PCI Express – Signal Integrity and EMI

Introduction

When distributing clock signals inside a system, the possibility of clock signals interfering with other parts of the system is always an issue. A broader concern is the system interfering with other systems.

The first defense against clock signals causing interference is proper design of PCB traces for good signal integrity of the clock signal.

To further lower interference or EMI, and to make it easier to comply with EMI requirements, Micrel provides spread spectrum modulation with some of its PCI-E clock generators.

HCSL for PCI Express

HCSL (high-speed current steering logic) is a differential logic where each of the two output pins switches between 0 and 14mA. When one output pin is low (0), the other is high (driving 14mA). The termination is 50Ω to ground so the signal voltage levels switch between 0V and 0.7V.

Termination

As mentioned above, the termination is very simple, with 50Ω to ground. The signal is transported across the PCB with matched traces with 50Ω impedance, and terminated with 50Ω resistors on one side. This means that there are two termination schemes:

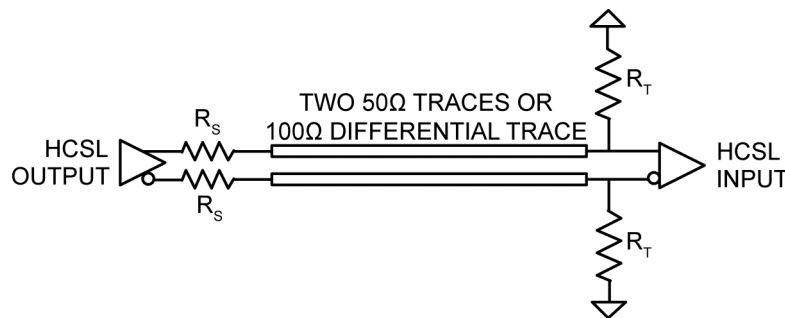1. 50Ω termination at the end of the trace, at the side of the HCSL input.

Figure 1. Termination at End of Trace

R_T is the 50Ω termination resistor.

R_S is a series resistor of 30Ω for debouncing.

HCSL drivers can be very fast and can cause ringing in the trace. The series resistor lowers the Q-factor for ringing to the point where the ringing is not significant.

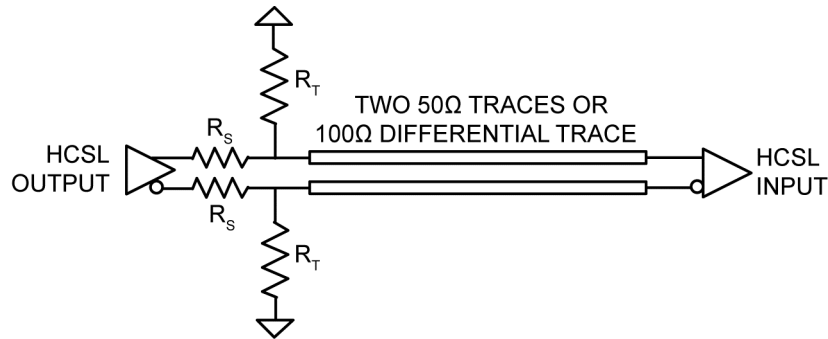2. 50Ω termination at the start of the trace, at the side of the HCSL output driver.

Figure 2. Termination at Start of Trace

In this case the termination is moved to the side of the output driver.

There are advantages to both termination schemes. When using termination scheme 1, the waveform signal integrity is good everywhere along the trace. When using termination scheme 2, the waveform signal integrity is good only at the end of the trace. The end of the waveform is more important, so it is fine to use scheme 2.

There is also an advantage to using termination scheme 2; the trace can be cut or left open (input IC not assembled) and it will not affect the driver side. This is especially important when the signal passes a connector of a plug-in board and the board must be hot-swappable. With this termination scheme, you can unplug the connection and the signal waveform at the driver side does not change; unplugging causes no unwanted side effects. For this reason, termination scheme 2 is preferred for HCSL for PCI Express systems.

Signal Levels

The signal levels at the input are typically 0mV for logic '0' and 700mV for logic '1', at each of the two pins of the differential signal.
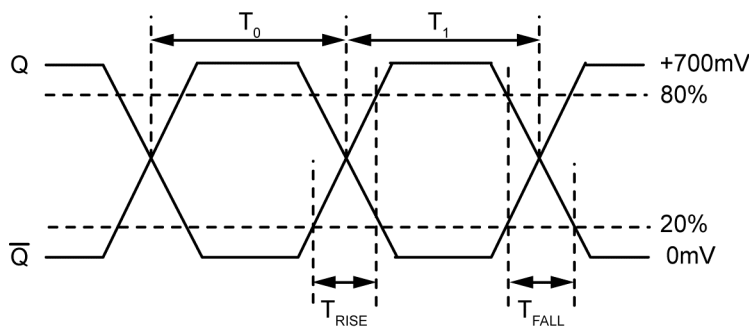

Figure 3. Signal Levels

The rise and fall times, T_{RISE} and T_{FALL}, are measured between 20% and 80% of the signal amplitude.

The duty cycle is the ratio between the logic '1' level and the total cycle time.

Accordingly, the duty cycle is $100\% \times T_1 \div (T_0 + T_1)$.

The signal high level needs to be between +600mV and +900mV.

The signal low level needs to be between −150mV and +50mV.

Spectrum of Square Wave Clock Signal

A square wave clock signal concentrates its power in narrow frequency harmonics. Figure 4 shows a 100MHz clock and its harmonics up to 1.5GHz.

The higher the frequency, the more of the signal in a trace causes electromagnetic radiation. This means that the higher harmonics of a clock signal are more likely to cross-talk than the lower harmonics. Adding spread spectrum modulation to the clock signal can significantly reduce the higher harmonics of a clock signal. Figure 5 shows the same clock with spread spectrum turned on.

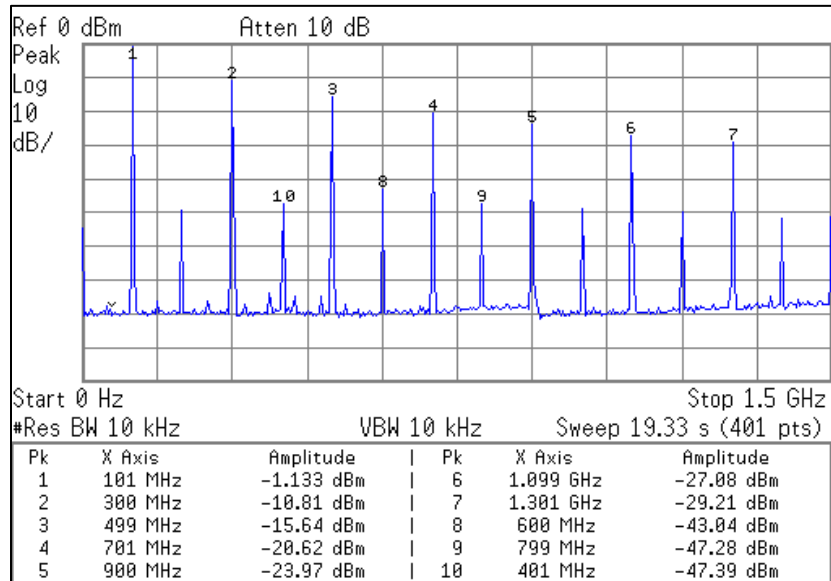Spread spectrum properties for this case are −0.50% magnitude and 32kHz rate.

Pk	X Axis	Amplitude		Pk	X Axis	Amplitude
1	101 MHz	−1.133 dBm		6	1.099 GHz	−27.08 dBm
2	300 MHz	−10.81 dBm		7	1.301 GHz	−29.21 dBm
3	499 MHz	−15.64 dBm		8	600 MHz	−43.04 dBm
4	701 MHz	−20.62 dBm		9	799 MHz	−47.28 dBm
5	900 MHz	−23.97 dBm		10	401 MHz	−47.39 dBm

Figure 4. Spectrum of 100MHz Square Wave

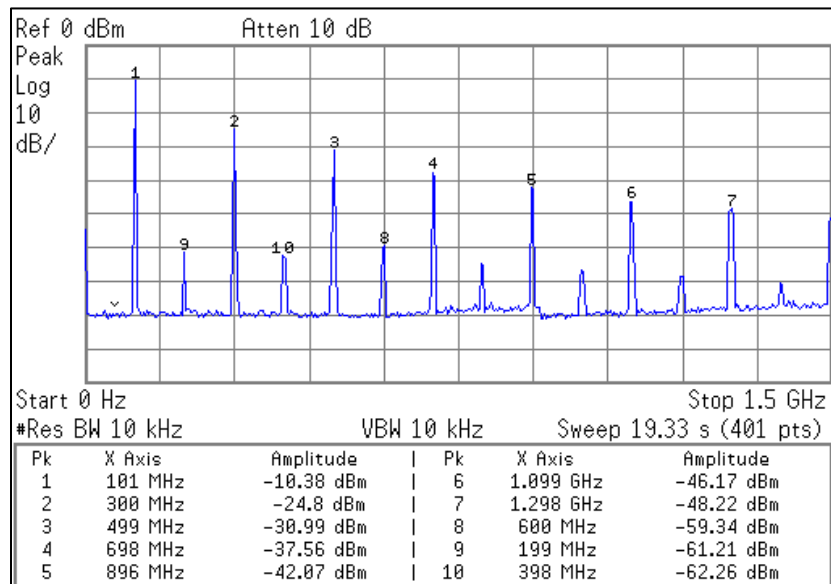| Pk	X Axis	Amplitude		Pk	X Axis	Amplitude
1	101 MHz	−10.38 dBm		6	1.099 GHz	−46.17 dBm
2	300 MHz	−24.8 dBm		7	1.298 GHz	−48.22 dBm
3	499 MHz	−30.99 dBm		8	600 MHz	−59.34 dBm
4	698 MHz	−37.56 dBm		9	199 MHz	−61.21 dBm
5	896 MHz	−42.07 dBm		10	398 MHz	−62.26 dBm

Figure 5. Spectrum of 100MHz Square Wave with Spread Spectrum

What is Spread Spectrum Modulation?

Spread spectrum is frequency modulation with a specific waveform. Micrel uses a triangular modulation waveform. The modulation "spreads" the power in each of the harmonics of the clock. Figure 6 shows the eleventh harmonic of a 100MHz clock with and without the spread spectrum modulation.
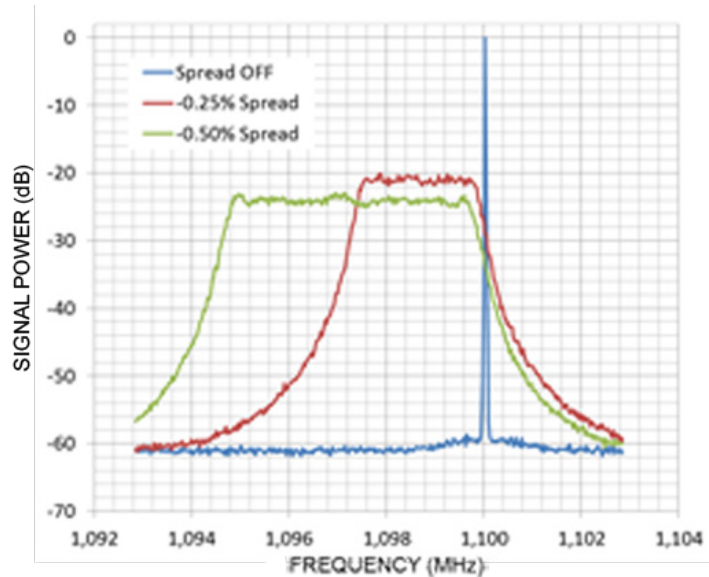

Figure 6. Spectrum of Eleventh Harmonic of 100MHz

The amount of modulation is indicated with a magnitude of a certain percentage of the carrier or harmonic frequency. You can see in Figure 6 that, with −0.25% magnitude, the 1.1GHz harmonic is spread over about 2.5MHz and with −0.50% it is spread out over about 5MHz.

The key reason for adding the spread spectrum modulation is clearly visible in Figure 6. The signal power remains at lower levels. Without spread, the power is concentrated and can peak high. The modulation spreads the power and as a result it remains lower. Rules for electromagnetic compatibility require the emitted signal levels to stay under a certain threshold. Spread spectrum modulation helps to achieve this.

Spread spectrum can be measured with a spectrum analyzer and also with a digital oscilloscope. Figure 7 is a screen capture of a digital oscilloscope where a jitter trend function is capturing the triangular modulation wave.

For the example in Figure 7 the carrier is 100MHz, the modulation rate is 34.1kHz, and the modulation magnitude is 2.6MHz or 2.6%.
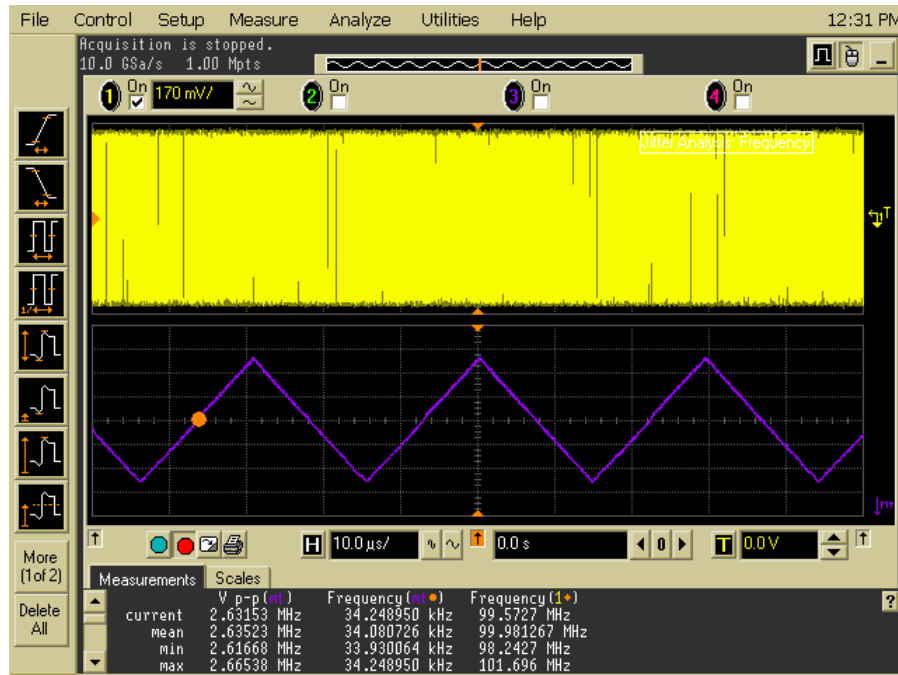
Figure 7. Spread Spectrum Modulation Waveform

The yellow trace is the clock and the purple trace is the frequency of the clock as a result of the jitter trend analysis. The oscilloscope can measure the properties of the trend wave. The frequency of the trend wave is the modulation rate and the peak-to-peak amplitude of the trend wave is the modulation magnitude.

Down Spread

Figure 6 shows how the signal power is moved to lower frequencies with spread spectrum modulation. This is called "down spread." Network clocks are often run at a maximum clock speed and when modulation is applied symmetrically around the carrier, the clock runs a little bit faster than the maximum about half the time. To remain compliant with the maximum clock frequency requirement, down spread is used.

Spread Spectrum Modulation = Jitter

Technically, spread spectrum modulation is jitter. A 100MHz clock has a cycle length of 10,000ps. Introducing 0.5% modulation magnitude adds 0.5% of 10,000ps or 50ps peak-to-peak of period jitter. In the case of 0.25% magnitude, the jitter is 25ps peak-to-peak. PCI Express has limits for period jitter and for that reason, 0.5% is the maximum magnitude that can be used and 0.25% and 0.5% are the only magnitudes offered with PCI Express clock generators. Other applications that are less sensitive to period jitter may be able to deal with 2% or more. Micrel has different clock generators for these applications.

Spread Spectrum Mathematics

The main question is, "How much will a certain magnitude of spread spectrum modulation reduce the EMI from clock harmonics?"

When EMI is measured, the equipment is configured with a certain bandwidth. In the above measurements, 10kHz bandwidth is used with the spectrum analyzer. When EMI requirements were first introduced, the main interference was with wideband FM radio that uses 120kHz bandwidth. This has become the standard for EMI testing.

The reason that spread spectrum modulation can reduce the measured signal strength is that the modulation is sweeping the signal frequency beyond the target's bandwidth. For example, a 1GHz harmonic with 0.25% modulation sweeps back and forth in a 2.5MHz range. When "observed" with 120kHz bandwidth, the signal spends only a fraction of 0.12/2.5 inside the 120kHz bandwidth. In dBs this is 10 LOG(0.12/2.5) = −13dB.

The generic formula is as follows:

$$R(dB) = 10 \times LOG(0.12/(Fc \times M/100\%))$$ Eq. 1

R is the EMI reduction in dB.

F_C is the carrier or harmonic, in MHz, for which to determine the EMI reduction.

M is the spread spectrum magnitude in %.

For example with −0.5% magnitude at a 900MHz harmonic:

$$R = 10 \times LOG(0.12/(900 \times 0.5/100)) = -15.7dB$$ Eq. 2