2.2.5. Bit rate limitations due to group-delay dispersion

As soon as the pulse duration broadens beyond the allocated bit slot duration, we need to insert an electronic repeater (we’ll see later how to avoid using a repeater) to regenerate the data stream. This condition can be written $B \Delta T < 1/4$, as $T_B = 1/B$, which allows us to determine the bit-rate distance product

$$BL|D|\Delta \lambda < 1/4 \Rightarrow BL < 1/4|D|\Delta \lambda. $$

The dispersion parameter $D$ (and the group-delay dispersion coefficient $\beta_2$) can be positive or negative. We will consider the ramifications of the sign in the following section. As an example, using a pulse central wavelength $\lambda_f = 1.3 \mu m$, the dispersion parameter nears its zero value for standard fiber, with a value of about $D = 1 \text{ ps/nm-km}$.

For many light sources, the spectral width is not negligible, and can serve as the dominate source of dispersion. An LED, for example, has spectral width typically ranging from $\Delta \lambda = 20$ to 150 nm. Since dispersion calculations can be performed either in terms of $\Delta \lambda$ or $\Delta \omega$, it is useful to consider the relationship between the two quantities

$$\frac{\Delta \lambda}{\lambda} = \frac{\Delta \omega}{\omega},$$

where the central wavelength/frequency are related by $\lambda \nu = c$, and $\omega = 2\pi \nu$. For a laser diode operating on multiple longitudinal modes, the source spectral width $\Delta \lambda \sim 2 - 4 \text{ nm}$, and for a single-mode diode, $\Delta \lambda \sim 0.1 \text{ nm}$. These spectral widths give bit-rate distance products $BL \sim 100 \text{ Gb km/s}$ and 1 Tb km/s, respectively, which are suitable for long distance communications.

In these examples, we have assumed that the pulse bandwidth is dominated by the source spectral width. Note that in dense WDM systems, the source spectral width must be much less than the channel spacing, which is typically 50 to 200 GHz. If the source $\Delta \lambda \approx 0$ as in a distributed feedback laser, then the pulse spectral width will be given by $\Delta \omega \sim 2\pi/T_B = 2\pi B$, and the group-delay dispersion limitation can be written

$$B \Delta T = BL|\beta_2|\Delta \omega = 2\pi B^2 L|\beta_2| < 1/4,$$

giving the distance limitation

$$L < \frac{1}{8\pi|\beta_2|B^2}. $$

Notice that now the maximum distance (or maximum repeater spacing) varies as bit rate squared.

If neither source spectrum or modulation spectral broadening dominate then both must be considered. The pulse spectral width is approximately the sum of the two (we’ll be more precise later).

2.2.6. Bit-rate and Bandwidth

Dispersion effects in fiber can cause a significant reduction in the data rate of an optical channel. The major factor of interest is the information-carrying capacity of the channel, which is characterized by either the bit-rate or the bandwidth. The bit rate is the number of bits that can be transmitted per second over a channel, measured in bits/sec. Bandwidth is the frequency range over which a signal can be transmitted without deterioration, measured in Hz. What the textbook really means by this bandwidth is the ultimate electrical bandwidth required to detect the signal, even though the bandwidth may be measured in the electrical or optical domains. The true
optical bandwidth is the range of wavelengths or frequencies required to carry the information, as would be measured with an optical spectrum analyzer. The reason why these two bandwidths are different is because of dispersion, which prevents us from making fully efficient use of the true optical bandwidth.

The bit-rate and electrical bandwidth are related to each other. The textbook places a limit on the optical modulation bandwidth (not to be confused with the spectral bandwidth of the optical channel $\Delta \nu$, which includes source spectral width and modulation):

$$ f_{3dB, optical} \leq \frac{1}{2\Delta T}. $$

An optical detector measures incident optical power and produces a photocurrent $I_p$ in response to the optical signal. Since electrical bandwidth is defined based upon power ($\propto I_p^2$), the following relationship holds between optical modulation bandwidth and received electrical bandwidth:

$$ f_{3dB, electrical} = \frac{\sqrt{2}}{2} f_{3dB, optical} = 0.707 f_{3dB, optical} = \frac{0.35}{\Delta T}. $$

The last term of the equation shows how pulse spread and electrical bandwidth are related.

The maximum bit-rate of a system is ultimately determined at the receiver, where the modulated optical signal is converted to an electrical signal. The different modulation formats (i.e. NRZ and RZ) require different bandwidths. For the return-to-zero (RZ) modulation format, the bit occupies about half of the bit time slot $T_B$, and optical modulation bandwidth is approximately equal to the bit rate, or $f_{3dB, optical} = B$, so that

$$ B_{RZ} \leq \frac{0.35}{\Delta T} $$

The pulse duration in the RZ format is defined as the pulse power full-width at half-maximum (FWHM).

For the NRZ format, the bit duration is approximately the bit time, so we have the approximate relationship $f_{3dB, optical} = B/2$. Therefore,

$$ B_{NRZ} \leq \frac{0.7}{\Delta T} $$

Many times, in the NRZ format, the pulse is characterized by its rise and fall times, much like a digital electronic system. We'll come back to this later.

So far, we've limited the maximum bit rate with the following expression

$$ B < \frac{1}{4\Delta T} = \frac{0.25}{\Delta T}. $$

From the above discussions, we see that this expression is approximately correct for RZ modulation, but is conservative by a factor of 2 to 3 for NRZ modulation. Nevertheless, the factor of 1/4 is generally accepted in the industry as a first-cut design guideline.