Optical Bandwidth Requirements for NRZ and PAM4 Signaling

WHITEPAPER

There is confusion about Optical Bandwidth and Electrical Bandwidth of optical channels and how these terms relate to Optical Reference Receivers (ORRs). PAM4 signaling has further complicated minimum bandwidth requirements in order for receivers to be spec compliant.

Up until recently, both optical and electrical bandwidth produced similar results when using 0.75 x baud rate; however, with the recent IEEE spec change to 0.5 x baud rate, electrical and optical bandwidths are no longer the same, thus causing confusion about the relationship between the two. This paper clarifies these terms by starting with the proper definitions, mathematically showing how they are related, and provides the basis to understand and confidently calculate optical and electrical bandwidth for an optical channel.

Optical bandwidth is defined as the frequency at which half the optical power is incident in the channel. Since power is measured in Watts we use $10*\log_{10}(W/W_o)$ to find the -3dB point. This is referred to as the optical decibel (dBo). In the formula, W_o is the power level in Watts at DC and is used to normalize the frequency response to be 0dB at DC.

For electrical channels where volts are used to measure signal levels, the **electrical bandwidth** is still defined as the point where half the power is incident (-3dB point). However, the equation changes to $10*\log_{10}(V^2/V_o^2)$. The voltage is squared because power is proportional to the square of the voltage, and V_o is the voltage at DC.

Using the rules of logarithms, we move the square from the voltage in front of the logarithm:

$$10*\log_{10}(V^2/V_o^2) = 2*10*\log_{10}(V/V_o) = 20*\log_{10}(V/V_o)$$

Optical receivers use what is known as a square law detector. Watts are converted directly into Volts. The conversion gain of the receiver is the ratio of Volts out to Watts in, V = cW, volts (V) equals Watts (W) times the conversion gain of the receiver (c). This equation defines a linear relationship between power and voltage that it is no longer quadratic.

With optical channels, the incident signal on the channel is delivered optically and measured in Watts. The usable signal after the O/E is measured in volts. We can then refer either to the bandwidth of the incident optical signal or to the bandwidth of the electrical signal at the output of the O/E. The bandwidth of the electrical signal out of the receiver is $20*\log_{10}(V/V_o)$, substituting V = cW into this equation we get:

$$20*\log_{10}(V/V_o) = 20*\log_{10}(cW/cW_o) = 20*\log_{10}(W/W_o)$$

This is the electrical dB (dBe) and is used to define the electrical bandwidth of the module. Remember the formula for the optical decibel ($10*\log_{10}(W/W_o)$) is provided above. The electrical decibel (dBe) is twice the optical decibel (dBo).

$$dBo = 10*\log_{10}(W/W_o)$$

$$dBe = 20*\log_{10}(W/W_o)$$

This 2x factor (dBe = 2 * dBo) is important below as we translate electrical bandwidth (BW) to optical bandwidth (BW) requirements.

Fourth Order Filters for NRZ Signals

IEEE defines the use of fourth order Bessel filters for scope reference receivers. These filters for NRZ signals are defined to be -3dBe at 0.75 * bit rate. In the example shown in the figure below, a 25Gbps ORR filter is shown. The -3dBe point is at 0.75 * 25 = 18.75 GHz. Note that the -6dBe point is 25.625 GHz (read from freq vs. dB graph below). Because the dBe = 2* dBo, the -6dBe point corresponds to the -3dBo point. For this filter, the -3dBo point occurs at 25.625 GHz, so conveniently the -3dBo point occurs almost exactly at the bit rate. This is true for any fourth order filters defined at 0.75 x bit rate. Therefore, for NRZ signaling we have generally used the term Bandwidth and ORR interchangeably. A 25 GHz optical (-3dBo) bandwidth is roughly the same as a 25Gbps ORR filter given the 0.75 x bit rate relationship.

Re-defined ORR for PAM4 Signals

Recently the 400GB-Ethernet taskforce re-defined the ORR for PAM4 signaling to be 0.5 x baud rate. With this new relationship, we can no longer use optical bandwidth and ORR filter bandwidth interchangeably. Therefore, an optical bandwidth requirement must be calculated.

How to determine optical bandwidth requirements

Here are two examples showing the process:

Example #1 – NRZ

There is no defined ORR filter for 56Gb/s NRZ signaling, but if we carry forward the relationships used for 25Gb/s where -3dBe is defined as 0.75 * bit rate, a proper ORR filter should have its -3dBo point at 56Gb/s * 0.75 = 42 GHz.

Example #2 – PAM4

53.125Gbaud PAM4 ORR has an electrical bandwidth of 26.56 GHz (53.125 * 0.5) and an optical bandwidth of 35.41 GHz (53.125Gbaud x 0.5 / 0.75). Thus, in the case of PAM4, a proper ORR filter should have its -3dBo point at 35.41 GHz.

	Bit Rate	***Optical***	***Electrical***
Units	Gbaud	GHz	GHz
Old Method	53.13	54.45	39.84
New Method	53.13	35.41	26.56

Table 1. Table shows the bandwidths of the old and new definition of ORR for a 53.125GBd PAM4 signal. In the old definition, there is a very close relationship between ORR bit rate and optical bandwidth. In the new version, these is no longer the relationship between bit rate and optical bandwidth.

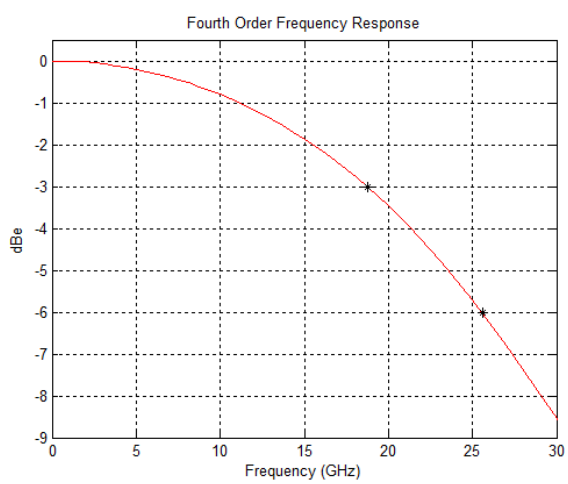

*Figure 1. Graph of an ORR (Optical Reference Receiver) at 25Gbps. Note that the -3dBe point is at 18.75 GHz and that the -6dBe (-3dBo) point is at 1.025 * 25 GHz = 25.625 GHz.*

Appendix – Additional information on calculations

The fourth order filter frequency response is defined in ITU-T G.691 to be

$$H(y) = \frac{105}{105 + 105y + 45y^2 + 10y^3 + y^4}$$

The constants in the numerator are the coefficients from a 4th order Bessel polynomial and y is a function of the frequency.

$$y(f_{BR}) = \frac{2.114 f_{BR} j}{0.75}$$

Here 2.114 is a used to adjust the response and the value 0.75 determines the point at which the filter is at half the power, $0.75\, f_{BR}$. For the new 400GB Ethernet standard the 0.75 would be

replaced by 0.5. The normalized frequency has been used which is defined to be the frequency divided by the baud rate

$$f_{BR} = \frac{f}{BR}.$$

Where f is the frequency and BR is the baud rate of the ORR filter.

For simplicity define H_y as a function of the normalized frequency.

$$H_y(f_{BR}) = H\big(y(f_{BR})\big)$$

Since we've normalized the filter by the baud rate, to calculate the response of a 10GBd ORR at 5 GHz simply take the ratio 5 GHz/10 GHz and insert into the equation above to get

$H_y(0.5) = 0.139 - 0.842j.$

Note that this is a complex value, we will need to take the absolute value before we can convert to dBs.

To verify that the -3dBe point of the filter is at 0.75 times the baud rate, evaluate the function H_y at 0.75.

$\left|H_y(0.75)\right| = 0.7071 = \frac{1}{\sqrt{2}}$

We can also show that the -6dBe point of the filter is 1.025 times the baud rate when H_y is evaluated at 1.025

$\left|H_y(1.025\right| = 0.4992 \approx 0.5$

Note that

$20*\log_{10}(0.7071) = -3$

$20*\log_{10}(0.5) \quad = -6$