Crosstalk Analysis of the Quad Independent Channel HOTLink II™ Device

Introduction

The HOTLink II™ family of physical layer (PHY) devices is a point-to-point or point-to-multipoint communications building block that provides serialization, deserialization, optional 8B/10B encoding/decoding and framing functions. The quad independent channel device is a member of this frequency agile family that can support serial data rates between 195 and 1.5 Gbps per channel. Within this device, all four channels can simultaneously operate at different data rates and transmit different types of data. In order to provide this flexible feature, each channel has its own transmit and receive Phase-Locked Loops (PLLs).

When channels operate at different frequencies within a device, a concern is that there may be a large amount of crosstalk between the channels that could affect the performance of the device.

This application note will show that the quad independent channel HOTLink II device operates reliably for large and small variations of frequencies across all channels. To show this, it will first provide a brief description of crosstalk and how it causes jitter within the device (specifically, the PLL). Then, it will describe the techniques for measuring crosstalk and the test equipment setup. Lastly, it will describe the performance of the device's transmitter and receiver PLL's for the worst case crosstalk scenarios. While the majority of the tests will be performed at video data rates, the results apply to any system that operates within the frequency range of HOTLink II devices.

The information provided by this application note will show the agility and reliability of this device for a wide range of applications.

Crosstalk

Crosstalk is the effect on a signal trace caused by cross-coupling with a neighboring trace. The trace that is being measured is referred to as the victim. The trace that is cross-coupled with the victim trace is referred to as the aggressor. A picture of this relationship is shown in *Figure 1*.

Crosstalk is dependent upon the edge rate of the aggressor signal; a faster edge induces more crosstalk. When the operating frequency of a HOTLink II device is increased, it increases its edge rate. Therefore, to test the worst case, the majority of the tests will have the aggressor channels switching at high frequencies (See appendix for experimental verification).

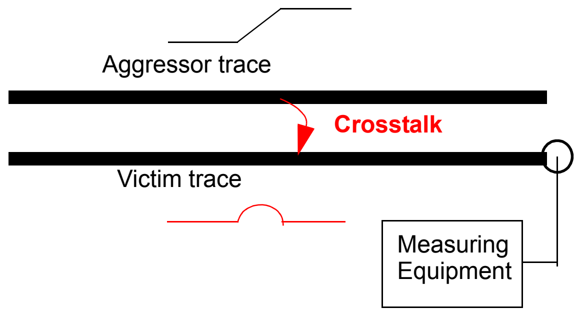

Figure 1. Victim and Aggressor Traces

Jitter

Crosstalk is a concern because it can be a major contributor to the amount of jitter present in a device. Simply stated, jitter is the deviation of an edge from its expected location. A large amount of jitter in a serial communications link may cause bit errors in the received serial bit stream.

Phase-Locked Loops

Within any HOTLink II device, there is a transmit PLL and a receive PLL. The quad independent channel HOTLink II device has four transmit and receive pairs, where each pair has its own reference clock. A concern is that when adjacent PLL's are switching at different frequencies, additional crosstalk may occur. This section will briefly describe the structure of the transmit PLL and the tests that will be performed to measure its performance. The receive PLL has similar frequency response characteristics and will be tested similarly.

The transmit PLL is a clock multiplier unit (CMU). It receives an input clock (REFCLK) and outputs a bit clock that has ten times the frequency of REFCLK. A diagram of a transmit PLL is shown in *Figure 2*. The amount of jitter that propagates through a PLL depends on where the jitter entered the PLL. If it enters via the REFCLK input, only low frequency components will pass through because the PLL acts like a low-pass filter. However, if jitter is injected inside the loop (by crosstalk between PLLs, for example), the system acts like a high-pass filter. Therefore, crosstalk between the PLLs can be a cause of jitter. To test the performance of the PLLs, three frequency variations between victim and aggressor REFCLKs will be performed: large frequency offsets (>100 MHz), small frequency offsets (< 1 MHz), and identical frequencies from different sources.

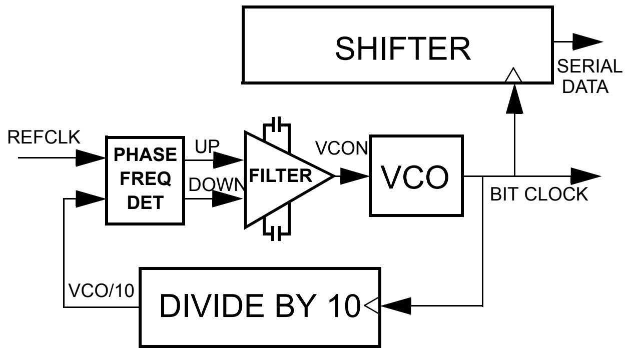

Figure 2. Transmit PLL

Jitter and Crosstalk Measurement Techniques

The tests performed for this app note will measure the effect of crosstalk in two ways: jitter in the time domain and crosstalk in the frequency domain.

To measure jitter in the time domain, the eye diagram of the victim channel's output will be observed on a wide-bandwidth oscilloscope. An eye diagram is formed by a superposition of waveforms. The phase of these waveforms with respect to one another is determined by the phase difference with the trigger signal. The amount of jitter will be obtained by analyzing the histogram formed at the eye crossing (shown in *Figure 3*). The eye crossing is the point at which the positive edge and negative edge intersect. When the waveform intersects the histogram window, a "hit" is recorded in the histogram. The histogram formed in *Figure 3* resembles a Gaussian distribution.

The two important values obtained from this measurement are the peak-to-peak jitter and the root mean square (RMS) value. The peak-to-peak jitter is the difference between the minimum and maximum time of hits in the histogram. This value is non-deterministic because of the nature of random jitter, but can provide helpful information when the test is performed for a long period of time. The RMS value (or standard deviation) converges to a stable value quickly. Assuming a Gaussian distribution, it can be proven that the peak-to-peak jitter will be greater than fourteen times the RMS value only once in 10^{12} bit periods.

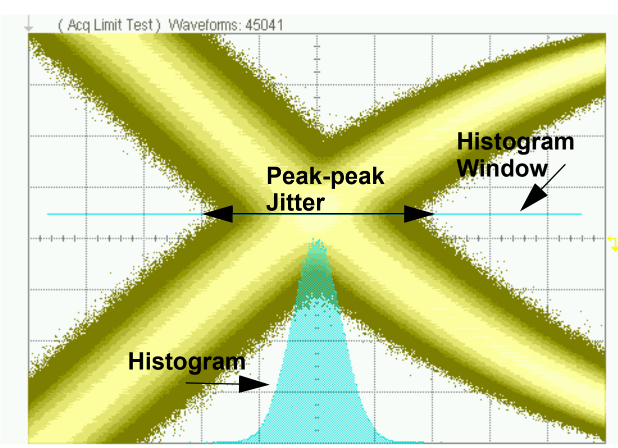

Figure 3. Jitter Measurements at the Eye Crossing

To measure crosstalk in the frequency domain, a high bandwidth spectrum analyzer will be used. The amplitude of the victim's fundamental frequency will be compared with the amplitude of the aggressor's fundamental frequency. The fundamental frequency of a signal is the lowest natural frequency and is also called the first harmonic. For example, a perfect square wave 20-MHz clock has a fundamental frequency of 20 MHz. Furthermore, it is composed of a sum of sinusoids at multiples (or harmonics) of the fundamental frequency. The most prevalent harmonics of a square wave are the odd harmonics. The first (20 MHz, in this example), third (60 MHz), and fifth (100 MHz) harmonics contribute to most of the shape of the square wave. Thus, if the crosstalk components are significantly smaller than the fifth harmonic, their impact will be negligible.

There will be two tests for any configuration of data and frequency: measuring the victim channel's performance with no aggressors enabled and measuring its performance with three aggressors enabled. For all of the tests, the victim channel will be channel A because it is located between two channels (B and D) on the device and the board (see *Figure 4*) and will thus incur more crosstalk than the outer channels (B and C). Therefore, channels B, C, and D will be aggressors on channel A.

The transmit input data will be either BIST or static data. BIST data is pseudo-random and is generated by the encoder block inside the device. The static data will be either a repeating D21.5 (1010101010) character or a repeating K28.7- (0011111000) character. As a serial bit stream, either sequence looks like a square wave, where the D21.5 sequence has a frequency that is five times higher than the K28.7 sequence. In fact, the K28.7 bit stream will have the same frequency as the reference clock. In the frequency domain, an ideal square wave has discrete peaks at odd harmonics of the fundamental frequency. These peaks have large amplitudes since energy is concentrated at narrow frequency bands. Crosstalk induced by these sequences will be more visible in the frequency domain than broadband data. Furthermore, it is easier to observe the crosstalk when the victim is transmitting D21.5's or K28.7's. Because there are very small frequency components between these peaks, the impact of an aggressor switching at a different frequency can be more easily seen on the spectrum analyzer.

The BIST data tests will be run for a longer period of time (2 hours) than the static data tests (30 minutes) since the static data sequences repeat every character compared to the BIST data sequence which repeats every 511 characters. The D21.5 character will be used for the high operating frequencies to yield the maximum frequency on the serial outputs. Similarly, the K28.7 character will be used for the low operating frequencies to yield the minimum frequency on the serial outputs.

Transmitter Testing

Transmitter Test Equipment Setup

Figure 4 shows the connections of the equipment with the CYV15G0404DXB Evaluation Board for the transmitter tests. The reference clock for each channel (REFCLKx) will be supplied by a different Agilent 8133A Pulse Generator. The RMS jitter from these generators is less than 5 ps (1 ps typical). The measurements performed on the transmit side will be taken at the serial output SEROUTA+. These measurements will be observed on an Agilent 86100A Wide-Bandwidth Oscilloscope and an Agilent E4407B Spectrum Analyzer.

Both primary and secondary output drivers are enabled in each channel to maximize the potential for coupling between channels. All aggressor primary serial outputs and SEROUTA- are looped back to their respective inputs with short cables. The secondary outputs are left unconnected. When all three aggressor transmit channels are enabled, their receivers will also be enabled and will be receiving the transmitted data. This is the worst case situation where all PLLs are active and possibly cross-coupling with other PLLs.

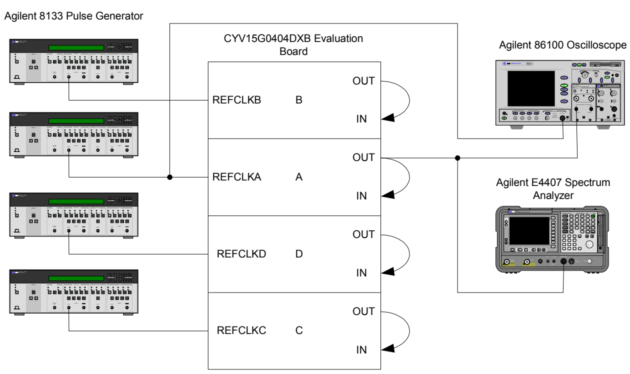

Figure 4. Transmitter Test Equipment Set-up

Transmitter Test Results

Test 1. Victim and aggressors both transmitting BIST at high frequencies

— Victim: Channel A @148.5 MHz

— Aggressors: Channel B @148.35 MHz, C @148.5 MHz, D @148.35 MHz

This test reflects a real world system where all four channels are transmitting data at similar frequencies. Note that channels A and C will have slightly different frequencies because they have two independent REFCLK sources. See *Table 1* and *Figure 5* for the jitter results.The peak-peak jitter increased by only 2.4 ps, a very small amount. Similarly, the standard deviation increased by only 0.72 ps.

	Jitter	
	Peak-peak (ps)	**Std. Dev. (ps)**
No Aggressors	114.3	13.47
All Aggressors	116.7	14.19

Table 1. Test 1 Results

Test 2. Victim transmitting low frequency K28.7's and aggressors transmitting high frequency D21.5's

— Victim: Channel A @ 27 MHz

— Aggressors: Channel B @148.5 MHz, C @148.5 MHz, D @148.35 MHz

This test measures the effect of large differences in operating frequency between the victim and adjacent channels. Transmitting K28.7's and D21.5's will provide a more descriptive spectral plot.

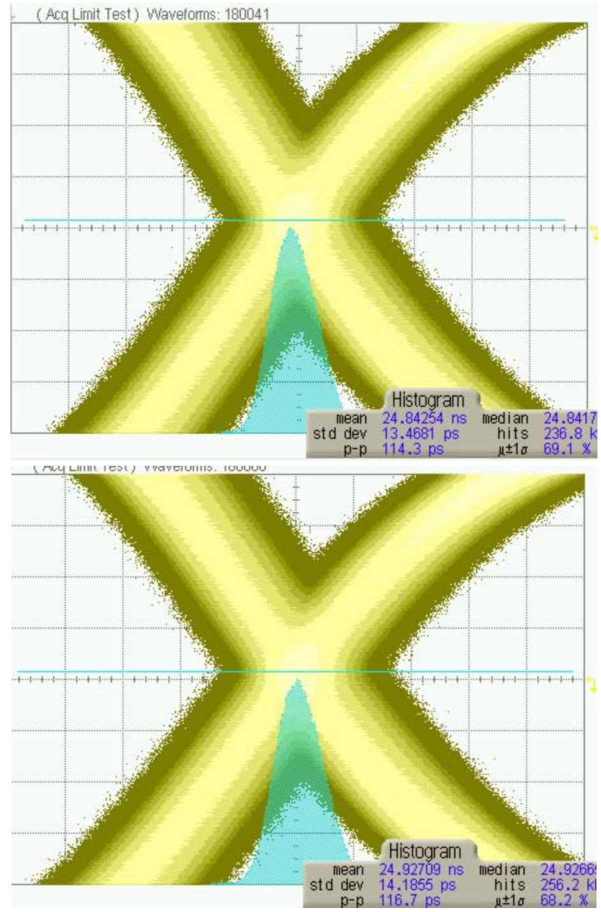

Figure 5. Eye Diagrams for Test 1 (BIST): No Aggressors (Top) and Three Aggressors (Bottom)

See *Table 2* and *Figure 6* for the jitter results. The resulting waveform does not form an eye because the character repeats every reference clock cycle (the trigger). The histogram window was set to the 50% amplitude swing level of the signal. For this test, the peak-peak jitter increased by 7.8 ps and the standard deviation increased by 0.29 ps.

	Jitter	
	Peak-peak (ps)	**Std. Dev. (ps)**
No Aggressors	112.0	12.74
All Aggressors	119.8	13.03

Table 2. Test 2 Results

See *Figure 7* for the spectrum analyzer results. The two views are spectral plots of channel A with all aggressors enabled. To display the smaller components, the amplitude is on a logarithmic scale (7-dB/ division). The top view shows all spectral components from 0 to 1 GHz. The fundamental frequency is the first large peak located at 27 MHz. The bottom view is zoomed in on the fifth harmonic (135 MHz) and the largest frequency component (148.4 MHz) due to crosstalk. This crosstalk component is 40 dB (100x) smaller than the fundamental frequency and 28 dB (25x) smaller than the fifth harmonic.

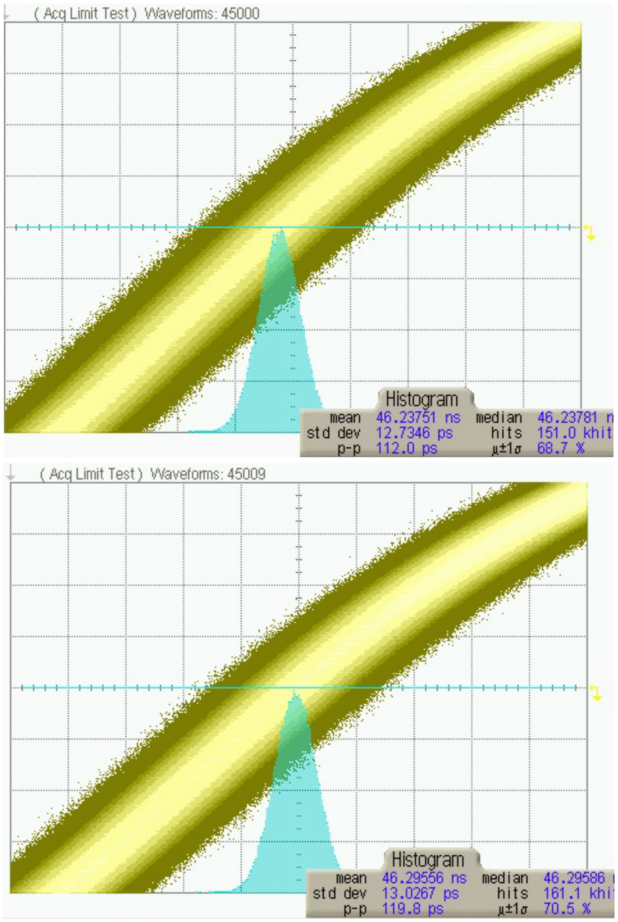

Figure 6. Eye Diagrams for Test 2 (K28.7): No Aggressors (Top) and Three Aggressors (Bottom)

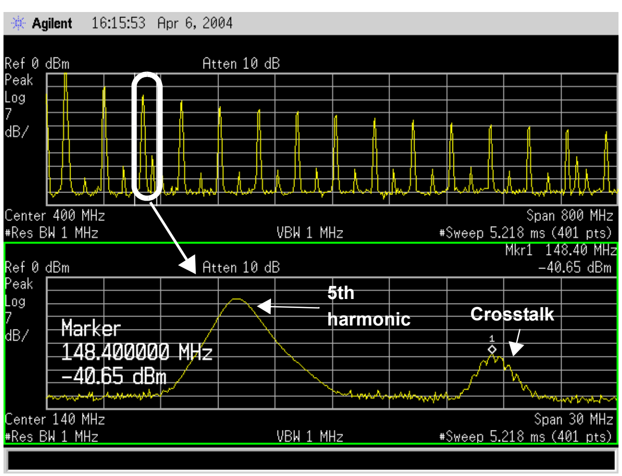

Figure 7. Spectral Plot of Test 2 (K28.7) with Three Aggressors

Test 3. Victim and aggressors both transmitting D21.5's at high frequencies

— Victim: Channel A @148.5 MHz

— Aggressors: Channel B @ 148.35 MHz, C @ 150 MHz, D @ 145 MHz

This test measures the effect of adjacent channels switching at high frequencies. Transmitting D21.5's will provide a more descriptive spectral plot.

See *Table 3* and *Figure 8* for the jitter results. The peak-peak jitter increased by 2.3 ps and the standard deviation increased by 0.36 ps.

See *Figure 9* for the spectrum analyzer results.The lower plot is a zoomed in view of the fundamental frequency of the victim (148.5 x 5 = 762.5 MHz) and the largest frequency component of the aggressors (Channel D: 145 x 5 = 725 MHz). The aggressor's frequency component is 42 dB (125 x) smaller than the victim's fundamental frequency.

	Jitter	
	Peak-peak (ps)	**Std. Dev. (ps)**
No Aggressors	74.7	8.60
All Aggressors	77.0	8.96

Table 3. Test 3 Results

Receiver Testing

Receiver Test Equipment Setup

Figure 10 shows the connections of the equipment with the CYV15G0404DXB Evaluation Board for the receiver tests. The input to the receive PLL is the serial data stream generated by the transmitter of the same channel. This reflects the worst case situation where both PLLs of all channels are running at different frequencies. To maximize the potential for cross-coupling, both output drivers will be enabled on every channel. However, only the primary outputs will be connected to the inputs. The secondary outputs will be left unconnected.

The same type of data will be transmitted as in the transmitter tests. The performance of the receiver will be determined by measuring the output of the receive clock RXCLKA+. The receive clock will be the recovered byte clock from the PLL (RXCKSELA= '0'). The measurements will be observed on an Agilent 86100A Wide-Bandwidth Oscilloscope and an Agilent E4407B Spectrum Analyzer.

Receiver Test Results

To form an eye diagram, the receive clock is set to a half-rate clock (RXRATEA = 1). For each trigger edge, the receive clock alternates between a positive edge and a negative edge.

Test 4. Victim and aggressors both transmitting BIST at high frequencies

- Victim: Channel A @148.5 MHz

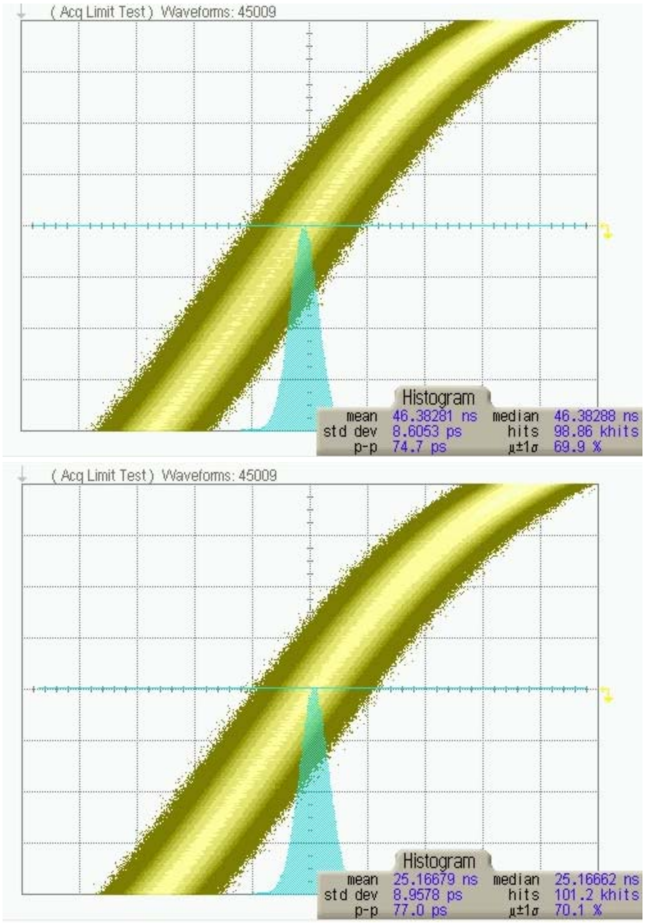

Figure 8. Eye Diagrams for Test 3 (D21.5): No Aggressors (Top) and Three Aggressors (Bottom)

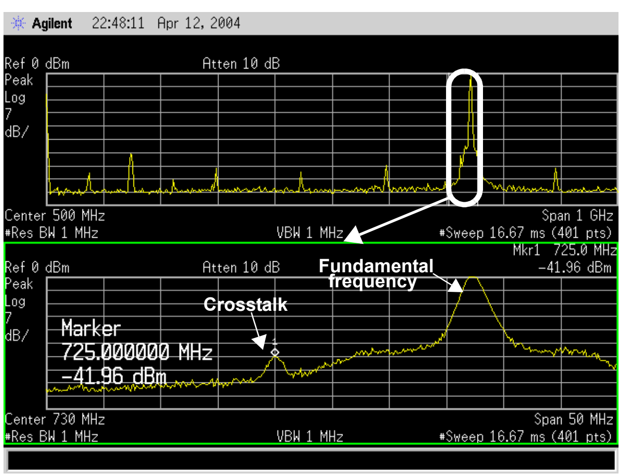

Figure 9. Spectral Plot of Test 3 (D21.5) with Three Aggressors

- Aggressors: Channel B @148.35 MHz, C @148.5MHz, D @148.35 MHz

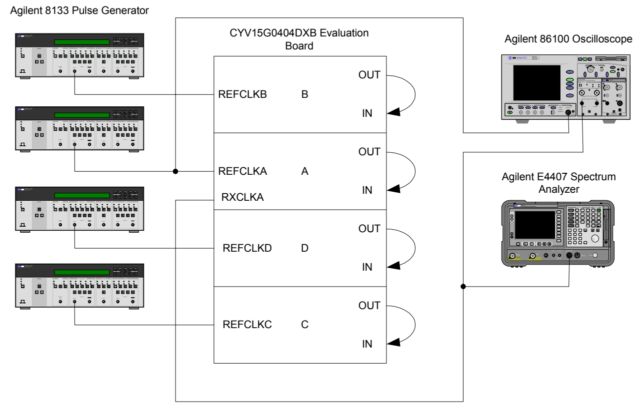

Figure 10. Receiver Test Equipment Set-up

This test reflects a real world system where all four channels are receiving data at similar frequencies. Note that channels A and C will have slightly different frequencies because they have two independent REFCLK sources. See *Table 4* and *Figure 11* for the jitter results. The peak-peak jitter increased by only 5.5 ps, a very small amount. Similarly, the standard deviation increased by only 0.96 ps.

	Jitter	
	Peak-peak (ps)	**Std. Dev. (ps)**
No Aggressors	115.1	12.00
All Aggressors	120.6	12.96

Table 4. Test 4 Results

Test 5. Victim transmitting low frequency K28.7's and aggressors transmitting high frequency D21.5's

- Victim: Channel A @ 27 MHz

- Aggressors: Channel B @148.5 MHz, C @148.5 MHz, D @148.35 MHz

This test measures the effect of large differences in operating frequency between the victim and adjacent channels. Transmitting K28.7's and D21.5's will provide a more descriptive spectral plot.

See *Table 5* and *Figure 12* for the jitter results. The peak-peak jitter increased by 8.5 ps and the standard deviation increased by only 0.33 ps.

See *Figure 13* for the spectrum analyzer results. The two views are spectral plots of channel A with all aggressors enabled. The top view shows all spectral components from 0 to 155 MHz. The bottom view is zoomed in on the 11th harmonic (148.5 MHz) and the largest frequency component (145 MHz) due to crosstalk. This crosstalk component is over 33 dB (45x) smaller than the fundamental frequency and 20 dB (10x) smaller than the 11th harmonic.

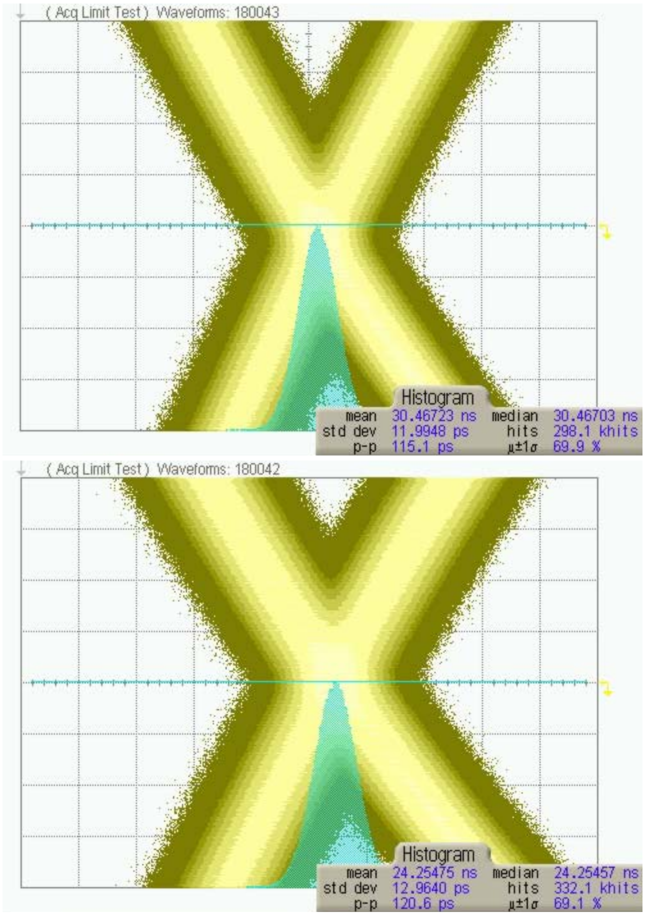

Figure 11. Eye Diagrams for Test 4 (BIST): No Aggressors (Top) and Three Aggressors (Bottom)

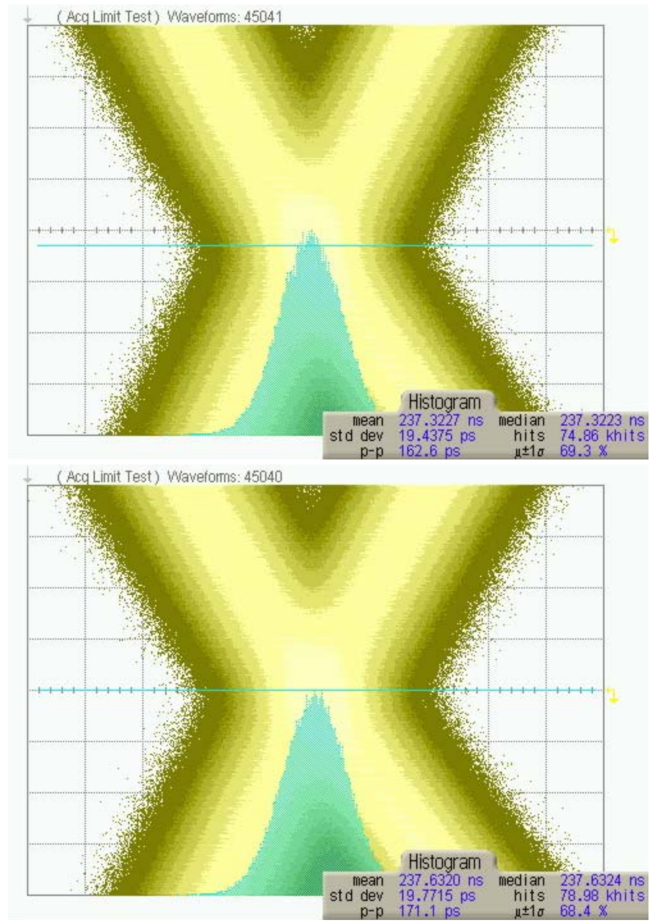

Figure 12. Eye Diagrams for Test 5 (K28.7): No Aggressors (Top) and Three Aggressors (Bottom)

	Jitter	
	Peak-peak (ps)	**Std. Dev. (ps)**
No Aggressors	162.6	19.44
All Aggressors	171.1	19.77

Table 5. Test 5 Results

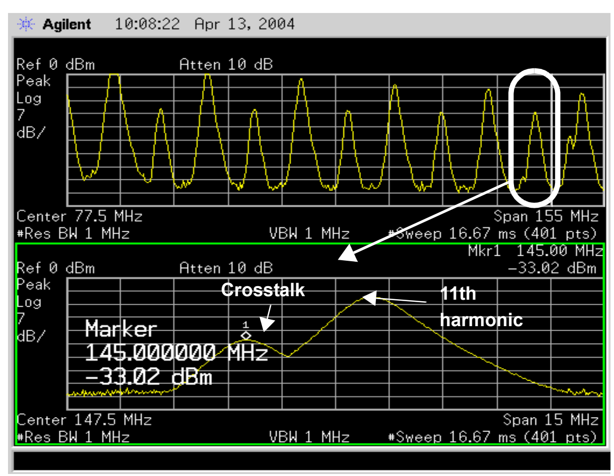

Figure 13. Spectral Plot of Test 5 (K28.7) with Three Aggressors

Test 6. Victim and aggressors both transmitting D21.5's at high frequencies

— Victim: Channel A @ 148.5 MHz

— Aggressors: Channel B @ 148.35 MHz, C @ 150 MHz, D @ 145 MHz

This test measures the effect of adjacent channels switching at high frequencies. Transmitting D21.5's will provide a more descriptive spectral plot.

See *Table 6* and *Figure 14* for the jitter results. The peak-peak jitter increased by 7.8 ps and the standard deviation increased by only 0.09 ps.

See *Figure 15* and *Figure 16* for the spectrum analyzer results. In *Figure 15*, the lower plot is a zoomed in view of the sixth harmonic of the victim (74.25 x 6 = 445.5 MHz) and the second largest frequency component of the aggressors (Channel D: 145 MHz). The aggressor's frequency component is 43 dB (141x) smaller than the victim's fundamental frequency and 30 dB (32x) smaller than the victim's fifth harmonic. In *Figure 16*, the lower plot is a zoomed in view of the eighteenth harmonic (18 x 74.25 = 1336.5 MHz) and the largest frequency component due to crosstalk (1.305 GHz). The aggressor's frequency component is 38 dB (80x) smaller than the victim's fundamental frequency and the fifth harmonic. Also, it is 10 dB (3x) smaller than the victim's eighteenth harmonic.

	Jitter	
	Peak-peak (ps)	**Std. Dev. (ps)**
No Aggressors	94.9	11.78
All Aggressors	102.7	11.87

Table 6. Test 6 Results

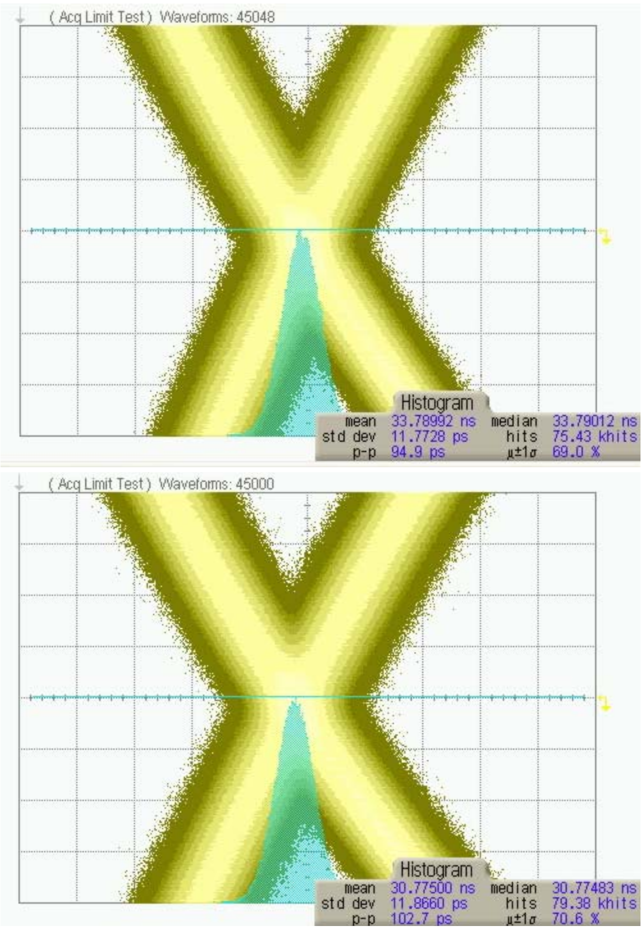

Figure 14. Eye Diagrams for Test 6 (D21.5): No Aggressors (Top) and Three Aggressors (Bottom)

Summary

For the transmitter, the effect of crosstalk was very small. The RMS jitter increased by less than 0.8 ps and the peak-peak jitter increased by less than 8 ps for all three tests. Furthermore, the spectrum analyzer plots showed that the largest crosstalk components were at least 100 times smaller than the fundamental frequency and over 40 times smaller than the fifth harmonic. Thus, the impact of crosstalk is negligible on the transmit side.

The receiver tests yielded similar results: the RMS jitter increased by less than 1.0 ps and the peak-to-peak jitter

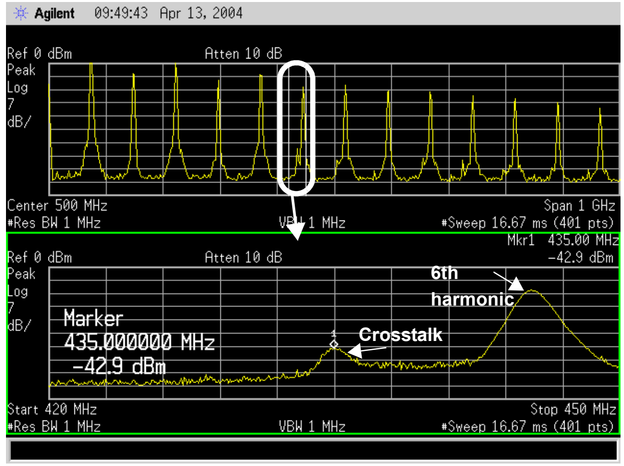

Figure 15. Spectral Plot of Test 6 (D21.5) with Three Aggressors–victim's Sixth Harmonic

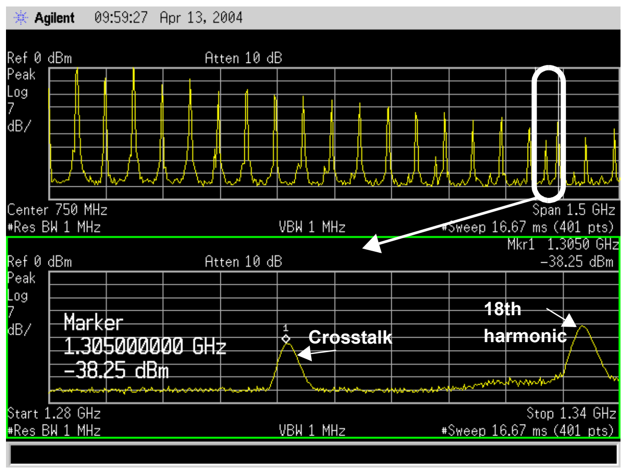

Figure 16. Spectral Plot of Test 6 (D21.5) with Three Aggressors–Victim's Eighteenth Harmonic

increased by less than 8 ps for all three tests. Also, the spectrum analyzer plots showed that the largest crosstalk components were at least 45 times smaller than the fundamental frequency and at least 40 times smaller than the fifth harmonic. Thus, the impact of crosstalk is negligible on the receive side as well.

In conclusion, the quad independent channel HOTLink II device can simultaneously transmit serial data at different frequencies across all four channels without experiencing deleterious effects due to crosstalk.

References

1. *HOTLink™ Jitter Characteristics*. Cypress Semiconductor application note. March 11, 1999. <http://www.cypress.com/cfuploads/support/app_notes/jitter.pdf>

1. *Measuring Crosstalk in LVDS Systems*. Cole, Elliot. Texas Instruments. January 2000. <http://focus.ti.com/lit/an/slla064/slla064.pdf>

Appendix
Frequency Sweep of Aggressors

This section will prove that the effect of crosstalk increases as the aggressor's edge rate increases. As described in the crosstalk section, the HOTLink II device increases its edge rate as its operating frequency increases. Thus, the effect of crosstalk should increase with operating frequency.

The test equipment setup is the same as the transmitter test setup, except only the spectrum analyzer is used to measure the serial output. For all of the tests, the victim channel (Channel A) will operate a constant frequency of 150 MHz. Conversely, the aggressor channels will sweep across the complete operating range (19.5 MHz–150 MHz) of the device. The Agilent E4407B has a Max Hold function that maintains the highest recorded amplitude for each frequency point. All channels will transmit D21.5 characters.

Figure 17 shows the spectral plot of channel A with no aggressors. The fundamental frequency is at 750 MHz and has an amplitude of approximately 0 dB.

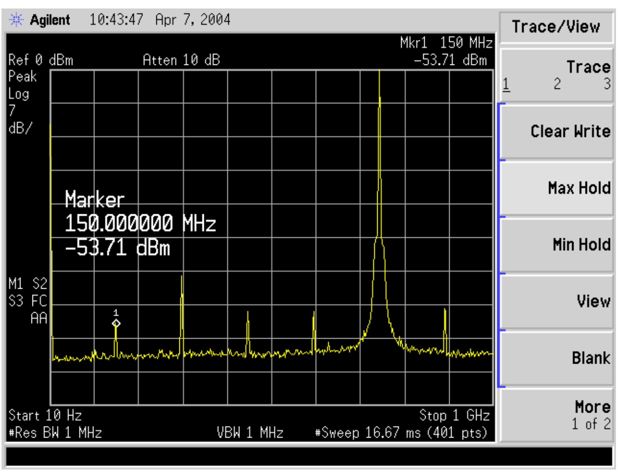

Figure 17. Channel A with No Aggressors

For the following measurements, as the aggressor's frequency is swept, the spectrum analyzer will be saving the highest value recorded at each frequency. *Figure 18* shows the spectral plot of channel A with the aggressor channel B swept across the whole operating frequency range. The effect of crosstalk can be seen at the lower frequency range (<150 MHz). While these values are less than 1/100th the size of the fundamental frequency, it is clear that the amplitude increases with frequency from 20–150 MHz. The same can be seen for the other channels (Channel C in *Figure 19* and Channel D in *Figure 20*). It is important to note that the amplitudes of higher frequency spectral components (e.g., the frequencies at which the serial data switches) are even smaller than –45 dB.

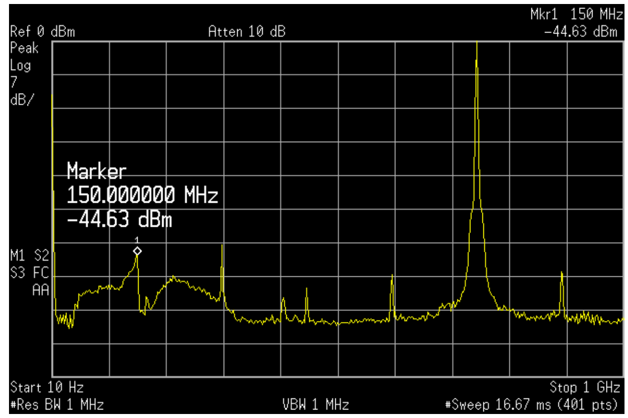

Figure 18. Channel A with Aggressor Channel B Sweeping Across the Operating Range

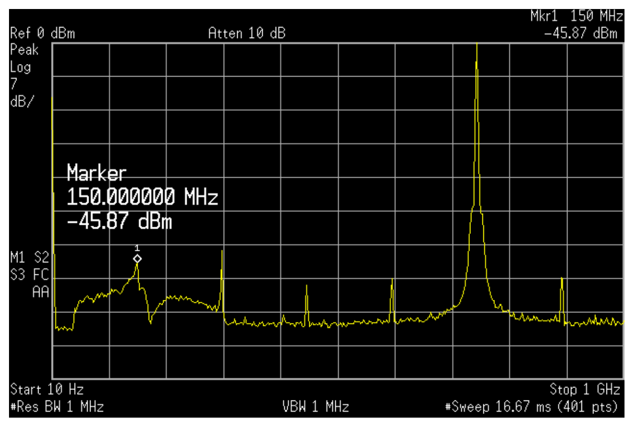

Figure 19. Channel A with Aggressor Channel C Sweeping Across the Operating Range

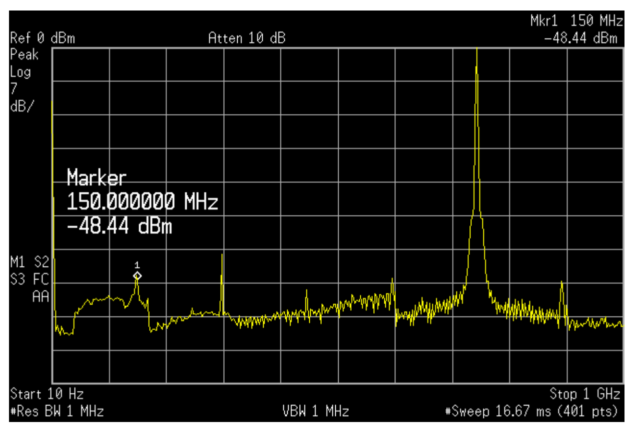

Figure 20. Channel A with Aggressor Channel D Sweeping Across the Operating Range

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