[Rule of Thumb #1: Bandwidth of a signal from its rise time]

Eric Bogatin - November 19, 2013

Eric Bogatin, Signal Integrity Evangelist, Teledyne LeCroy, embarks on a mission to spell out some common rules of thumb in a new series of columns. Here is the first rule of thumb and first challenge.

$$BW[GHz] = \frac{0.35}{RT[nsec]} \quad \text{or} \quad RT[nsec] = \frac{0.35}{BW[GHz]}$$

Where:
RT = the 10-90% rise time of a square wave in nsec
BW = the bandwidth of the signal, in GHz

This rule of thumb relates the bandwidth of a signal with the rise time of the signal.

Remember: before you start using rules of thumb, be sure to read the Rule of Thumb #0: How to use them wisely.

What is Bandwidth?
Bandwidth is the highest sine wave frequency component that is significant in a signal. Because of the vagueness of the term "significant," unless detailed qualifiers are added, the concept of bandwidth is only approximate.

Bandwidth is a figure of merit of a signal to give us a rough feel for the highest sine wave frequency component that might be in the signal. This would help guide us to identify the bandwidth of a measurement instrument needed to measure it, or the bandwidth of an interconnect needed to transport it.

The origin of this simple rule of thumb relating the rise time of a signal and the highest sine wave frequency we need to consider in the signal is based on a very simple type of signal.

We assume the signal is a 50% duty cycle clock signal that has a finite 10-90 rise time. For this specific waveform, we can estimate the highest sine wave frequency needed to recreate the rise time.

Consider first an ideal clock signal. The spectrum of an ideal 50% duty cycle square wave, with 0 psec rise time, has frequency components only at multiples of the clock frequency (harmonics). The amplitude of the even harmonics is 0. The amplitude of the odd harmonics is given by,

$$A = \frac{2}{\pi n}$$

where n is the harmonic number.

This is one of the few Fourier Transforms I can do by hand. If you have never done one before, I strongly recommend you try this one.

For example, the amplitude of the n = 1 first harmonic is 2/(3.1416 x 1) = 0.64. The amplitude of the 3rd harmonic, n = 3 is 2/(3.1416 x 3) = 0.21. Each harmonic amplitude drops off like 1/f, since each harmonic is a higher frequency. Figure 1 shows the calculated harmonic amplitudes of a 1 GHz ideal clock frequency signal for many harmonics.

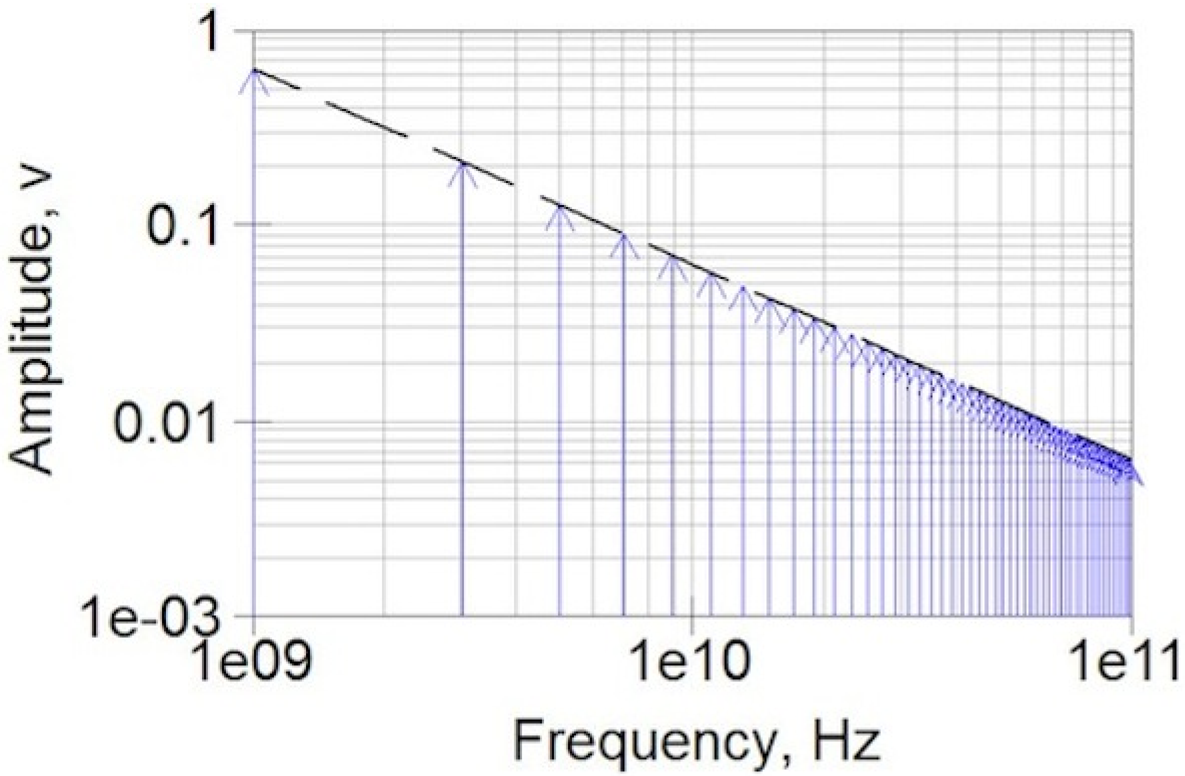

Figure 1. Spectrum of an ideal 1 GHz clock signal, created from a numerical FFT solution, compared with the analytically calculated harmonic amplitude. Note the amplitudes drop off like 1/f.

What is the highest sine wave component in an ideal square wave? Even though they drop off rapidly and get smaller and smaller, every one is critically important to recreate the 0 psec rise time of the ideal square wave. But what if we don’t need such a short rise time?

Rise Time and Bandwidth
To find the relationship between the rise time of a signal and its bandwidth, we are going to engineer a specific spectrum so we know exactly what the bandwidth is and measure the actual 10-90 rise time we are able to achieve for that time domain signal.

We start with the spectrum of the ideal square wave and select just the first n harmonics, with the amplitudes as they are in the ideal spectrum. The amplitudes of all the harmonics in the spectrum above n are set to 0. The highest sine wave frequency component in the spectrum is absolutely unambiguous, we engineered it to be n.

We take this frequency domain spectrum and turn it back into a time domain signal. We measure the 10-90 rise time of the resulting signal. Figure 2 shows the recreated time domain waveforms from these engineered-bandwidth spectra, for the case of including just up to the n = 1 harmonics, just up to the n = 3, just up to the n = 17 and just up to the n = 19 harmonics. For each engineered waveform, we show just the expanded view of the rising edge of the signal.

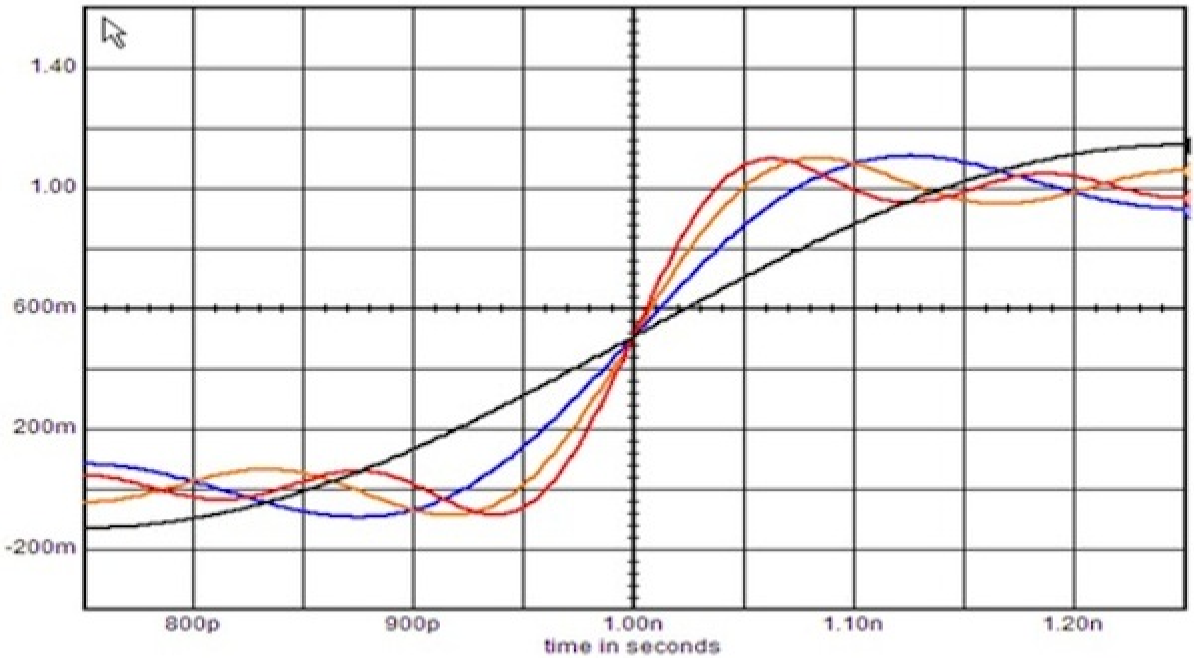

Figure 2. Recreated waveforms from engineered-bandwidths, as the highest harmonic included increases.

For each waveform, we know precisely what the bandwidth is. We engineered it to be n. We can measure the 10-90 rise time off the graph. When we compare the engineered bandwidth to the 10-90 rise time, we see a pattern, as shown in Figure 3.

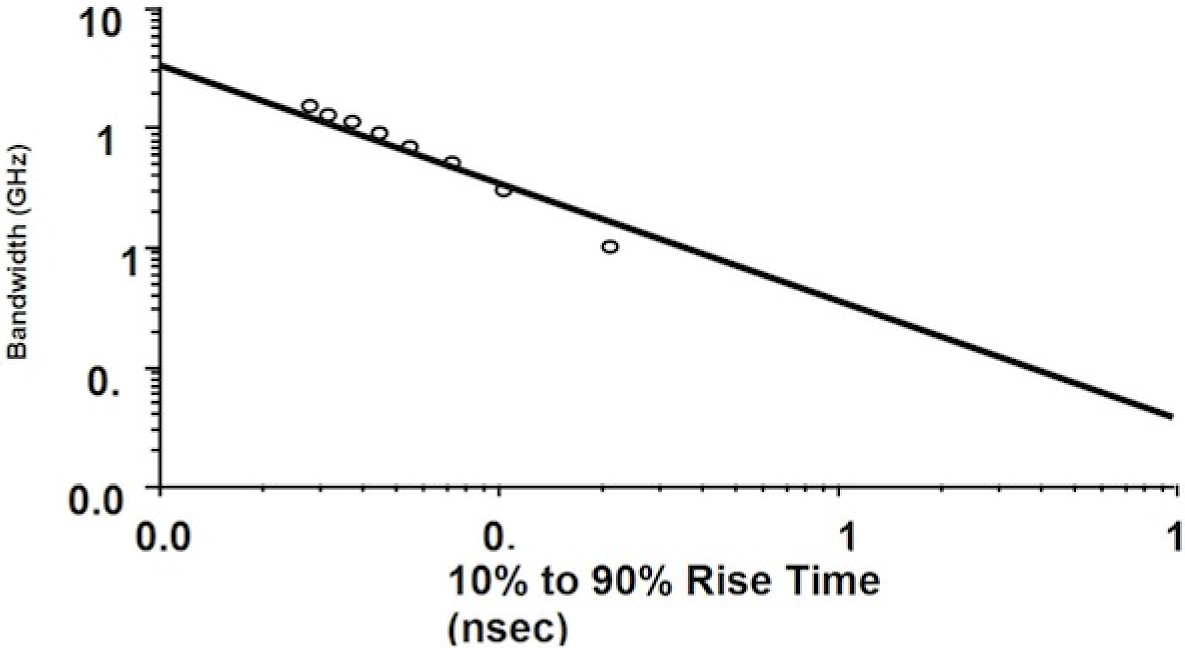

Figure 3. The 10-90 rise time plotted for each waveform, compared to the engineered bandwidth of the waveform.

On this plot, I drew a straight line to empirically match the bandwidth to the rise time. It is

$$BW[GHz] = \frac{0.35}{RT[nsec]}$$

For example, when the rise time is 1 nsec, the highest sine wave frequency component I need in the spectrum to create this 1 nsec rise time signal is 350 MHz. If the rise time is 350 psec, I only need frequency components up to 1 GHz to re-create the rising or falling edge of the signal.

If you are worrying about whether the 0.35 should be 0.5, don't use this simple relationship. If it is important to know whether the bandwidth of a signal is 1.3 GHz or 1.5 GHz, don't use the single term, bandwidth, to describe your signal. You should probably use the entire spectrum of the signal.

Now you try it:

1. What is the bandwidth of a DDR signal with a 0.3 nsec rise time?

2. What is the bandwidth of a USB signal with a 50 psec rise time?

3. What is the rise time for a signal if it has a bandwidth of 3.5 GHz?

Leave your answers and your own examples in the comments section

Next rule of thumb: RoT #2: Bandwidth of a signal from its clock frequency.

Also See:

- [Rule of Thumb #0: How to use them wisely]
- [Small signal bandwidth in a Big Bandwidth era]