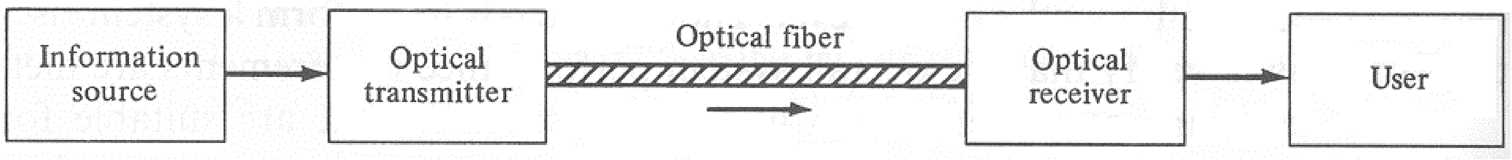
Digital Transmission System

Point-To-Point Links

The simplest transmission link is a point-to-point line that has a transmitter on one end and a receiver on the other, as is shown in figure



This type of link places the least demand on optical fibre technology and thus sets the basis for examining more complex system architecture.

The following key system requirements are needed in analysing a link:

- The desired (or possible) transmission distance
- The data rate or channel bandwidth
- The bit error rate (BER)

Digital Transmission System

Point-To-Point Links

To fulfil these requirements the designer has a choice of the following components and their associated characteristics:

- Multimode or single-mode optical fibre
  - Core size
  - Core refractive-index profile
  - Bandwidth or dispersion
  - Attenuation
  - Numerical aperture or mode-field diameter
- LED or laser diode optical source
  - Emission wavelength
  - Spectral line width
  - Output power
  - Effective radiating area
  - Emission pattern
  - Number of emitting modes

Digital Transmission System

Point-To-Point Links

- *pin* or avalanche photodiode
  - Responsivity
  - Operating wavelength
  - Speed
  - Sensitivity

Two analyses are usually carried out to ensure that the desired system performance can be met:

- *Link power budget*
- System *risetime budget*

Digital Transmission System

Point-To-Point Links

– System considerations

In carrying out a link power budget, we first decide at which wavelength to transmit and then choose components that operate in this region.

Having decided on a wavelength, we next interrelate the system performances of the three major optical link building block: that is, the receiver, transmitter, and optical fibre.

In choosing a particular photodetector, we mainly need to determine the minimum optical power that must fall on the photodetector to satisfy the bit-error-rate (BER) requirement at the specified data rate.

The system parameters involved in deciding between the use of an LED and a laser diode are

- Signal dispersion
- Data rate
- Transmission distance
- Cost

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Point-To-Point Links

– System considerations

For the optical fibre, we have a choice between single-mode and multimode fibre, either of which could have a step- or graded-index core. This choice depends on the type of light source used and on the amount of dispersion that can be tolerated.

When choosing the attenuation characteristic of as cabled fibre, the excess loss that results from the cabling process must be considered in addition to the attenuation fibre itself. This must also include connector and splice losses as well as environmental-induced losses that could arise from temperature variations, radiation effects, and dust and moisture on the connectors.

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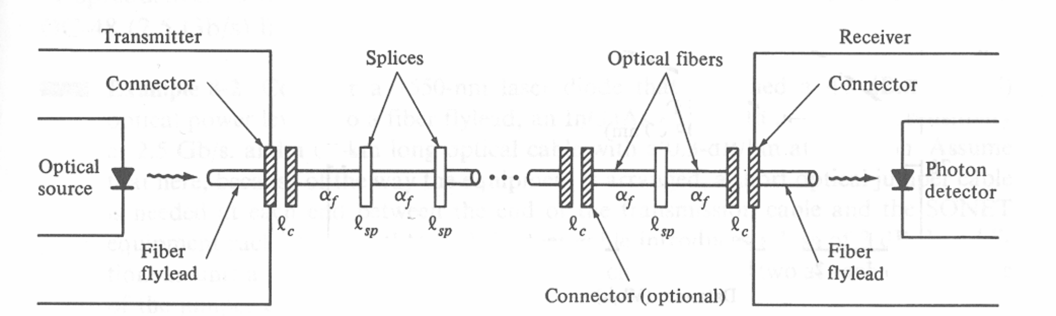
Point-To-Point Links

– Link Power Budget

An optical power loss model for a point-to-point link is shown in figure



The link los… …tributions of each element in the link. Each of these loss elements is expressed in decibels (dB) as

$$loss = 10\log\frac{P_{out}}{P_{in}}$$

where

- P_{in} is the power emanating into the loss element
- P_{out} is the power emanating out of the loss element

Digital Transmission System

Point-To-Point Links

– Link Power Budget

The link loss budget simply considers the total optical power loss P_T that is allowed between the light source and the photodetector, and allocates this loss to cable attenuation, connector loss, splice loss, and system margin. Thus, if P_S is the optical power emerging from the end of a fibre flylead attached to the light source, and if P_R is the receiver sensitivity, then

$$P_T = P_S - P_R = 2l_c + \alpha_f L + \text{system margin}$$

where

- l_c is the connector loss
- α_f is the fibre attenuation (dB/Km)
- L is the transmission distance
- system margin is nominally taken as 6 dB

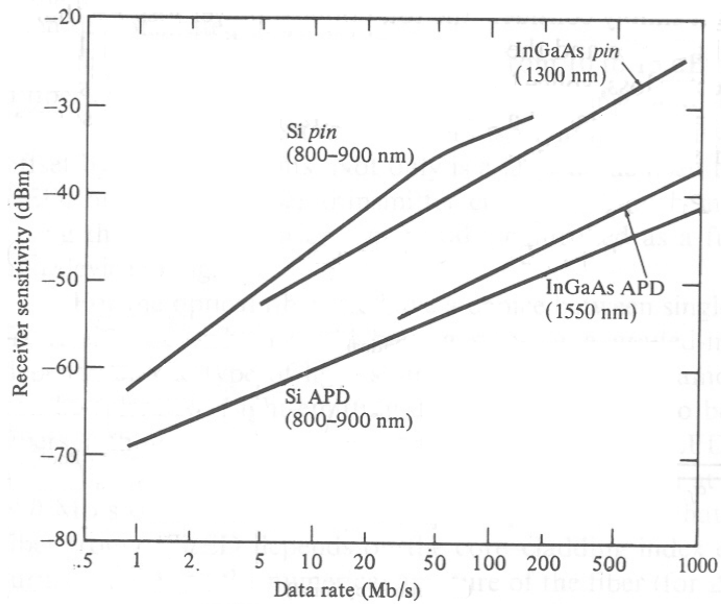
Digital Transmission System

Point-To-Point Links

– Link Power Budget

Example 1

To illustrate how a link loss budget is set up, let us carry out a specific design example. We shall begin by a specifying a data rate of 20 Mb/s and a bit-error rate of 10^{-9}. For the receiver, we shall choose a silicon *pin* photodiode operating at 850 nm. Figure below shows that the required receiver input signal is -42 dBm.



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Point-To-Point Links

– Link Power Budget

Example 1

We next select a GaAlAs LED that can couple a 50 μW average optical power level into a fibre flylead with a 50 μm core diameter. We thus have a 29 dB allowable power loss. Assume further that a 1 dB connector loss occurs when the fibre flylead is connected to the cable and another 1 dB connector loss occurs at the cable-photodetector interface. Including a 6 dB system margin, the possible transmission distance for a cable with an attenuation of α_f dB/Km can be found from

$$P_T = P_S - P_R = 29\ dB = 2(1\ dB) + \alpha_f L + 6\ dB$$

If α_f = 3.5 dB/Km, then a 6.0 Km transmission path is possible.

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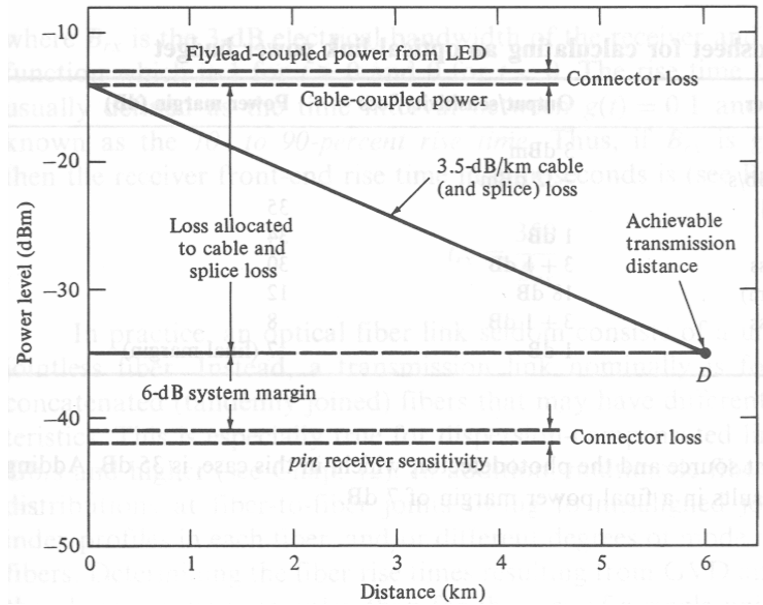
Point-To-Point Links

– Link Power Budget

Example 1

The link power budget can be graphically represented as is shown in figure.



The vertical axis represents the optical power loss allowed between the transmitter and the receiver. The horizontal axis give the transmission distance.

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Point-To-Point Links

- Link Power Budget

  Example 2

  Consider a 1550 nm laser diode that launched a +3 dBm optical power level into a fibre flylead, an InGaAs APD with -32 dBm sensitivity at 2.5 Gb/s, and a 60 Km long optical cable with a 0.3 dB/Km attenuation. Assume that here a short optical jumper cable is needed at each end between the end of the transmission cable and the SONET equipment rack. Assume that each jumper cable introduces a loss of 3 dB. In addition, assume a 1 dB connector loss occurs at each fibre joint.

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Point-To-Point Links

- Link Power Budget

  Example 2

  Table below lists the components in column 1 and the associated optical output, sensitivity, or loss in column 2. Column 3 gives the power margin available after subtracting the component loss from the total optical power loss that is allowed between the light source and the photodetector, which, in this case, is 35 dB. Adding all the losses results in a final power margin of 7 dB.

TABLE 8-1
Example of a spreadsheet for calculating an optical-link power budget

Component/loss parameter	Output/sensitivity/loss	Power margin (dB)
Laser output	3 dBm	
APD sensitivity at 2.5 Gb/s	−32 dBm	
Allowed loss [3 − (−32)]		35
Source connector loss	1 dB	34
Jumper + connector loss	3 + 1 dB	30
Cable attenuation (60 km)	18 dB	12
Jumper + connector loss	3 + 1 dB	8
Receiver connector loss	1 dB	7 (final margin)

Digital Transmission System

Point-To-Point Links

– Rise Time Budget

A rise-time budget analysis is a convenient method for determining the dispersion limitation of an optical fibre link. This is particularly useful for digital systems. In this approach, the total rise time tsys of the link is the root sum square of the rise times from each contributor ti to the pulse rise-time degradation:

$$t_{sys} = \sqrt{\sum_{i=1}^{N} t_i^2}$$

The four basic elements that may significantly limit system speed are

- The transmitter rise time t_{tx}
- The group velocity dispersion (GVD) rise time t_{GVD} of the fibre
- The modal dispersion rise time t_{mod} of the fibre
- The receiver rise time t_{rx}

Digital Transmission System

Line Coding

In designing an optical fibre link, an important consideration is the format of the transmitted optical signal. This is of importance because, in any practical digital optical fibre data link, the decision circuitry in the receiver must be able to extract precise *timing information* from the incoming optical signal.

In addition, since errors resulting from channel noise and distorsion mechanisms can occur in the signal-detection process, it may be desirable for the optical signal to have an inherent error detecting capability.

These features can be incorporated into the data stream by restructuring (or encoding) the signal. This is generally done by introducing extra bits into the raw data stream.

Digital Transmission System

Line Coding

Signal encoding uses a set of rules arranging the signal symbols in a particular pattern. This process is called *channel* or *line coding*.

One of the principal functions of a line code is to introduce redundancy into the data stream for the purpose of minimising errors that result from channel interference effects. Depending on the amount of redundancy introduced, any degree of error-free transmission of digital data can be achieved, provided that the data rate that includes this redundancy is less than the channel capacity.

The three basic types of two-level binary line codes that can be used for optical fibres transmission links are

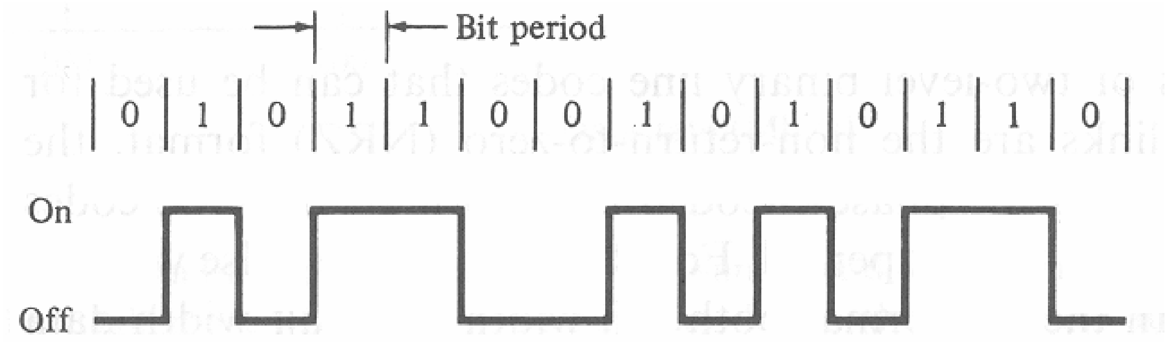
- The non-return-to-zero (NRZ) format
- The return-to-zero (RZ) format
- The phase-encoded (PE) format

Digital Transmission System

Line Coding

– NRZ Codes

A number of NRZ codes are widely used, and their bandwidths serve as references for all other code groups. The simplest NRZ code is NRZ-level (or NRZ-L), shown in figure.



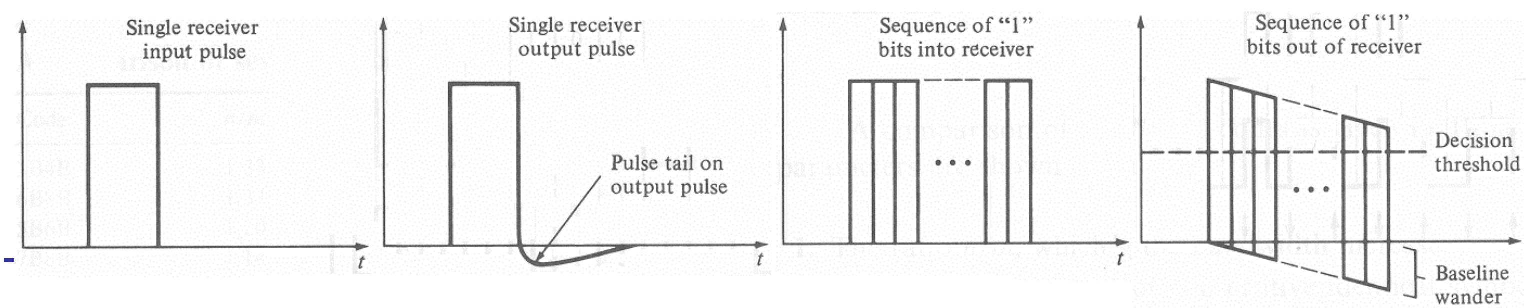
For a serial data stream, an on-off (or unipolar) signal represents a 1 by a pulse of current or light filling an entire bit period, whereas for a 0 no pulse is transmitted. These codes are simple to generate and decode, but they posses no inherent error-monitoring or correcting capabilities and they have no self-clocking (timing) features.

Digital Transmission System

Line Coding

– NRZ Codes

The minimum bandwidth is needed with NRZ coding, but the average power input to the receiver is dependent on the data pattern. For example, the high level of received power occurring in a long string of consecutive 1 bits can result in a baseline wander effect, as shown in figure.



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low-frequency characteristics of the ac-coupling filter in the receiver. If the receiver recovery to the original threshold is slow after the long string of 1 bits has ended, an error may ocuur if the next 1 bit has a low amplitude.

Digital Transmission System

Line Coding

– NRZ Codes

In addition, a long string of NRZ ones or zeros contains no timing information, since there are no level transitions. Thus, unless the timing clocks in the system are extremely stable, a long string of N identical bits could be misinterpreted as either N-1 or N+1 bits.

Two common techniques for restricting the longest time interval in which no level transitions occur are the use of block codes and scrambling.

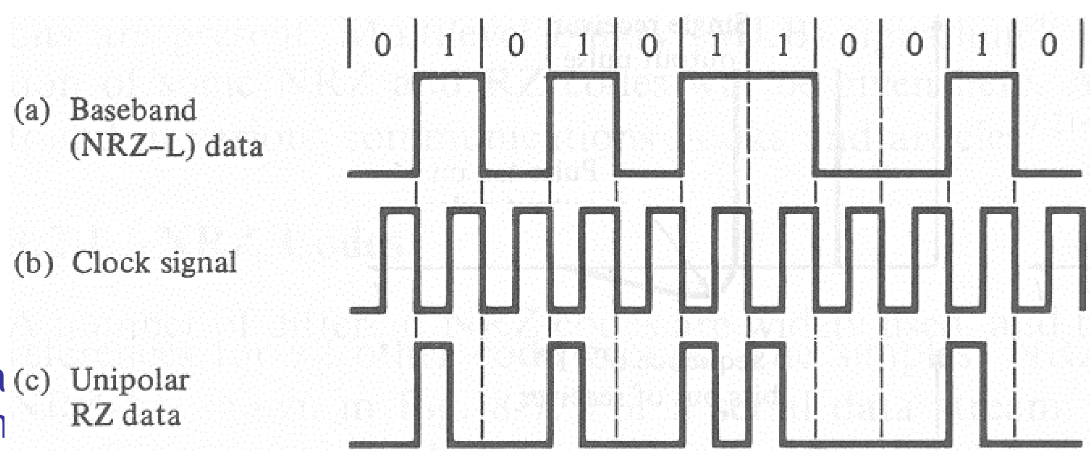
Scrambling produces a random data pattern by the modulo-2 addition of a known bit sequence with the data stream. At the receiver, the same known bit sequence is again modulo-2 added to the received data, and the original bit sequence is recovered. Although the randomness of scrambled NRZ data ensures an adequate amount of timing information, the penalty for its use is an increase in the complexity of the NRZ encoding and decoding circuitry.

Digital Transmission System

Line Coding

– RZ Codes

If an adequate bandwidth margin exists, each data bit can be encoded as two optical line code bits. This is the basis of RZ codes. In these codes, a signal level transition occurs during either some or all of the bit periods to provide timing information. A variety of RZ code type exist. In the unipolar RZ data, a 1 bit is represented by a half-period optical pulse that can occur in either the first or second half of the bit period. A 0 is represented by no signal during the bit period. The baseband (NRZ-L) with the RZ data is shown in figure.



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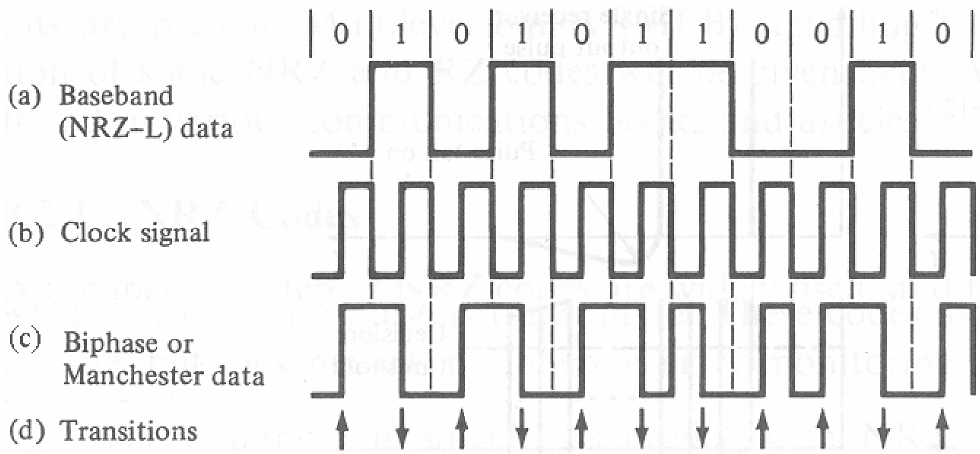
Line Coding

– RZ Codes

A common data format not having this limitation is the *biphase* or *optical Manchester* code shown in figure.



Note that this is a unipolar code, which is in contrast to the conventional bipolar Manchester code used in wire lines. The optical Manchester signal is obtained by direct modul-2 addition of the baseband (NRZ-L) signal and clock signal. In this code, there is a transition at the centre of each bit interval. A negative-going transition indicates 1-bit, whereas a positive-going transition means a 0 bit was sent. Since it is an RZ-type code, it requires twice the bandwidth of a NRZ code.

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Line Coding

– Block Codes

An efficient category of redundant binary codes is the *m*B*n*B block code class. In this class of codes, blocks of *m* binary bits are converted to longer blocks of *n* > *m* binary bits. These new blocks are then transmitted in NRZ or RZ format. As a result of the additional redundant bits, the increase in bandwidth using this scheme is given by the ratio *n*/*m*. The *m*B*n*B block codes provide adequate timing and error-monitoring information, and they do not have baseline wander problems, since long strings of ones and zeros are limited.

A convenient concept used for block codes is the *accumulated* or *running disparity*, which is the cumulative difference between the numbers of 1 and 0 bits. The key factors in selecting a particular block code are low disparity and a limit in the disparity variation. A low disparity allows the dc component of the signal to be cancelled. A bound on the accumulated disparity avoids the low-frequency spectral content of the signal and facilitates error monitoring by detecting the disparity overflow. Generally, one chooses codes codes that have an even *n* value, since for odd values of *n* there are no coded words with zero disparity.

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Line Coding

– Block Codes

A comparison of several *m*B*n*B codes

Code	n/m	N_{max}	D	W (%)
3B4B	1.33	4	±3	25
6B8B	1.33	6	±3	75
5B6B	1.20	6	±4	28
7B8B	1.14	9	±7	27
9B10B	1.11	11	±8	24

A comparison of several *m*B*n*B codes is given in table above. The following parameterare shown in this table:

- The ratio n/m, which gives the bandwidth increase.
- The longest number N_{max} of consecutive identical symbols
- The bounds on the accumulated disparity D.
- The percentage W of n-bit words that are not used.

Suitable codes for high data rates are the 3B4B, 4B5B, 5B6B, and 8B10B codes

Digital Transmission System

Error Correction

For high-speed broadband networks, the data-transmission reliability provided by the network may be lower than the reliability requested by an application. In this case, the transport protocol of the network must compensate for the difference in the bit-loss rate. The two basic schemes for improving reliability are

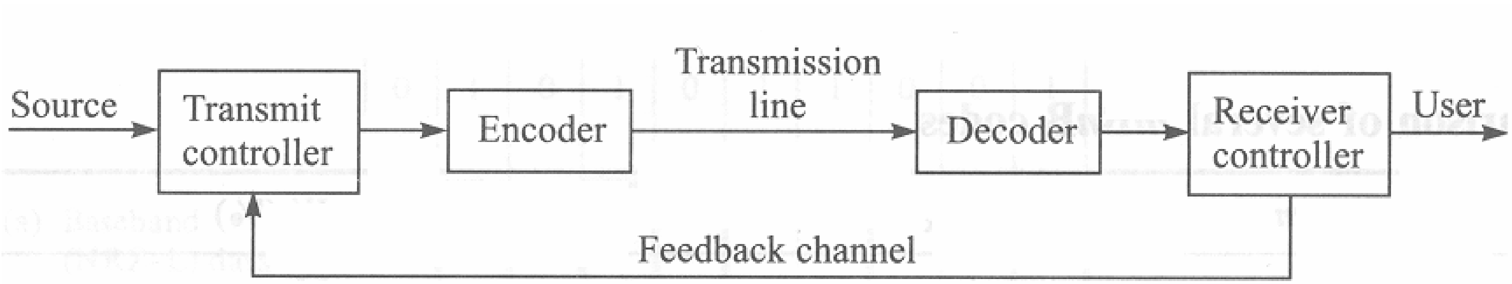
- Automatic repeat request (ARQ).
- Forward error correction (FEC).

Digital Transmission System

Error Correction

– Automatic Repeat Request (ARQ)

The ARQ scheme have been used for many years and are widely implemented. As shown in figure below, the technique uses a feedback channel between the receiver and the transmitter to request message retransmission in case errors are detected at the receiver.



Since each such retransmission adds at least one roundtrip time of latency, ARQ may not be feasible for applications that require low latency.

Digital Transmission System

Error Correction

– Forward Error Correction (FEC)

In FEC techniques, redundant information is transmitted along with the original information. If some of the data is lost or received in error, the redundant information is used to reconstruct it. Typically, the amount of redundant information is small, so the FEC scheme does not use up much additional bandwidth and thus remains efficient.

The most popular error-correction codes are *cyclic codes*. These are designated by the notation (*n*,*m*), where *n* equals the number of original bits *m* plus the number of redundant bits. Some examples that have been used include

- (224,216) shortened Hamming code.
- (192,190) Reed-Solomon code.
- (255,239) Reed-Solomon code
- (18880,18865) and (2370,2358) shortened Hamming codes.

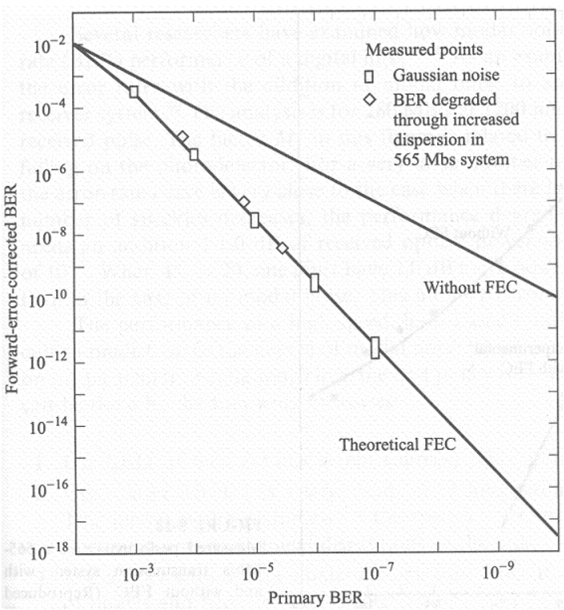
Digital Transmission System

Error Correction

– Forward Error Correction (FEC)

The results of the (224,216) code are shown in figures.

(a)



(b)

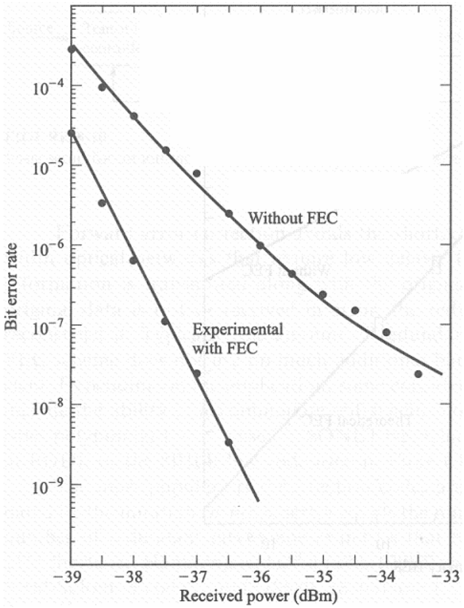


Figure (a) is a plot of a FEC-decoded BER versus the primary BER. The data is from an experiment using a565 Mb/s multimode laser system operating @ 1300 nm. The relative performance improvement using FEC increases as the error probability decreases.

Figure (b) shows the measured BER performance as a function of the received power level with and without FEC. Analogous to figure (a), the performance improvement with FEC is significant.

Digital Transmission System

Noise effects on system performance

Since now, we have assumed that the optical power falling on the photodetector is a clearly defined function of time within the statistical nature of the quantum detection process. In reality, various interactions between spectral imperfections in the propagating optical power and the dispersive waveguide give rise to variations in the optical power level falling on the photodetector. These variations create receiver output noises and hence give rise to optical power penalties. The main penalties are due to

- Modal noise.
- Wavelength chirp.
- Spectral broadening induced by optical reflections back into the laser.
- Mode partition noise.

Modal noise is not present in songle-mode links; however, mode-partition noise, chirping, and reflection noise are critical in these systems.

Digital Transmission System

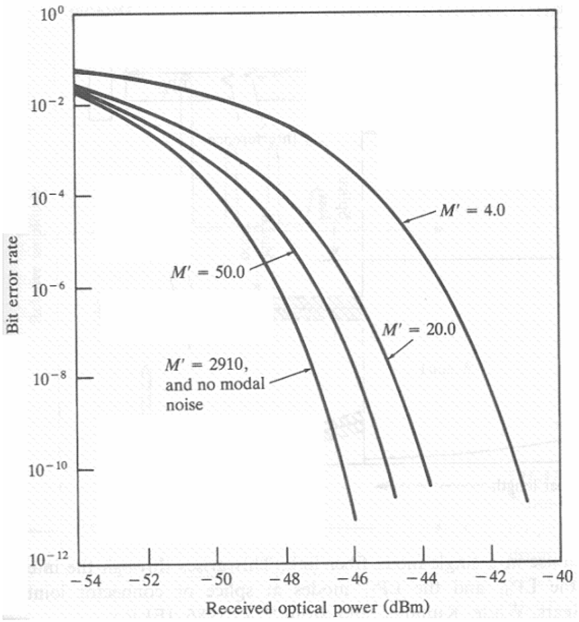
Noise effects on system performance

– Modal Noise

Modal noise arises when the light from a coherent laser is coupled into a multimode fibre. The following factor can produce modal noise in an optical fibre link:

- Mechanical disturbances along the link.
- Fluctuations in the frequency of an optical source.

figure below illustrates the error rates with the addition of modal noise to an avalanche-photodiode receiver system.



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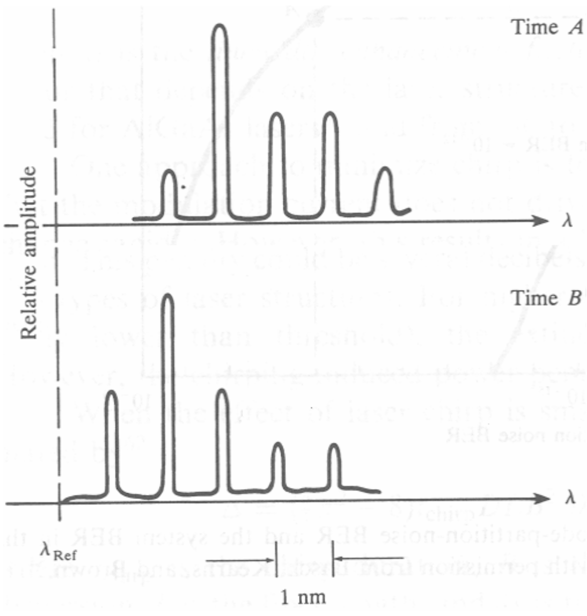
Noise effects on system performance

– Mode-Partition Noise

Mode partition noise is associated with intensity fluctuations in the longitudinal modes of a laser diode; that is, the side modes are not sufficiently suppressed. This is the dominant noise in single-fibres. Intensity fluctuations can occur among the various modes in a multimode laser even when the total optical input is constant, as exhibited in figure below. This power distribution can vary significantly both within a pulse and from pulse to pulse.

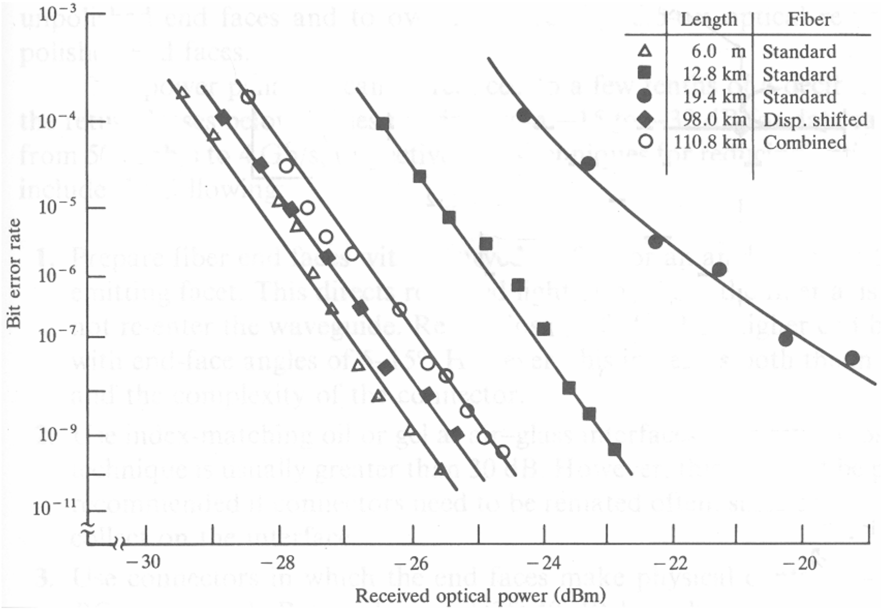


Digital Transmission System

Noise effects on system performance

– Chirping

A laser which oscillates in a single longitudinal mode under CW operation may experience dynamic line broadening when the injection current is directly modulated. This line broadening is a frequency “chirp” associated with modulation-induced changes in the carrier density. Laser chirping can lead to significant dispersion effects for intensity-modulated pulses. Figure below illustrates the effect of chirping at a 5 Gb/s transmission rate in different single-mode fibre links.



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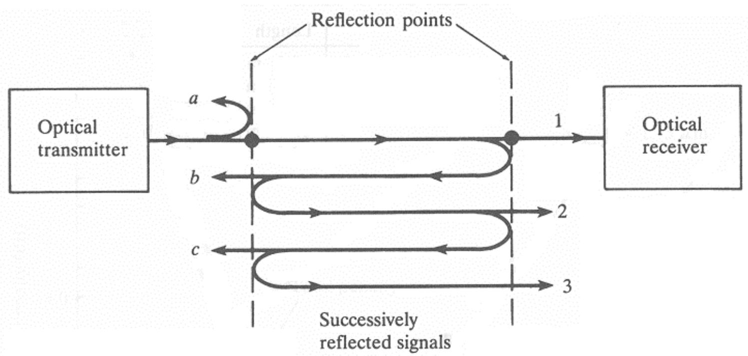
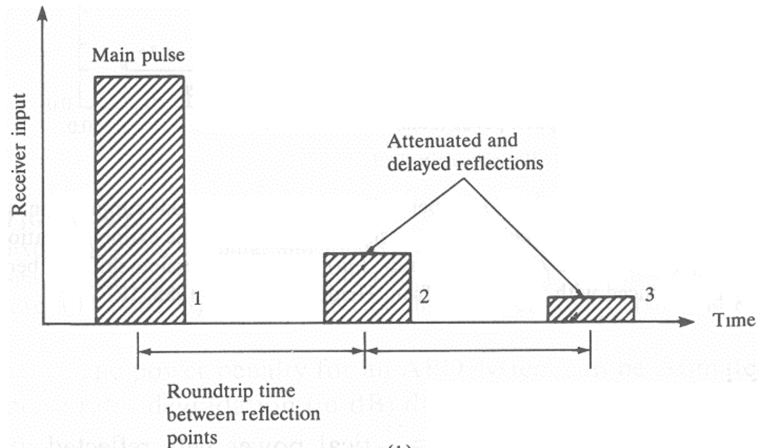
Noise effects on system performance

– Reflection Noise

When light travels through a fibre link, some optical power gets reflected at refractive-index discontinuities such as in splices, couplers, and filters, or at air-glass interfaces connectors. As shown in figure (a), multiple reflection points set up an interferometric cavity that feeds power back into the laser cavity. A second effect is the appearance of spurious signals arriving at the receiver with variable delays, thereby causing intersymbol interference. Figure (b) illustrates this.



(a)



(b)