What is the bandwidth of a high speed serial-link signal?: Rule of Thumb #11

Eric Bogatin - May 07, 2014

This rule of thumb enables us to estimate the highest frequency to worry about for a data signal.

Spoiler summary: At the Tx, it is 2.5× the bitrate. At the Rx, in a lossy channel, it is the Nyquist: BW = ½ bitrate.

Remember: Before you start using rules of thumb, be sure to read the Rule of Thumb #0: Use rules of thumb wisely.

Previous: Rule of Thumb #10: How much attenuation is too much?

In the time domain, a waveform can sometimes be very complicated. Our goal in establishing a simple rule of thumb is to find a way of taking complex behavior and approximating it in terms of a few, easy to calculate figures of merit.

Of course, as we say over and over again, the value of a rule of thumb is to help calibrate our intuition and get us a rough answer quickly. It should never be used to sign off on a design.

If we take a data pattern that is encoded as non-return to zero (NRZ) and look at a highest transition rate signal (which would have the highest bandwidth), with a data pattern of 10101010, it will look like a clock signal. An example is shown in **Figure 1**.

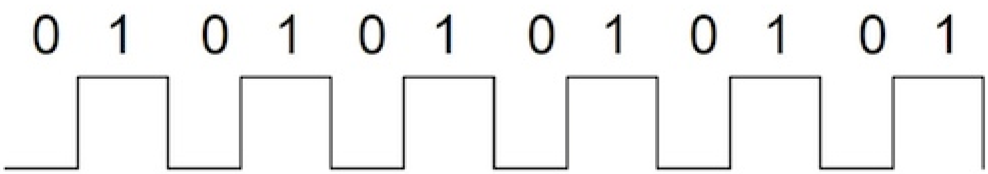

Figure 1 A data pattern with the highest transition rate looks like a clock waveform.

In this example, there are two bits of data encoded per period of the clock cycle. The unit interval of the data is one-half the clock period. This means the underlying clock frequency in the data pattern is half the bit rate. We call this underlying clock frequency the Nyquist frequency, not to be confused with the Nyquist sampling rate. Because there are two bits per clock cycle, the bit rate is higher than the Nyquist, and the Nyquist is half the bit rate.

If all we know is the clock frequency of a clock signal, we can estimate its bandwidth based on the assumption that the rise time is 7% of the period. Then, the bandwidth is the 5^{th} harmonic of the clock frequency. This was introduced as Rule of thumb # 2. This suggests the first half of this new rule of thumb:

> *For a PRBS signal, the bandwidth as seen when the rise time is the shortest, at the Tx, will be 5 × Nyquist = 5 × ½ bitrate = 2.5 × bitrate.*

For example, if the bit rate is 10 Gbps, the bandwidth, as seen at the Tx, will be about 25 GHz.

Of course, this assumes the rise time will be very short: 7% the period of the clock signal, or 14% of the UI. If the bit rate is being pushed to the limit, the rise time may be as long as 25% of the UI, in which case the bandwidth will be less than 25 GHz. That's why we really have to know the rise time. But if we don't know the rise time, "all we have is a hammer", and we may overestimate the bandwidth.

As the signal propagates down the channel, the rise time will increase due to frequency-dependent losses. This will decrease the bandwidth of the signal. The bandwidth at the Rx will be different than at the Tx.

In most channels, the attenuation scales roughly with frequency. If there is -3 dB attenuation at the Nyquist, there will be three times this, or -9 dB attenuation, for the 3^{rd} harmonic, and -15 dB attenuation for the 5^{th} harmonic. This means that all the higher harmonics will be dramatically attenuated compared to the first harmonic at the Nyquist. **Figure 2** shows the eye diagram for a signal that has a very high bandwidth at the Tx, but passes through a lossy channel with -3 dB attenuation at the Nyquist. It looks almost like a sine wave at the Rx.

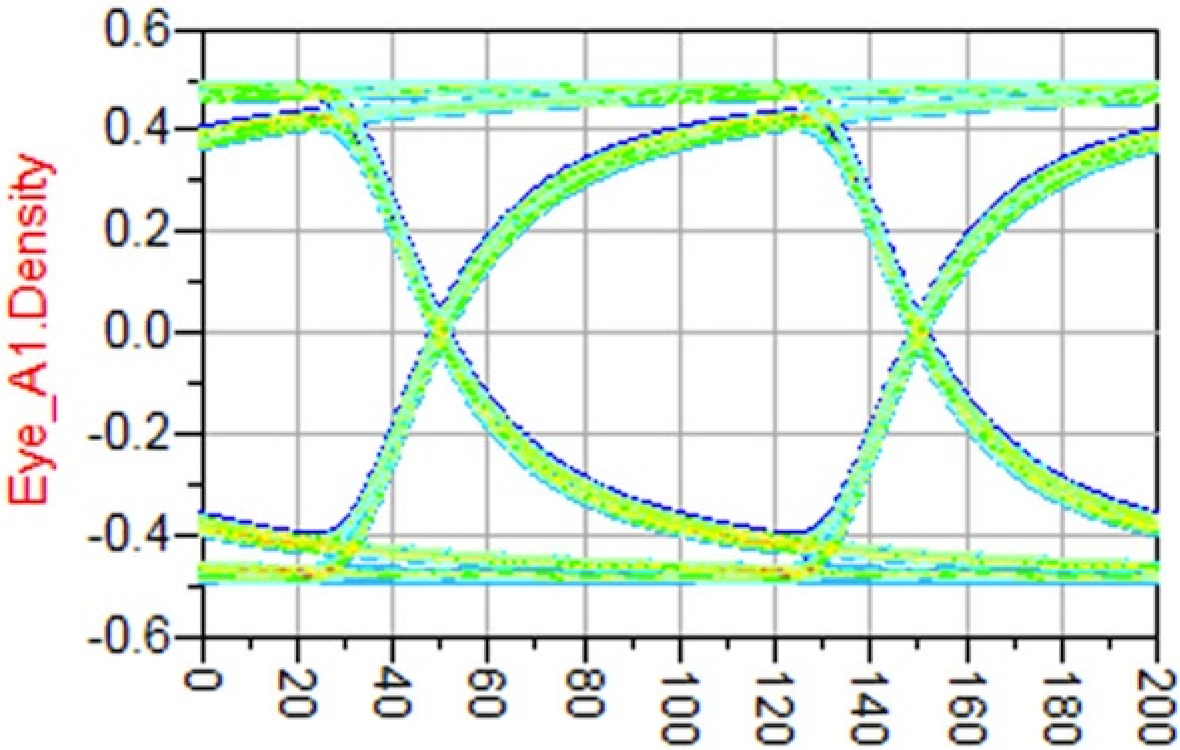

Figure 2 Eye diagram of a PRBS signal at the RX, passing through a channel with -3 dB attenuation at the Nyquist. The Nyquist is the highest sine wave frequency that survives (simulated with Agilent's ADS).

This is the origin of the second half of the rule of thumb. In a lossy channel, the first harmonic of the underlying clock is the highest frequency component that survives the losses, and the bandwidth of the data signal is the Nyquist:

At the Rx, the BW = ½ bitrate.

For example, at the Rx, the BW of a 10 Gbps signal through a lossy channel will be about 5 GHz.

Now you try it:

1. I want the bandwidth of my scope to be at least twice the bandwidth of my signal. To see the waveform at the Tx for a PCIe gen II signal, what is the minimum bandwidth scope I should use?
2. At the Rx, what is the bandwidth of a USB 3.1 signal passing through a long cable?

Next rule of thumb: RoT #12: How much return loss is too much?