Estimation of Optical Link Length for High-Speed Aplications

Nataliya Varbanova[1], Krasen Angelov[2], Stanimir Sadinov[3]

Abstract – **In a fiber-optic link for high data rates, the system can be limited either by the losses (attenuation-limited transmission) or, assuming that the link is not limited by the source or detector speed, by the dispersion of the fiber (dispersion-limited transmission).**

Therefore a major task when designing optical links is the estimation of the optical link length in terms of various limiting factors.

Keywords – **optical link length, optical attenuation, optical dispersion.**

I. Introduction

Data transmission speed via optical link actually is not infinity. In a fiber-optic system at long distances or high data rates, the system can be limited either by the losses (attenuation-limited transmission) or, assuming that the link is not limited by the source or detector speed, by the dispersion of the fiber (dispersion-limited transmission) [1,4,9,11].

Estimation of maximum optical link length mainly depends on the following aspects:

- Source selection;
- Power budget;
- Dynamic range;
- Timing analysis (e.g. performance of the equipment);
- Attenuation-limited transmission length;
- Dispersion-limited transmission distance.

In optical links, dispersion is the phenomenon in witch the parameters of the medium are dependent on frequency of signals spreading through the medium or alternatively when the group velocity depends on the frequency [1,11].

Dispersion is sometimes called chromatic dispersion to emphasize its wavelength-dependent nature, or group-velocity dispersion to emphasize the role of the group velocity.

There are generally two sources of dispersion: material dispersion and waveguide dispersion [1,4,9,11]. Material dispersion comes from a frequency-dependent response of a material to waves. Waveguide dispersion occurs when the speed of a wave in a waveguide (such as an optical fiber) depends on its frequency for geometric reasons, independent of any frequency dependence of the materials from which it is constructed. In general, both types of dispersion may be present, although they are not strictly additive. Their combination leads to signal degradation in optical fibers for telecommunications, because the varying delay in arrival time between different components of a signal "smears out" the signal in time.

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II. Components and System Requirements

Fig. 1 shows the three primary components in a fiber-optic link: an optical transmitter, a fiber-optic cable, and an optical receiver [1-3,5,10,12]. In the transmitter, the input signal modulates the light output from a semiconductor laser diode, which is then focused into a fiber-optic cable. This fiber carries the modulated optical signal to the receiver, which then reconverts the optical signal back to the original electrical RF signal.

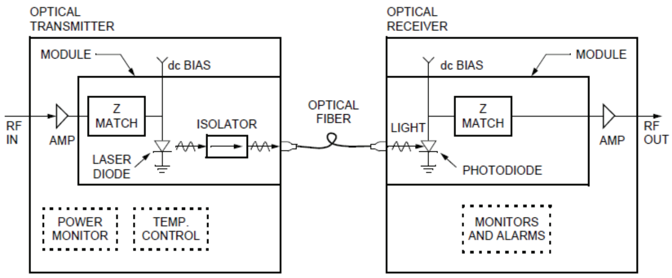

Fig. 1. Basic block diagram of the main components of the optical communication link

A. Source selection

The starting point for a link design is choosing the operating wavelength, the type of source (i.e., laser or LED), and the fiber type (single-mode or multi-mode fiber) [2,10,12]. In a link design, it is usually known the data rate required to meet the objectives. From this data rate and an estimate of the distance, it is chosen the wavelength, the type of source, and the fiber type.

Source data rate-distance performance limits are summarized in Table 1.

The choice of fiber type involves the decision to use either multi-mode or single-mode fiber [1,4]. And if the fiber is multi-mode, whether to use graded-index or step-index profiles. This choice is dependent on the allowable dispersion and the difficulty in coupling the optical power into the fiber.

TABLE I
SOURCE PERFORMANCE LIMITS

Source type	Short wavelength	Long wavelength
LED	< 150 Mbps.km	< 1,5 Gbps.km
Laser	< 2,5 Gbps.km	< 25 Gbps.km

If a LED is chosen, then the obvious choice of fiber is a multi-mode fiber because the coupling losses into a single-mode fiber are too severe. For a laser source, either a multi-mode or single-mode fiber can be used. The choice depends on the required data rate, as losses in both types of fiber can be made quite low [7].

B. Power budget

With a tentative choice of source, it is known the power P_T, available to be coupled into the fiber. If the receiver power P_R is necessary to achieve the required performance, then the ratio P_T/P_R is the amount of acceptable loss that can be incurred and still meet the specifications [7-10,12]. This can be expressed by

$$L_{losses,[dB]} + l_M = 10\log\left(\frac{P_T}{P_R}\right), \tag{1}$$

where l_M is the system margin.

The losses L_{losses} can be allocated in any desired approach by the system designer. Generally, the probable losses will be as follows:

- The source-to-fiber coupling losses l_T, *dB*;
- The connector insertion losses l_C and the splice insertion losses l_S;
- The fiber-to-receiver losses l_R (these losses is usually negligible);
- Additional losses l_A for device aging effects and future splicing requirements;
- Fiber attenuation losses αL (where α is the attenuation rate per kilometer of fiber and L is the fiber length).

Therefore Eq. (1) can then be expressed as:

$$10\log\left(\frac{P_T}{P_R}\right) = L_{losses,[dB]} + l_M = \alpha L + l_T + nl_S + l_R + l_A + l_M \,. \tag{2}$$

After solving Eq. (2) for the system margin l_M , the result will be:

$$l_M = P_{T,[dBm]} - P_{R,[dBm]} - \alpha L - l_T - nl_S - l_R - l_A \,. \tag{3}$$

A positive system margin ensures proper operation of the circuit; a negative value indicates that insufficient power will reach the detector to achieve the required *BER* [6].

C. Dynamic range

Using a "best case/worst case" approach it can be examined whether the link has sufficient dynamic range [4,5,10,12].

In Eq. (2) l_M can be written as follows:

$$l_M = l_{TR} - l_{SYSTEM} \,, \tag{4}$$

where l_{TR} is the ratio of the transmitter power to the required receiver power, expressed in dB, a l_{SYSTEM} is the total sum of the all system losses, given by:

$$l_{SYSTEM} = \alpha L + l_T + nl_S + l_R + l_A \,. \tag{5}$$

The dynamic range of the system is found by calculating the maximum and the minimum system margins. The two computations are summarized by

$$l_{M,\max} = l_{TR,\max} - l_{SYSTEM,\min} \,, \tag{6}$$

$$l_{M,\min} = l_{TR,\min} - l_{SYSTEM,\max} \,.$$

The system dynamic range $DR_{[dB]}$ is given by the difference in the values from Eq. (6):

$$DR_{[dB]} = l_{M,\max} - l_{M,\min} \,. \tag{7}$$

The optical receiver must have an equivalent dynamic range in order for the system to work properly [6]. The basic concern is to keep the power at the receiver above the minimum detectable power of the detector $P_{R,\,min}$ and below the maximum-rated power of the detector $P_{R,\,max}$. From Eqs. (2) and (3) the received power is deduced to be

$$P_{R[dBm]} = P_{T[dBm]} - l_{SYSTEM} \,. \tag{8}$$

Therefore the two boundary conditions will be respectively [9]:

- Maximum power output combined with minimum fiber attenuation;
- Minimum power output combined with maximum fiber attenuation.

D. Timing analysis

Rise time is a parameter of fundamental importance in high speed transmissions, since it is a measure of the ability of a circuit or system to respond to fast input signals. Rise time refers to the time required for a signal to change from a specified low value to a specified high value.

Rise time of a fiber-optic system Δt_{sys} is given by [1,10,12]:

$$\begin{aligned}\Delta t_{sys} &= \left[\sum_{i=1}^{N} \Delta t_i^2\right]^{\frac{1}{2}} = \\ &= \left[(\Delta t_S)^2 + (\Delta t_R)^2 + (\Delta t_{mat})^2 + (\Delta t_{modal})^2\right]^{1/2} = \end{aligned}, \tag{9}$$

where Δt_i is the rise time of each component in the system. The four components of the system that can contribute to the system rise time are as follows:

- Rise time of the transmitting source Δt_S;
- Rise time of the receiver Δt_R;
- Material-dispersion delay time of the fiber link Δt_{mat};
- Modal-dispersion delay time of the fiber link Δt_{modal}.

Modal-dispersion delay time of the fiber link Δt_{mat} is given by [1,10,12]:

$$\Delta t_{mat} = -\frac{L}{c}.\frac{\Delta\lambda}{\lambda}.\left(\frac{\lambda^2 d^2 n}{d\lambda^2}\right). \quad (10)$$

For a step-index fiber with length *L*, the modal-dispersion delay is given by

$$\Delta t_{\text{modal}} = \frac{L(n_1 - n_2)}{c}, \quad (11)$$

and for a parabolic-index fiber the delay is estimated as:

$$\Delta t_{\text{modal}} = \frac{L}{c}.\frac{NA^2(0)}{8n_1^2}, \quad (12)$$

where *NA* is a numerical aperture.

If the system rise time is calculated, than using this value, it can be calculated the data rate that the system can support as [1,10,12]:

– for NRZ coding: $B_R \le \frac{0,7}{\Delta t_{sys}}$; (13)

– for RZ coding: $B_R \le \frac{0,35}{\Delta t_{sys}}$. (14)

The modal dispersion delay time depends linearly proportional to the distance. The modal dispersion contribution is small for short distances. To reduce the material dispersion, inspection of Eq. (10) reveals that $\Delta\lambda$ should be reduced. There are two methods by which this can be achieved:

1) To use an LED with a longer wavelength (while keeping $\Delta\lambda$ constant);
2) To use a laser source with its reduced value of $\Delta\lambda$.

E. Estimation of the maximal optical link length

To estimate the maximum optical link length in presence of dispersion and attenuation limitations in the fiber, as a function of the transmission data-rate speed in the fiber are derived the following relations [10,12]:

• Material Dispersion-Limited Transmission Length:

$$L_{\max} = \frac{0,35c\lambda}{B_R\Delta\lambda\left(\frac{\lambda^2 d^2 n}{d\lambda^2}\right)}. \quad (15)$$

• Modal Dispersion-Limited Transmission Length:

$$L_{\max} = \frac{2,8.c.n_1^2}{[NA(0)]^2 B_R} = \frac{1,4.c.n_1^2}{n_1^2\Delta B_R} = \frac{1,4.c}{\Delta B_R}. \quad (16)$$

• Attenuation-Limited Transmission Length:

$$L_{\max\,(att)} = \frac{P_{T[dBm]} - P_{R[dBm]}}{\alpha_{fiber}} = \frac{P_{T[dBm]} - (-65,0 + 20\log_{10}(B_R))}{\alpha_{fiber}}. \quad (17)$$

III. Results

As an example, the estimation of a maximal length of high-speed optical link for short distances can be considered, as shown on Fig. 2. The link parameters are as follows [13-15]:

– Optical source type: LED;
– Optical source power: $P_T = 2\ mW$;
– Optical wavelength: 850 *nm*;
– Multi-mode fiber with graded-index ($g = 2$);
– Data rate: < 500 *Mbps*;
– $BER = 1.10^{-9}$;
– Optical receiver with pin-photodiode with sensitivity – 40 *dBm*.

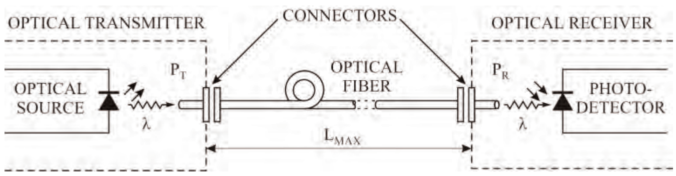

Fig. 2. Estimation of optical link length for high-speed aplications

Graphic appearance of the resulting dependencies of the maximum distance of transmission as a function of transmission speed in various limiting factors was carried out based on Eqs. (15) to (17) and is shown on Fig. 3.

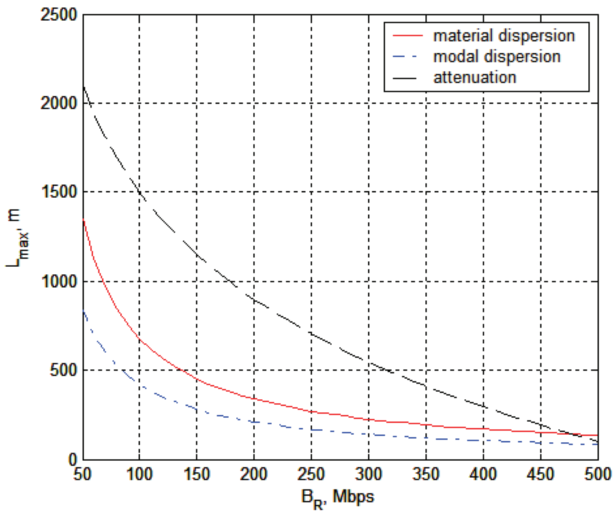

Fig. 3. Comparative effect of limiting factors on the length of the optical link

IV. Conclusion

Optical link design must meet both the link power budget and the system rise time analysis. In the link power budget analysis one first determines the power margin between the optical transmitter output and the minimum receiver sensitivity needed to establish a specified *BER*. Once the link power budget has been established, the designer makes a system rise time analysis to ensure that the dispersion limit of the link has not been exceeded.

In designing an optical-fiber system, one should take into account that the individual component parameters can vary considerably.

From the obtained results, the following important conclusions can be made:

- At lower data rates the main restriction on the length of the line comes from the dispersion; the modal dispersion has slightly more influence than the material dispersion;
- At higher data rates the maximal link length fell sharply as the fiber attenuation effect has a noticeable influence.

From the obtained results it is clear that taking into account the dispersion indicates a significant influence in determining the exact maximal optical link length.

It should be noticed that if the length of the line is greater than the fiber optic cable length, the optical splices must be taken into account in total attenuation calculations.

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