest contiguous green region

A contiguous green region indicates an uninterrupted space of settings which yield a BER equal to or better than the target BER. The size of this region is a good indicator of the overall health and performance of the high-speed link. A link with a larger contiguous green region (Figure 7a) generally has more margin and a better minimum BER versus a link with a smaller green region (Figure 7b).

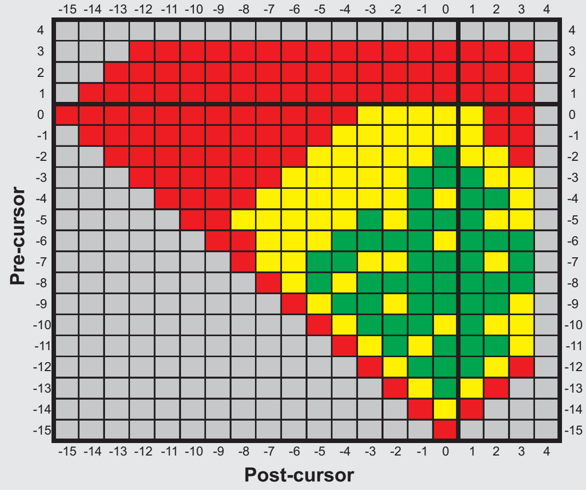
Figure 7. Green box (GB) test results



(a) Large green region

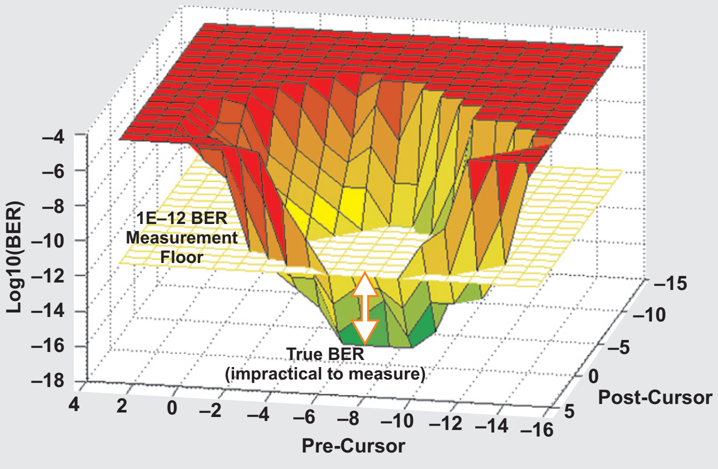


(b) Smaller green region

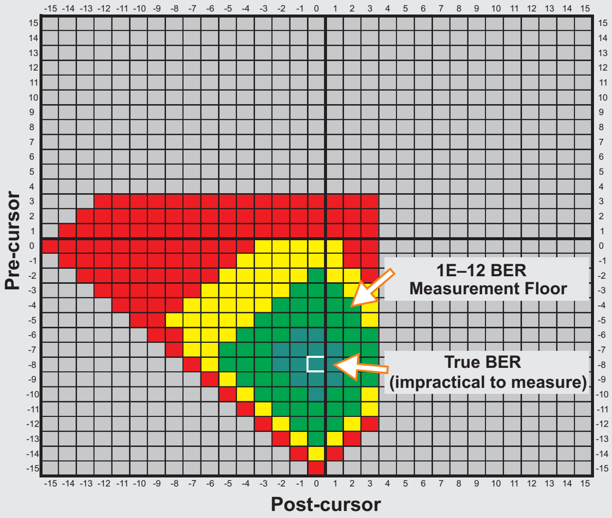


(c) Non-contiguous green region

Figure 8. Bit error rate versus pre- and post-cursor



(a) 3D view



(b) 2D view (shown from top down)

One warning sign to look for is when the green region is non-contiguous (Figure 7c). This usually indicates instability or inconsistency in one of the following:

- Test procedure: The order in which operations are executed, when each component of the link is initialized, and so forth.
- Receiver adaptation: How the RX CTLE and/or DFE converge to a solution from one run to the next.
- Test apparatus: Power-supply noise, temperature and environmental affects, loose connections, and so on.

The reason for choosing the center of the largest contiguous green region as the optimum setting is based on the principle that the green region will continue to shrink as the measurement time increases. Figure 8 shows an example of how a measured BER of 1E–12 may correlate to a true BER of <1E–17. Selecting a setting in the middle of the green region provides the most margin to achieve lower BER as the green region shrinks over time.

Other considerations

- Most applications require a lower BER than the target used for GB testing. To understand how quickly the green region collapses over time, try running a second GB test targeting a BER that is at least one order of magnitude lower (for example, 1E–12 versus 1E–11). This will make the test ten times longer for each point. Compare the size of the green region in the two tests to gain insight into the region's stability.
- It may be useful to define metrics to characterize the size of the green region to compare one channel's performance versus another. One such metric is the *green radius*, the distance between the center of the green region and the nearest setting with non-zero errors. The larger the green radius, the more margin a link has.
- Each BER test in a GB sweep should be independent, meaning no matter which direction you sweep, you should get similar results each time. If you get substantially different results depending on the direction you sweep, this indicates a flaw in the test procedure which causes one test to be dependent upon another. If the receiver is not properly reset for each test point, or if the adaptation is not allowed to complete/settle, this can be one symptom.

Conclusions

Green box (GB) testing is a widely used method for tuning link performance based on a figure of merit that truly matters: bit error rate. The procedures and metrics proposed here allow you to take a systematic approach to testing link margin and identifying optimum link settings to get the best performance out of your high-speed system.

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