David Bozarth
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Sonoma State University
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Final Exam

12.0 *Remarks*

For system component types and specifications I rely primarily upon tables from the text such as Table 5.5 (Commercial Fibers), Table 6.2 (Diode Light Sources), Table 7.4 (Photodetectors), and Table 8.1 (Source-Fiber Coupling Losses). Where possible I will specify actual commercial components using current published specs. I don't expect to use actual price or availability information for this design project, but I will seek a best estimate of cost-performance optimization.

12.1 *Transmit a video signal having a bandwidth of 4.5 MHz over a 10-km path. The SNR at the receiver must be 48 dB or more. Use analog modulation.*

For simplicity, choose direct intensity modulation (IM). A simple design employs a low-cost laser diode source operating at 1300 nm, standard single-mode fiber, and a PIN photodiode detector. (If time permits, I will see about substituting lower cost, low-loss multimode fiber, which may present challenges with source-fiber coupling to the larger-diameter core, and modal distortion over the considerable transmission distance.)

source	**laser diode**	**fiber** (1300 nm)	**Corning SMF-28e**	**detector** (1300 nm)	**PIN InGaAs**
line width $\Delta\lambda$	5 nm	mode field dia.	9.2 ± 0.4 μm	responsivity ρ	0.6 A/W
rise time t_r	1 ns	numerical aperture NA	0.14	rise time t_r	0.3 ns
wavelength λ	1310 nm	loss	0.35 dB/km	junction C_d	5 pF
		pulse spread $\Delta(\tau/L)$	0 ps/km	dark current I_d	10 nA
				gain M	1

Fig. 1: Component specifications

<u>Determine power required at receiver to meet the specified Signal-to-Noise Ratio (SNR)</u>

We assume that the SNR of the PIN diode detector will be thermal-noise limited. Assuming also a unity gain receiver and 100 % signal modulation, we have

$$P = (1 / \rho) * \sqrt{[8 * SNR * k * T_e * \Delta f / R_L]}$$

where P is required power in watts, ρ is responsivity in A/W, k is Boltzmann's constant, T_e is Kelvin equivalent noise temperature of the receiver, Δf is system bandwidth, and R_L is load resistance of the detector.

Assuming ambient temperature 300 K and an amplifier noise figure F = 3 dB, we have

$$T_e = F * T = 600 \text{ K}$$

To determine the detector load resistance, we use

$$f_{3dB} = (2 * \pi * R_L * C_d)^{-1}$$

Here, f_{3dB} is the unity-gain bandwidth of the detector, and C_d is the junction capacitance of the detector. Setting

$$\Delta f = 4.5 \text{ MHz} < f_{3dB}$$

so the detector will not use all the available bandwidth, we have

$$R_L \leq 7.07 \text{ K}\Omega$$

A convenient choice is: $\mathbf{R_L = 6.8 \text{ K}\Omega}$ Recalculating the actual **receiver bandwidth**,

$$\mathbf{f_{3dB}} = (2 * \pi * R_L * C_d)^{-1} = \mathbf{4.68 \text{ MHz}}$$

This figure, in excess of the specified system bandwidth, ensures that the spec can be met. We can now calculate the power required at the receiver:

$$P = 2.82 \ \mu\text{W}$$

Adding some margin for noise and component degradation, choose $\mathbf{P = 3 \ \mu W}$. The **average photocurrent** is

$$\mathbf{I} = \rho * P = \mathbf{1.8 \ \mu A}$$

Since this figure exceeds the detector dark current I_D by some 2 orders of magnitude, I_D can be ignored.

Checking the prior assumption about thermal noise limitation, the thermal noise current is

$$i_{NT(avg)} = \sqrt{[4 * k * T_e * \Delta f / R_L]} = 3.38 \text{ nA}$$

The shot noise current is

$$i_{NS(avg)} = \sqrt{[2 * e * I * \Delta f]} = 1.64 \text{ nA}$$

This shows both that the thermal-noise limitation assumption was correct, and that shot noise is a significant contributor. If the power budget becomes tight, we must revisit the SNR-based calculation of required receiver power.

We check also that the average current will not over-drive the detector. The maximum current before saturation is

$$I_{max} = V_B / R_L = 735\ \mu A$$

where V_B is the bias voltage of the detector, assumed to be 5 V. Comparing this with the expected current 1.8 μA, we see there is plenty of headroom.

Power budget

Assume a power output of 1 mW (0 dBm) from the laser diode. Required power level at the receiver is 3 μW (-25.2 dBm).

Fiber attenuation over 10 km should be under 4 dB. Assume 2 connectors with 1 dB loss each, 1 dB combined reflection loss, and 6 dB combined area mismatch loss. The fiber is available as a single 10 km length. Assume a few splices for maintenance with combined loss of under 1 dB.

The loss budget is (4 + 2 + 1 + 6 + 1) dB = 14 dB

We are left with a power margin of (25 – 14) dB = **9 dB**

Bandwidth budget

The total system rise time t_S is related to the rise times of the light source, fiber, and photodetector respectively as

$$t_S^2 = t_{LS}^2 + t_F^2 + t_{PD}^2$$

The laser diode rise time is published as under 1 ns. The system rise time is found by

$$t_S = 0.35 / f_{3dB} = 77.8 \text{ ns}$$

The detector has a very fast intrinsic rise time, so the detector circuit rise time can be assumed as limiting. It is

$$t_{PD} = 2.19 * R_L * C_d = 74.5 \text{ ns}$$

To stay within the available bandwidth, we need

$$t_F \leq \sqrt{[\ t_S^2 - t_{LS}^2 - t_{PD}^2\ ]} = 22.5 \text{ ns}$$

Allowing some margin, we require the rise time across the 10 km fiber to be under 22 ns.

The fiber rise time and electrical bandwidth are related by

$$t_F = 0.35 / f_{3dB(ele)}$$

Electrical and optical bandwidth are related by

$$f_{3dB(ele)} = 0.71 * f_{3dB(opt)}$$

The fiber optical bandwidth can be found from the overall pulse spread:

$$f_{3dB(opt)} = (2 * \Delta\tau)^{-1}$$

By inspection we can see that fiber rise time is closely equivalent to total pulse spread.

The system operates near the wavelength of zero material dispersion: to find pulse spread per unit length, we need consider only waveguide dispersion M_g. At 1310 nm, waveguide dispersion should be under 4.3 ps $(\text{nm km})^{-1}$. Thus for a spectral width of 5 nm,

$$\Delta(\tau/L) = M_g * \Delta\lambda = 21.5 \text{ ps}$$

Over the 10 km haul, expected maximum pulse spread is 215 ps, fiber optical bandwidth is 1.65 GHz, and **fiber rise time is 212 ps**. This is well within our design objective of **22 ns**.

<u>Conclusion</u>

The design objectives are met with this combination of source, fiber, and detector.

12.3 *Transmit a 2-Gb/s NRZ signal over a 100-km path without the use of repeaters. The error rate must be 10^{-9} or better.*

Since there is a single digital channel to transmit, we will modulate the carrier intensity directly using PCM/IM. This is a very long distance, very high bit rate application using non-zero-dispersion shifted fiber at long wavelength. Primary limitations are likely to be those of performance and component availability, rather than of cost.

source	laser diode	fiber (1550 nm)	Corning LEAF	detector (1550 nm)	APD InGaAs
line width $\Delta\lambda$	0.2 nm	mode field dia.	9.6 ± 0.4 μm	responsivity ρ	12 A/W
rise time t_r	0.05 ns	numerical aperture NA	0.14	rise time t_r	0.25 ns
wavelength λ	1550 nm	loss	0.22 dB/km	junction C_d	1 pF
		material dispersion M	4 ps / (nm km)	dark current I_d	100 nA
				gain M	20

Table 2: Component specifications

Bandwidth budget

For an NRZ data link, the system rise time should be limited to about ⅔ of the bit period. Here the bit period τ is ½ ns, so we have

$$t_S \ \leq \ 0.7 * \tau \ = \ 0.35 \text{ ns}$$

From Table 2, 0.05 ns $\leq$ t_{LS} . Earlier we found that $t_S \approx \Delta\tau$. The source line width is 0.2 nm. At 1550 nm, material and waveguide dispersion are

$$M_m = -4 \ \text{ps (nm km)}^{-1}$$
$$M_g = +4.4 \ \text{ps (nm km)}^{-1}$$

Pulse spread per unit length is

$$\Delta(\tau/L) = | M_m + M_g | * \Delta\lambda = 0.08 \text{ ps / km}$$

Thus the fiber rise time over 100 km is 8 ps. The photodetector rise time must be limited to

$$t_{PD} \leq \sqrt{[\ t_S^2 - t_{LS}^2 - t_F^2\ ]} = 0.346 \text{ ns}$$

Choose 0.34 ns as the upper limit on t_{PD} . The detector's intrinsic (carrier transit-time limited) rise time is 0.25 ns (Table 2). The intrinsic and circuit-limited components of detector rise time are related by

$$t_{PD}^2 = t_{TR}^2 + t_{RC}^2$$

For the circuit-limited component of detector rise time, we have

$$t_{RC} \leq \sqrt{[\ t_{PD}^2 - t_{TR}^2\ ]} = 0.23 \text{ ns}$$

$$t_{RC} = 2.19 * R_L * C_d$$

Since the detector capacitance is 1 pF, then for the load resistor we have $R_L \leq 105\ \Omega$. We choose **R_L = 100 Ω**

Power budget

An ideal quantum-limited receiver for this system would have sensitivity determined by the specified bit error rate, data rate R, and detector responsivity . The BER 10^{-9} corresponds to the number of photoelectrons per positive pulse period $n_S = 21$. We have a relation for required power at the receiver

$$P = e * n_S * R \ / \ \rho = 0.56 \text{ nW} = -62.5 \text{ dBm}$$

where e is the electron elementary charge in coulombs.

Because of the small value of load resistance, however, we should expect thermal noise to degrade the receiver sensitivity. We assume non-ideal APD receiver sensitivity of -40 dBm, and laser source power of 3.2 mW (5 dBm).

An assumed loss budget is: source coupling (3 dB), 2 connectors (2 dB), 50 splices for setup and maintenance of the link (5 dB), and fiber attenuation (22 dB). The power available at the receiver is 5 dBm - 32 dB = **- 27 dBm** = 1.995 μW

The power margin for noise and degradation is (- 27 + 40) dB = **13 dB**

At a glance, this design appears to meet the spec with plenty of margin.

Problem

Checking the implied assumption about shot noise limitation, the thermal noise current is

$$i_{NT(avg)} = \sqrt{[\ 4 * k * T_e * \Delta f \ / \ R_L\ ]} = 814 \text{ nW}$$

The shot noise current is

$$i_{NS(avg)} = \sqrt{[\ 2 * e * I * \Delta f\ ]} = 124 \text{ nW}$$

This system is strongly thermal-noise limited at the detector, not shot-noise limited. It is not clear that the avalanche photodiode receiver will work for this system.

Conclusion

Thermally-limited receiver design methods given in the textbook are targeted for data rates under 1 Gbps. Here we are trying to transmit NRZ data at twice that rate. It would be worth conducting a literature search for other methods.

One possibility would be to demultiplex and transmit 4 signals at 500 Mbps each, then recombine (multiplex) them after the receiver stage.